CONTROLLING AND OPTIMIZING OF ENERGY STREAMS IN LOCAL BUILDINGS IN A FIELD TEST

Vincent BAKKER, Albert MOLDERINK, Johann HURINK, Gerard SMIT
University of Twente – NL
v.bakker@utwente.nl

Stefan NYKAMP
Westnetz GmbH – DE
stefan.nykamp@westnetz.de

Jens REINELT
RWE Effizienz - DE
jens.reinelt@rwe.com

ABSTRACT

Demand side management is one of the novel techniques enabled by introducing ICT in the distribution grid. Controllable assets and energy buffers make it possible to maintain a properly functioning grid, improve the efficiency of the grid and prolong the current grid infrastructure. This work describes the development and techniques of a Home Energy Controller (HEC), located in a building. The HEC is a system that controls (smart) appliances in a building to exploit local optimization potential. Furthermore can it offer flexibility to a (DSO owned) Smart Operator to maintain a properly functioning grid. The paper describes the requirements of the system and provides a system design for the HEC.

INTRODUCTION

Due to increasing energy prices and the greenhouse effect more efficient energy supply is desirable, preferably based on renewable sources. The shift towards a sustainable energy supply is often called the energy transition. The current energy supply chain is based on large scale generation on a number of central places, a tree topology of the grid, a inflexible consumer side of the chain and no buffering, meaning that almost all flexibility is on the generation side. On the other hand, energy generation based on renewable sources is often less flexible than the current generation and a large share of this generation is distributed and connected to/via the lower (voltage) levels of the grid tree.
Therefore, the energy transition urges for more flexibility in other parts of the energy supply chain and will have a severe impact on the grid, probably resulting in high investments. Smartening the grid and transforming the domestic customers from static consumers into active players in the production process can help to overcome these issues. This flexibility on the consumers side (or demand side) of the energy supply chain is called Demand Side Management (DSM). DSM incorporates in this context load shifting/shedding, buffering and distributed generation in the MV and LV network. To reach this flexibility at the large group of consumers, a smart grid is necessary. A smart grid is an ICT layer on top of the physical layer of the grid, monitoring and steering multiple grid assets, including the energy streams in the grid via DSM to exploit the flexibility on the consumer side.
This work is part of the 'Smart Operator' project, in cooperation with a consortium of RWE Deutschland AG (project manager), PSI AG, PSI Nentec GmbH, Horlemann Elektrobau GmbH, Hoppecke GmbH & Co. KG, Maschinenfabrik Reinhausen GmbH, Stiebel Eltron GmbH & Co. KG, the University of Aachen and the University of Twente. The goal of this project is to develop and introduce a hierarchical decentralized and 'smart' steering system, the Smart Operator. This system monitors the entire low voltage grid and - if required - triggers steering signals to prevent potential grid instability and impermissible voltage values. The focus of the grid operation is also to prevent overload of grid assets. To achieve this there are several possibilities, such as operating a storage asset, on-load-adjusting of the tap changer at the substation and exploiting the flexibility of local consumption and/or generation of energy in households and buildings via a set of so called Home Energy Controllers (HECs).
This paper focuses on the development of the HEC, located inside a building. A HEC is able to monitor and control a group of appliances and is a gateway to the houses' optimization potential. For the appliances the HEC determines the optimal dispatch timetable, given a certain optimization objective. Different optimization objectives are applicable, e.g. maximize the self-consumption of locally generated energy. Furthermore, the HEC may adapt the local energy profile to react on incentives and steering signals provided externally, for example by a Smart Operator.
The remainder of this paper is organized as follows; the HEC control system is based around Triana, which is described in more detail in the background section. Furthermore, the background section describes how the Triana approach is applied within the Smart Operator project. Next, the design choices and actual software design is given. We finalize this paper with some results and conclusions.

BACKGROUND AND REQUIREMENTS

The house-level control is based on Triana, a generic control framework for Smart Grids, developed by the University of Twente [1]. It is a control methodology, capable of steering large fleet of buildings. Within this project, only a subset of Triana is used. We first give a generic description of Triana, and then specify which elements are used within this project.
Triana consists of three steps (see Figure 1):
1. In the first step the HEC learns the behavior of the

residents and the influence of external factors like the weather. The expected energy profile and corresponding possibilities to change this profile, i.e. the scheduling freedom, are forecasted e.g. 24 hours ahead. This step is performed locally.
2. The forecasted scheduling freedom is used by a central planner to exploit the optimization potential and to work towards an (global) objective.
3. The third step uses the steering signals of the planning step as input, in combination with information about the current status of the devices in the building and the grid. In this final step, a local real-time control algorithm decides at which times devices are switched on/off, when and how much energy flows from or to the buffers and when and which generators are switched on.

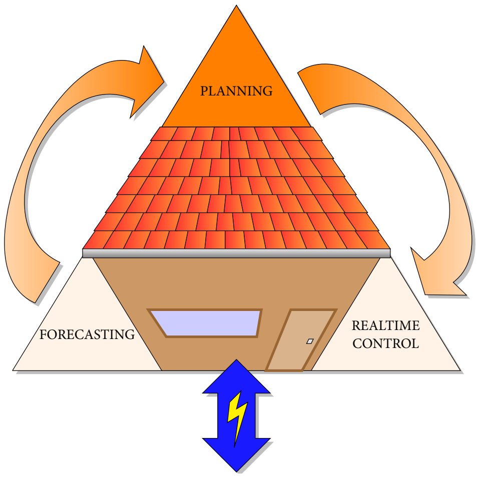

Figure 1. The three steps of Triana

The Triana approach provides a scalable, hierarchical approach to manage a large fleet of buildings. Planning is performed by a hierarchical system consisting of a top planner, multiple levels with intermediate grid planners and at the bottom of the structure the individual building controllers. Using this approach, a large group of buildings can be efficiently controlled.

Smart operator and HEC

Within this project, only a subset of the Triana approach is used. Instead of using a hierarchical planning method, a Smart Operator is used as a (single) central controller. The Smart Operator's main purpose is to keep the grid functioning properly. Moreover, it is not responsible for exploiting the optimization potential of the group of buildings for other purposes than grid stability.
The Smart Operator, described by Willing et al. in more detail [5], can control a) local grid transformers that can regulate the voltage in nine steps of 2.5% each, b) central storage systems and if these two are not sufficient, c) further steerable grid components such as grid separation switches, and d) ask HECs located in the grid to adjust their load.
The Smart Operator continuously requires the expected energy demand of the buildings located in the grid. Therefore, during normal operation, the HECs provide the Smart Operator five different (feasible) usage profiles, including a local preference for each profile. The Smart Operator will analyze the provided profiles and check whether the combination of the profiles will not cause problems. It will give feedback to the HECs which profile to achieve, preferably the profile which is also preferred by the HEC.
Whenever a HEC switches an appliance (based in the currently selected profile/planning), the other available profiles are not valid anymore. More precisely, each profile has a corresponding dispatch schedule for each appliance, and choosing a dispatch for an appliance invalidates other dispatch schemes. Therefore, after each decision the feasibility of the current profiles is checked. If necessary a new set of profiles is provided to the Smart Operator. The HEC thus has to make sure it always has a set of five feasible profiles available for the Smart Operator.
The HEC will frequently generate forecasts and new planning, to keep the Smart Operator informed about future energy demand. This way, the Smart Operator can foresee problems before they occur.

Events

The Triana concept is verified and studied very well using a developed energy stream simulator. This simulator is based on discrete time, with a fixed time interval. At the start of each simulator time interval, a decision by the controller is taken. However, in reality time is not discrete, and the system has to respond when required. Therefore, the original Triana design needs to be transformed from a design with fixed decision moments to a real-time system. Furthermore, it must be able to cope with events, for example when a resident presses a button or changes the thermostat settings. Furthermore, these events need to be handled quickly, to make the system responsive to the residents and make sure the system reacts fast enough to mitigate grid problems.

Flexibility

The HEC must be able to steer a large number of different kind of appliances, since each building is different and has different (smart) appliances installed. Furthermore, the design must be such that new (kind) of appliances can be added easily, without creating a complete new design. Therefore, a powerful yet flexible control algorithm is required to steer a wide variety of appliances.
Furthermore, vendors will create new generations of smart appliances and maybe new standards to communicate with these appliances. The system should be designed such that it is easily adaptable and these new technologies can be plugged in easily.

DESIGN

As said before, the HEC is based around the Triana control methodology. The functionality of each step should be present in the HEC. In Figure 2, a graphical overview of the information and events flowing in the system is depicted. For each step, the (functional) design is described on the following subsections. This results in the overall design, which is described at the end of this section.

Forecasting

One of the advantages of the Triana approach is that it generates a planning, optimizing the energy consumption over a longer period in the future. This way, better results can be achieved than with using purely reactive systems [4]. Furthermore, you can still reserve some flexibility for real-time reactions to the Smart Operator. In order to generate a planning in advance, information about the future to determine the flexibility is needed. For example, to determine the possible runtimes of a heat pump, forecasts of the expected heat demand are required [1].
The information required for each device to generate a forecast is very device specific, and requires different kinds of data. However, generally in this project a forecast is generated based on historical (usage) data and weather data. This process depicted in the top of Figure 2, where environment data (including weather data) is transferred from the Smart Operator (SmOp in the figure) to the building. Here, for each device required, forecasts are generated, which are used in the planning phase.

Planning

During operation, the controller will make decisions on when to switch on/off the appliances, based on the current situation and what is the best option, given the planning. The planning is used to generate the optimal dispatch for each appliance, given a certain objective (for example, maximize the self consumption of local generation). Furthermore, the Smart Operator always requires a set of feasible profiles to select from, in case of emerging grid failure (arrow 2 in Figure 2). The planner will generate a number of feasible energy profiles, from which the Smart Operator can choose. In the Triana approach, each device is responsible for creating a planning. Each device implemented in the system requires a planning routine, which based in the current state, forecasts, device constraints and steering vector generates an optimal dispatch for itself [2]. This steering vector contains values describing how desirable energy production/consumption is for each time interval. The output of this planning is an energy profile. For each device, an energy profile is chosen such that the combined energy profile is optimal.

Real time control

The real-time control step is the end responsible process for actually switching the appliance. It should stick to the planning as good as possible, given the current situation, forecast errors and most importantly, the user comfort. The control loop is triggered on an event, for example a user pressed a button on a device, a timer event or a request from the Smart Operator (see arrow 5 and 8 in Figure 2).
One of the requirements of a control system is that it should be able to cope with a large set of different kind of appliances. Therefore, there must be a generic interface to

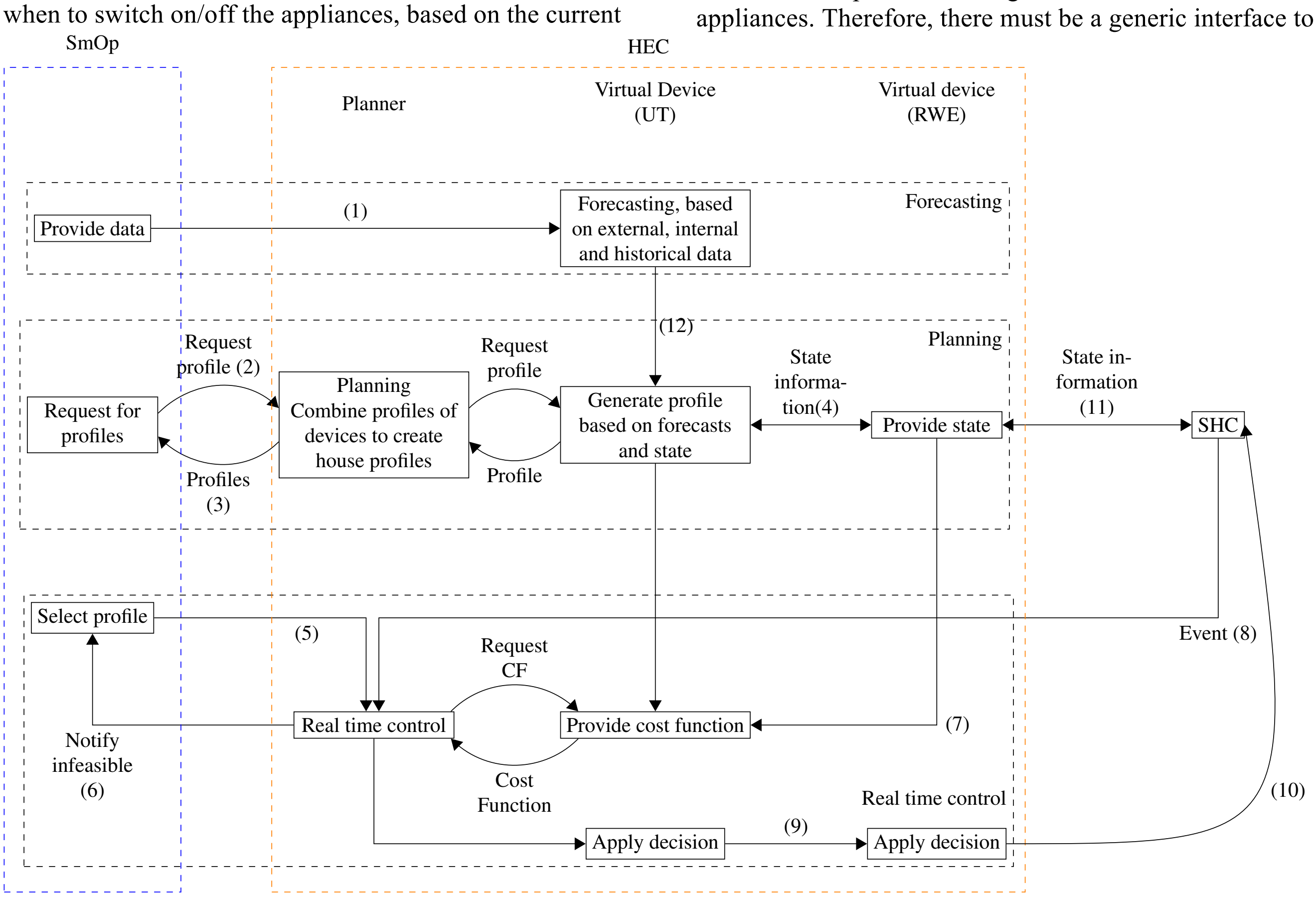

Figure 2. Flow chart

control an appliance, which is applicable and suitable for all kind of appliances. Most control methodologies use the concept of cost functions. A cost function expresses the constraints and preferences of an appliance. At a certain point of time, it describes the possible options an appliance offers and for what (virtual) costs. For example, a freezer might generate a cost function with two options: switch on or switch off, where the preferred option is to switch on, since the internal temperature is close to allowed upper bound.

When a decision has to be made, the controller requests the set of options to all appliances (see Figure 2). Via an ILP the real-time controller choses the best option for each appliance [3]. This option is communicated back to the individual devices. The provided cost functions already include the preferences of the planner, and therefore the ILP can be solved very fast. This ensures a responsive control system.

Software Design

From the design described above, a software design has been created, of which a subset the most important classes is depicted in Figure 3.

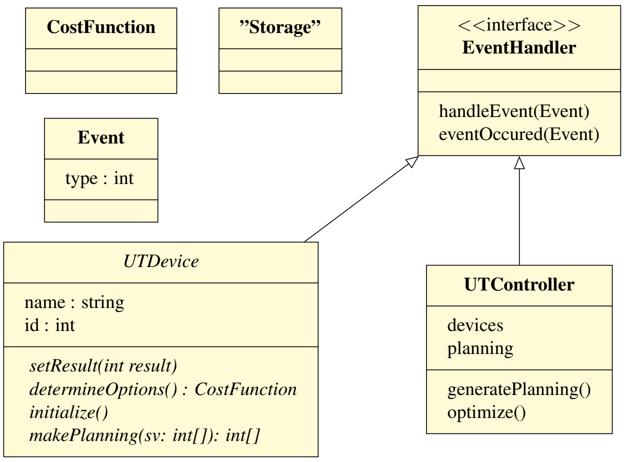

Figure 3. Class diagram of the HEC

The most important class is the UTDevice, which is a representation of an actual device present in the building/house. It has a certain state (on/off, temperature etc.), which determines the possible options. A backend of RWE is responsible for communication with the actual device. It takes care of applying the chosen decision and providing the required state information to the control system. Splitting up the device in two parts makes the system more flexible, allowing an upgrade/replacement of the communication layer.

The UTDevice is an abstract class. This abstract class provides the interface to support the three steps of the Triana approach. The makePlanning() function enables the controller to ask for a planning for the device. Each implementation of the device can than, based on the state, forecast and steering vector (provides as an argument) determine its own best dispatch. Since the forecasting of each device is very device specific, each device is self-responsible for its forecasting routines. Via the storage class, the required historical information can be accessed/stored, including the weather data.

To support the real-time controller step, two abstract functions are used: determineOptions() and setResult(). The determineOptions() requests a cost function from each device, and via the setResult() the selected option is communicated back to the device.

Decisions have to be taken when an event occurs (timer event, press of a button etc.). Therefore, an event class is used to represent different kind of events. The EventHandler interfaces, implemented by both the UTDevice as the UTController ensure that all entities in the system can trigger events and have the routines to handle these events. For example, the RWE backend can notify an UTDevice a button was pressed. The UTDevice will signal the UTController, which will than take a decision.

RESULTS

The Triana methodology can successfully be transformed into a design, suitable for the Smart Operator project. The requirements of always having a planning available, allowing the addition of new (kind) of appliances, and handling events are met. Furthermore, by splitting up the design in a pure control part and a communication part, the system is flexible to support different kinds of communication standards. An implementation of the design will be tested in a field trial Summer 2013 in a kindergarten in Haren, Germany with an evaluation of the chosen soft- and hardware.

AKNOWLEDGEMENTS

This research is conducted within the DREAM project (11842) supported by STW, Deutsche Bundesstiftung Umwelt (project 30466) and Stadt Haren.

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