A fully operational virtual energy storage network providing flexibility for the power system

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Abstract

Swisscom Energy Solutions has developed and realized a virtual energy storage network “tiko” which connects more than 10000 electric heating devices throughout Switzerland, such as heat pumps and hot water boilers (tiko.ch). A central back-end system communicates with locally installed metering and control devices via the mobile communication system and in-house power line carrier technology. All loads are permanently monitored and controlled in a way that ensures the consumers’ comfort is not affected. The flexibility of the aggregated load is used to provide primary and secondary control for the power transmission system operator Swissgrid. Since 2014 the system is fully operational, technically and commercially. The project is realized in partnership with electric utilities and heat pump vendors. It is one of the most advanced smart grid installations in the world and the first one that successfully enables small private loads to participate in realtime power grid frequency control. The customers benefit from various functionalities accessible via webpage and smartphone applications. Users can see the instant and historical power consumption of their heating devices and benchmark themselves with other participants in the tiko network. The app allows users to easily put the heating system in an energy saving mode. Users receive alarms whenever the tiko system detects a problem, before they suffer any loss of comfort. Electricity suppliers and distribution grid operators benefit from increased customer retention, access to realtime consumption data, extension or replacement of the standard ripple control, and the possibility of active network management.

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Keywords: demand response; demand management; energy storage; primary control; secondary control; frequency control.

1. Introduction

In an electric power system, production and demand of energy has to be balanced at all times. Traditionally, the demand is taken for granted and the control of the demand/generation balance is done on the generation side only. Conventional power plants adapt their power output dynamically in order to ensure the system balance. Alternatively, part of the balancing can be done on the demand side by controlling electrical loads. One important prerequisite for demand management is an infrastructure that enables monitoring and control of the loads. But influencing electrical loads means also that related services or processes might be affected. Therefore only limited industrial, commercial, and residential loads are suitable for demand management applications. In the residential sector, heating systems turned out to be a reasonable option for demand management since the heating of houses is usually not time critical. Thanks to the thermal inertia of heating systems and houses, it is

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possible to slightly displace the operation of heating systems without significantly influencing comfort in the building.

Swisscom Energy Solutions has taken this idea and realized a virtual power plant that connects more than 10000 electricity-based heating devices such as heat pumps, direct electric heaters, night storage heaters, and hot water boilers throughout Switzerland. The total installed power of the pool adds up to 50 MW. Figure 1 shows a map of tiko participants. This paper outlines the basic concept, practical application, and operational experience with this virtual power plant that has been gained since its market entry in 2014.

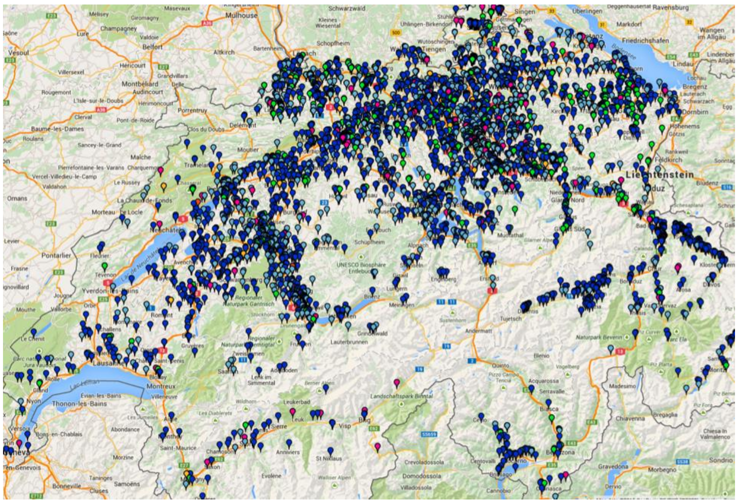

Fig. 1. tiko participants in Switzerland.

2. Demand Management

In the following subsections, a number of potential applications of demand management are outlined. In contrast to demand response, where electricity customers are incentivized to react on certain signals, demand side management directly controls the loads in a top-down approach [1].

2.1. Peak Shaving

One of the most obvious and simplest applications of demand management is peak shaving. The typical aggregated load of a larger group of customers shows clear peaks over the day. In central Europe, peaks in the consumption of residential customers are usually observed at noon and in the evening. Electricity suppliers have an interest to avoid buying electricity at high price periods. Distribution grid operators are usually penalized according to their peak exchanges with the superior grid level. Therefore ripple control systems are used throughout Europe that allow devices to operate only during certain hours a day. Traditionally, electric hot water boilers in Switzerland are blocked by the utility’s ripple control during the day, and relieved for charging during the night. Also heat pumps are often connected to ripple control clusters that are used for example to block heat pumps during peak consumption hours.

2.2. Ancillary Services

In an electric power system, production and demand of energy has to be balanced at all times. Traditionally, the control of this balance is done on the production side. Power plants react on control signals from the grid operator, or directly react on the system frequency by changing their power in-feed to the grid accordingly. Demand management systems can be used to contribute to the system balance by actively managing electric loads instead of generation. If ancillary services should be generated at the demand side, loads have to be actively supervised and controlled on a realtime basis.

Within the Continental European interconnection, ancillary services for active power balancing are divided into three different qualities: primary, secondary, and tertiary control. In the following, we focus on the two close-to-realtime applications primary and secondary control. Tertiary control is not a control in the technical sense, but manually activated power, ramping up or down within 15 minutes after call.

In most European countries, ancillary services are organized in a market-oriented manner by the transmission system operator [3]. Possibilities of entering these markets with virtual power plants based on demand management of decentralized resources are limited. However, within the past years, ancillary services markets have been opened for alternative providers in many countries. In Switzerland, a pooling model has been introduced in 2013 that allows alternative providers to participate in ancillary service markets even on the lowest voltage level with residential loads.

2.2.1. Primary Control

Primary control is directly related to the system frequency. Whenever the frequency exceeds certain limits around 50 Hz, primary controlled units adapt their active power exchange in a linear manner related to the frequency deviation [2]. The time to achieve the required power is limited by 30 seconds. In case of full activation of primary control at frequency deviations of +/-200 mHz or more, the full power has to be activated for at least 15 minutes (in some countries 30 minutes). The required frequency response defined by Swissgrid is shown in Figure 2.

In Continental Europe, primary control is the most dynamic and therefore also the most advanced ancillary service to produce. It directly acts against frequency deviations and helps to stabilize the system immediately. In normal operation, frequency deviations are low and only a small part of the primary control power is activated. Typically, the system frequency crosses 50 Hz every few seconds or minutes, which means that the sign of the activated primary control power changes in a similar manner. Figure 3 shows a typical frequency measurement and related primary control activation.

Primary control is a defined ancillary service product that is procured by the Swiss transmission system operator in weekly auctions. The product is symmetric, which means that only symmetric capacities can be offered. Prequalified ancillary service operators bid their capacities, and in case of acceptance they have to provide the capacities during the following week. Positive and negative power has to be activated depending on the measured frequency excursions. For demand response systems, it means that loads have to be switched off or on to change the total consumption of the pool accordingly.

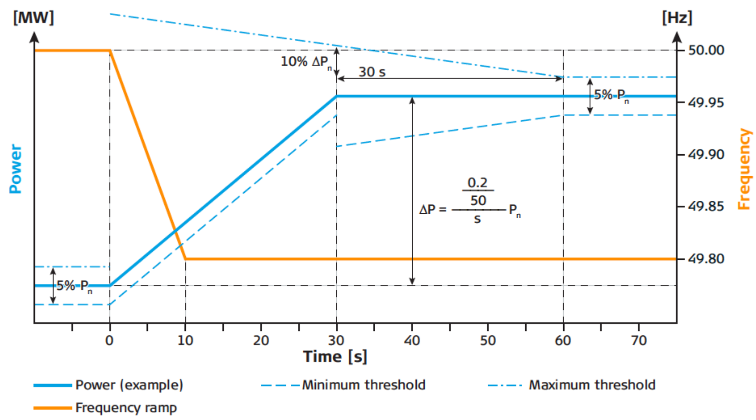

Fig. 2. Primary control quality criteria [4].

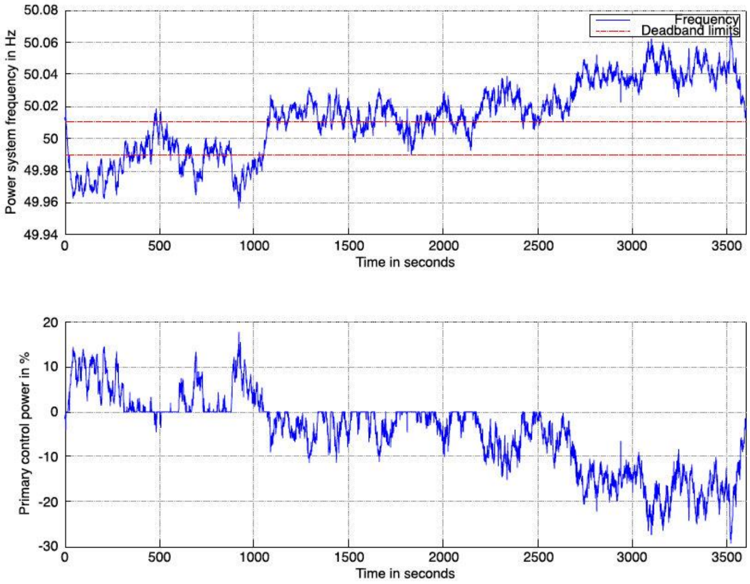

Fig. 3. Example for power system frequency and related primary control activation.

2.2.2. Secondary Control

Each transmission system operator is in charge of keeping its control area balanced in terms of actual power exchanges compared to scheduled exchanges [2]. This is the main purpose of secondary control. Scheduled exchanges are compared with measured cross-border flows, and the difference is compensated using a central secondary controller that processes the control error and sends activation signals to power plants or demand management systems. These actors adapt the total power injection or consumption according to the received signal. In Switzerland, the timeframe for following the secondary control signal is 20 seconds. Beyond a defined tolerance area around the signal (see Figure 4), the integrated absolute error must remain below 1% [5].

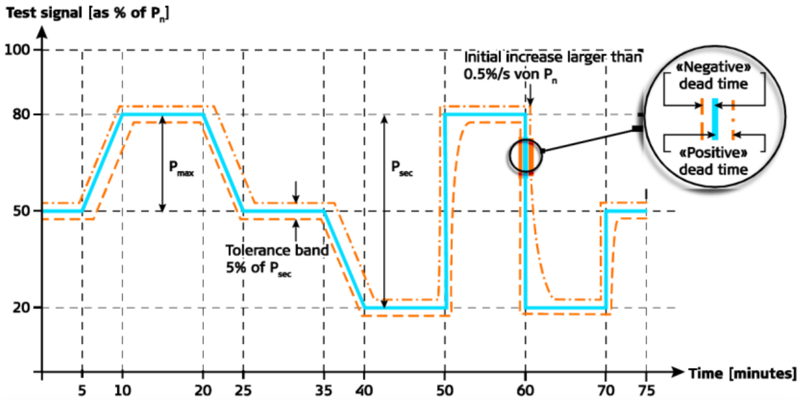

Fig. 4. Secondary control quality criteria [5]. The positive dead time is limited to 20 seconds.

Compared to primary control, the secondary control signal changes significantly slower, but more energy is activated in average. Similar to primary control, symmetric secondary control capacities are auctioned on a weekly basis. In Switzerland, activation of the secondary reserves is done pro rata, which means that all resources are activated at the same percentage at the same time. This results in a continuously changing signal as shown in Figure 5.

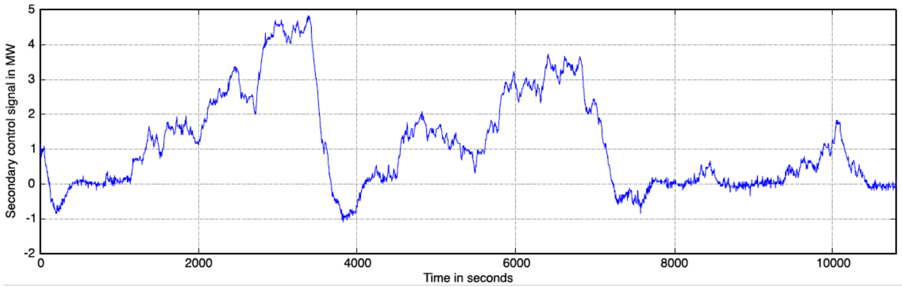

Fig. 5. Typical secondary control signal during three hours.

2.3. Application for Heating Devices

Residential heating systems are usually subject to high thermal inertia in the range of hours or even days. Especially modern, well-insulated houses with floor heating show high inertia. Blocking central heating devices in private homes for short times usually does not affect comfort. At the same time, electricity based heating systems have high nominal power and consume a significant amount of energy. Compared to other devices in a private residence, electricity based heating gives a high amount of flexible energy that can be controlled with very limited impact on customer comfort. Therefore heating systems are in general well suited for being used in demand management systems. However, device properties, local weather conditions, thermal characteristics of the house, customer behaviour, and other parameters have to be managed on an individual level in order to ensure customer comfort, both in terms of room temperature and hot water. Continuous estimation and monitoring of the customer comfort allows the operator to fully exploit the available flexibility without keeping too much security margins, and avoids unacceptable comfort loss.

It is obvious that most common electricity based heating systems, such as heat pumps, cannot be controlled in a way that their power consumption follows a dynamic signal. However, collecting a high number of on/off-type devices into a pool, thereby establishing a virtual power plant, allows modulation of the total power consumption of all devices in a dynamic and precise way. This is the key approach for providing ancillary services with electricity based heating systems. Symmetric ancillary services products require positive and negative activation, which means that the system must be able to increase or decrease the total power consumption of all connected loads. Positive activation (reduction of consumption) can be done by switching off systems that are heating. Negative activation (increase of consumption) can be realized by switching on devices that are requested to heat.

3. The tiko System

3.1. Overview

For the outline in this paper, the tiko system is divided into five parts (see Figure 6):

- Actors and sensors: two basic components are used to connect a heating device to the tiko network. A metering and control device, so-called “K-Box,” measures the active power consumption of the connected device. It also contains a relay that is used to control the device in an on/off manner. Metering and control actions are communicated within the house on power line carrier (PLC) basis.
- Gateway: A second box, so-called “M-Box” serves as a gateway between the in-house PLC network and the mobile communication network, which connects the device to the backend system. An industrial 3G network or the Internet of the customer can be used to transfer data between the customer residence and the backend system.
- Backend: A backend system collects all information about the connected devices, combines it with additional information such as parameters derived from consumption history, local weather conditions, individually estimates the state of each heating device and decides upon allowed and necessary control actions. It controls the devices in a way that the overall pool consumption follows the required activation signal.
- Frontend system: Customers can monitor the consumption of their devices in realtime, receive alarms if the devices show unexpected behaviour, and they can realize energy savings by putting the devices in an energy saving mode. Also, customers have the chance to benchmark their consumption with other participants in the tiko network.

- Other systems: Besides the basic functionalities, the tiko system is supported by various other components such as rollout and installation tools, customer support portals, ERP system, energy scheduling, capacity planning, and operation cockpits for primary and secondary control.

Fig. 6. tiko system overview.

3.2. Actors and Sensors

Most grid operators require that all technical units of a virtual power plant have to be individually monitored in realtime when used for primary or secondary control. Therefore, all heating devices in the tiko network are connected to the grid through a so-called “K-Box” (Figure 7). This box is a three-phase, class B power meter that measures the active power consumption of the device every second. It can be installed in 400 V systems with currents up to 63 A. The measured power is transmitted through PLC (in-house) and 3G to the backend system and further processed for estimating the device state and flexibility, and to calculate control decision variables. Also, the aggregated power of all devices has to be sent to the transmission grid operator in order to enable online supervision of procured reserves.

Fig. 7. Picture of K-Box (left) and M-Box (right).

Additionally to the power meter, the K-Box contains a relay that is used to switch the heating system. Note that the K-Box does not disconnect the main supply of the heating device. Instead, the relay contact will be integrated in the ripple control circuit that is traditionally used by the electric utility. The utility can always block the device whatever tiko does. Only in times when the utility allows the device to operate may tiko shift the consumption.

Another sensor that can be connected to the tiko system is a temperature sensor. It is only used for special applications such as commercial and industrial heating systems. Residential tiko installations do not need temperature sensors.

3.3. Gateway

The K-Box power measurements are sent to a communication gateway called “M-Box” (Figure 7). Between the K-Box (usually installed in the basement of the house) and the M-Box (plugged in the living area), power line carrier (PLC) is used. The M-Box transfers information from the PLC to a separate, industrial 3G mobile communication network. If no 3G signal is available, the M-Box can also be connected to the customer local area network through an Ethernet plug. Besides these modules, the M-Box also contains a frequency measurement unit.

3.4. Backend

Heating devices are blocked by switching the relay in the K-Box. Operating devices will stop heating, and not operating devices will be prevented from starting. The simple on/off interface allows tiko to connect all common types of heat pumps and other heating devices to the tiko system. Today more than 5000 heat pumps from more than 80 different vendors are connected to tiko. Another 5000 heating devices such as direct electrical heating, electrical storage heating, and hot water boilers are connected as well, all using the same technology (K-/M-Boxes).

The main core of the tiko system is an algorithm that determines the control actions for the devices. Individual control decisions for all devices in the system are derived from various parameters ensuring that the influence on customer comfort does not exceed predefined limits. Big data analysis is used to determine the usual behaviour of the heating devices depending on local weather conditions and other parameters. Individual, dynamic device limits are combined with fixed limits, which apply to all devices of a certain category, for example air-water heat pumps or direct electric heaters. Besides comfort limits, switching limits prevent the system from performing too many switching actions per device and day. Switching limits have been developed with heat pump vendors, independent experts, and heat pump compressor producers. The switching limits relate not only to the number and duration of switches per day, but also to the actual moment of a switch during a heat pump cycle. Figure 8 shows an example of a control action performed by tiko on an air-water heat pump. In this specific case, comfort limits allow an interruption to the heating cycle for 52 minutes. The typical heat pump is switched less than five times a day by tiko in average.

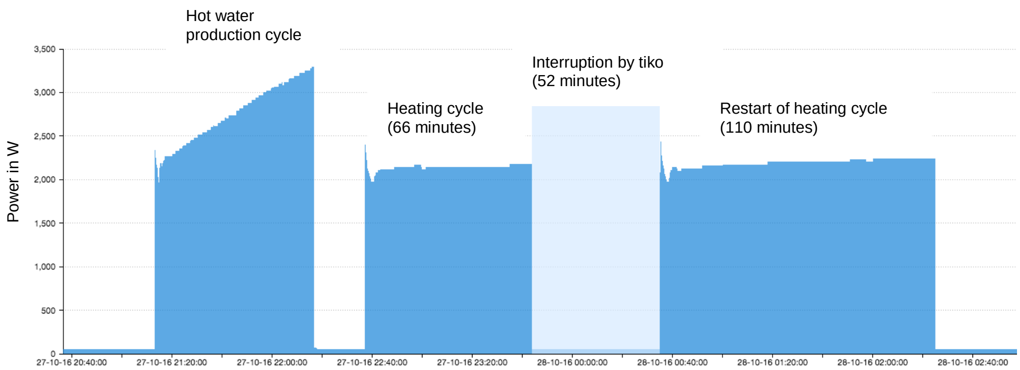

Fig. 8. Heat pump cycle interrupted by the tiko control.

3.5. Frontend

The frontend system allows the customer to use tiko and experience various functionalities.

- Visualisation: The frontend web and smartphone applications allow the homeowner to see the instant and historical consumption of heating devices, in resolutions up to 5-minute. The data can also be downloaded for further analysis.
- Eco Mode: Users can reduce the energy consumption of the devices on selected days by 40% or 60% compared to normal consumption if the building is not used. It can be done also remotely when travelling using the tiko app. When Eco Mode is used, the temperatures in the house will be reduced significantly.
- Alarming: The power consumption of the devices is continuously observed and compared to the usual behaviour of the system at given local weather conditions, as well as to the behaviour of other tiko participants in the region. Whenever the power consumption is unusual, the customer will receive an alarm message by SMS, email or push message.
- Benchmarking: The tiko app enables users to benchmark their heating system’s energy consumption with other homes in the tiko community.

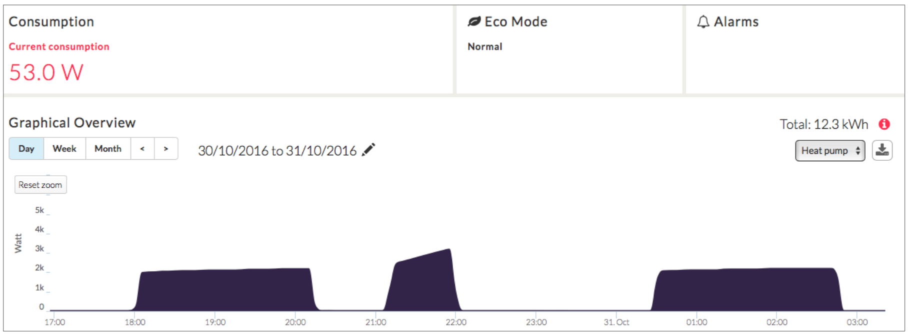

Fig. 9. Screenshot of the tiko web application.

3.6. Other systems

A number of additional software modules have been developed that allows tiko to rollout and to operate the system in an efficient manner:

- Rollout and installation planning tools allow coordination of home installations and management of the logistics.
- An ERP system and a customer support portal allow management of customer calls and communicate with tiko participants.
- Production screens for primary and secondary control enable to supervise production, receive alarms in case of failures or mismatches or other issues.

3.7. Value Propositions

For the homeowners, the main value propositions are transparency of their energy consumption for heating, comfort security ensured by the alarming system, and the possibility of realizing energy savings using the Eco Mode, as outlined before.

tiko is offered to residential customers in partnership with utilities and vendors of heating devices. Utilities offer the service to their customers thereby strengthening the customer relation and increasing customer retention. Utilities can also benefit from the detailed consumption data provided by the tiko system. In some areas of Switzerland, the electricity demand for heating represents up to 40% of the total load during the cold season. Having detailed consumption data available at close-to-realtime allows tiko not only to identify and categorize the customers better, but also to improve forecasts and schedules.

Vendors of electricity based heating devices, such as heat pumps, direct electric heaters, or electric night storage heaters can also benefit by providing this additional service to their customers. The collected consumption data enables analysis of the operation of a large number of devices spread out all over the country in detail.

3.8. Integration Aspects

Connecting such a large number of devices in an economically reasonable way is only possible because the same technology is used for all device types. The standard on/off ripple control interface is available on almost all devices installed in Switzerland and can be utilised with the same hardware component. Also, the installation is carried out quickly and related costs are acceptable. A deeper integration with the internal control of the devices would result not only in higher technical complexity but also larger installation effort. Handling of many different, proprietary solutions would also be a significant burden for software integration. The additional flexibility that could be gained with deeper integration of the devices is low and does not justify the related costs.

Switching the devices in an on/off manner is done in a way that does not significantly influence the devices' efficiency or lifetime. As mentioned above, device specific limits are considered in the control algorithms that ensure not only the customers' comfort but also the properties of the devices. Swisscom Energy Solutions has made in-depth investigations together with scientists and experts from industry into the influence of tiko switches on the operation of heat pumps. Up to now, the conclusion is that tiko does not significantly influence the overall performance of heat pumps. Thanks to the transparency that is given by the tiko system and made available to heat pump manufacturers, many heat pumps could be improved by changing control parameters.

4. Operational Experience

4.1. Monitoring of Heating Systems

The detailed power consumption data collected by the tiko system allows tiko to draw conclusions related to the performance of heating systems. Unfavourably parameterized heat pumps can be identified based on their individual consumption patterns. For example, heat pumps with very short cycles and too many starts per day can be identified and parameters can be adjusted. Indicators can be derived from the power consumption and other data that may point to emerging problems or the need for service. First steps in exploiting consumption data for device analysis have been made. Systematic big data analysis applied for preventive service of heat pumps is under development.

4.2. Prequalification

Resources that want to participate in the ancillary services market have to pass a technical prequalification test. The test is specific for the service that should be offered. Technical prequalification requirements are defined by the transmission grid operator, and they have to be proven by the applicant by performing a prequalification test [4,5].

The tiko system is prequalified for primary, secondary, and tertiary control in Switzerland. The technical prequalification test for secondary control was passed in 2013, and since 2014 this service is offered and produced on a regular basis. In 2016 the system was also prequalified for primary control, which has been produced as an alternative to secondary control. Finally the system was prequalified for tertiary control, which represents another commercial fallback option if both auctions, for primary and secondary control, were not successful.

4.3. Technical Operations

The tiko system is actively participating in the Swiss markets for primary and secondary control. The system is operated from the tiko control centre 24x7 hours/week and has reliably delivered the services at all times since 2014. The quality of the service is permanently analysed, monitored, and compared to the prequalification criteria. Figure 11 shows a screenshot of the production screen for secondary control. Figure 12 shows an example of primary control.

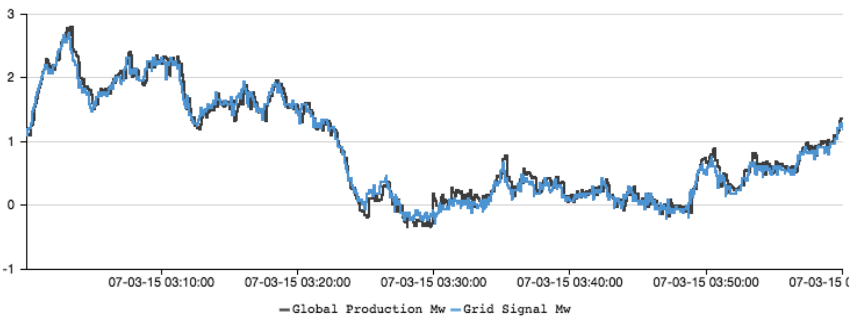

Fig. 11. Screenshot of the tiko secondary control monitor. Blue: control signal. Black: tiko response. Values in MW.

The main operational challenge is capacity planning for creating the market bids. Auctions are done on a weekly basis for the following week. The capacity of the virtual power plant depends heavily on the heating demand, which is in turn depending on the weather conditions. Not only temperature, but also solar radiation and the variations of the temperatures during the day are important factors in determining the heating demand. At the end, the challenge is to forecast the weather up to 12 days in advance. Since this cannot be done precisely, dynamic security measures have to be considered and capacity planning has to be performed in a careful, conservative way.

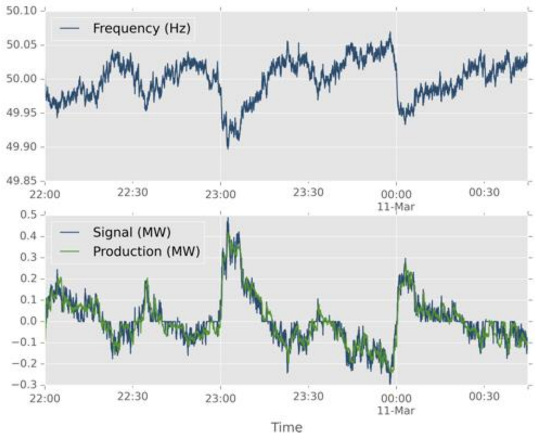

Fig. 12. Example for production of primary control.

4.4. Commercial Operations

Today the tiko pool connects more than 10000 heating devices. More than half of the devices are heat pumps, another large share are electric storage heaters, and the rest are hot water boilers. The latter ones are mostly loaded during the night, when most of the Swiss utilities offer low tariffs. This means that the total load in the tiko pool shows its peak demand during the night, whereas the minimum appears at noon, where most of the heating devices are blocked by the ripple control of the local utility. Creating a weekly bid of symmetrical primary or secondary control power means that the bid size is determined by the minimum flexibility during the week. In order to fully exploit the flexible capacity of the tiko pool, hydropower generators are combined with the demand response pool. The symmetrical power offered is then dynamically shared between hydropower and demand response capacity. Over noon, hydropower delivers the major part, whereas during the night, the demand response capacity provides most of the capacity. The capacity share is done on a timescale of up to 15 minutes. This combination of hydropower and demand response capacity turns out to be not only technically, but also economically very efficient. Producing symmetrical ancillary services during all hours of a week has a high opportunity cost for hydropower plants during the night hours, since energy prices are low. The combination with the demand response peak capacity during the night relieves the hydropower plants from hours of high opportunity cost and allows them to produce mainly at attractive times during the day.

5. Conclusion and Outlook

It has been demonstrated by Swisscom Energy Solutions that demand management based on residential heating devices can be used to provide ancillary services such as primary control and secondary control. Key elements for a successful solution are:

- Value propositions for all involved parties
- Simple and cost-efficient hardware and installations
- Secure and reliable communication
- Efficient handling of big amounts of data
- Simple and efficient control algorithms

Functionalities of the tiko system are continuously further developed and optimized. In 2016, the product “tiko sun” was launched that integrates residential photovoltaic generation. Besides that, two niche products have been launched for special electric heaters: “tiko mountain” offers solutions for the electric heaters in mountain railway infrastructures, and “tiko church” connects the electric heating systems of churches. Stationary batteries for photovoltaic applications are another development that will be put into operation in 2017.

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