Integration of Heterogeneous Industrial Consumers to Provide Regulating Power to the Smart Grid

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***Abstract*— In this paper, we propose a framework to utilize the flexibility of consumers in the future smart grid with a high share of fluctuating power. The focus is on industrial cases, where a total power consumption of a few number of consumers are large enough in order to bid in the market. Heterogeneous consumers, namely, supermarket refrigeration system and chiller with ice storage have been studied. Two common control approaches which are direct control and indirect control have been formulated. We have simulated different scenarios to compare these approaches for a heterogeneous portfolio of the flexible demands.**

I. INTRODUCTION

Utilization of consumers in power management systems by changing the time and amount of energy usage is called demand-side management (DSM). Nowadays, demand side management is becoming more of interest due to growing share of fluctuating renewable such as wind and solar in power generation. For instance, in Denmark, the goal is to obtain 50% of electricity consumption from wind by 2020. Wind energy is notoriously difficult to both control and store which implies that as the penetration of wind increases, it will become increasingly difficult to maintain balance between production and consumption. Rather than placing the entire burden of maintaining this balance on production units, it has recently been proposed to involve the consumer side in the balancing task. By taking the advantage of modern technologies and communication links, we will move toward a more reliable and flexible grid, so-called smart grid [1]. In the future smart grid, consumption units will have an active role in providing ancillary services to mitigate the effects of intermittent resources.

Various types of consumers ranging from home appliances to industrial enterprises can be utilized in power management system. The focus in this paper is on industrial cases. Flexibility characteristics of the consumers are different. Some consumers are flexible in power consumption. They are able to follow a continuous power reference. Some consumers are flexible in terms of the starting time. When they start to operate, they have a fixed power consumption profile and a specified run time. In [2], a taxonomy of consumers which covers a wide range as ”Bucket, Battery and Bakery” has been presented. Our case studies which are supermarket refrigeration and chiller with ice storage are matched to the ”Bucket” model. A ”Bucket” is an energy integrator which is able to store electrical energy in form of thermal energy while respecting the constraints on the energy level and the power consumption.

Integration of consumers to the grid can be implemented with different policies. In the literature, two main schemes have been studied which are entitled direct control and indirect control [3],[4]. Direct control is a two-way communication approach between the consumers and a control agent based on a contract agreement. In the contract phase, both sides agree on the type of power services and the signals to be exchanged. In this approach, the control agent has direct access to the local controller at each consumer site and it can send command to change their consumption. On the contrary, in indirect control, there is no feedback from the consumers to the grid operator. In this scheme, some incentive signals such as price signal are used to motivate the consumers to change their consumption. Compared to the direct control, this approach does not require heavy computation at the grid operator. However, the main difficulty here is to distribute appropriate price signal. To that end, price responsiveness of the consumers should be estimated. This process deals with uncertainty which is the weakness of the indirect control.

In practice, home owners are not willing to permit their appliances to be controlled directly by a third party. Moreover, handling a large number of small energy consumers with the direct approach will lead to a high computation load which makes it impossible to apply. Therefore, the price signal control is more suitable for controlling residential units. As an example, in [5], several models (FIR, non-linear FIR and ARX) has been proposed to identify the price-power consumption relationship of a price responsive unit. The model then has been used by a price generator which has the objective of following a constant power reference based on the identified parameters. It is shown that by applying the designed controller to a residential space heating, 11% of the mean daily heating consumption could be shifted. However, industrial enterprises are large energy consumers. A few number of them can be aggregated under a centralised scheme to bid in the market.

In our previous work [6], we proposed a controller design based on the direct approach to provide downward regulating power from the consumption units in an optimal way. Downward regulating power can be obtained by decrease in production or increase in consumption. In this paper, We first complete the direct control design by explaining the information flow between the consumers and the controller and simulating more scenarios. Afterwards, We propose a control set-up based on the indirect approach. Our proposed direct set-up is similar to the one in [7]. However, in [7],

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each consumer is modelled as a simple storage without considering the differences between them. Here, we model the consumers such that the differences are taken into account to some extent. In this way, we can utilize the flexibilities in a more optimal way. The rest of the paper is structured as follows. In section II, we describe our case studies. In section III, the direct and indirect set-up are explained. Finally in section IV, different scenarios for simulation are presented and the simulation results are provided.

II. Case Studies

In both supermarket refrigeration system and chiller, a vapour-compression cycle is utilized to remove heat from a cold reservoir and expel it to a hot reservoir. Basically, this cycle has four components including an evaporator, a compressor, a condenser and an expansion valve. Compressor is the main power consumption unit in this cycle.

A. Supermarket Refrigeration System

In supermarkets, a large amount of refrigerated foods which are preserved in cold rooms and display cases can act as a thermal storage to store electrical energy. Temperature of the cold rooms can vary within a certain limits, $T_{cr,min} \leq T_{cr} \leq T_{cr,max}$, without deterioration of food quality. This property opens a space for the system to offer flexibility to the grid. Dynamic of the cold room can simply described by a first order equations:

$$m_{\text{food}} c_{\text{p,food}} \frac{dT_{\text{cr}}(t)}{dt} = \dot{Q}_{\text{load,cr}}(t) - \dot{Q}_{\text{e}}(t) \quad (1)$$

$$\dot{Q}_{\text{load,cr}}(t) = UA_{\text{amb,cr}}(T_{\text{amb}} - T_{\text{cr}}(t)) \quad (2)$$

$$\dot{Q}_{\text{e}}(t) = COP_{\text{refrig}} P_{\text{refrig}}(t) \quad (3)$$

where $\dot{Q}_{\text{e}}$ represents the rate of heat removed from the cold room by the evaporator and $\dot{Q}_{\text{load,cr}}$ is the rate of heat load from the surrounding. m_{food} and $c_{\text{p,food}}$ are the mass and specific heat capacity of the refrigerated foods and $UA_{\text{amb,cr}}$ is the overall heat transfer coefficient between the ambient and the cold room. Power consumed by the compressor is stated by P_{refrig}. COP_{refrig} is the coefficient of performance of the refrigerator. Normally, COP varies based on the temperature difference between hot side and cold side. Here, COP_{refrig} is assumed to be constant. Cold rooms in the supermarket can be seen as a bucket with a time varying leakage. To develop a state space model for the downward regulating power scenario, we define $x_{\text{r}} =: m_{\text{food}} c_{\text{p,food}}(T_{\text{cr,int}} - T_{\text{cr}})$ and $u_{\text{r}} =: P_{\text{refrig}}$ as the system state and input, where $T_{\text{cr,int}}$ is the initial cold room temperature right after it is decided to deliver power services. The following linear state space model describes the energy changing after the delivery time:

$$\dot{x}_{\text{r}}(t) = A_{\text{r}} x_{\text{r}}(t) + B_{\text{r}} u_{\text{r}}(t) + D_{\text{r}} \quad (4)$$

$$A_{\text{r}} = \frac{UA_{\text{amb,cr}}}{m_{\text{food}} c_{\text{p,food}}} \quad (5)$$

$$B_{\text{r}} = COP_{\text{refrig}} \quad (6)$$

$$D_{\text{r}} = UA_{\text{amb,cr}}(T_{\text{cr,int}} - T_{\text{amb}}) \quad (7)$$

B. Chiller with Ice Storage

In air conditioning system, chiller is used to remove heat from a liquid, typically brine, via a vapour-compression cycle. The chilled brine circulates through the air handling units where it absorbs heat from the surrounding air. The conditioned air is then distributed to the building to provide satisfactory comfort level. Depending on the system structure, there could also be other heat exchangers like a water loop between the brine and the air. The basic idea of adding ice storage to this system is to shift the consumption from on-peak hours to off-peak hours. The chiller can run during the night to produce ice. During the day, the chiller is turned off and the ice tank serves the cooling load from the building exclusively. Although the ice tank is primarily designed for load shifting, it can also be utilized for smart grid purposes such as providing regulating power.

The flexibility of ice storage is quite large compared to the cold storages in supermarket due to the large latent heat of water. Moreover, the tank can be isolated in a way that the wasted thermal energy is almost zero. Fig. 1 shows a diagram of chiller in conjunction with the ice storage. By adjusting the three-way valves, the system will be able to operate in different modes. There are three basic operation modes. In direct cooling mode, the ice storage is not utilized and the chiller operates to satisfy the cooling load from the building while in passive cooling, the chiller is off and the cooled brine is provided by melting ice in the ice tank. To charge the ice tank and produce ice, the system operates in charging mode. In order to develop a simple bucket model for the ice storage, we assume that the storage is always in two-phase. This is a reasonable assumption as the thermal energy exchange during the two-phase situation is rather large compared to when there is just water or ice in the tank. By taking this assumption, the following equation governs the rate of change of mass of water:

$$L_{\text{w}} \frac{dm_{\text{w}}(t)}{dt} = UA_{\text{b,it}}(T_{\text{b}}(t) - 0) \quad (8)$$

where m_{w}, T_{b}, L_{w} and $UA_{\text{b,it}}$ are the mass of water, brine temperature, latent heat of water and overall heat transfer coefficient between the brine and the ice tank respectively. 0°C in the equation indicates the temperature of ice. However, the ice storage is solely utilized when the brine temperature is below $0^o C$, otherwise heat transfer could not occur between the brine and the water. Assume there is a linear relationship between the brine temperature and the power consumption as $T_{\text{b}} = \alpha P_{\text{chill}} + \beta$, the ice storage is only in the loop when $P_{\text{chill}}(t) > P_{\text{threshold}}$, where $P_{\text{threshold}}$ is the amount of power which provides brine temperature equals to zero degree. By defining $x_{\text{ch}} =: L_{\text{w}}(m_{\text{w,int}} - m_{\text{w}}(t))$ and $u_{\text{ch}} =: P_{\text{chill}}$ as the system state and input, the dynamic of the ice tank can be represented by the following state space model. $m_{\text{w,int}}$ is the initial mass of water in the tank right after it is decided to deliver power services.

$$\dot{x}_{\text{ch}}(t) = \begin{cases} B_{\text{ch}} u_{\text{ch}}(t) + D_{\text{ch}} & u_{\text{ch}}(t) > P_{\text{threshold}} \\ 0 & u_{\text{ch}}(t) \leq P_{\text{threshold}} \end{cases} \quad (9)$$

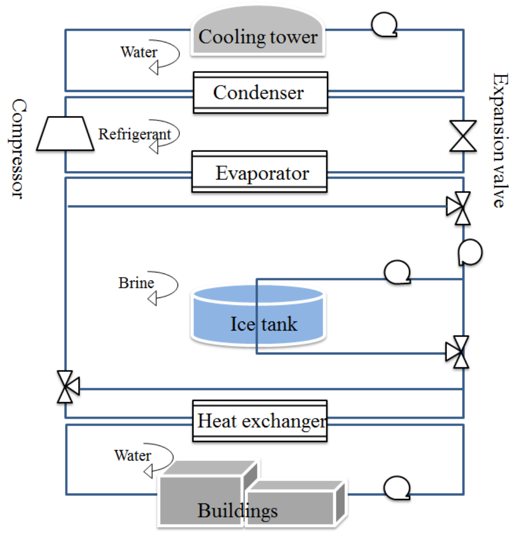

Fig. 1. Simple diagram of chiller in conjunction with ice storage

$$B_{\text{ch}} = -\alpha U A_{\text{b,it}} \tag{10}$$
$$D_{\text{ch}} = -\beta U A_{\text{b,it}} \tag{11}$$

III. Proposed Control Structure

Balance between production and consumption of electricity should be kept all the time in the power grid. Balance responsible parties (BRP) are trading companies which have the responsibility of supplying energy for a number of consumers in their balance area during a given period of time. They trade power in different markets for instance in a day-ahead market. Both loads and generations fluctuate constantly due to the actual stochastic nature of the loads, unexpected failure of generation units or intermittent resources like wind and solar. To maintain the balance instantaneously and continuously, transmission system operator (TSO) procure ancillary services which can include active or reactive regulating power. TSO is a non-commercial organization which is responsible of reliable and secure operation of the whole power grid. By utilizing the flexibility of consumers, BRP will be able to reduce the cost of deviation between the power which is bought/sold one day ahead and the actual consumption/production. In other words, anticipated consumption is becoming more close to the actual consumption. Moreover, BRP can contribute in providing ancillary services by offering upward/downward regulating power which is derived from the consumption units exclusively. In the following, a direct and an indirect set-up for providing downward regulating power are introduced.

A. Direct Setup

A three-level hierarchical structure is proposed which consists of BRP at the top level, a central controller, so-called aggregator in the middle and a number of consumers at the bottom (Fig. 2). The aggregator signs a contract with the BRP where it commits to follow a power reference within a certain period of time, which is called the activation time. Duration of the activation time and the range of power reference are specified in the contract. On the other hand, consumers sign a contract with the aggregator where they commit to follow the power reference they receive from the aggregator. When the

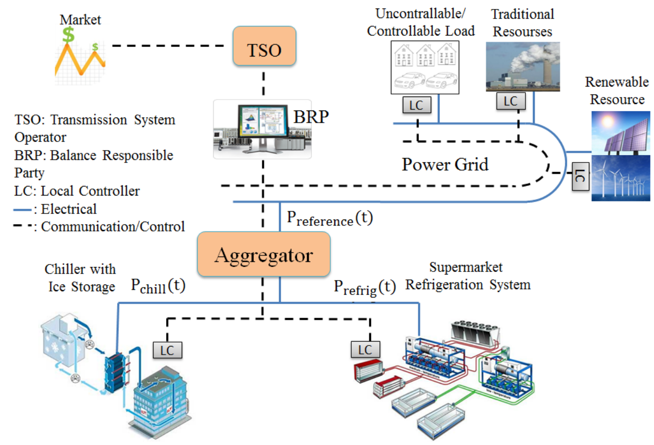

Fig. 2. Direct Control Setup

aggregator is activated, it receives the power reference from the BRP. The task of the aggregator is to split up the power between the consumers in an optimal way with considering the constraint of the consumers. To solve the optimization problem, the aggregator requires a model of the consumers that describes the thermal energy changes in the system. The models can be described by the parameters which are listed in table I. These parameters should be sent to the aggregator when it is activated by the BRP.

TABLE I
Information Flow Between the Consumers and the Aggregator

Supermarket Refrigeration System
- average COP of the refrigeration system
- minimum and maximum power consumption
- maximum amount of energy to be delivered in upward regulating
- maximum amount of energy to be stored in downward regulating
- baseline power consumption before the activation
- average time constant of the display cases
Chiller with Ice storage
- average COP of the chiller in direct cooling mode
- minimum and maximum power consumption
- maximum amount of energy to be delivered in upward regulating
- maximum amount of energy to be stored in downward regulating
- threshold power consumption
- brine temperature in direct cooling mode

Here, we formulate the optimization problem at the aggregator to procure downward regulating power. In this case, the aggregator is actually faced with the problem of storing some extra energy in the thermal storages at its disposal. The more energy can be stored during the activation, the more energy can be retrieved after the activation by turning off the compressors. The optimization is thus formulated as below:

$$\max_{u_r, u_{ch}} (x_r(t_f) + x_{ch}(t_f)) \tag{12}$$

$$s.t.\ x_r(k+1) = A_r x_r(k) + B_r u_r(k) + D_r \tag{13}$$

$$x_{ch}(k+1) = x_{ch}(k) + \delta(k)(B_{ch} u_{ch}(k) + D_{ch}) \tag{14}$$

$$0 \le u_r(k) \le u_{r,max} \tag{15}$$

$$0 \le u_{ch}(k) \le u_{ch,max} \tag{16}$$

$$x_r(k) \ge m_{food} c_{p,food}(T_{cr,int} - T_{cr,max}) \tag{17}$$

$$x_r(k) \le m_{food} c_{p,food}(T_{cr,int} - T_{cr,min}) \tag{18}$$

$$x_{ch}(k) \ge L_w(m_{w,int} - m_{w,max}) \tag{19}$$

$$x_{ch}(k) \le L_w(m_{w,int} - m_{w,min}) \tag{20}$$

$$u_r(k) + u_{ch}(k) = P_{reference}(k) \tag{21}$$

$$T_b(k) \le T_{b,max} \tag{22}$$

$$\delta(k) \in \{0, 1\} \tag{23}$$

where Eq. (13) and Eq. (14) are the equivalent discrete time models. Eq. (22) is considered to satisfy the cooling load from the building. t_f in Eq. (12) indicates the end of time horizon which is equal to the duration of the activation time. As we can see, the above optimization problem is a mixed integer problem due to Eq. (14). The integer value, δ, is associated to conditions in Eq. (9) such that:

$$\delta(k) = \begin{cases} 1 & u_{ch}(k) - P_{threshold} > 0 \\ 0 & u_{ch}(k) - P_{threshold} \le 0 \end{cases} \tag{24}$$

We apply the method proposed by Bemporad and Morari in [8] to convert the above Eq. (24) to the following inequalities:

$$P_{threshold}\delta(k) \le u_{ch}(k) \tag{25}$$

$$-(u_{ch,max} - P_{threshold} + \epsilon)\delta(k) \le -u_{ch}(k) + P_{threshold} - \epsilon$$

where ϵ is a small positive scalar. By defining a new variable $z(k) = \delta(k)u_{ch}(k)$, Eq. (14) can be replaced with the below equation and inequalities:

$$x_{ch}(k+1) = x_{ch}(k) + B_{ch} z(k) + D_{ch}\delta(k) \tag{26}$$

$$z(k) \ge u_{ch}(k) - u_{ch,max}(1 - \delta(k)) \tag{27}$$

$$z(k) \le u_{ch,max}\delta(k) \tag{28}$$

$$z(k) \le u_{ch}(k) \tag{29}$$

$$z(k) \ge 0 \tag{30}$$

B. Indirect Setup

As we mentioned before,in the indirect approach, there is no feedback from the consumers to the grid operator. In practice, the grid operator generates price signals by estimating the price responsiveness of the consumers to change the power consumption. In this paper, we consider a simple set-up as shown in Fig. 3. Since we want to compare the direct and indirect approach, we assume that the aggregated consumption is available for the price generator. Given this assumption, the uncertainty arises from the estimation process is not included in the indirect set-up. The Price generator aims to produce the price signal in a way that the aggregated power consumption follows a power reference,

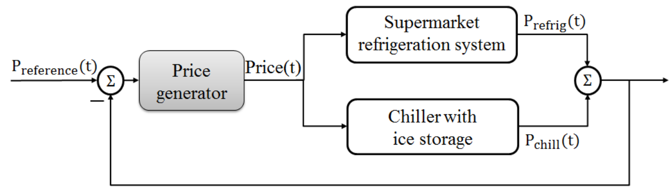

Fig. 3. Indirect Control Setup

$P_{reference}(t)$. Here, a simple PI controller is considered as the price generator.

On the other hand, consumers should be equipped with the price-responsive controllers. A model predictive controller (MPC) could be a good candidate. We propose the following cost functions for the MPC controllers at the supermarket and chiller:

MPC cost function for the supermarket:

$$\min_{u_r} \left(\text{Price(k)} \times \frac{UA_{amb,cr}}{COP_{refrig}} \sum_{k=1}^{N} (T_{amb} - T_{cr}(k)) \right) - \left(\text{Price}(0) \times \frac{UA_{amb,cr}}{COP_{refrig}} (T_{amb} - T_{cr,max}) \times t_{r,off}(N) \right) \tag{31}$$

$s.t.$

$$t_{r,off}(N) = \frac{-m_{food} c_{p,food}}{UA_{amb,cr}} \text{Ln}\left(\frac{T_{cr,max} - T_{amb}}{T_{cr}(N) - T_{amb}} \right) \tag{32}$$

$$T_{cr,min} \le T_{cr}(k) \le T_{cr,max} \tag{33}$$

$$Eq.(1), Eq.(2), Eq.(3), Eq.(15)$$

MPC cost function for the chiller:

$$\min_{u_{ch}} \left(\text{Price(k)} \times \sum_{k=1}^{N} u_{ch}(k) \right) - \left(\text{Price}(0) \times \frac{\dot{Q}_{load,b}}{COP_{chill}} \times t_{ch,off}(N) \right) \tag{34}$$

$s.t.$

$$t_{ch,off}(N) = \frac{x_{ch}(N)}{\dot{Q}_{load,b}} \tag{35}$$

$$Eqs.(25-30), Eq.(16), Eq.(19-20), Eq.(22)$$

where $\dot{Q}_{load,b}$ in Eq. (34) is the cooling load from the building. We again consider a downward regulating power scenario where the price generator decreases the current price to see the increase in power consumption. In this situation, consumers may decide to store some extra energy in their thermal storages at a lower cost. Thus, they can benefit thereafter by turning off their devices when the price returns back to the original value, which is called Price(0) here. The first part of the MPC cost functions represents the cost of energy consumption during the prediction horizon, N, at the lower price while the second part indicates the revenue that can be achieved during the off-time period. $t_{r,off}$ and

$t_{\text{ch,off}}$ in Eq.32 and Eq.35 describe the off-time period for the supermarket refrigeration system and the chiller system respectively. The compressor of supermarket refrigeration remains off until the cold room temperature reaches the maximum level, $T_{\text{cr,max}}$, whereas the compressor of chiller is off as long as the stored energy, $x_{\text{ch}}(N)$, can satisfy the cooling load from the building, $\dot{Q}_{\text{load,b}}$, in passive cooling mode.

IV. Simulation Results and Discussion

In this section, simulation results for the direct and the indirect set-up are presented. Numerical values which are used for the simulation are as follows: $m_{\text{food}} = 200kg$, $c_{\text{p,food}} = 2.01kJ/kg^{\circ}C$, $UA_{\text{amb,cr}} = 0.3kW/^{\circ}C$, $COP_{\text{refrig}} = 3$, $T_{\text{cr,min}} = -20^{\circ}C$, $T_{\text{cr,max}} = -10^{\circ}C$, $m_{\text{w,max}} = 500kg$, $UA_{\text{b,it}} = 1kW/^{\circ}C$, $\alpha = -3^{\circ}C/kW$, $\beta = 15^{\circ}C$, $T_{\text{b,max}} = 8^{\circ}C$ and $u_{\text{ch,max}} = u_{\text{r,max}} = 10kW$. We assumed that there is no ice in the ice storage and the cold storage is at the maximum temperature in the beginning of the activation. Fig. 4 shows the simulation results for the direct control set-up. The activation time is equal to one hour. Simulations are done for the different values of power reference. The upper plots show the thermal energy that is stored in the cold room and the ice storage during the activation while the lower plots show the power that is dedicated to each one. As we can see, depending on the power reference, the aggregator may dedicate the extra power to the supermarket, to the chiller or to both of them. In general, for the low power reference, the aggregator prefers to utilize the flexibility of the supermarket than the chiller. This is because of two reasons. On one hand, for the low power reference, the heat load to the surrounding in the cold room is rather low. On the other hand, with utilizing the chiller in case of low power reference, most of the power is just used to provide $P_{\text{threshold}}$ rather than to freeze the water. Therefore for $P_{\text{reference}} = 5.2kW$, the supermarket is just utilized. In this scenario, $P_{\text{chill}} = 2.3kW$ which is needed to satisfy cooling load from the building. For $P_{\text{reference}} = 6.5kW$, it is still better to use the supermarket since this amount of power is not enough to provide the threshold power. The supermarket requires to consume at least $2.5kW$ to keep the temperature at the maximum level and the threshold power is equal to $5kW$. However, the cold room is saturated after a while which means that the aggregator cannot store energy anymore and the chiller should also be utilized. In this scenario, the aggregator first devotes all the power $(6.5kW - 2.3kW)$ to the supermarket. This reduces the cold room temperature. After that, the aggregator will be able to dedicate $6.5kW$ to the chiller while the supermarket consumes no power. As soon as the cold room temperature reaches $T_{\text{cr,max}}$, the aggregator returns back to the supermarket. Switching between the supermarket and the chiller continues as long as the required energy to be stored in the ice storage. As it is shown, at the end of the horizon, the supermarket is just utilized. When the power reference increases, the more power that is assigned to the chiller, the more energy can be saved. For high power references, the threshold power can be provided for the chiller which leads to store energy without loss, whereas in the supermarket, the loss increases when the power increases. For $P_{\text{reference}} = 12kW$, the aggregator tends to assign the maximum power to the chiller that is equal to $10kW$. However the rest of the power, $12kW - 10kW$ is not enough for the supermarket to maintain the temperature at the maximum level. In this scenario, switching occurs between the two cases just to keep the cold room temperature at T_{max} and the ice storage is mainly used to store the extra energy. For $P_{\text{reference}} = 13.5kW$, the aggregator uses both systems from the beginning of the activation time simultaneously. There is only a switching from the chiller to the supermarket at the end.

For the indirect control set-up, we consider a duration of one hour for the simulation ($t_{\text{f}} = 1hour$). Prediction horizon for the MPC controllers is chosen as: $N = \frac{t_{\text{f}}}{2}$. We simulate a scenario where the price generator wants to follow a $P_{\text{reference}} = 12kW$ while the aggregated consumption is $P_{\text{refrig}} + P_{\text{chill}} = 2.5kW + 2.3kW$. As we can see in Fig. 5, the price generator reduces the price to motivate the consumers to consume more. This causes the significant increase in the power consumption of the consumers such that the aggregated consumption exceeds the power reference. To compensate the deviation, the price generator increases the price consequently and this process continues during the whole horizon. The power consumption of the supermarket and the chiller fluctuates during the activation. The aggregated power consumption cannot follow the power reference exactly. As it is shown in Fig. 6, the average of the power can follow the power reference with a small error.

Simulation results show that with the direct set-up, the aggregator will be able to follow the power reference, whereas in the indirect set-up, this is not achieved. With the proposed indirect set-up, the control agent can follow the energy reference since the average power consumption is close to the power reference. However, this result is obtained by taking the assumption that the aggregated consumption is available for the price generator. In practice, the price generator has to estimate the power which leads to more error. On the other hand, the direct set-up requires the computational complexity and information exchange. Therefore it is not applicable for aggregating a large number of consumption units. Another thing we can see from the results is that with considering a heterogeneous portfolio, the aggregator utilizes the flexibility of the consumers in a clever way. For instance, for low power references, it prefers to use the supermarket while for the high power references, the chiller is solely utilized. For power references between these values, both of them are used by the aggregator. This means that by aggregating a heterogeneous portfolio, the aggregator will be able to offer a wide range of power services in the grid. In our future paper, we will show that a heterogeneous portfolio can do better than a homogeneous one in the direct framework.

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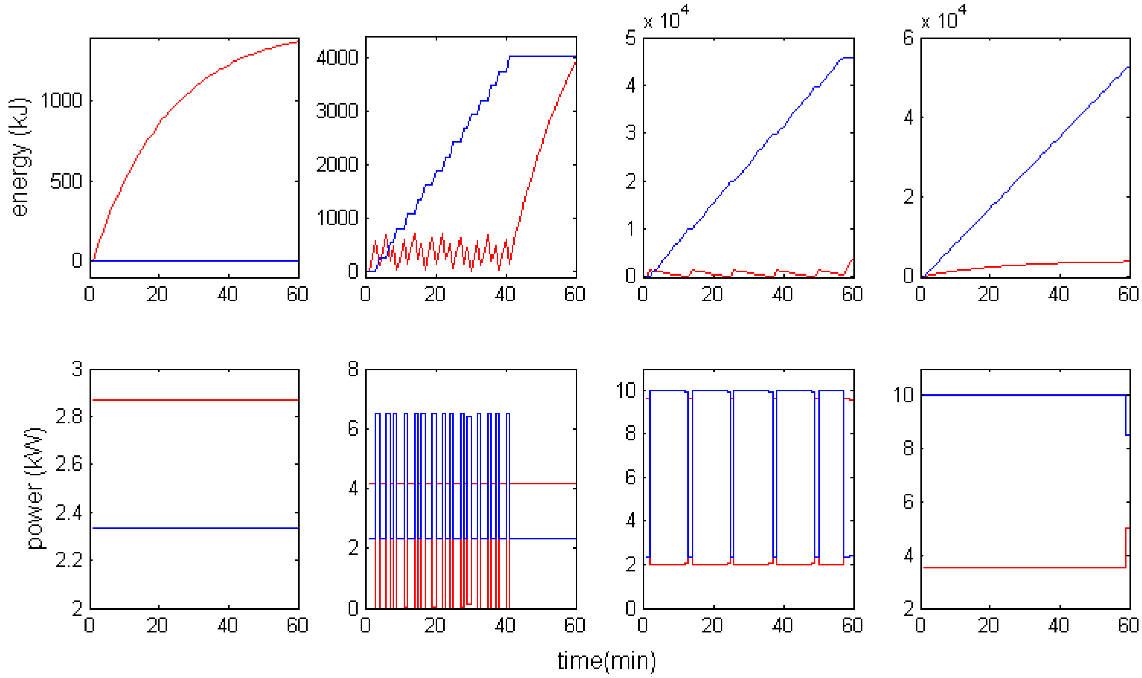

Fig. 4. Direct control set-up: The upper figures show the thermal energy that is stored in the cold room (red) and the ice storage (blue). The lower figures show the power that is dedicated to the supermarket (red) and the chiller (blue). Power references are chosen as $P_{\text{reference}} = 5.2kW$, $P_{\text{reference}} = 6.5kW$, $P_{\text{reference}} = 12kW$ and $P_{\text{reference}} = 13.5kW$ from left to right

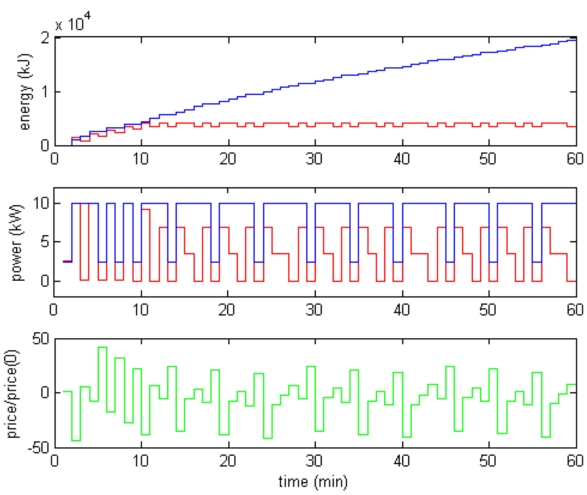

Fig. 5. Indirect control set-up: The top figure shows the thermal energy that is stored in the cold room (red) and the ice storage (blue). The middle figure shows the power that is dedicated to the supermarket (red) and the chiller (blue). The bottom figure shows the price signal divided by the initial price. Power reference is chosen as $P_{\text{reference}} = 12kW$

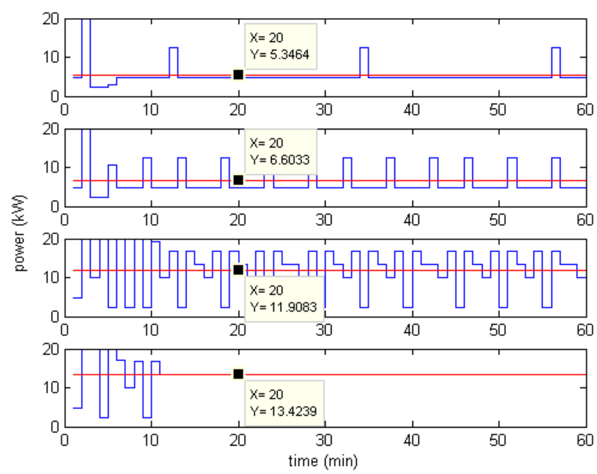

Fig. 6. Indirect control set-up: The aggregated power consumption (blue) and the average of the aggregated power consumption (red). Power references are chosen as $P_{\text{reference}} = 5.2kW$, $P_{\text{reference}} = 6.5kW$, $P_{\text{reference}} = 12kW$ and $P_{\text{reference}} = 13.5kW$ from top to bottom.

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