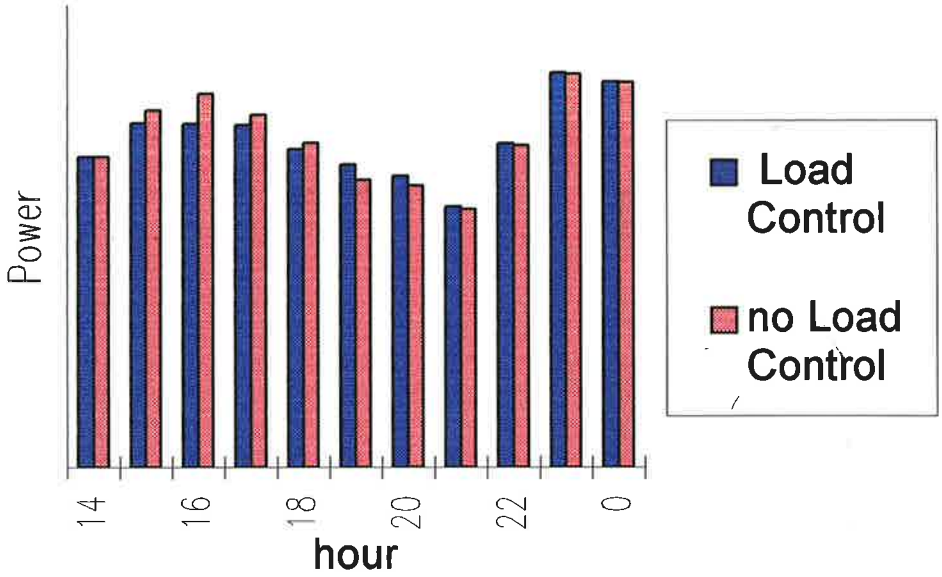
EDISON

Research report ENE6/12/97

OPTIMISATION OF LOAD CONTROL

Final report of the project

Pekka Koponen
VTT Energy



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Pekka Koponen

VTT Energy

P.O. Box 1606, FIN-02044 VTT, FINLAND

Phone +358 9 4561, Telefax +358 9 456 6538

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VTT ENERGY

Research organisation and address VTT Energy, Energy Systems P.O. Box 1606 FIN-02044 VTT, FINLAND	**Customer** Research program for distribution automation, EDISON
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OPTIMISATION OF LOAD CONTROL,
FINAL REPORT OF THE PROJECT

Pekka Koponen

Summary

The results of the project “Optimisation of load control” are summarised. The application of optimisation methods to various tasks related to load control was studied. 1) Minimisation of the power costs of a space heating and ventilation customer with time variable prices was demonstrated. 2) A linear load control response model was added in a power purchase optimisation model. 3) The response models of direct load control were updated and developed. The new models were fitted to field test data using non-linear constrained optimisation. 4) Direct load control sequences were optimised. Also the effects of the electricity market deregulation on the need, benefits and organisation of load control are discussed.

Principal author and Project manager Pekka Koponen Research scientist Pekka Koponen	**Reviewed by** Seppo Research professor Seppo Kärkkäinen
Approved by Pekka Pirilä Pekka Pirilä Research Manager, Energy Systems	**Availability statement** Public

Abstract

The results of the project "Optimisation of load control" are summarised. The application of optimisation methods to various tasks related to load control was studied. 1) Minimisation of the power costs of a space heating and ventilation customer with time variable prices was demonstrated. 2) A linear load control response model was added in a power purchase optimisation model. 3) The response models of direct load control were updated and developed. The new models were fitted to field test data using non-linear constrained optimisation. 4) Direct load control sequences were optimised. Also the effects of the electricity market deregulation on the need, benefits and organisation of load control are discussed.

Foreword

This project is a part of the EDISON research program for distribution automation. The project was financed by TEKES and VTT. The leader of the research program Matti Lehtonen, the control group of the project and research professor Seppo Kärkkäinen helped to define the scope of the project, motivated and gave advice and feedback during the project. Veikko Kekkonen from VTT Energy added the load response model to the power purchase optimisation package of VTT Energy. Kari Keränen and Juha Räty from Enermet Oy provided a prototype for scheduling direct load control sequences. They also helped me in finding suitable utility companies for field tests. The load control response field tests were carried out by Keski-Suomen Valo Oy, Koillis-Pohjan Sähkö Oy and Oulun Seudun Sähkö In those utilities Juhani Öhman, Arto Liikanen, Heikki Ruikkala and Kari Kuusela prepared and organised the field tests according to my wishes. Magnus Wistbacka from VTT Energy helped in time series analysis of the field test measurements. I want to thank them all for their invaluable contributions.

Espoo 20 November 1997, Pekka Koponen

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1. Introduction

Electricity cannot be stored in large quantities. That is why the electricity production and consumption are always almost equal in power supply systems. If this balance were disturbed beyond stability, it would be necessary to disconnect parts of the power transmission and distribution system until a new stable equilibrium is reached. The balance between supply and consumption is mainly maintained by controlling the power production, but also the electricity consumption, or in other words, the load is controlled. Controlling the load of the power supply system is important, if easily controllable power production capacity is limited. Temporary shortage of capacity causes high peaks in the energy prices in the electricity market. Load control either reduces the electricity consumption during peak consumption and peak price, or moves electricity consumption to some other time. Thus load control replaces some expensive, inefficient and polluting peak power production. The main purpose of load control is to reduce power purchase costs by trimming marginal power production cost variations and allowing more efficient production, transportation and distribution of electricity.

Load control affects the load faster than other methods for load management, such as providing information to customers. The delay may be less than a second or even a day depending on load control and data communication solutions. There are two types of load management: direct and indirect. Direct load control means that the provider of the electricity controls the customer's load. When the customer controls his own load based on time variable prices, it is called indirect load control or price control.

The project Optimisation of Load Control is part of the EDISON research program for distribution automation. The following areas were studied:
- optimisation of space heating and ventilation, when electricity price is time variable
- load control model in power purchase optimisation
- optimisation of direct load control sequences
- interaction between load control optimisation and power purchase optimisation
- literature on load control
- optimisation methods
- field tests and response models of direct load control
- the effects of the electricity market deregulation on load control

This report summarises the results.

Literature review on load control is in Appendix A. It consists of the following chapters:
- dynamic tariffs (real time tariffs)
- direct load control
- experiments where both direct and indirect load control are applied
- load estimation and prediction
- data communication in load control.

Literature on optimisation methods has also been studied. The focus has been on methods for solving dynamic constrained non-linear optimisation problems. Also evolutionary optimisation methods have been studied. Literature review on direct load control response models is included in reference /3/.

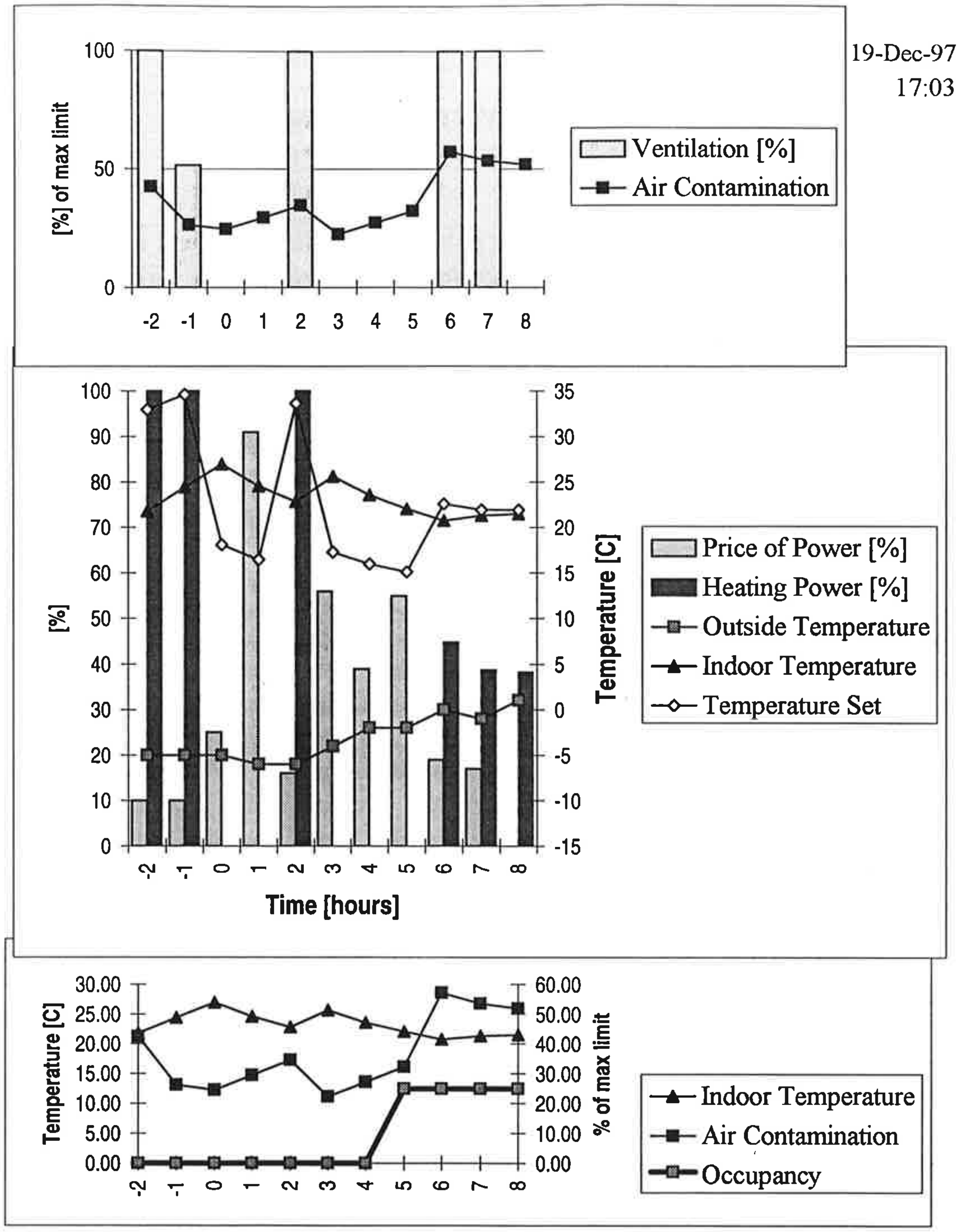
2. Optimisation of space heating and ventilation with time variable prices

Optimisation of energy use for space heating was demonstrated and studied by simulations. A simple differential equation model of heat flow and storage of a building was constructed. The variables of the model were indoor temperature, wall temperature and indoor air contamination (CO_2 content). In addition to two uncontrollable input variables, occupancy and outside temperature, the model has two controllable input variables: space heating power and ventilation. The time variations of the control inputs were optimised. Loss of comfort in the building and energy costs were minimised using a constrained non-linear optimisation method. This task is reported in reference /2, p 749 - 752/. Figure 1 shows an example solution in a possible user-interface.

Among other things the following was observed.

1) Variable ventilation rate makes the model non-linear. Otherwise the model is linear with control constraints.
2) In the optimal solutions controllable ventilation rate increases the potential to reduce energy costs considerably. When heating power is reduced or cut off, the indoor temperature drops faster than the wall temperatures mainly because of the heat losses caused by ventilation. Thus variable ventilation rate makes it possible to shift more space heating load away from high price periods.
3) Both direct and indirect optimisation approaches were tested. The direct optimisation method has wider convergence region than the indirect method. The indirect method is more accurate, but this is not essential in this problem.
4) When the number of time steps was increased to 16, the method became too sensitive to the starting guess. However, about 48 time steps would be ideal for the problem.
5) By using optimisation the customer can take advantage of dynamic tariffs much better.
6) Contrary to usual direct load control, the method prepares for high price periods by increasing the temperature in advance. A separately controllable heat storage would increase the potential for this kind of optimisation significantly.

This modest task has not been continued since March 1996. The model could be made more realistic by adding a heat storage, which represents the internal walls and other internal masses of the building. Also heat flow between the ground and the building should be modelled.



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	Power Costs	Comfort	End State	Total Criterion
Weights	100	80	240	
Costs	3627	836	190	4653

Figure 1. An example of heating and ventilation load optimisation.

3. Load control model in power purchase optimisation

A simple space heating load model with linear dynamics was developed and added to a power purchase optimisation program, which has been developed in VTT Energy Systems. The load control model represents a space heating customer with dynamic price control. The model includes time variable state and control constraints. The performance of the optimisation system with the new model was tested only with simulations. The power purchase model was based on data from a distribution utility, which has its own thermal power plant and contracts to use the production of some other power plants. In the test runs an imaginary power sales price was successfully used to tune the characteristics of the load control solution.

This approach has some limitations:
- The ventilation rate cannot be varied in the model, because it would make the model non-linear. It would be possible to construct a linear approximation near the normal operating point, but this was not tried.
- The load control model could only be used for day or week optimisations and not in the optimisation of the power purchase plan of a year. The optimisation program includes two methods. One is normal Linear Programming (LP) and the other is a special method for large dynamic LP problems and is called DLP. DLP solves the power dispatch for each hour of the year in about the same time as the normal LP solves the same problem for a week or two. The load control model introduced often caused convergence problems to the DLP solution. With normal LP the model works fine.

In the solutions there were too many small control actions. A cost per control action in the criterion was clearly needed. However, this possibility had been removed from that version of the optimisation program we used. Tests with a program version with this feature have not yet been carried out.

The model helps the power purchase optimisation to anticipate the load control response and its effect on the marginal power prices, see figure 2. Thus it will improve the interaction of the power purchase optimisation and the optimisation of load control.

The model enhances the use of the power purchase optimisation as an interface between the electricity spot market and load control. The spot market cannot directly deal with dynamic interactions such as the after-peak of load control. The model takes care of the energy storage effects. In the power purchase optimisation both purchase and sales can be presented as standard spot market products. Thus it is also possible to sell load control capacity to the spot market.

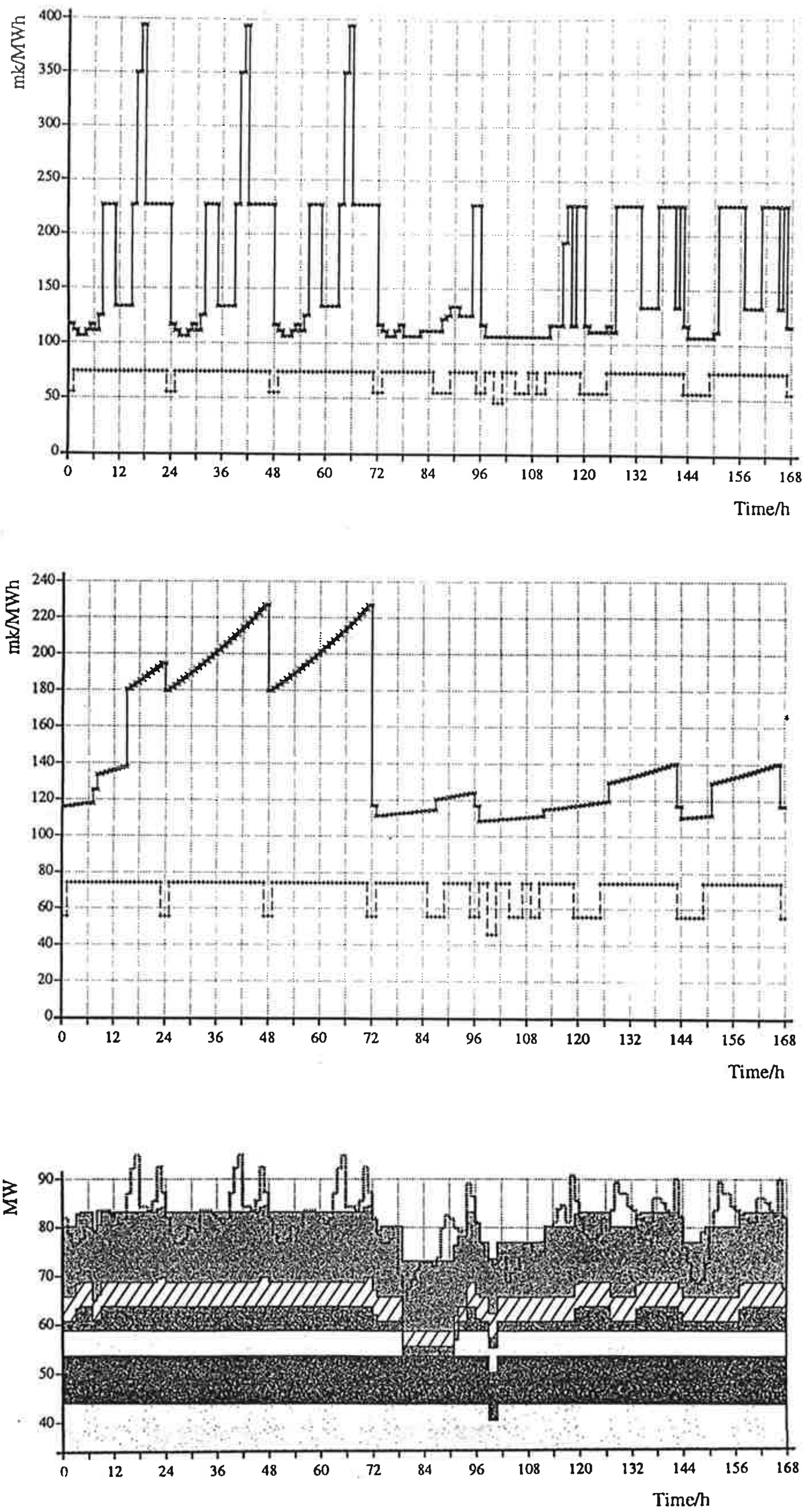


Figure 2   A simulation example of power purchase optimisation with a load control model. In this case the amount of controllable load is exaggerated. Explanation:

Top	*Marginal prices of electricity and heat without load control*
Middle	*Marginal prices of electricity and heat with load control*
Bottom	*Electricity production and trade dispatch with load control, the dotted line is the total demand without load control.*

The linear model allows advance heating before high price periods. The power purchase optimisation package with load control model was also used to study how the costs and benefits of load control are shared between the power utility and its customer. In order to achieve this both the utility benefits and the customer losses in terms of money were compared. The indoor temperature of the customer was allowed to vary between limit values (20 ± 1 °C) without any cost. The electricity price between the utility and its customer in the optimisation criteria was varied. The values of the criterion with and without load control were compared for each price. An example of the results is shown in figure 3. When this price is zero, the optimisation maximises the common benefit of the utility and the customer. When the price is increased above the power purchase prices, the utility benefit increases at the expense of the customer. This happens because the indoor temperature is unnecessarily increased and some load may also be shifted to a period that is more expensive to the customer. Therefore the common benefit decreases. Especially with a linear optimisation criterion it is better to minimise the common electricity costs within the constraints instead of maximising the utility benefits. The real sales price can be different and the common benefits can be shared somehow. In the competitive electricity market it is wise to maximise the common benefit because the customer is free to choose from whom he buys the electricity.

When the customer costs are ignored, the indoor temperature is at its maximum limit unless there is a need to shift some load to a later time. Thus after-peaks are typical just like in usual direct load control. When the common benefit is optimised, the indoor temperature is risen above its minimum level only when purchase prices increase. Thus

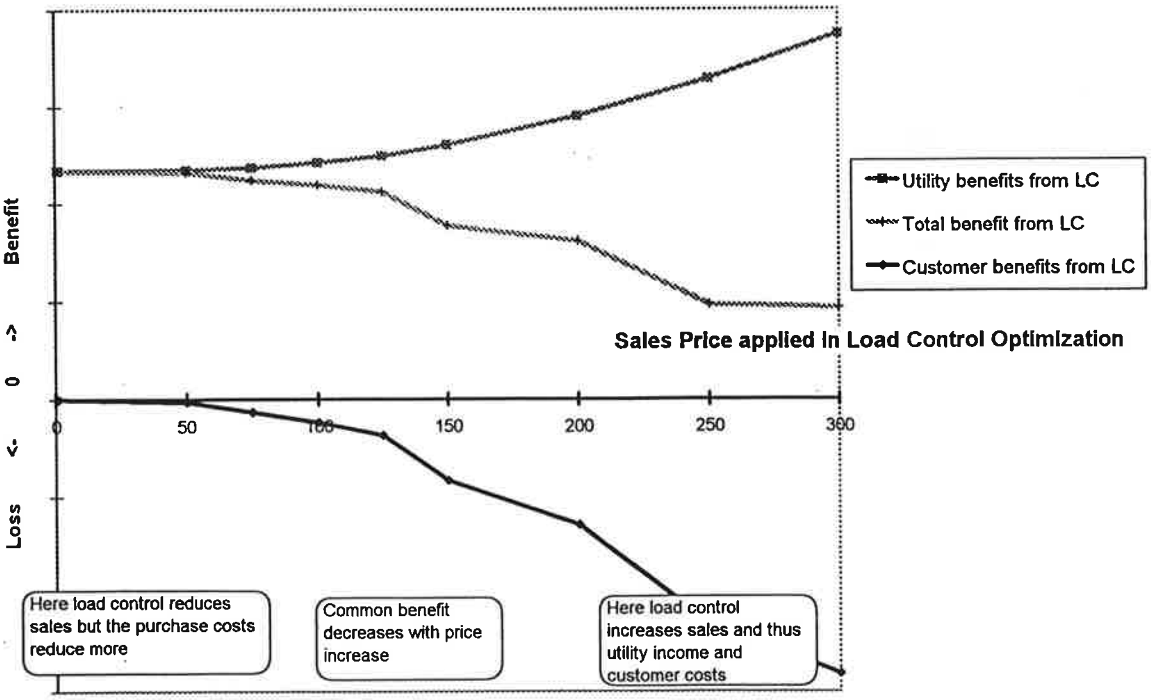


Figure 3. Especially when linear criteria are applied, the customer costs must not be ignored. The benefit scale in the figure represents the difference of the value of the criteria with load control and the criteria value in the same case without load control.

some load moves from the peak load to before it. In this way the optimisation sales price and the temperature limits can be used to tune the characteristics of the solution.

In the figure 3 the curves show the benefit of load control compared with the same case without load control. The customer load control benefit curve starts from zero because at zero price the customer costs are zero in both cases. The curve represents a situation where load control is never allowed to decrease the indoor temperature under the level without load control. If load control were allowed to decrease the temperature, the benefits would be somewhat bigger and the customer benefit curve would first increase before turning down. When the real sales price is different from that used in the optimisation, the total load control benefit curve remains the same but the customer and utility benefit curves change from those in the figure 3.

4. Optimisation of direct load control sequences

Most existing load control systems for space heating are implemented in a way that requires the use of control sequences. Thus the optimisation of these sequences is needed. This type of direct load control system is very simple to install, but can only partially utilise the load control potential of space heating. By using a little more advanced load control it is possible to save significantly more in the power purchase costs without losing more comfort. Also total shutdowns and after-peaks could be eliminated and with them most of the need to optimise the sequences. However, the change of the customers' terminal units would be too expensive.

Many utilities in Finland have systems for direct load control of electric space heating. These systems send, via the distribution line, commands to shut down the heating for a specified time. Typical for this type of control is that immediately after the shut down period there is an after peak in the load, because the indoor air temperature is heated as soon as possible back to its set-point value. The re-heating of the structures of the building is much slower and has a time constant of one to several days. The responses of this kind of systems are described in more detail later with the field tests.

To limit the load control induced loss of comfort experienced by the customers, the load control agreements contain limitations on the length of the control periods and minimum intervals between them. This type of modelling of customer comfort is very rough because the temperature drop in the house depends on other things such as: outside temperature, ventilation, activities in the house and the possible use of other forms of heating. Some houses can also be in a wrong load control group because their insulation is actually too poor. Thus these rules need to have safety margins that are usually unnecessarily large but in some situations inadequate for some buildings.

In these direct load control systems the loads are divided into load control groups for the following reasons. 1) Different buildings have different responses and different allowed control times and recovery times; thus within each group the buildings should be similar. 2) After-peak is smaller, when load controls do not end at the same time; otherwise the network might be overloaded. 3) By controlling the loads in a sequence it is possible to shift the load over a much longer time without breaking the rules agreed in the contracts.

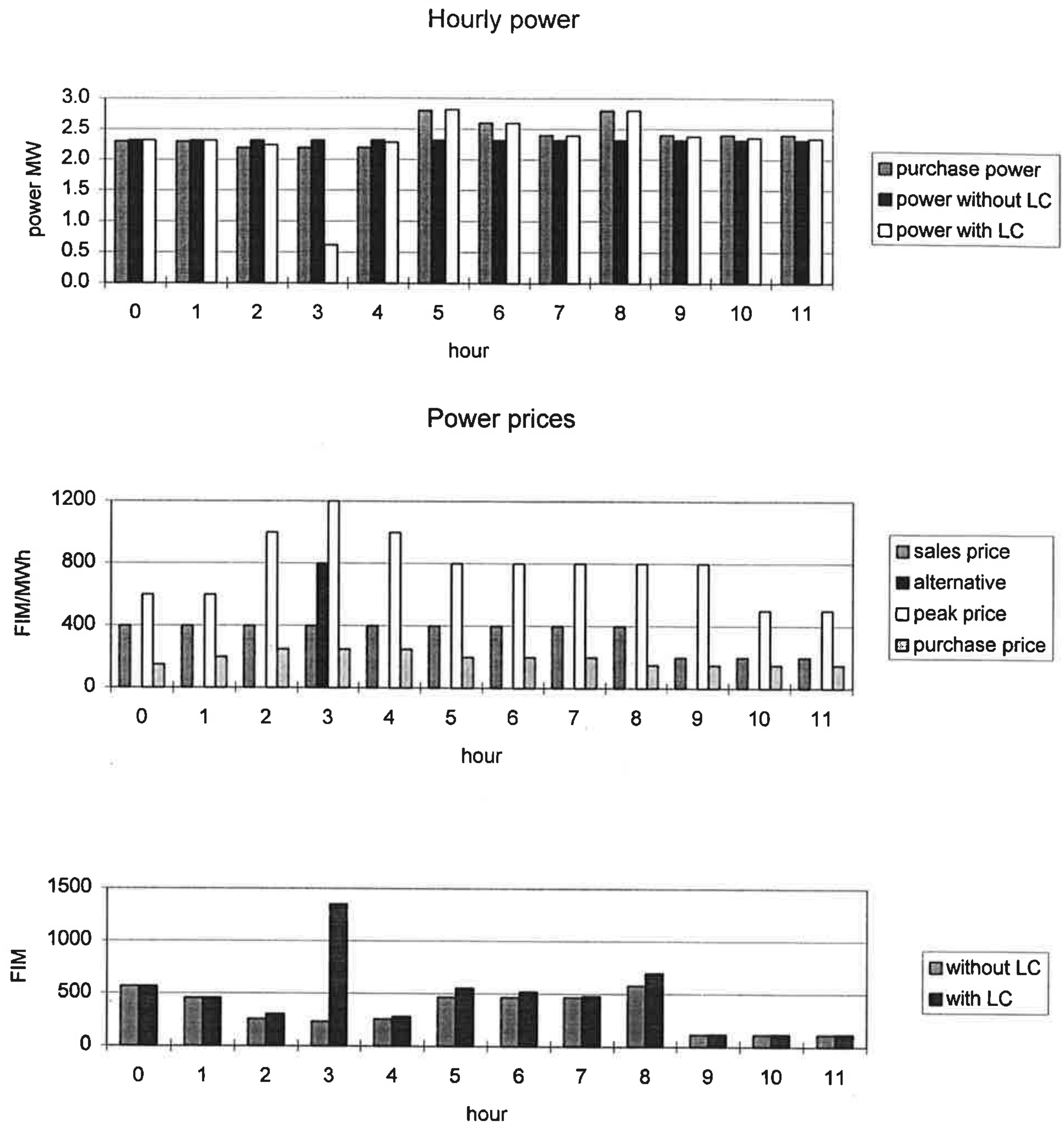
Enermet has built a prototype program for the optimisation of direct load control sequences. The executable of this program was received. The program consists of several separate heuristic methods and a method based on dynamic programming. The heuristic methods are faster, but also the dynamic programming method solves the problems fast enough. The dynamic programming method optimises each load control group only separately. Otherwise the solution time requirements would be totally unrealistic. Thus the dynamic optimisation method does not reach the optimal solution of a combination of several groups. In order to know how far the solutions are from the global optimum a suitable reference method is needed. As the prototype developers warned the interfaces of this version are still inadequate and the input and result data is in many separate files and does not include any identification information. The format in which the load response models are fed in, is not practical. It requires unnecessary interpolation first in preparing the models outside the prototype and then in the opposite direction within the prototype, when the model is used in the optimisation.

Also our own optimisation experiments with this problem have been carried out. The purpose has been to get some reference solutions for the evaluation of the Enermet prototype and possibly to find an alternative with a more straightforward interface to the load control response models. Two evolutionary optimisation methods were tried, because they are suitable for searching for the global optimum of the problem. With these methods it is also easy and flexible to add heuristics, which limit the search space. It is necessary to limit the search space somehow to keep the solution time acceptable. The methods are evolution strategies /6/ and genetic algorithms.

It was learned that evolution strategies are suitable for finding reference solutions. However, so far, it has not been fast enough for normal online use. Tests using genetic algorithms have also been started. In addition mixed integer programming (MIP) as in reference /4/ or non-linear constrained optimisation could be used to solve direct load control scheduling. The scope of this project is too wide and resources too limited for thorough study and evaluation of all possible approaches.

In figure 4.a there is an example of a load control sequence optimisation. Loads with and without load control are compared. In this test case, the load is close to and sometimes even above the purchased power, when there is no load control. It is assumed that when exceeding peak power it can be bought from the electricity spot market. In addition there is an opportunity to sell electricity to the market at a good price. The solution uses the different possibilities to maximise the net income.

The control signals of the optimised load control in the figure 4.a are shown in figure 4.b. The solution consists of rather many small control actions, because the rules on control action length and frequency have been replaced by a quadratic criterion on the estimated indoor temperature. This temperature estimate is directly available from our new direct load control response model that is described later in this report. This approach gives more benefit in the power costs for the same loss of comfort. It also



	Without LC	With LC	Difference
Total	4098	5572	1473 FIM

Figure 4.a. An example of load control sequence optimisation; the problem was solved using evolution strategies;

Top	*Purchase power and power with and without load control*
Middle	*Prices*
Bottom	*Net income without and with load control.*

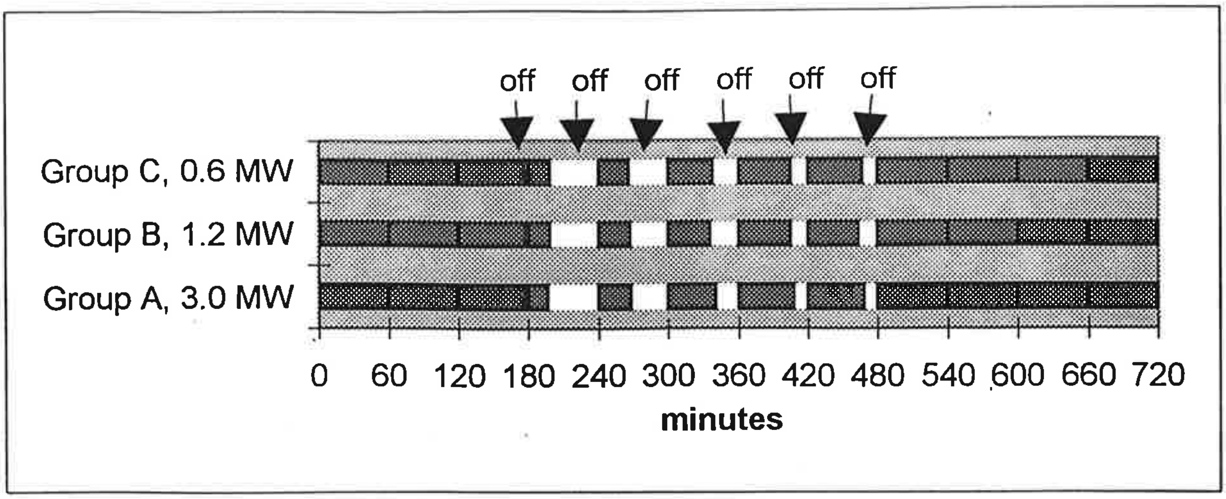


Figure 4.b Load control signals in the example of the figure 4.a; three load control groups are controlled. In the optimisation criterion the weight was for indoor temperature 10, for control action 1 and for after peak height 0.

reduces interactions between the load control groups in the solution and may make the problem easier to solve.

Simultaneous control of groups creates, however, high after-peaks which can increase distribution losses and overloading in the distribution network. In weak networks some power quality problems may also result from the rapid increase in the load. If needed, distribution costs or a term that limits the after-peak can be added to the optimisation criterion.

The solution in the figures 4.a and 4.b the search space was limited by allowing only control actions that end, when the hour changes. This heuristics is based on the fact that such control actions postpone load as much as possible. Only slightly better solutions have been found without this constraint. However, thorough verification of the validity of this or other heuristics would require more time than what was available. For example the need to limit the after peak for network capacity constraints may reduce the usefulness of this heuristics.

5. Interaction of load control optimisation and power purchase optimisation

Load control consists of two optimisation problems with different objectives. One minimises the purchase costs of the power needed and the other maximises the comfort or the profit of the customer, see figure 5. Alternative interaction principles are needed depending on the characteristics of the loads and control systems of the customers. Description of this interaction problem, different alternative configurations, previous work and some simulations were reported in /2/. The simulations of price control comprised the following basic cases: 1) space heating and ventilation, 2) other continuous processes and 3) a series of interconnected batch processes. Especially dynamic price control requires that the consumers of electricity have adequate automation systems for control, scheduling and operation planning of their processes and facilities. The production, operation and maintenance plans created by these automation systems also give the planned electricity consumption of the process or building. These forecasts of consumption are useful for power purchase optimisation. Also the interaction of power purchase optimisation with systems for direct load control was considered.

A demonstration program for optimisation of direct load control sequences was received from Enermet Oy. The work to connect it with the power purchase optimisation program with the load control model was started. The purpose was to test and develop the interaction of these two optimisation programs by simulation. This task has not been completed.

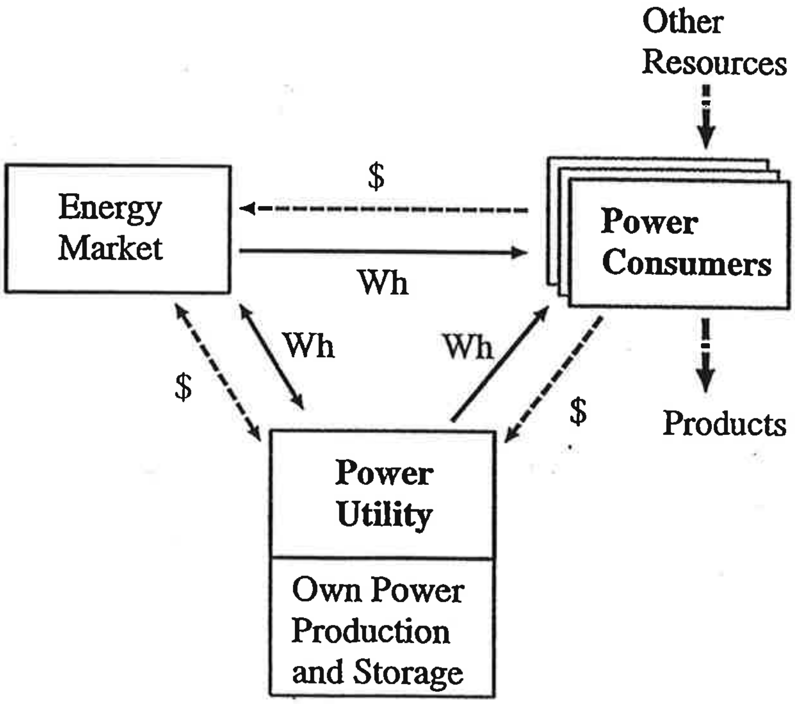


Figure 5 The interaction of the utility and its customer in load control

6. Field tests of direct load control response models

Accurate response models of load control are very important for the success of load control optimisation. In order to verify and develop these models, field tests with direct load control systems in three utilities (Koillis-Pohjan Sähkö, Oulun Seudun Sähkö and Keski-Suomen Valo) have been carried out. In two of the utilities the power measurements were collected from substations and in one only the total utility load was recorded. The utilities implemented necessary changes to their systems and prepared data and descriptions about the characteristics of the controlled loads.

The field tests started on 16 December 1996 and ended 24 January 1997. An example of measurement data is shown in figure 6. (After 15:00 a data communication failure and half an hour later a system failure show their effects on the recordings. The ripple in the data is caused by the rather large measurement pulse size.) The weather conditions were not good for load control tests, because all the cold periods were too short. It was impossible to identify the parameters of our traditional load control response models with required accuracy directly from this data. However, the plan was also to test a new physically based model structure and it worked well. The new load control model has more parameters, but this is compensated for by its ability to use prior information on the thermal properties of the houses. For example authority requirements on buildings, for the particular temperature zone, give very good prior estimates for the insulation, ventilation and heating parameters of the model. The effect of outside temperature is also built in the model structure.

The field tests and our new load control response model are documented in /3/. Also a literature review on response models for direct load control is included.

In the figure 7 an example of the response of the model is shown The measured load represents two ski resort areas and the measurement of a reference day has been subtracted. Four different load control groups were controlled, one at a time. The outside temperature was around - 19 °C. The parameters of the prediction model are identified from load control tests of normal houses in an other nearby utility. Advance information on the group sizes and heat storage capacity was used to scale the respective parameters of the model.

In figures 8 and 9 the response of our new model is compared with a load control response model /5/ developed earlier at VTT. The figure 8 shows also the measured response to which the models were fitted. The measurement curve shown is the difference of a test day and the average of several reference days. During the test the temperature was around -7 °C. In the figure 9 the responses of the two models are compared when the temperature is -30 °C.

Advanced load control terminals may control the set-point temperature or limit the after-peak by other means. It is easy and straight-forward to include such features in the new load response model. With the earlier model that would have been very difficult.

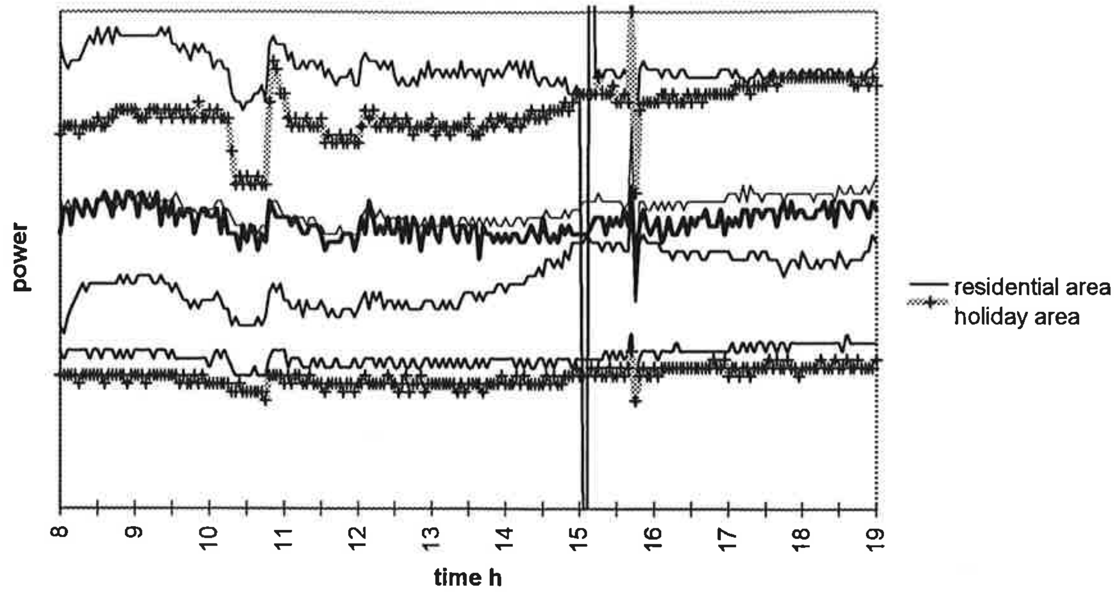


Figure 6. An example of primary substation load measurements, 16 December 1996; four load control groups were controlled one at a time starting at 10:15, 11:30, 13:15 and 14:20 The respective groups are 1) direct, 2) partially storing, 3) storing and 4) partially storing heating.

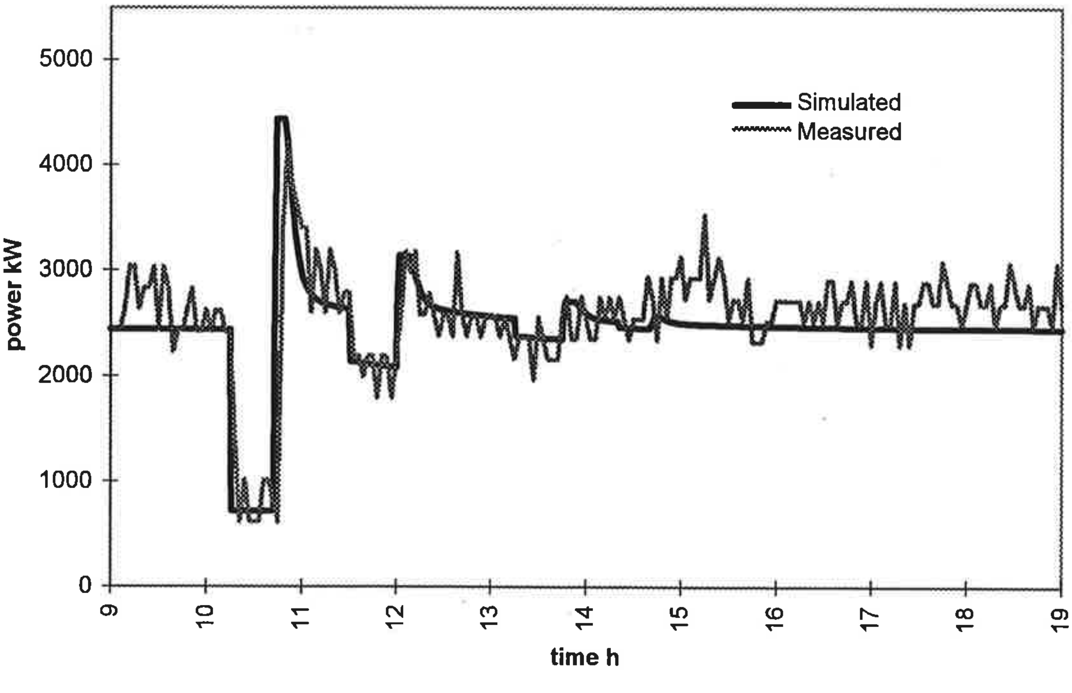


Figure 7. An example of the prediction performance of the model, 16 December 1996. The measurement is the power of the holiday areas in figure 6 with a reference day subtracted. The simulation parameters are based on tests on an other day with residential customers in a nearby utility and prior information on the group size and heat storage capacity.

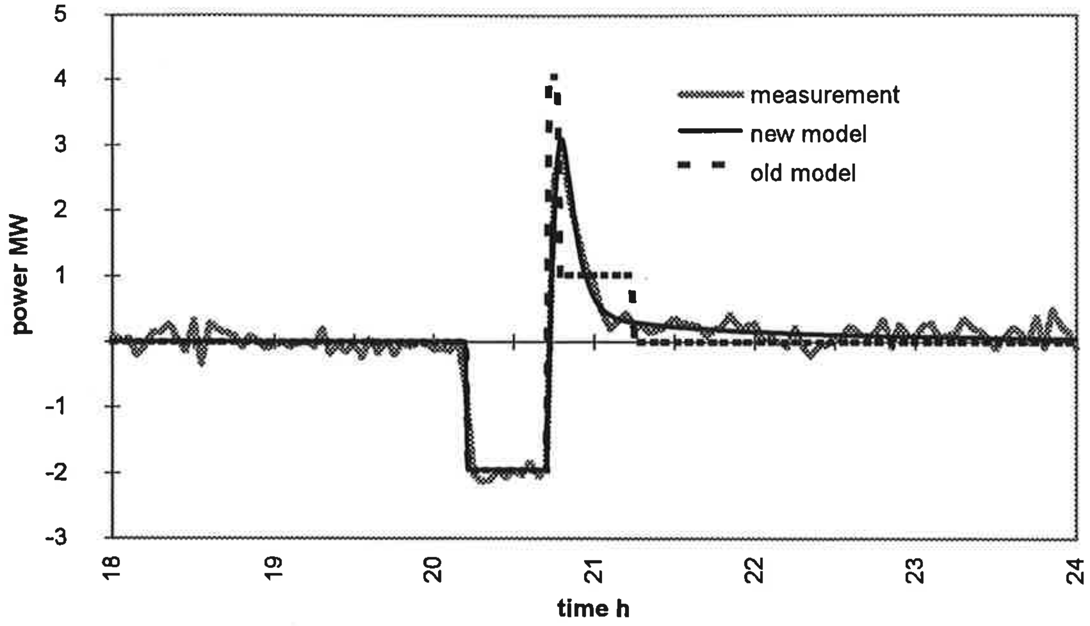


Figure 8. Comparison of the new /3/ and the old /5/ load response model. Both models are fitted to the measured response that is also shown. Outside temperature is -7 ° C.

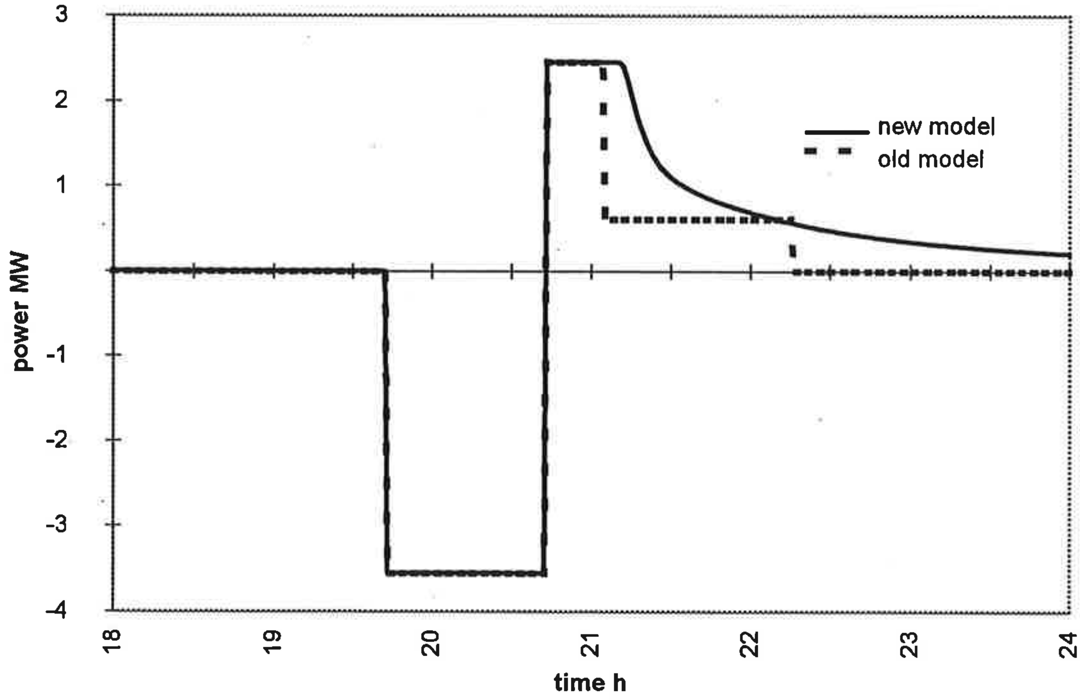


Figure 9. Comparison of the new /3/ and the old /5/ load response model, when the outside temperature is -30 ° C.

7. Managing uncertainty of predictions

Control capacity is necessary in order to prevent high power purchase costs. These costs may result for example from a sudden need to buy electricity when the load is higher than predicted. This control capacity consists of controllable power production and controllable loads. If the difference is known for example the previous day, indirect load control is applicable. Direct load control can have a much faster effect on the loads. Direct load control capacity may thus be like an insurance against unpredictable load peaks.

The uncertainty needs to be taken into account in the optimisation of the load control actions. The best solution for a deterministic case may be too sensitive to disturbances and relatively small prediction errors may turn it very expensive.

8. Effects of electricity market deregulation on load control

The new competitive electricity market improves the transparency of power production cost variations. Thus it improves the possibilities to substitute load control for controllable power production on a national level. However, the required changes in the company structures make the access to load control methods and the co-ordination of different load control objectives more difficult than before.

The power transmission and distribution network operators and the electricity trade business operations have been separated. The network company must treat all electricity sales companies equally. Load control is mainly used to reduce peaks in power purchase costs. However, load control systems are often integrated in network automation systems and owned by the network company. This means that the network company should sell load control services to electricity sales companies or the relevant customers. The sales company and the customer need to agree on the terms that are applied in load control. The sales company must somehow tell the network company when the loads shall be controlled. Instead of two parties there are now three or more parties that need to make agreements before load control can be applied.

Of course, the electricity sales company can arrange the load control without using the services of the network company. The sales company can have a load control system of its own or buy the services for example from a metering company. The customer may easily change sales companies. This may make the sales companies reluctant to invest in load control terminals and systems.

Network capacity constraints and losses must be taken into account when controlling the loads. If electricity sales companies are allowed to control loads without taking the network limitations into account, there is a risk that load control worsens the reliability and quality of power supply, causes high distribution losses and reduces the age of network components in some residential areas. There, dense application of time-of-use-tariffs and load control increases the network peak load in addition to moving it to periods of low market prices. Load control can also be used to postpone investments in distribution networks. The often conflicting load control interests of sales companies and network companies need to be balanced somehow.

Typically direct load control causes a high load peak immediately after the end of the load shed period. This is sometimes problematic for the network loading and for the scheduling of load control actions. This after peak could easily be avoided by improving the interaction of the temperature control and the load control terminal. The changes to already installed terminals are expensive to make, however.

With the deregulation, public market places for electricity have been introduced. Especially the daily spot markets have consequences on load control. In practice the capacity components and limits in tariffs are becoming less restricting than before. The tariffs are more often based on hourly energy; thus the energy price for each hour is agreed in the tariff. The variations of power production and purchase costs become more visible to the customers. This increases the motivation of the customers to control their loads according to the variations in energy prices. Thus the customers will control their loads themselves more than before. The price elasticity of the demand increases. This reduces the need and potential for direct load control.

During winter 1996/1997 the spot prices in Finland were always so low that they do not justify investments in load control systems. Some reasons for the low spot market prices can be found. The spot market tends to reflect the instantaneous variable costs of marginal power production. The winter was mild without significant forced power plant shutdowns. In this situation many market actors seemed to sell their excess spot energy close or sometimes even under the prices of their long term purchase contracts. On the other hand, the temporary water shortage in Norway and Sweden raised the price level.

Stronger international transmission links and markets mean that the national power consumption and production is not so dominant for the prices. The power price differences between countries become smaller.

From the first of January 1998 the Finnish Electricity Exchange EL-EX will belong to the Finnish Power Grid company. The purpose of this arrangement is that EL-EX will join to the Nordic Power Pool. Reasons for that may have been a relatively small exchange volume and the fact that the price differences between the spot markets in Sweden and Finland have become small, because many market actors participated both of them. Point transmission tariffs are applied only within each country. Finland may become one of the market areas in the Nordic Power Pool.

In Finland the reserves for power production capacity and control power are limited. If a shortage of these occurs, sudden peaks in the market prices will result. In such a situation load control is a useful and valuable resource.

The sanctions for exceeding the capacity limit were very high in the wholesale tariffs before the market deregulation. The investments in direct load control systems were clearly profitable in those circumstances for utilities with scarce control power resources.

Those who have operating load control systems can now sell the load control energy to the market when there are large rapid price changes. However, bidding mechanisms that can take into account the special characteristics of load shifting may need to be developed.

In the new market situation there are several sales companies selling to the same network. The effects of load control need to be known in order to determine the commercial power balance fairly. Can this be done, if the hourly customer loads are not measured? Measurements at the substation and our new load control response models will tell the load control response accurately enough, if the model parameters are appropriate for the load group. However, only the total response of the group is known. Individual malfunctioning or tampered terminals or loads in the wrong load group cannot be singled out from the substation measurements.

The effect of electricity market competition on supply on demand control in the UK is discussed in /1/. Since privatisation of the UK electricity industry, classical Demand Side Management techniques have not been valid in England and Wales, where the only commercial link between generation and distribution is through the electricity pool. Now demand control is used mainly to avoid the need for distribution system reinforcement. Difficult access to a demand control facility means a less economic supply, over-engineered in the longer term and potentially affecting supply quality and even security in the short term.

9. Profitability of direct load control

Risk management of the commercial power balance is the main incentive to investment in direct load control systems. The load predictions are uncertain and the price for exceeding all the contracted capacity is very high. The price of this balance energy is defined in a contract with a balance responsible power supplier. It is also very expensive per energy unit to purchase capacity that is needed only with a very small probability and even then a very short time. In the competitive market this price depends on the supply and demand of such capacity. Either investments in new peak power plants or load control systems are started somewhere, when the predicted demand and prices are high enough for that. Thus investments in the peak power capacity (e.g. gas turbines) and load control can be seen as alternatives on the national level. Via the electricity market these alternatives are reflected to individual market actors.

The public electricity marketplaces sell and buy energy and not capacity. However, to buy capacity can be seen as buying an option to buy energy at a fixed price. Such derivatives help to reduce investment risks and energy price variation risks. Public market for these derivatives has not developed well and does not give information that is needed to assess the profitability and timing of long term investments. Thus assessment of profitability must be based mainly on predictions on the growth of power demand and production capacity.

In the new competitive market several electricity companies sell in the same power distribution network. This makes the forecasting of loads more difficult and more uncertain than before. This increases the need for controllable loads. On the other hand it is usually possible to purchase the needed power from the energy market even at a very short notice. Only if this fails, load control becomes important. Then it is also possible to sell the load shift to those needing it.

To assess the profitability of a load control investment we need to estimate the value of the peak power capacity it replaces. This might be annually of the order 100 000 FIM - 200 000 FIM / MW. To reduce evening peak load by 1 MW we need about 5 MW installed controllable space heating capacity because the length and frequency of the control actions is limited, loads are not at maximum and because the load control actions have an after-peak. How much controllable load is needed depends mainly on the time and shape of the load peak and the outside temperature. The maximum annual value of 1 MW of controllable space heating load might then be somewhere between 10 000 - 40 000 FIM. Even during a shortage of capacity the increased price elasticity of power demand will probably prevent the value of load control becoming higher. The value of load control is much smaller, when there is excess (peak) production capacity in the market which means that energy can be bought close to the variable costs even during the peak load.

Load control can give some benefits also, when the marginal purchase energy price peak is not extremely high. But these benefits are much smaller, annually maybe roughly around only 600 FIM / 1 MW, if the spot market price variations are as small as they have now been. (h * 40 FIM / MWh * 50% *30 times = 600 FIM / MW). Price variations will become larger when a shortage of power production capacity occurs. It is difficult to assess the benefits of spot market price based load control on the national level, because the interactions with the balance control market need to be analysed first.

Direct load control can be valuable for balance control purposes. However, some issues on trading of load control for such purposes need to be solved and decided first. On the spot market of the Nord Pool where energy is traded for the next day the price variations are much smaller than in the Swedish balance adjustment market where energy is traded about two hours before its actual consumption. In the balance control market the energy is traded about 30 minutes before the actual consumption and the price variations are very large. In the Swedish balance control market the prices have varied from -5 to 900 SEK / MWh, which is about from -3.5 to 630 FIM / MWh. In Finland such a balance control market is new and there are very few actors in it. Because fast, reliable response is needed, controllable power must be known in advance. Load response models updated using real time measurements of immediate load from the network are needed for this. The measurements and models make it possible to verify the response, too. If certain controllable loads were reserved for the balance control market, their use for other purposes would not be allowed either.

The benefits can not be realised, if the systems are not maintained and if its operators are not trained to use it.

The profitability of the load control depends mainly on the development of the peak prices in the electricity market These are difficult to predict.

10. Suggestions for further research

The new direct load control response models need some further field tests for verification. Also the effects of sauna, cooking and other activities on the load control response need to be identified and modelled. These require some load control tests of individual groups, when the outside temperature is low long enough. After that load control sequences could be field tested also.

The direct load control scheduling methods need some further development before test use or integration with power purchase optimisation is appropriate. Simulations of the combination of the power purchase optimisation and scheduling of load control sequences are needed to verify the suggested interaction principle. The potential benefits of load control in the new electricity market situation can be more accurately assessed using the same simulations and optimisation methods.

The developments in various areas change the possibilities and potential for load control. Data processing, data communication, building automation and home automation make new more advanced load control methods possible. The heat losses of buildings have become smaller and heat pumps and heat recovery can greatly reduce the electricity consumption of space heating. Continuous development of the competitive energy market is also anticipated. Research to adjust the load control methods and systems is needed.

Some methods for bidding load control to the market are needed. The problem is the increased load after the control of space and water heating. The high after peak could be eliminated by smarter load control terminals at the customers, but it is too expensive to replace the existing terminals. Similar shift of consumption appears also, when controlling some industrial loads. One way to handle this is to use power purchase optimisation with a load control model. Possibility to sell to the market at predefined prices is included in the model. Marginal price is also one of the results. In principle it is also possible to bid with a load control model to those who have power purchase optimisation. Or the spot market itself might have this kind of optimisation tool as its interface to load control bids. In practice the maintenance of the load control model in the power purchase optimisation need to be made much easier than what it is now. The above principles and others need to be developed and compared in order to make it possible to offer load control to electricity spot market and balance control market. The use of direct load control for the balance control market should be developed because the profitability of direct load control may be much higher in the balance control market than in the spot market, when the bidding problems are solved.

11. Conclusions

Optimisation methods are necessary in order to get the potential benefits of the load control systems. In this respect it does not matter, if the load control is direct or indirect. The basic space heating problem with a constant ventilation rate and continuous control signals can be solved fast enough using linear programming. Varying the ventilation rate increases the load control potential of space heating loads but makes the model non-linear and thus more difficult to solve. Existing direct load control systems have other difficulties that result from agreed constraints on control signals and overly simple customer side control logic. The optimisation problems can be solved with available methods but the length of the solution time makes it necessary to simplify the problem formulation in online tasks.

New load control response models were developed and the field test results are promising but some more field test data is needed. The new model structure is linear with control constraints and it combines a-priori information on load groups with measured response data for the prediction of load control responses.

The deregulation of the electricity market has put load control in a new situation. The profitability of load control is now very difficult to estimate and more companies need to be involved before load control can be put into practice. The use of indirect load control will increase because the power production costs are more visible to the customers. Direct load control is needed only, when there is a sudden large shortage of easily controllable production capacity. The load shifts by direct load control can rather easily be sold to those who need it. The network limitations need to be somehow taken into account in the planning and scheduling of load control. How it can be done without violating the competitive electricity market framework is a major challenge. Distribution tariffs may be the major instrument to achieve this. For the load control optimisation methods this means that often the distribution costs probably need to be included either in the optimisation criterion or constraints.

Bidding mechanisms of direct load control need to be developed. Especially the use of load control for the balance control market requires it and controllable load may be significantly more valuable in the balance control than in the spot market.

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A. Literature on load control

The first chapter covers literature on both dynamic tariffs and price control. It is possible that the price control signal and the actual tariff are different. This is also the case in some of the referenced experiments. Thus the tariff is not necessarily dynamic although price control is applied. In the next chapter literature on direct load control is discussed. Both direct and indirect load control are needed and included in the same systems. Such experiments are described in the third chapter. Finally, some references on load prediction and data communication for load control are mentioned.

The difference between direct load control and indirect load control is the following: direct load control is used, when the supplier of the electric energy sends commands when and which loads are turned on or off. When the electricity company sends a price signal and the customer´s control system decides the load control actions on the basis of prices, we speak of indirect load control. In some of the references the words direct and indirect load control are used to refer to the organisation rather than the technical structure of the system and even some types of price control are called direct. We use the terms on the basis of technical aspects.

A.1 Dynamic tariffs (real time tariffs) and price control

The competition in energy market is assumed to lead to the development of tariffs that better reflect the power purchase costs and give the customers incentives to adapt the timing of the consumption to the marginal costs of power supply. Traditional time of use tariffs take into account the average seasonal and daily variations in load. However, the power purchase prices vary even more because of the changing conditions in power production and consumption, such as outside temperature and process failures. That is why real time tariffs or dynamic tariffs have been developed. Different versions of them have been applied, see for example (Räsänen and Hämäläinen 1995, Kallio and Salo 1994, Lestanguet E and Pinta J-C 1995, Cirillo et al. 1995, Morovic et al. 1995, Flood et al. 1994, Strong 1995). The price information for a day is typically transmitted to the customer in the previous evening. In some of the experiments the prices are sent even much more often. In the experiments described by Räsänen and Hämäläinen (1995) the ratio of the highest and the smallest energy price has been 8:1 and 12:1 and in some others (Lestanguet E and Pinta J-C 1995, Cirillo et al. 1995) close to 20:1 or even 27:1 in one of the cases described by Kallio and Salo (1994). According to Rouvali (1993) p. 66 in Finland real time tariffs or dynamic tariffs would concentrate over 20% of the customers electricity costs to 15 wintertime working days in contrast to traditional tariffs where these costs are covered by annual capacity charges. It seems that there in the assumed dynamic tariff the power purchase costs of the power utilities or a specific utility are considered but not the possible limitations in the power distribution capacity. However, when dynamic tariffs or load control is applied in some residential areas it is necessary to take into account the dimensioning and costs of the distribution network. Kallio and Salo (1994) report that the consumption in Finland depends very much on temperature, that the last 5 to 10 % of the generating capacity is only required for 100 to 200 hours per year and that these hours occur during 10 to 20 days of peak consumption.

The financial benefits of real time tariffs for both the customer and the utility are estimated by Cirillo et. al. (1995), Kallio and Salo (1994 p. 370-371) and Rouvali (1993 p. 63-71). In all of them the costs or inconvenience caused by load shedding to the users of the building are neglected in the benefit analysis. They are implicitly taken into account in the design of the automatic load control strategy by Cirillo et. al. (1995) and Rouvali (1993) while in the four experiments described by Kallio and Salo the customer response was manual and based on light panel information. The omission of other customer costs than the electricity costs from the analysis is natural, when the benefits are estimated from the electricity company's point of view, because it is only the customer who knows the time to time other losses and costs or the value of inconvenience. However, it is important to remember this when interpreting the results.

With dynamic tariffs the customer in his load control response can take into account the various things that are important to him in a much more explicit and straightforward manner than with direct load control. In many of the experiments referenced the view has been so supplier oriented, that this has not been fully noticed, although in competitive market it is in the suppliers interest too, to find the common optimum. The following exaggeration may clarify the need to include the customers costs and comfort in the benefit analysis and in the load control optimisation model. If load shedding never causes any trouble and a temperature drop of 0.5 C degrees is irrelevant to the customer, why does he not just reduce the temperature set point and save energy all the time unless when there is an immediate need to store heat.

According to Vanlommel (1994) the dynamic tariffs provide an effective way to obtain an efficient allocation of resources and to prevent wasteful use of electric energy, but their major disadvantages for electric utilities are increased administration and communication costs, the unpredictability of customers' demand and possibly of utilities' revenues and the need for instantaneous supply-demand balancing.

It is also possible to agree, that the maximum power allowed to the customer is limited during a certain number of days by sending a notification the previous evening (Rouvali 1993, p. 63).

Rouvali (1993, p. 69) analyses the feasibility of dynamic tariffs from the point of view of space heating of residential customers. There the customers' response to high temporary energy prices is a reduction of the set point temperature of the interior by 2 degrees C. The high energy price is supposed to last from 9 to 18 o'clock during a working day. The reasons for this choice are not reported but the time of use tariffs used for the analysis are. The latter show a high price period from 8 to 22. In Finland the peak consumption is in January or February either from 7 to 10 or from 17 to 20 o'clock according to SENER (The association of electric utilities in Finland). The typical unoccupied period is also from 8 to 17. That is why the temperature set point should rather be raised back to normal between the morning and evening peak hours. The price among other things could determine the exact time. There may also be potential in storing heat by raising the temperature set point before the morning peak load period. It is not obvious, how these changes influence the total annual benefit, the result of the analysis.

Lestanguet and Pinta (1995) review TEMPO, a new tariff package of EDF and feedback on it: EDF has for over 30 years been using time dependent tariffs (fixed hourly and seasonal periods tariffs). As a result the national load curve in France is today flattened very well. Because the power supply production cost does not solely depend on time but also on conditions prevailing at the time, traditional tariffs, differentiated according to pre-set periods, make wide ranging averages of highly different cost situations. Thus peak power generation capacity has to be implemented to cover a short randomly occurring demand. That is why EDF started 1985 a tariff package that uses a fixed duration peak period (22 days for 18 hours) selected in real-time by EDF. The new TEMPO tariff extends this approach. It consists of three types of days as well as high and low load hours. The customer is informed on the following day's type in the previous evening at 8 p.m. So far this new tariff type has been offered to residential customers only. The authors suppose that by the end of 1995 about 10,000 customers have chosen the TEMPO tariff. The experience has been mainly positive and EDF has decided to launch a market campaign offering the TEMPO tariff to the public. Both the utility (EDF) and the customers win compared to traditional tariffs. In addition to residential customers the TEMPO tariff will be available in 1997 to agricultural, professional and community public service customers too. Tariff comparison services and software have been found to be the best way to market the new tariff.

Morovic et al. (1995) describe the field-tests of a real time load dependent electricity rate in Eckernförde, Germany. 1000 randomly chosen households participate in the test. The effects of the new rate are evaluated using a longitudinal section test and measurements from the seven transformer stations that feed the participating households. The electricity price to be transmitted to the consumer is calculated from the grid load. The price information is transmitted to the consumer as impulses, whose tact frequency is proportional to the price. Loads under variable prices are compared to the loads of the same time of the previous year. Participants have responded by shifting loads within workdays and from weekdays to weekends. An average load reduction of 20-25% during the peak load period is reported.

Cirillo et al. (1995), Vold et al. (1996) and Flood et al. (1994) present the combination of real time pricing and automated control of large commercial buildings. The described buildings are very large hotels with a power consumption of several megawatts. In this scale dynamic tariffs are clearly beneficial to both the customer and the power company. Automatic control is reported to be superior to manual response to real time tariffs. The prices are hourly price profiles that are sent in advance, probably the previous evening. In this scale dynamic tariffs are clearly beneficial to both the customer and the power company. Koponen et al. (1991) describe a simulation prototype of the power management of a large industrial company that has production plants in several sites. There the use of dynamic electricity tariffs and bidding is demonstrated also inside the company in addition to the power purchase.

Zarnikau (1990) and Räsänen (1995) tell about the customer responses to real-time pricing of electricity.

Strong (1995) describes the trial results of the CELECT project of EA Technology in UK and the new ETHOS project. CELECT is an integrated approach to load management, domestic space and water heating, and telecontrol. Cost messages and weather forecasts are sent by radio. In each cost message the prices are given for 24 hours in half an hour increments. Both storage and direct heating are controlled in each heater. Optimisation is carried out in each heater for user comfort requirements, for complex tariffs or costs and for 24 hours temperature forecasts. The control and optimisation system in each heater is continually learning room thermal characteristics. The system is invisible to the user. Strong (1995) shows cost profiles in the messages that have the same shape exaggerated as the national average power consumption and the average pool price. They all have three peaks, the lowest one in the night, one before midday and the highest one at 18 o'clock. The very high price (25 pence/kWh) period is from 16 to 19. Low price (2 or 2,5 pence/kWh) periods are from 4 to 7, from 14 to 16 and from 21:30 to 0:30. (During the day the average pool price varied between 1 and 3 p/kWh in a figure shown.) Because there are three low price periods a day the system can move the heating loads there. For comparison simulated responses are given to a two rate tariff, to a constant tariff and to a night and day tariff. The tests consisted of 10 initial field trials over the winter 1993/94 and further 60 installations in 1994/95. Although the time variable prices are used in the optimisation of heating, the bills of the customers are usually based on a flat but reduced tariff in the CELECT trials. The initial feedback from these trials has been very good. Users have experienced enhanced comfort and controllability and the demand has been shifted away from the expensive 16:00 to 19:00 period. Also energy consumption has been reduced.

The electric heating elements applied in CELECT have two parts that can be individually controlled: direct heating and heat storage. Thus the heat storage can be loaded during night time, but during high price hours it is possible to heat the house without heating the heat storage first. In addition to savings in energy costs this gives a faster and more accurate control response.

In CELECT the Echelon LonWorks network in power line is used for data communication within the house. The distributed structure of the system together with the high price of power line communication modems have made the CELECT system rather expensive and prevented the commercial success of the system. More centralised and less costly solutions are being developed.

ETHOS is a trial of interactive value added services in over 1000 European homes in UK, France, Italy and Denmark. In the ETHOS project the principles and components in

CELECT are further developed and applied to the EHS (European Home Systems) bus system by EA-technology and EDF in order to get the home data communication network costs lower. EA-technology participates also DICE, an EU-project, that continues the development of EHS based components for this application area, by developing electric water heating systems.

Ygge and Astor (1995), Ygge (1996 and 1997) and Akkermans and Ygge (1997) study distributed decision-making in load management. There the distributed load controllers belong to the same utility. The decision making by multiple autonomous agents is the main issue. Individual loads and devices are equipped with these small software agents that manage loads in terms of auction with software agents representing the utility. The agents bid to buy and sell power. The authors state that the optimal situation is achieved in just a few negotiation rounds. An issue that needs further study and experimentation is the determination of the utility functions. It is important to note that the data communication needs increase with the autonomy of the agents. The feasibility of the agent approach in load management increases when the data communication costs shrink. This seems to be a matter of time.

(My own experience with some industrial loads (Koponen et. al. 1991) is that complex process dynamics with interactions and scheduling lead to the explosion of the combinations in a very few time steps when determining these utility functions unless the search space is very much limited. Simple load dynamics with weak process interactions are much easier and they may also be more relevant here. Competitive energy spot market with enough volume buffers the effects of individual loads and power plants. Thus it makes the determination of the relevant part of the utility function of a power utility much easier to solve than before.)

Bhushan and others (1996) suggest the use of power pool price that depends on the network frequency. Power production and loads could be controlled on the basis of frequency measurement. Data communication would not be needed. They state that this is important in India.

A. 2 Direct load control

Direct load control is a more traditional way to cut high cost power purchase. Typical targets for direct load control are street lighting and electric storage heaters of water and space. In space heating the direct load control is subject to a set of rules or constraints that are meant to protect the customer from suffering too much from the load control. Maximum number of control actions, maximum lengths of load-off times and minimum lengths of recovery periods are examples of these constraints.

In the optimisation of load control the constraints of direct load control do not always reflect the real interests of the customer especially during long load peaks or extreme weather conditions. From the utility's point of view these constraints may then mean both decreased possibilities to gain benefit and unnecessary irritation of some customers at the same time. Data communication costs and techniques have influenced in the design of these constraints. In this respect he situation is changing, because the progress in data communication is rapid.

The potential of both direct and indirect load control in Finland is estimated by Rouvali (1993). Advance notification in direct load control would make it possible to use the available heat storage capacity more efficiently for load control. However, the utility will not benefit at all unless the load-off times are made longer (Rouvali 1993 p. 44-45). Advance notification would also increase the potential of customers to switch to alternative fuels during peak loads.

Traditionally direct load control has switched off the power of heat radiators for a given period and after it the indoor temperature has been allowed to return back to its set-point as soon as possible by applying maximum heating power. That is why load control period is followed by a high increase in load. This after-peak can be harmful for the network. It makes it necessary to plan load control sequences where the after-peaks are compensated by the control of an other group. It does not improve the customer comfort either. The after peak of a house can be avoided for example by controlling the temperature set-point or limiting the power during the recovery. Some Swedish experience in such methods is described in Anon. (1991). There the power limiting is based on a repeating ON-OFF cycle where the length of the ON an OFF cycles is adjusted. This approach makes it also possible to have longer load-off periods by only limiting the power during the load-off periods.

Vercherin and Spala (1995) describe the new ripple control system of EMASZ, one of the six Hungarian electricity utilities. Customer groups with heat storage equipment are connected to the network gradually in the heating periods at night and reheating periods during the day. All loads are not connected simultaneously because the peak of an individual heat load is when switching ON and then it decreases exponentially. There is also a load management program on the central operation level that constructs a load schedule taking into account the load predictions and avoids the overload. The impact of the system on load conditions is shown by comparing the load data before and after the installation of the system. 58 % of the customers are included in the load control. The utility load curve has been levelled and its daily peak period has shifted from 19:00 to 23:00. They conclude that the costs on purchasing electrical energy can be significantly decreased by centralised ripple control.

Persson (1996) discussed the application on direct load control to damping power oscillations in the frequency range 0,1 - 1 Hz. Such oscillations typically appear in long transmission networks. The purpose is to utilise the energy storage of thermal loads in order to damp power oscillations. This is done by exactly timing the on and off switchings of the loads, not so much the length of on/off periods.

Heikkinen (1995) has developed and simulated a load management algorithm for an energy system including wind power. The idea of the algorithm is to minimise utility's peak power costs.

Kennedy and others (1996) among other things shortly present the direct load control system of Florida Power Corporation. Approximately 500 000 customers have agreed to a programme under which they receive rebates on their power bill in return allowing the power corporation to control energy intensive appliances in their homes during peak demand times. Air heaters, air conditioners, water heaters and pool pumps are controlled. The load control switches are one-way VHF-radio receivers. Also broad band communication (Cable Television network) together with a gateway to a CEBus-network over the electrical wiring in the house are introduced.

Kulkarni and others (1996) report on an load shedding system that is implemented using knowledge based programming techniques. The purpose of the system is to prevent overloading of the feeders and to keep the voltage levels acceptable. Feeder loads are forecast using artificial neural networks and the actions are decided using a rule base.

A.3 Experiments where both direct and indirect load control are applied

Kakimoto (1995) outlines KEPCO´s (Kyushu Electric Power Co. Inc.) pilot test plan for a DSM system which uses an information transmission network. Prospective deployment is being forecast considering a scenario for DSM based on the results of the test of customer load equipment control. For KEPCO air-conditioners used for cooling account 40% of the summertime demand peak. In the tests fibre optic cables connected the control centre, computers and customer terminals. These have functions for measurement, load control and collecting utility information. Air Conditioners were equipped with control units, which collected customer reaction to room temperature and load control. A mix of residential, commercial and industrial areas were selected for the experiment. In the basic tests direct load control was applied for 5 years consisting of night-time load levelling by water heaters and daytime peak clipping and peak shifting by different air conditioners. Kakimoto explains the control methods applied. Pilot tests for DSM utilization are planned to take place from 1995 to 1998 as the system is implemented in 1995 - 1997. Control groups are used as a basis for comparison. Indirect load control by changing peak time rates and peak time rates which vary by month will be applied. Direct load control of air conditioners will be applied for the fourth group.

A.4 Load estimation and prediction

Electricity trade and real time tariffs do not remove the need to predict the load accurately and reliably. They rather increase it. Already now the utilities use the predictions to plan and optimise their power purchase and prediction as well as the load control. The planned or predicted energy consumption of the customers is valuable for the participants of the energy trade, because it makes it possible for them to buy less reserve capacity. Thus in the load estimation the load predictions of large customers complement the network measurements and the load models from load research, that are described by Seppälä and Kärkkäinen (1995). Of course the uncertainty of the predictions must be known also. It is also important to model the responses of the loads to control actions.

The modelling of the response for space heating loads is easier than for water heating. This is due to varying water usage patterns and differences in water heating equipment.

The transient response of a thermostatically controlled electric space heating following an outage has been developed by (Athow and Law, 1994). This is equivalent to modelling the after peak of space heating.

A.5 Data communication in load control

Ripple control techniques are described by Vercherin and Spala (1995). Ripple control enables switching commands to be broadcast via the power distribution network to thousands of receivers. Ripple control system is only suitable for one-way communication. Typically the carrier frequency of ripple control is between 167Hz and 340Hz. Because the frequency is low, the attenuation is low, but the communication capacity small (narrow bandwidth).

Two way communication in low voltage networks is possible using distribution line carrier (DLC) techniques. The European standard EN 50065-1 (1991) applies to signalling in low voltage electrical systems in the frequency range 3 kHz to 148,5 kHz and has a status of a Finnish national standard. Signal frequencies above 148.5 kHz are prohibited. The standard EN-50065-1 is not applied in North America and Japan. There only the frequencies above 530 kHz are prohibited. The attenuation for DLC signals is much stronger than for ripple control especially in transformers. Thus a concentrator that sends the load control signals is used in every low voltage network for example in a DLC system described by Mahler and Häuser (1995, pp.226-227).

Salo and others (1996) present a system concept, where ripple control system and a low voltage distribution line carrier (LV-DLC) are combined under the same central unit. The load control commands are sent using ripple control. In addition they show a summary of performance measurements in pilot systems in three different areas (suburban area, city area, and a factory). The LV-DLC in the system is based on the Echelon LonWorks network technology. Both frequency bands A (9 - 95 kHz) and C (125 - 140 kHz) were measured and no significant differences between them were found in the communication capacity. Distances over 400 meter needed a repeater for reliable communication. Also Edlich and others (1996, p. 173-181) present a system where ripple control and DLC are combined.

A canadian company Nordel has announced a system that gives enough data transmission capacity for normal Internet connections. This system is developed for cable networks and possibly uses high frequency ranges that are prohibited. Probably shielding and filters are used to prevent the signals from disturbing others.

The Radio Teleswitching System (RTS) is a service that British Broadcasting Corporation (BBC) broadcasts from three transmitters as amplitude modulation of a 198kHz carrier. Radio teleswitches are used in two ways: storage space and water heating loads can be switched ON an OFF or price can be varied. The use of the radio teleswitch system is described by Booth and others (1995). Also in Germany long-wave (129kHz) teleswitching is applied, see Fuchs and Saupe (1996).

A data communication scenario for DSM (Demand Side Management) is described by Kakimoto (1995). It is based on multi-purpose utilisation of the fibre optic transmission media and an integrated distribution automation system. Kakimoto estimates that if usage rate of cable television, that uses the same media exceeds 56%, this DSM system will become profitable. It would be interesting to know, what usage rate of cable television alone without DSM would be profitable.

For load control signals to reach the controllable appliances, a communication network in the house, such as LonWorks or CEBus, is often needed in addition to the communication between the electricity company and the utility. See for example Haaser and Barry (1995).

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B. The structure of the direct load control response model

Appendix B