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Theme 2: Opportunities and Challenges with Operation using Flexibility

Smart decentralised energy management

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Abstract: The German–Finnish research project FUture Smart Energy shows, how flexible devices, consuming or producing electricity in electric grids, can be self-organised in a fully decentralised way, using autonomous algorithms integrated with the devices' controllers. By shifting operation time, existing flexible devices are hereby utilised as 'virtual batteries', providing high storage capacity and power. To gain sufficient flexibility, a large number of devices like combined heat and power generators, heat pumps (HP), heaters, coolers, charging stations, pumps, household appliances and industrial plants, has to be coordinated. This results in a high system complexity for which the evaluated method provides an easy, resilient, cyber-secure and cost-effective solution. This novel technology uses a new market approach for electric energy systems. A real-time price signal is generated directly out of grid state variables, like frequency, voltage, power or current, and broadcast to the flexible devices. Without a need for central control, the flexible devices react like a natural swarm to the price signal. The system is easily and highly scalable, as adding and removing flexibilities does not imply adapting a central control system. The system can be operated parallel or in addition to existing energy markets.

1 Introduction

Future energy systems face two main challenges: Fluctuating generation and decentralised allocation of generators and consumers; both of which impact the electric grids, especially in medium-voltage (MV) and low-voltage (LV) range.

In the German–Finnish research project FUture Smart Energy (FUSE) [1] these issues are addressed from multiple perspectives. While the Finnish partners concentrate on predictive maintenance (PM) for MV equipment, the German partners research on utilising flexible loads and generators to balance generation and demand and to counteract grid congestions. Moreover, artificial intelligence is applied by Deutsches Forschungszentrum für Künstliche Intelligenz (DFKI) to monitor and forecast grid state as well as energy demand and available flexibility. For monitoring and PM as well as for energy management a communication and visualisation system is designed. This paper focuses on the control of flexible devices, applying and enhancing proprietary technology of Easy Smart Grid GmbH (ESG) [2].

1.1 Need for flexibility

In order to fulfil the international targets on climate protection agreed on Conference of the Parties No. 21 (COP 21), Paris 2015, energy has to be de-carbonised within the next 2 decades. The main energy source will be electricity from wind and sun, harvested from mainly decentral plants with strongly fluctuating power, depending on the season, daytime and weather [3].

In tomorrow's decentral energy world, flexible devices in the industry, municipal estates, stores, offices, households etc. could offer a large potential as 'virtual batteries', minimising the need for electricity-to-electricity storage. However, the safe and economic coordination of such a multitude of flexibilities creates several challenges.

1.2 Challenges of conventional control via scheduling

Conventional energy management systems control flexible devices by explicit control signals that switch the devices on and off and change their power rate, if applicable (direct load control [4]). The control signals are scheduled in advance to ensure a proper balance of generation and demand at any time. The schedules are typically resulting from trading available flexibility within various energy markets, e.g. the European Energy Exchange. As market deals in advance never fully meet the real-time balance of energy, balancing power has to be provided, requiring additional markets for primary, secondary and tertiary reserves [5].

Moreover, for congestion management, redispatch and curtailment measures have to be taken additionally, needing extra trades. For the increasing number of congestion events in MV and LV grids, even more scheduling markets are proposed [6].

The current market system, based on scheduling, forms a strong barrier for the activation of the flexibility of small devices. Complexity – and therefore transaction cost and exposure to failure – grow with the number of participants. To overcome this problem and to improve controllability and resilience, the German Association of Electrical Engineers (Verband der Elektrotechnik Elektronik Informationstechnik e.V. (VDE)) has proposed the 'cellular approach' [7] which is used as a base for the proposed new system design in FUSE.

2 Methodology

2.1 Decentral energy management via' soft control'

The market and control system proposed for FUSE is based upon real-time price signals, representing the grid state of a defined grid cell in correspondence to its neighbouring cells or as an isolated cell (island mode). The flexible devices react on the signals individually to optimise their economies by deciding to switch on or off – buy or not buy, sell or not sell – respecting their internal needs and restrictions. This allows for distributed demand-side management (d-DSM), i.e. the (automated) adaptation of the demands of distributed energy consumers to variations in energy production. As the prices adapt to the grid state in real-time (seconds), a stable state is reached very fast. The price definition, using the grid as a decision feedback loop, is very near to 'Walras' auctioneer' [8], who knows all participants' bids at any time. The decision speed and precision allow the combination of energy markets and grid control to create one single system.

2.2 Generation of price signals from grid state

Two different types of price signals are generated, using grid state variables which indicate the following:

(i) The deviation of energy balance from the target (normally zero) within an allowed range (balance indicator, BI) and/or
(ii) the deviation of grid load from normal within an allowed range (congestion indicator, CI).

The necessary grid state variables should be measured locally, which means as near to a flexible device as possible, to avoid large ICT effort and to minimise the danger of failures and manipulation. Specialised power line communication (PLC) with a low bit rate is proposed as a resilient solution for BI/CI communication. LV network stations are proposed to be used as communication terminals to receive high-level price signals from the DSO control centre and forward them via PLC to grid terminals and devices.

2.2.1 Grid frequency as BI: Grid frequency directly indicates the balance of generation and consumption in an AC grid. The measurement could be made directly in each device. The signal can neither be hacked nor disturbed – only if the grid itself is physically attacked.

2.2.2 Voltage or current as CI: Abnormal voltage indicates congestion (CI) of a grid section, e.g. by high solar energy generation or high load by car charging. It can be measured at all grid terminals. The same is valid for abnormal electricity current load of a transformer or a feeder in a local network station, distribution board or grid terminal. In principle, all congestions – even joint loads between balancing zones that are currently managed with re-dispatch – may be measured and converted into price signals for 'soft control'.

2.2.3 Power balance as alternative BI: Depending on the market design, also the power balance at single or multiple connection points of a grid cell to ambient (e.g. a living quarter or a factory) can be transformed into a BI price signal. This also includes the power balance of large cells like the balancing zone of a Transmission System Operator (TSO) or a Distribution System Operator (DSO). Alternatively, also the deviation of a balanced group (e.g. virtual power plant) from the target may be priced and communicated in this way.

2.2.4 Generalised metrics: To make communication easy and price signals comparable, it is proposed to normalise the price signals. BI and CI are represented by a real number between the following values:

−1.0 (lowest allowed frequency, voltage, current or power balance; maximum energy scarcity; highest price) and
+1.0 (highest allowed frequency, voltage, current or power balance; maximum energy surplus; lowest price).

The correlation of a grid state variable to a price signal may be linear as well as not linear. It may be adapted automatically by applying system identification.
BI and CI can (but do not have to) be correlated with flexible energy tariffs and grid fees as well as with flexible allocations.

2.3 Reaction of flexible devices on price signals

Within FUSE, proprietary algorithms to optimise the reaction of flexible devices on the price signals are developed. The optimisation target is to minimise cost (as a consumer) or maximise earnings (as a generator). The algorithms generate decisions based on the current and forecasted price signals as well as on the devices' current and forecasted flexibility. The current algorithms only use BI as a price signal. Combinations with CI are under evaluation.

2.3.1 Flexibility: The currently available flexibility of a device is normalised in the algorithms, using a 'flexibility reserve' (FR) variable which can have values between:

0.0 (no available flexibility to shift operation time) and
1.0 (maximum available flexibility to shift operation time).

In general, two types of flexibility can be defined: (i) buffer flexibility and (ii) process flexibility. Devices with buffer flexibility have a buffer storage for energy or material. It enables the device to shift its operation time independent from the demand to a certain degree. An example is a heat pump (HP) with hot water buffer storage. FR is equivalent to the state of charge of the buffer from 0.0 (empty) to 1.0 (full). Devices with process flexibility have to fulfil a certain task within a specified time period, larger than the time needed to fulfil the task. An example is charging an electric vehicle (EV). When the necessary time is much shorter than the available time, FR is defined near 1.0. FR is defined at 0.0 when the necessary time and the available time are equal.

2.3.2 Decision making: Fig. 1 shows the basic process of decision making for a flexible device with 'soft control'.
The algorithm basically only uses BI and FR for the decision to switch on or off and to define the set power P with which the device shall run. The algorithm is designed to make predictions on BI as well as on FR, using historical data, autonomously. Optionally, external forecast time series for BI ($BI_{FC}[\ldots]$) and FR ($FR_{FC}[\ldots]$) can be utilised to enhance performance. Using specified parameters, the algorithm is adjusted to operational constraints of the device (e.g. minimum runtimes, to ensure safe and economic operation).

2.4 Algorithm design and testing

The algorithms have been designed and documented in pseudo-code, using function blocks, flow charts and statecharts. Each function block is tested individually and in a functional combination.

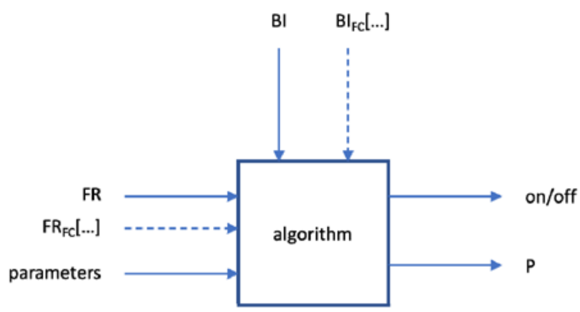

Fig. 1 *Basic process of decision making*

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Test data is provided for realisation in different software environments. For pre-tests, basic demonstrator tests and simulation environments have been established.

In the sustainable electric networks and sources of energy (SENSE) smart grid laboratory of Technische Universität Berlin (TUB) [9], currently, a microgrid is set up for FUSE, to implement and evaluate the algorithms in various devices. The supply area of an emulated 100 kVA transformer will represent a mix of industrial, service sector and household facilities, typical for European countries, together with regenerative energy generators, using real and emulated as well as merely simulated loads and generators. The performance of energy management in collaboration with monitoring and PM will be tested and demonstrated in the following three use cases:

(i) connected cell with a high degree of self-sufficiency,
(ii) cell with frequency stabilisation and congestion and
(iii) cell in island mode.

Additionally, the algorithms developed in FUSE have been applied in a detailed simulation for a living quarter in the demonstration project, Smart Grid ohne Lastgangmessung Allensbach-Radolfzell (SoLAR) [10].

3 Results

Some exemplary results of pre-simulations and application of the algorithms are given to show the performance of the algorithms developed so far.

3.1 Realistic simulation of a living quarter

Fig. 2 shows the effect of ‘soft control’ in a living quarter on two days in summer. The quarter consists of 12 semidetached houses,

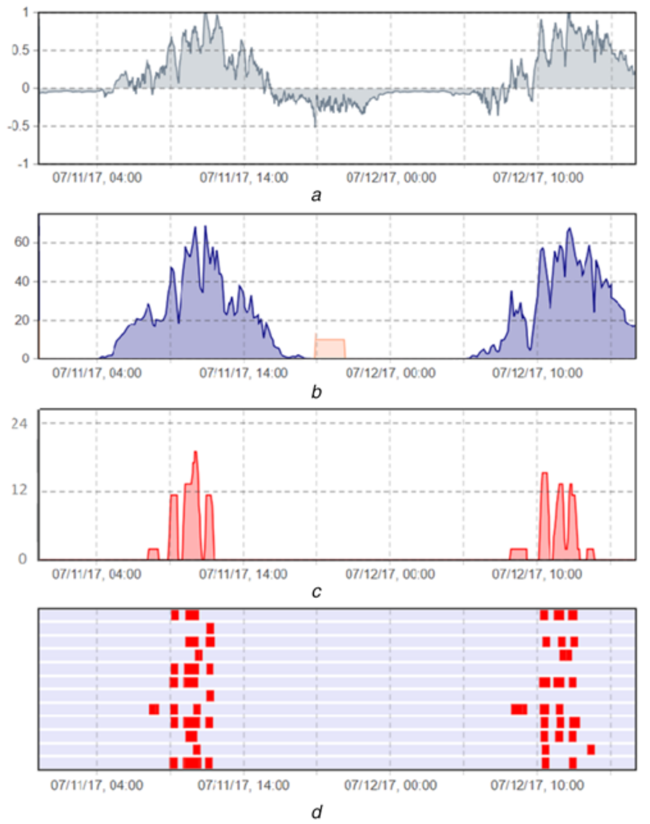

Fig. 2 *Simulation with d-DSM, summer*

(a) BI out of power balance at the connection to the external grid, ***(b)*** PV (dark/violet) and CHP (salmon) power generation, ***(c)*** HPs’ total power demand, ***(d)*** Operating times for hot water (dark/red) of the 12 HPs

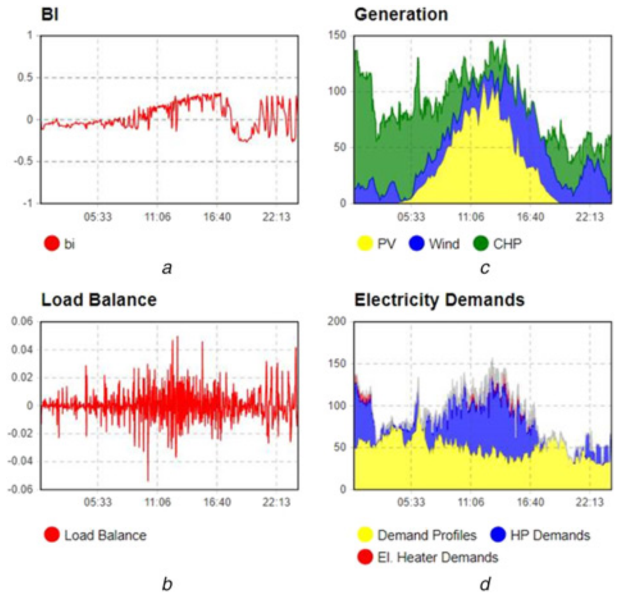

Fig. 3 *Simplified simulation of an isolated grid cell*

(a) BI generated out of grid frequency, ***(b)*** Load balance of the cell’s inertia in relation to the max. power, ***(c)*** PV (yellow), wind (blue) and CHP (green) generation, ***(d)*** Demand profile (yellow), HPs (blue) and EHs (red) (values in (*c*) and (*d*) aggregated bottom-up)

equipped with 1 HP each, and 3 apartment buildings with 13 households, all supplied with heat from a single combined heat and power (CHP) generator. Electricity for the whole quarter is produced by the CHP and photovoltaic (PV) systems on the rooftops of the houses. The BI is generated out of the power deviation from zero at the quarter’s connection point to the outer grid. The BI is broadcast to the 12 HPs and the CHP. The goal of the system is to maximise the self-supply rate of the quarter.

HPs and CHP consider a minimum runtime of 30 and 120 min, respectively. The HPs run at times when BI indicates the highest surplus, i.e. lowest prices. Moreover, the HPs directly react to generation setbacks, provoked by clouds. The CHP shifts its operation time to the strongest scarcity of energy to obtain maximum earnings.

3.2 Simplified simulation of an isolated grid

In a simplified simulation, a basic algorithm has been pre-tested in an isolated grid. The simulation comprises PV and wind generators as well as 12 CHPs, 23 HPs and 12 electric heaters (EHs) in 28 buildings. The need for heat as well as the number and types of devices are chosen in a way that there is always enough flexibility available to fully balance the generation and demand of electricity.

Fig. 3 shows the cell’s behaviour in island mode. The BI is representing a grid frequency between 49 and 51 Hz (Fig. 3*a*). To stabilise the grid, (virtual) inertia is necessary, which is excited with a maximum of about 5% of the maximum grid power (Fig. 3*b*). The electricity generation (Fig. 3*c*) shows a good real-time fit to the demand (Fig. 3*d*).

4 Conclusion

The evaluations on ‘soft control’ in FUSE and SoLAR have successfully shown that basic algorithms for buffer flexibilities that react on a suitable BI price signal have already good results in connected as well as in isolated grid cells. The devices shifted their operation in a way that (i) they reduced their energy cost or increased their earnings and (ii) the grid balance was supported in an optimum way. It could be proven that a swarm system can reach intelligent behaviours with simple decentralised algorithms.

In the next steps, the algorithms will be extended to control buffer devices with only short-term flexibility (like fridges) and devices with process flexibility (like EV or dishwashers) as well as industrial processes. CI price signals are to be evaluated, also in combination with a BI signal.

A strong focus will be given to stability. The aim is to evaluate general rules for stability to be implemented into 'soft control' algorithms.

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