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A closer Look on Load Management

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***Abstract*—The rising share of energy generation of renewable energies leads to a more volatile energy generation. Large conventional generation capacities have to be kept in the system in order to smooth out the generation patterns of distributed generators. The controllability of electricity generation is on decrease. To improve adaptability of power systems due to these new challenges, the concept of load management gains in importance. This paper provides a closer look on the potential of specific consumption processes for load management measures. It proposes a new solution to enhance the idea of the interruptible load for demand side management relying on the particular properties of inert thermal processes. A general taxonomy is given, whereas two different options for inert thermal processes are discussed and compared in detail.**

I. Introduction

IN the context of upcoming challenges for our energy supply systems, i.e. the need for more efficiency and a considerable increase in utilization of distributed generation (DG), the concepts of load management (LM) and demand side management (DSM) seem to be inevitable to reach these objectives. In current power systems, the balance between electrical power generation and demand is only maintained by measures on the (centralized) generation side following prospected load charts. Although this concept has proven to be adequate in the past, recent developments are considered to invoke major changes in future systems. The time variance of supply from renewable energy resources, which generally does not match the load profile, may lead to congestion or energy surpluses. Higher flexibility is needed, but goes along with a decrease in efficiency. This is especially true for large power plants. As more and more generation capacity is either replaced by distributed generation of renewable energy sources or by new-generation power plants, which are optimized for high efficiency rather than for flexibility, the basis for balance energy provision becomes narrower and narrower. Here, exploiting potentials of the demand side comes into the focus. The basic idea of short-term DSM is to use existing flexibilities in consumption processes to gain influence on the overall consumption pattern (load profile). The utilization of the large and distributed potential on the demand side has already been discussed in the past decades, but apart from course-grain approaches, such as loading of thermal storages during the night for electrical heating, implementations of short-term DSM are rare [1]. Among numerous reasons, this is primarily true because of the low urgency for system changes, the high (but meanwhile decreasing) costs for the coordination infrastructure needed, and also because of the lack of solutions for integrating the small flexibilities of millions of loads into the grid operation. The increase in urgency for change is just a matter of time. Ongoing research in the frame of the KNIVES and the IRON Project (Keio Univ. Network oriented Intelligent and versatile Energy saving System [2], Integral Resource Optimization Network [3]) shows that the benefit of a communication infrastructure supporting electricity grid operations is either already higher than the associated costs or will be so very soon. This paper takes a closer look on potential loads for DSM in order to reveal what can be expected from individual DSM contributors. The derived model of the individual resource potential is subsequently discussed in the context of collective resource management.

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II. Terminology

Due to the high number of partly interchangeable terms in this field, some of the most frequently used terms shall be explained in detail.

A. Load Management and Demand Side Management

Demand Response (DR), Demand Side Management (DSM), and Load Management (LM) are the prevalent, generally interchangeably used terms describing concepts of influencing loads in the power grid. DSM contains the planning, implementation and evaluation of methods to influence the amount and timing of energy use [4]. In general, *short term DSM* and *long term DSM* can be distinguished. While long term DSM refers to the general planning and optimization of energy loads without 'on-line' intervention in the processes, short term DSM concentrates on the optimization of the actual load charts. The objective is to coordinate interruptible loads in order to reduce congestions on the power grid. The model presented in this work has its application in short-term DSM.

B. Load shedding and load curtailment

The main goal in load shedding or curtailment is to cut or reduce loads in critical grid situations without consideration of the user process functionality. Load shedding that is motivated by grid stabilization is usually interfering with customer interests and can only be applied in emergency situations. A minor group of loads, such as lighting in unoccupied rooms etc. can also be curtailed without loss of user comfort. However, in the context of sustainable energy usage, these loads should be switched off in general rather than be used in DSM operations. Modern DSM has to undertake its measures without noticeable changes in the performance of user processes. Therefore, load shifting is the preferred option of intervening with load operations.

C. Load shifting

The main goal of load shifting is not to reduce energy consumption in long-term, but to reduce peak loads by shifting consumption to off peak times. As a short term method it allows improving the balance in load charts, without the decrease of functionality for end users. The control of load shifts, distributed storages and curtailment of interruptible loads are the major tools for this strategy. Based on their specific processing, properties and energy storage functionality, there is the possibility to reschedule energy consumption of certain loads. Energy can either be stored in real energy storages, such as thermal storages, or as conceptual energy storages that can be exploited by rescheduling a process to a later point in time (load shift).

III. Applications for DSM resource models

With the introduction of locally aggregated distributed energy resources in combination with control of end-user energy consumption – so called micro grids [5] – DSM has become an important factor. In the U.S. and especially the States New York and California projects have been introduced to enhance the electrical power system, e.g. the Distributed Energy Resource Integration program.

In 2002 the national government of Japan has released a Basic Law on Energy Policy Making to ensure reliability in supply under free market principles and environmental aspects. In 2005 the wholesale electricity market has been opened, introducing Japan Electric Power Exchange [6].

Also in Europe national and EU wide projects, e.g. DISPOWER [7], have been founded and deployed that include DSM as important aspect.

In general, two kinds of DSM activities can be distinguished: individual operation on the basis of per-load cost optimization in the presence of time-variant energy pricing or coordinative operation in order to achieve certain load charts (mostly aiming to avoid consumption peaks and also economically motivated). While the first model can make use of a human operator (although automation would be preferable), coordinated DSM measures of multiple loads to achieve a common optimization goal can only effectively be realized using automated control algorithms. For these, adequate resource models such as the one presented in this work are needed.

IV. Energy storage in DSM loads

Load shifting can be performed in various processes, e.g. washing, cleaning, heating, chilling, and pumping. These electricity-consuming processes have, depending on the application, certain degrees of freedom in their time schedule. Each potential DSM load has a certain individual capability that it can commit to the DSM framework. This capability has usually two dimensions: energy and time. The consumption of certain portion of energy E_p can be pre- or postponed for a certain time t_{store} (load shifting). In case of load shedding, this time can be assumed to last infinitively. The load shifting capability of a certain load can be described as the product $E_p t_{store}$. The energy portion E_p itself splits up into power and time (of interruption). Different combinations of power and time constitute the same energy portion. It can be seen as the task of a DSM algorithm to manage the optimal scheduling of these energy portions, driven by a certain goal. The method can be used for peak reduction, but also for other options such as the provision of short-term balance energy are also possible. For an efficiently implementation, such an algorithm needs precise but preferably simple models of the properties of DSM loads. In the following sections, such a description model for the dominant class of DSM loads is derived.

V. Model for inert thermal processes

In general, it is difficult to derive reasonably accurate models for the consumption behavior of potential DSM loads due to the individual characteristics and the stochastic behavior of each single process. However, a particular type of consumption process, which plays a major role among DSM loads, can be described using a standardized model. Electrical heating and cooling applications in the domestic and industrial sector have one important property in common: electrical energy is transformed into thermal energy, and due to the inertia of this process, this can be seen as type of energy storage. To maintain constant thermal conditions, thermal energy losses due to intentional or un-intentional leakage in thermal insulations have to be balanced with further energy transformation. This is true for both heating and cooling processes. Thus, a simplified but general model for such different applications as supermarket refrigerators, vending machines, air-conditioned offices, heat pumps, cold storage rooms, boilers and many others can be derived.

Tab. I. Thermal and equivalent electrical variables

Thermal	Electrical
Power $P=Q/t$	Current I
Temperature T	Voltage U
Resistance R_{th}	Resistance R
Capacitance C_{th}	Capacitance C

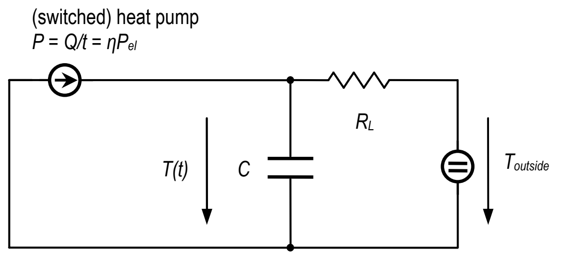

Fig. 1. Equivalent electrical circuit model for a thermal process

A. Thermal capacitance

Compared with the definitions of thermal and electrical variables, the following equivalent electrical circuit elements can be found for thermal variables (see also Tab. I):
Thermal capacitance C_{th}:

$$C_{th} = \frac{dQ}{dT} \quad \text{(where } Q \text{ heat quantity, } T \text{ temperature)} \tag{1}$$

Thermal resistance R_{th}:

$$R_{th} = \frac{T}{P} = \frac{T}{\frac{dQ}{dt}} \quad \text{(where } P \text{ thermal power)} \tag{2}$$

This results in the simple electrical circuit depicted in Fig. 1, which models the behavior of the thermal system. In this circuit, C stands for the thermal capacity of the thermally insulated room; R_L stands for the thermal leakage due to non-ideal insulation.

VI. Analysis of Storage Losses

With the basic model for interruptible thermal processes the losses of this system can be analyzed for a better understanding of how DSM measures will influence these losses. Losses are of importance in two aspects: first, losses during DSM operation shall in total be no higher than losses during normal operation. Second, the time period for which an inert thermal process can be interrupted from power supply is strongly dependant on heat flux and heat losses.

A. Types of losses in examined processes

As shown in Fig. 2, there are two points of energy losses: first the non-ideal conversion from electrical to thermal energy, modeled by the parameter $\eta = P_{therm}/P_{el}$, and second the thermal losses due to the non-ideal isolation, modeled by the parameter R_L. In general there are three different principles to exchange heat between materials/bodies of different temperature.

- *Solar/heat radiation*: This takes effect e. g. in case of windows exposed to sunshine. However, solar radiation is hard to predict and depends on weather conditions and angle of incidence. It plays a role for air conditioning, but usually not for cooling applications. It will be assumed that radiation has little effect and therefore can be neglected in this model.
- *Heat conduction*: This is the major factor and directly linked with insulation. It can be evaluated empirically or approximated due to certain assumptions of insulation.
- *Mass transport/convection*: has an effect for different types of (air-conditioned) sites: supermarkets, banks etc. It has a high effect where air exchange is high and can cause high losses. This effect can be modeled by assuming R_L in Fig. 1 being time-variable.

B. Temperature changes due to heat conduction

In general, media of high heat capacity are preferred in DSM process manipulation: water (water heating systems, water boiler), wood (wooden walls, roof, etc.), ground, in contrast to the storage with media of low specific capacity, e.g. air, metal (lead, copper).

In case the difference between the temperature outside and the temperature within the system (ΔT) is not adhered through heat generation, an exponential decrease of ΔT is expected as described in (3).

$$\Delta T\,(t) = T_{outside} - T_{inside} = \Delta T_{t=0} \cdot e^{-\frac{t}{R_L C}} \tag{3}$$

For small time periods and large time constants the function can described as linear approximation in 0+:

$$\Delta T(0+) \approx \Delta T_{t=0} \cdot (1 - \frac{t}{R_L C}) \tag{4}$$

From (4) it can be seen that if we can assume that $R_L C >> t$ then $\Delta T = const$. Consequently, good insulation and first of all high capacitance are proffered properties for potential DSM load processes.

C. Approximation of losses

It is assumed that $\eta = P_{therm}/P_{el}$ is almost constant over the temperature range in which the system is operated. So,

$$E_{loss,conv} = (1-\eta) \cdot E_{el}. \tag{5}$$

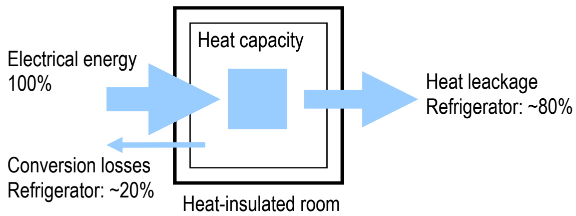

Fig. 2. Energy flows in a thermal process (e.g. refrigerator)

During normal operation, R_L is also constant. All thermal energy that is supplied to the system will leave it via R_L. The energy losses over R_L can be calculated as

$$E_{loss,leack} = \int P_{loss}(t)dt = \int \frac{T_{outside} - T(t)}{R_L}dt \approx \frac{T_{outside} - T_{set}}{R_L}t \quad (6)$$

(Where T_{set}: set-point of the temperature regulator)

D. Loss balancing during DSM operation

Assuming that in average $T(t)$ equals the temperature set-point T_{set} of the temperature regulator in the process, the thermal energy losses are approximately proportional to

$$T_{outside} – T_{set}. \quad (7)$$

This means factually that, when storing additional energy in the system by changing (e.g. decreasing for a cooling process) the temperature set-point, the system losses increase linearly to the set-point change. However, this also means that if the set-point is changed in the opposite direction (increased for a cooling process, decreased for a heating process), the losses are linearly reduced. Thus, by taking care that the thermal process runs as long with an increased set-point as it runs with a decreased set-point, the average additional loss during DSM operation compared to normal operation can be kept zero. Due to the fact that losses are smaller than normal for low temperature differences between inside and outside, even other non-linear loss effects can be compensated by operating the system longer time periods with a reduced set-point. Although this need for compensation of losses imposes additional restrictions on the overall DSM load scheduling, these can be handled fairly well as shown in Section VIII.

VII. Model refinement

The temperature profile of a body or media (gas) is composed by the rate of its internally-generated heat, the capacity to store some of this heat, and its rate of thermal conduction to its boundaries (where the heat is transferred to the surrounding environment). Since not only air, but also the repository (e.g. building) itself stores heat, which improves the capacity and therefore the slow decrease of temperature, an enhanced model allows a more accurate approximation (see Fig. 3).

The enhanced model shows a low pass filter characteristic, if P_{pump} is missing, in the simplest way (without the consideration of the window and the door):

$$RC = (R_{1-wall} + R_{n-wall}) \cdot (C_{inside} + C_{center}) \quad (8)$$

The approximation of the insulation in Japanese buildings [9] is shown in equation (9).

$$R_{wall/roof} = A \cdot \Delta T \cdot i \quad (9)$$

The resistance R [kcal/h] based on the insulation of the wall or the roof depends on the area of the wall, the temperature difference ΔT [K] and an insulation factor i [kcal/m^{2}K], which can be approximated by the values given in Tab. II and III.

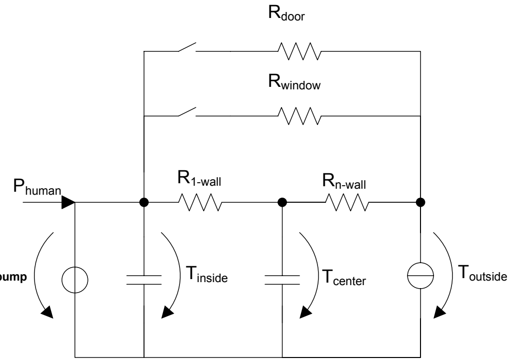

Fig. 3. Enhanced model of the electrical circuit model under consideration of heat storages in the building [8]

Tab. II. Insulation of walls [9]

i [kcal/m²K]	Wood	Concrete: 120mm		Concrete: 150mm	
		cavity	No cavity	cavity	No cavity
cooling	1.66	1.23	2.12	1.20	2.03
heating	2.32	1.56	2.56	1.51	2.43

Tab. III. Insulation of roof [9]

i [kcal/m²K]	Wood	Concrete: 120mm	Concrete: 150mm	Concrete: 200mm
cooling	3.15	2.70	2.95	2.67
heating	3.32	2.80	3.10	2.79

VIII. Two options for active load shifts

Electrical appliances are commonly not designed for taking part in DSM measures. Consequently, in most cases it is not trivial to interface the load with the DSM automation infrastructure. Depending on the kind of interface, it might be possible to gain influence on the temperature set-point of the system to alternatives for load shifts exist. The basic load profiles of both variants are shown in Fig. 4. Although two-point temperature controllers are common, in the diagram a linear temperature controller is assumed for clarity.

A. Set-point variation

Where it is possible to gain access to the temperature regulator of a process, variant A, ‘set-point variation’ can be realized. Since the process temperature is proportionally increasing or decreasing with the energy level of a thermal storage (depending on whether heating or cooling is performed), charging and discharging the storage can be easily achieved by varying the temperature set-point. Without DSM, the system is operated at a neutral temperature set-point $T_{set,0}$. Two other set-points $T_{set,-1}$ and $T_{set,1}$ can be found for a most applications, so that

$$E(T_{set,-1}) < E(T_{set,0}) < E(T_{set,1}), \quad (10)$$

(Where $E(T)$ is the system energy level of the temperature T) and the system operation is not negatively influenced by the operation at a varied set-point temperature. The energy E_p shifted by this approach is given by the heat capacity of the thermal storage and the set-point difference. While E_p is clearly restricted, the storage time t_{store} is usually not. It does not matter whether a freezer operated at -18 °C or -21 °C in terms of user comfort. Energetically, this does of course matter, but this is exactly the effect that is exploited here: by operating the system at -21 °C, thermal energy is stored that can be released when returning to the -18 °C set-point.

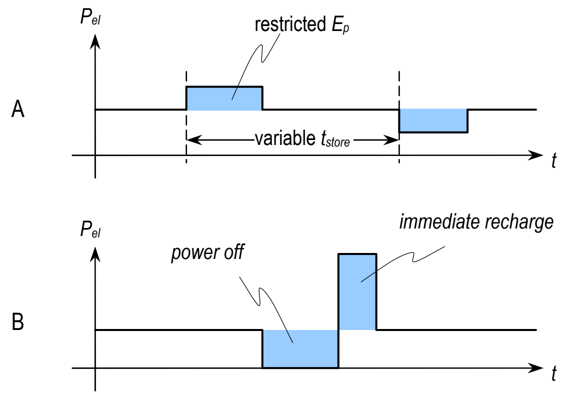

Fig. 4. Two different types of basic load shift functions. A set-point variation, B immediate recharge

Using set-point variation, storages can be pre-charged before the load reduction or post-charged after the load reduction or both. In order to achieve a maximum load reduction in a certain time interval, storages can be operated symmetrically around this interval as shown in Fig. 5. Here, a cooling process is utilized to reduce power consumption during peak electricity demand. It is pre-charged in times of low demand, holds the additional energy portion to release it during the peak and finally post-charges after the peak. The system temperature and the system power consumption are shown, whereas the power essentially is the derivation of the temperature curve. Nevertheless, as discussed in Section VI, the temperature does also linearly influence the losses and therefore the power consumption. However, from Fig. 5 can be seen that despite this, the total energy consumed by the process is the same for DSM and non-DSM operation.

The requirement for realizing the set-point variation option is, as mentioned before, that the regulator set-point setting can actually be accessed electronically. In many cases, thermal regulators are even so simple that they can easily be replaced by automatically configurable counterparts.

The advantage of influencing the regulator set-point is that the regulator itself takes care of all side effects or unpredictable events such as an opened refrigerator door. Although these events result in increased energy consumption, they would also occur without DSM measures and therefore can be modeled as a consumption that is independent of the storage process.

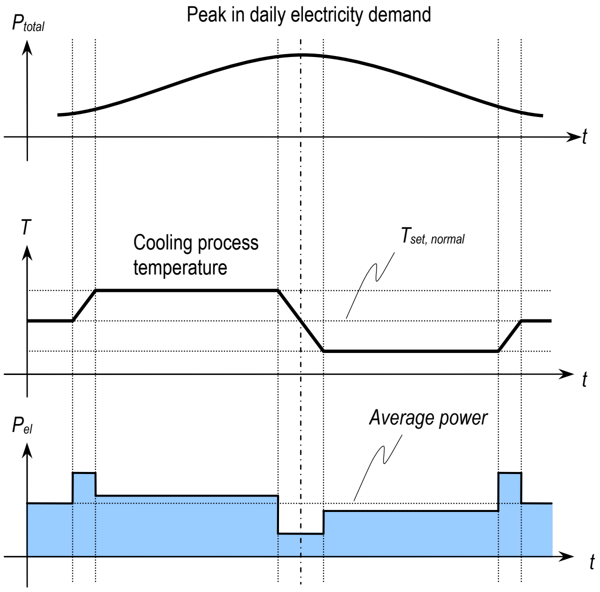

Fig.5. Symmetric storage management

B. *Immediate recharge*

An alternative to the previously discussed storage utilization method is the 'immediate recharge' option (see Fig. 4). This is the option of choice when no access to the process set-point can be gained and the only accessible interface to the process is its power cable. Then the load is simply switched off. During power-down, the energy level of the system is falling slowly (e.g. the water temperature of a boiler is decreasing). After a specific time, power is supplied to the system again, and the temperature controller will immediately start to 'recharge' the system, which usually takes significantly less time than the previous discharge process. There are two drawbacks of this method: First, the discharge time is determined externally. To avoid the temperature to be out of range, a temperature sensor has to be added to the storage. Second, the storage time is restricted to the time it takes to discharge the storage. In contrast to variant A, it is strongly depending on the thermal isolation (and isolation changes over time).

IX. Measurement Results

The simple thermal model shown in Fig. 1 has been verified using a small 45 l standard household refrigerator. Measurements were conducted with an additional temperature sensor connected to an external temperature controller. The purpose of the experiment was also to analyze the reaction of the tested device on frequent interruptions of power supply. Fig. 6 depicts exemplarily the temperature and power data for a 3 K set-point change. From the measurement data collected, C and R_L were calculated according to the model shown in Fig. 1 as C = 4500 J/K and R_L = 0.4 K/W. The frequent cut from the mains supply did not cause any problems.

Measurement data match the RC modeling well, although data can better be matched with a series of RC elements as suggested in Section VII.

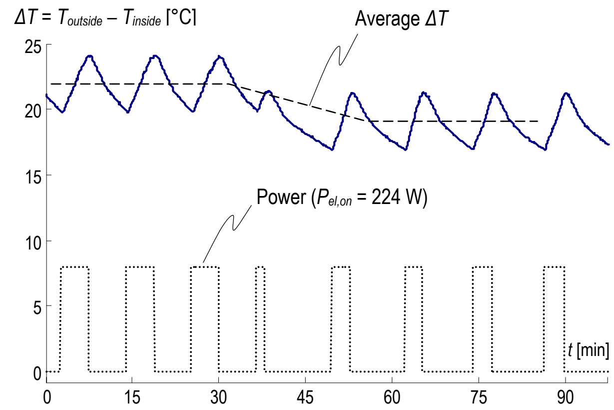

Fig. 6. Measured temperature difference ΔT and power supply to the system for a 3 K set-point change (45 l Refrigerator)

X. Conclusion and Future Work

For effective collective DSM operations, models for the behavior of individual DSM resources are needed. Using these models, an algorithm for DSM operation can schedule load shifts and/or storage charges/discharges that are necessary to adjust the load chart of the collective DSM system in respect to time-dependent needs in the power system.

The key group of loads that can be used for user transparent DSM measures are inert processes, mainly of thermal nature. For this type of loads it was shown that a very simple first order approximation of the behavior of the thermal system is possible. Measurements have been conducted on an example appliance, showing that the model is valid for this case. In order to gain more precision, it is possible to refine the model using multiple RC elements connected in series. The refined model can be applied to any case of thermal storage from small-size refrigerators to whole buildings. Nevertheless, due to the fact that transparent DSM operation does usually imply only small temperature set-point changes, in most cases the simpler first order model can be applied.

The load shift potential of the example appliance is small, therefore a large number of processes with a preferably higher capacitance than that of the measured 45 l refrigerator have to be used within a DSM framework in order to gain substantial influence on the overall power profile.

Two different load shift variants have been introduced for thermal systems. Systems with accessible temperature set-points offer more flexibility in terms of DSM scheduling than those where only the power supply can be interrupted.

Subsequent work will be conducted in two areas: first, the model parameters for a wider range of potential DSM loads will be measured or estimated, and second the integration of the model into a real-time DSM algorithm will be investigated. This algorithm should be able to shape the load profile of the DSM system according to the current needs of the power system and at the same time be able to react on real-time changes in the DSM loads (such as changes in R_L).

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