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Cold storage devices for smart grid integration

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Abstract

The application of cold storages has the potential to act as controllable load within a smart grid environment. To bring this vision into practice several technical conditions have to be fulfilled. The work presented in this paper focused on the development of a suitable cold storage, a high resolution state of charge sensor for the cold storage, means for an effective control of the heat transfer from the cold room to the cold storage, and the control hard and software of cold storage applications for different energy supply modes.
A domestic refrigerator without freezing compartment served as a demonstration model to investigate the interaction of the different components.

Cold storage; loop heat pipe; PCM; state of charge sensor; grid integration

1. Introduction

Refrigeration technology contributes with approx. 14 % to the electric power consumption in Germany (reference year 2009). About 71 TWh were used for domestic refrigeration, supermarket refrigeration, food production, air conditioning, industrial processes, and other purposes. With 24 TWh domestic refrigeration had a share of one third of the electrical consumption of all cooling and refrigeration demands [1]. In contrast to mechanical energy or light "cold" is a product of electrical energy which can be stored by comparatively simple technical means. Therefore, cold storage is an interesting instrument to level out differences in electrical supply and demand within grids with

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fluctuating sources. The theoretical potential of this idea has already been discussed in literature to some extent [2-9]. In contrast to potential estimations practical applications are quite rare, see e.g. [10].

Within the framework of a research and development project ILK Dresden developed and demonstrated components which are necessary for smart grid integration of a refrigeration system. The components were integrated and tested in a domestic refrigerator without freezing compartment. Different operation modes are proposed.

2. Results

In general, four components are required to decouple the temporal conjunction of cooling demand and electrical energy consumption and to use this ability for grid feedback: a cold storage, means to provide the required amount of cold to the refrigerated room, a state of charge (SOC) sensor for the cold storage, and a control unit with an interface to fetch energy supply information.

2.1. Cold Storage

Domestic refrigeration without freezing was chosen as target for the technology development of a cold storage application. This requires cold room temperatures between +4 °C and +10 °C. In general, water is an excellent cold storage material for this temperature region because large amounts of “cold” can be stored in the phase change from solid to liquid (330 J/g) at 0 °C. Unfortunately, numerical calculations and experimental investigations showed that a storage temperature of 0 °C is too high to maintain a cold room temperature of +4 °C at any operation conditions. Therefore an eutectic solution of potassium bicarbonate (storage temperature -6 °C, melting enthalpy 280 J/g) was applied as phase change material (PCM). The cold storage of the demonstration model comprises an insulated HDPE tank, a finned-type evaporator of the cooling unit which replaces the rear-wall evaporator of a standard refrigerator, and the eutectic brine.

2.2. SOC sensor

The knowledge of the state of charge of the cold storage is essential for an effective operation of the cooling unit. However, the problem of SOC determination of PCM storages is not generally solved [11]. Therefore, various principles (electrical, optical, volumetric) of SOC detection were tested experimentally. Finally, a conductive silicone membrane was applied to generate the SOC signal. This material has the property to change its electrical resistance according to the applied strain. To utilize this behavior the cold storage tank was tightly sealed with such a silicone membrane. When the cold storage is charged by ice formation the volume of the PCM increases and the silicone element is stretched. The electrical resistance of the element grows nearly linearly with increasing PCM volume.

Figure 1 shows results obtained from freezing and thawing experiments of a water filled cylindrical tank covered with a silicone membrane at one front side.

Several experiments were carried out to determine mathematical expressions for SOC calculations from measured resistances with satisfying accuracy. In the demonstration model the silicone membrane is covered with an elastic insulating mat. Furthermore, a temperature sensor inside the PCM tank (0 % SOC) and an end position switch (100 % SOC) for calibration purposes contribute to precise SOC values with high resolution.

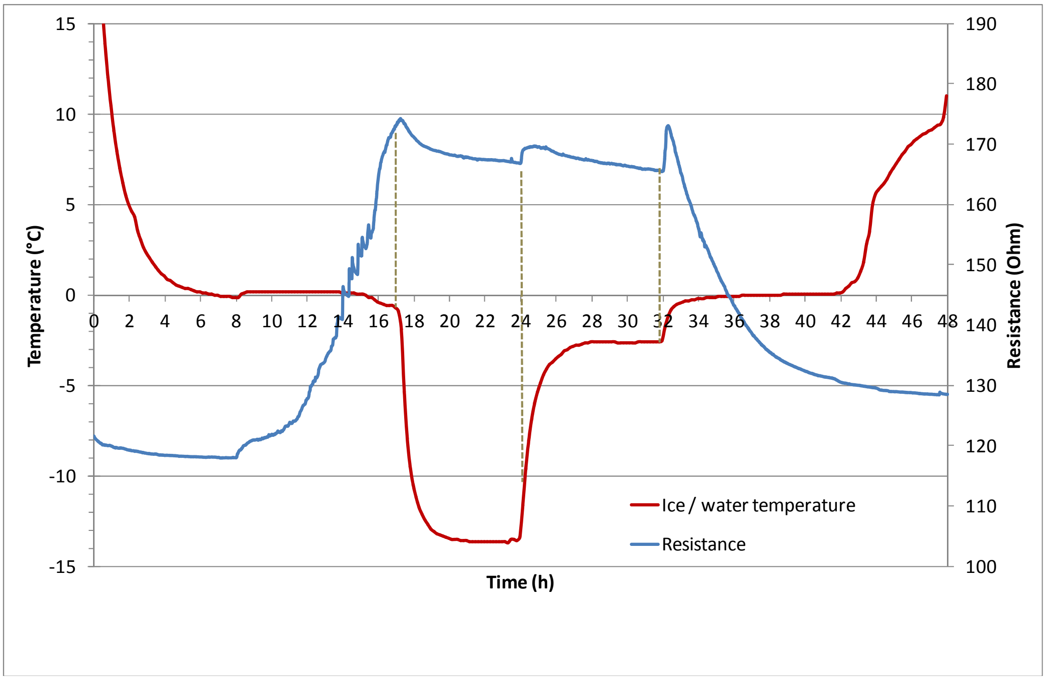

Fig. 1. Water in a cylindrical tank with silicone membrane: temperature of the water and resistance of the membrane during freezing and thawing

2.3. Cold room temperature control

Standard cold room temperature control works in on-off mode in most cases. When the temperature inside the cold room rises too high the cooling unit is switched on and restores the desired temperature. This is in contradiction to the aim of decoupling of cooling demand and electrical energy consumption. In a cooling system with PCM cold storage the melting material provides a continuous “source of cold” at a fairly constant temperature level. However, in most cases the application has quite variable cooling demands. They arise, for example, from door openings, exchange of refrigerated products, or varying ambient conditions. Therefore, it was necessary to integrate technical means for a controlled and adjustable heat transfer from the cold room to the cold storage. As an additional requirement this control system should avoid any electrical power consumption. A valve-controlled looped thermosyphon was applied to fulfill this specification. A sketch of the principle design is given in Figure 2.

The condenser of the thermosyphon was integrated into the cold storage and the cold storage was located above the cold room. The condenser is tilted slightly so that liquid working fluid accumulates at the outlet of the condenser. The connection of the liquid outlet to the evaporator is blocked by a self-operated temperature regulator valve with a temperature sensor inside of the cold room. The evaporator of the thermosyphon which is in close contact to a planar heat exchanger is situated at the rear of the cold room. A return pipe for gaseous working fluid closes the loop.

When the temperature inside the cold room is too high the self-operated valve opens and liquid working fluid enters the evaporator. The excess heat of the cold room evaporates the working fluid and the cold room is cooled. The gaseous working fluid returns to the condenser and is liquefied there again. When the cold room is cold enough the valve closes and the loop is interrupted. The set point of the temperature regulator valve can be adjusted manually. This arrangement makes the temperature control of the cold room independent from electrical energy consumption.

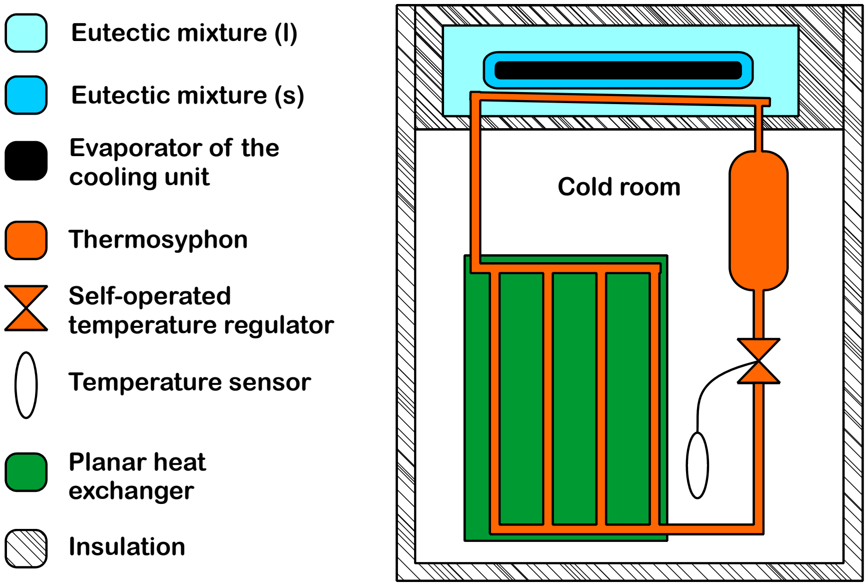

Fig. 2. Principle design of the temperature control arrangement, (l) = liquid, (s) = solid;

2.4. Control Unit

The control unit has several functions: determination of the SOC of the cold storage, detection of grid information, and deduction of switching decisions for the cooling unit. Yet, the control unit is not responsible for the temperature control of the cooling room. This functionality is taken solely by the self-operated temperature regulator.

In the demonstration model a micro controller with display, current source and analog inputs for resistance measurements, real time clock, and Wi-Fi connectivity was used.

2.5. Parameters of the demonstration model

The technical parameters of the demonstration model were as follows:

- standard domestic refrigerator without freezing compartment, 290 l usable capacity;
- capacity of cold storage: 13.5 l;
- latent heat storage capacity: 0.91 kWh;
- area of the thermosyphon evaporator: 0.41 m²;
- working fluid of thermosyphon: R134a.

To reduce experimental effort for the adaption of the cooling unit (determination of refrigerant charge and length of capillary tube) a liquid receiver and a thermostatic expansion valve were integrated. For safety reasons the demonstration model was charged with refrigerant R134a [12] instead of R600a. The demonstration model was equipped with several sensors and a data acquisition system. Figure 3 shows a photograph of the cold room of the demonstration model.

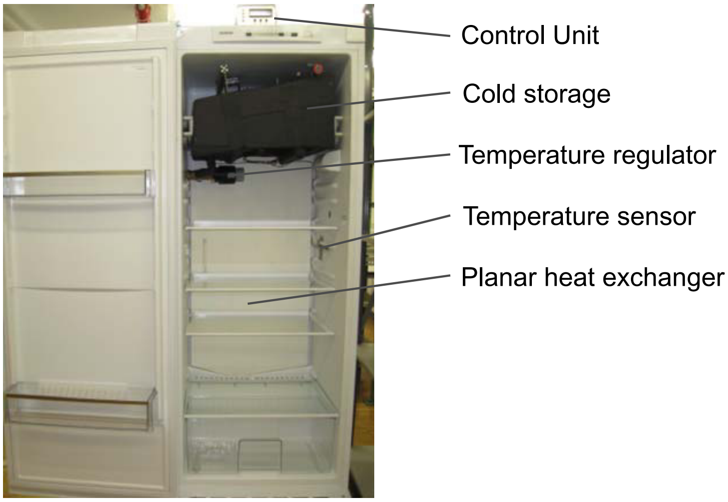

Fig. 3. Cold room of the demonstration model

2.6. Operation of the demonstration model

The following diagram (Figure 4) displays some operation characteristics of the demonstration model.

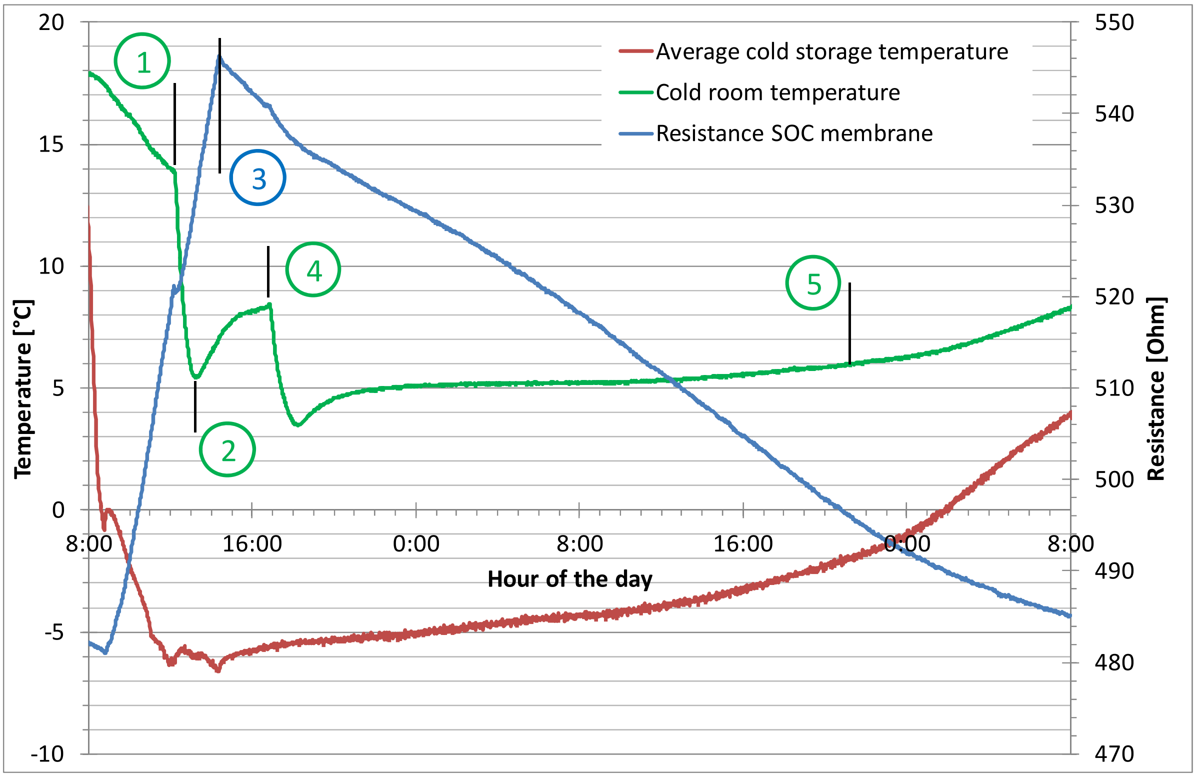

Fig. 4. Operation of the demonstration model

The x-axis in Figure 4 is a time axis and covers two days. The y-axis at the left hand side shows the measured temperatures and is valid for both the red curve (average temperature of two measuring points inside the cold storage) and the green curve (cold room temperature). The blue curve gives the resistance values of the SOC sensor for that measurement (right y-axis). The numbered circles mark special points in time which will be explained below.

The experiment started with a cool down process of the cold storage. The cold room temperature decreased quite slowly because the temperature regulation valve was closed. At point (1) it was opened to a set point temperature of about 8 °C (the manual adjuster was not yet calibrated at the time of the experiment). After that change the cold room temperature showed a rapid decrease to 5.5 °C which was a slight overshooting (2). At point (3) the cold storage was fully charged and the cooling unit was switched off for the rest of the experiment (at 14:31 o'clock at day "one"). Point (4) indicates a correction of the set point temperature at the regulation valve to about 5 °C. The stable temperature of the cold room was achieved again after slight overshooting. Due to increasing cold storage temperature the cold room temperature exceeded 6 °C at 21:05 o'clock at day "two". This point is marked with (5). The time difference between switch-off of the cooling unit and a temperature rise by 1 K (from 5 °C to 6 °C) was 30:43 hours in this experiment. The resistance measurement of the SOC sensor shows a steep increase during charging of the cold storage and a flat nearly linear decrease during discharge.

This and further experiments confirmed the following thermal performance data of the demonstration model:

- operation independent from the grid for more than 24 hours for 5 °C cold room temperature and 22 °C ambient temperature;
- lowest achievable cold room temperature: 0 °C;
- maximum adjustable cold room temperature at ambient temperature of +16 °C: +7.5 °C;
- temperature constancy inside cold room: ±1 K;
- accuracy of SOC determination: ±10 %;
- average power consumption during storage charging: 135 W;
- average charging time within 24 h at 22 °C ambient temperature without load: 3 h 17 min.

3. Discussion

The demonstration model is just one example for a small cooling application with integrated storage capability. The presented technical solutions provide the basis for a great variety of grid connected cold storage applications in terms of size, temperature, and field of application. This includes e.g. normal refrigeration and deep freezing in households and supermarkets, cold stores, IT system cooling, as well as air conditioning applications.

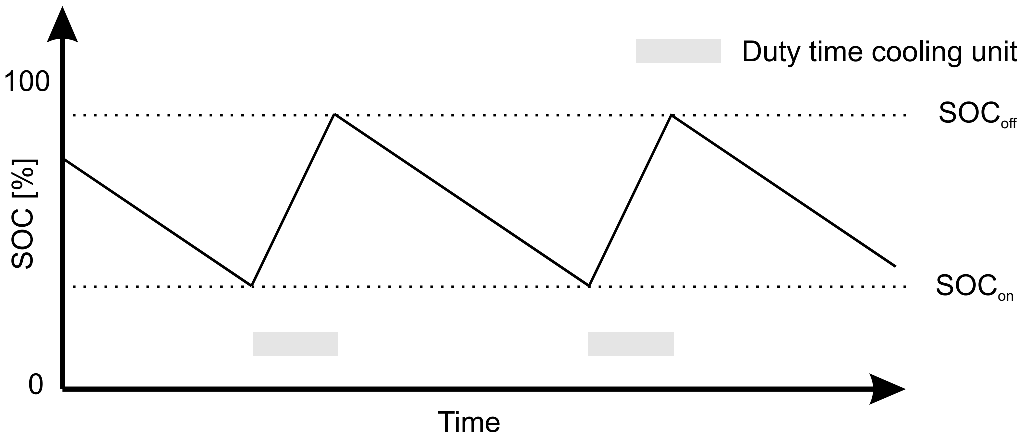

Fig. 5. Operation of a cold storage application without external intervention

The temporal independency of the operation of the cooling unit offers interesting operation options. Figure 5 shows the control of a cold storage application (CSA) without external intervention.

It displays the curve progression of the state of charge of a CSA. The cooling unit is switched on when the SOC falls to a lower limit (SOC_{on}) and is switched off when the SOC reaches SOC_{off} which normally happens when the storage is fully charged. The temperature of the cooling application is not displayed because it is maintained in the requested interval as long as the SOC is above 0 %.

There may be preferred operation times under certain grid configurations, such as a cheap night tariff or the existence of a PV system which generates electricity at lower costs than the grid supply during daytime. If preferred operation times exist two additional switching levels should be programmed in the control unit of the CSA. The operation of the cold storage application could then work as shown in Figure 6.

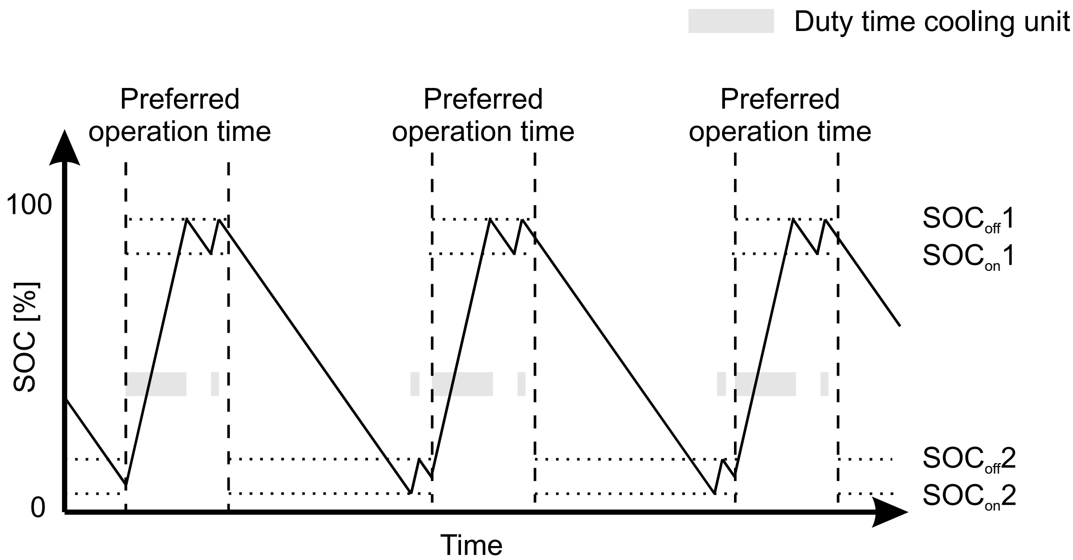

Fig. 6. Operation of a CSA with preferred operation times

There are two SOC intervals for the operation of the CSA: one interval at comparatively full storage levels ($SOC_{off}1$ and $SOC_{on}1$) and one interval at comparatively low storage levels ($SOC_{off}2$ and $SOC_{on}2$). During the preferred operation time the upper SOC interval is valid, the lower SOC interval is effective during remaining times. When the preferred operation time begins the upper interval becomes valid and the cooling unit starts charging the storage. When the preferred time is over a long discharge period begins, see Figure 6. This regime results in a predominant operation of the cooling unit within the preferred operation times. This is illustrated by the gray bars in Figure 6 that mark the duty time of the cooling unit. Most of the electrical consumption of the cooling application is shifted to the preferred operation times in that way.

In case of a data link between an electricity generator (e.g. PV-generator or mini-CHP) and the CSA periods of excess energy can be notified more precisely. Then, the charging process is triggered by an external signal. The CSA demonstration model comprises a Wi-Fi connectivity and an operation mode as shown in Figure 7 was implemented into the control unit. In case there is only an excess energy trigger the upper SOC start level ($SOC_{on}1$) becomes irrelevant.

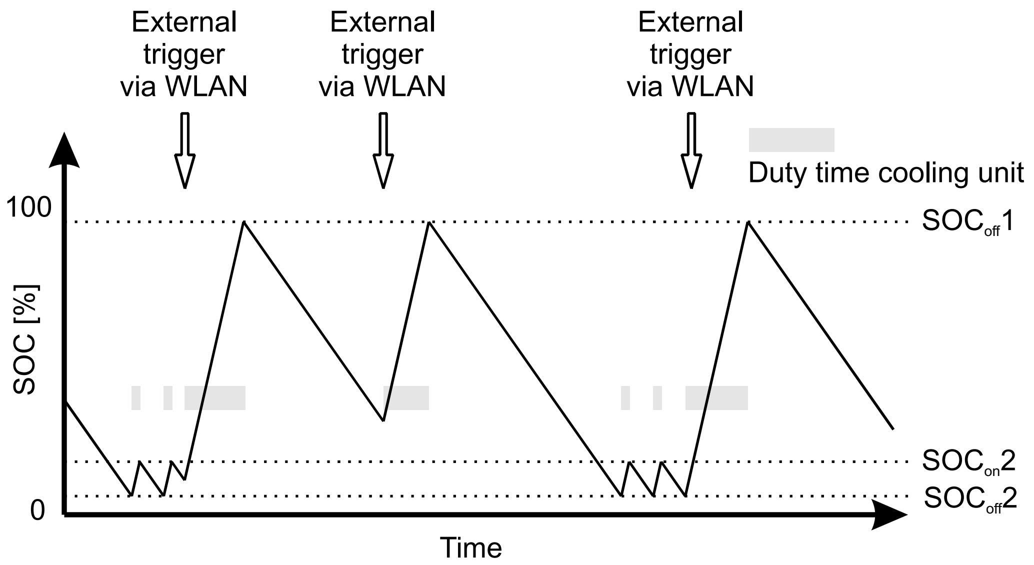

Fig. 7. CSA operation for externally triggered electricity consumption

When the CSA is sufficiently large or many small CSAs are connected via data link to a large capacity group, respectively, these units are able to provide balancing power to fluctuating grids. To provide positive as well as negative balancing power the switching levels for normal operation $SOC_{off}1$ and $SOC_{on}1$ should be located at intermediate charging levels of the cold storage. If positive balancing power is required running CSAs can be stopped immediately (Figure 8). In times when negative balancing power is needed the CSAs in discharge mode can be started without delay (Figure 9).

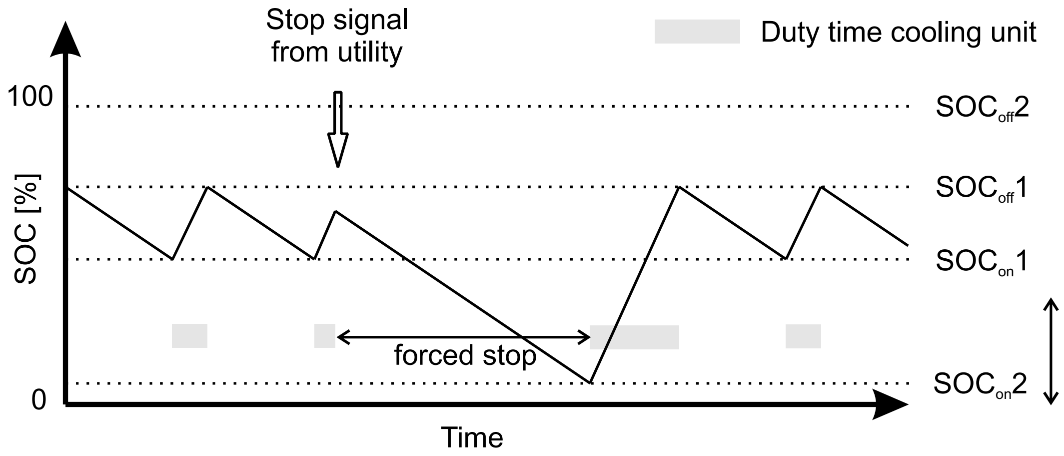

Figure 8: CSA providing positive balancing power

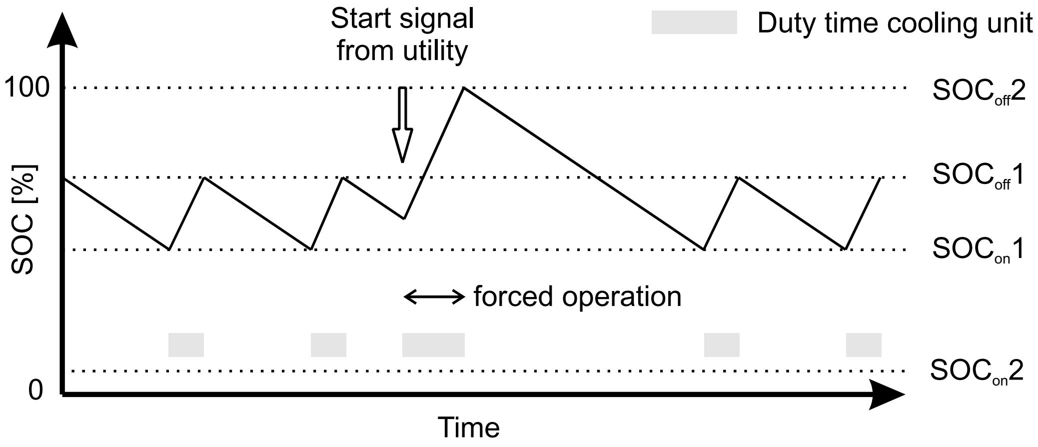

Figure 9: CSA providing negative balancing power

If a group of similar CSAs is applied as balancing element synchronization of the SOC of the individual CSAs may become a problem: after a common start a nearly synchronous stop follows with undesired consequences to the grid. To avoid this case the start signal could be combined with the transmission of individual $SOC_{off}2$ levels which should be stochastically distributed over the population of controlled CSAs. Of course it is also possible to implement fixed but different $SOC_{on/off}2$ levels into the control units of each individual CSA. The variable SOC switching levels are symbolized by the small vertical arrow in Figure 8 and 9, respectively.

4. Conclusion

Cold storage technologies in combination with the required peripheral components (state of charge sensors, control and communication elements) provide the capability to act as a compensating part in energy supply systems with fluctuating sources. Other fields of application are the optimization of the self consumption of electricity from photovoltaic systems, the operation with variable electricity tariffs, and refrigeration systems for regions with unstable energy supply. A high resolution SOC sensor and an independent cold room temperature control are essential for an optimum exploitation of the benefits of a cold storage.

The demonstration model presented in this paper is just one small-scale example for a great variety of conceivable cold storage applications with interesting feedbacks to the electrical energy supply.

Acknowledgement

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