Integrated Approach for Smart Grid Data Acquisition, Transmission and Evaluation

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***Abstract*—In order to handle the fluctuating energy production in distribution grids so-called smart grid components are introduced and storage systems are a key enabling technology to meet energy production and demand. Furthermore they can help to relieve network capacities in regions with weak grid infrastructure.**

This paper summarises smart-grid components, their interoperability and potentials of centralised control. After describing concepts and limits of data acquisition and transmission in a system with heterogenous components we advocate a central platform for data evaluation based on the infrastructure of the programming language *R* including a server based installation of *RStudio*. Here we present three applications in the fields of economy, physics and mathematics. We evaluate a battery electrical storage system (BESS) participating in the German Primary Frequency Responce (PFR) market that proves to give increasing profits esp. with the advent of decreased investment costs for Li-Ion battery systems. Then we describe the method of state-estimation that is used to derive consistent (operational) state-vectors from potentially error-prone (pseudo-) mearurements of an electrical grid. These estimated state-vectors consist of voltage magnitude and phasor for each bus of an electrical grid and are usually derived from incomplete data including voltage magnitude, (re-)active power, current or phasor values of the analysed system. Finally we give a brief outlook towards a global mathematical optimisaton model for a battery storage system that uses economical and physical constraints and objectives. The objectives are maximisation of self-consumption, minimisation of peak loads, minimisation of investment costs and maximisation of profits from trading with energy. Here mathematical optimisation is implemented as a tool in our common platform such that experts may iteratively combine different aspects of an optimal (dis-)charge schedule e.g. input of cost and profit margins computed for participation in PFR market or compute a schedule with maximal self-consumption with respect to a previously computed minimum peak load. Further development towards detailed storage models and variable input values will help to derive and implement controls of BESS that improve the operation of a smart grid and its costs.

I. Introduction

In the year 2014 about 26 % of the electricity in Germany was produced by renewable energy sources. With about 15.8 % of the total amount of renewable energy sources, photovoltaics and wind power plants produced the lion's share of renewable energies in the German electricity market (cf. Fig. 1) [1]. The global trend still shows a high rate of increase in photovoltaic energy production [2] and the renewable energy act EEG[1] assures sustained growth of renewable energies in the field of electricity production.

[1]Erneuerbare-Energien-Gesetz (EEG)

By the year 2020 about 35 % of the electricity should be produced by renewables and by 2050 it should be 80 % of Germany's total production of electricity. These power generators do not follow production schedules but depend predominently on weather conditions.

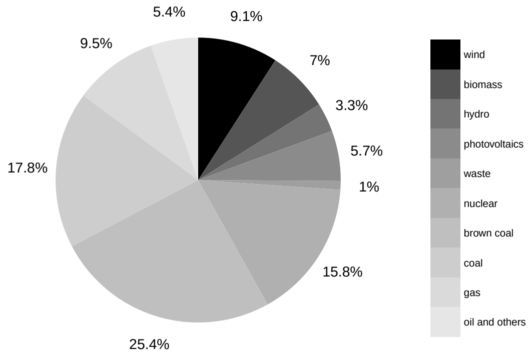

Fig. 1. Electricity generation in Germany in 2014 [1]

Due to the installation of decentralised power generation, the main task of the electrical grid and the distribution grid has changed. Originally the electrical grid was planned as a one way road with larger centralised power plants that were operated by fossil fuels and were installed in the Extra High Voltage or High Voltage grid. The energy subsequently was transported and distributed to the customers (e.g. households, small factories and businesses) that have been connected to the Medium and Low Voltage layers of the electrical grid. In Fig. 2 the amount and types of installed renewable power plants are summarised for the different voltage layers of the German electrical grid in 2014. The figure shows that in total more than 61 GWp (70 %) of the renewable power is installed in the distribution grid, i.e. the renewable energies are produced very much decentralised.

With respect to photovoltaics the share of installed capacities in the distribution grid and hence the extent of decentralisation even gets more obvious. About 34.5 GWp (93 %) of the photovoltaics power is installed in the distribution grid and about 22.6 GWp (61 %) is installed in the low voltage grids. Furthermore photovoltaics are predominantly installed in rural areas because of the larger available surface on rooftops of agricultures and family homes. This again counteracts the original design of the German electrical grid as in these regions the grid infrastructure has been less elaborated due to the lower load concentration compared to urban areas.

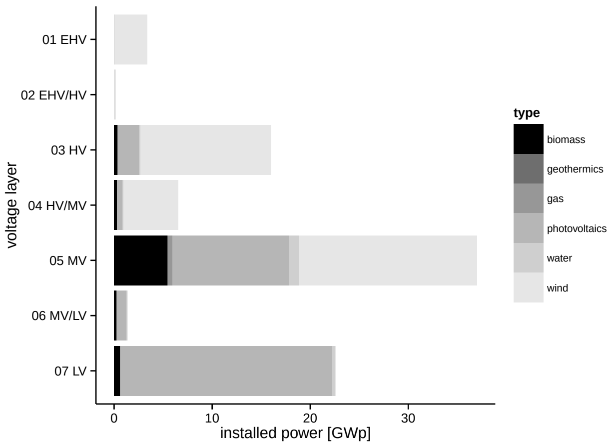

Fig. 2. Types of renewables installed in the layers of the electrical grid in Germany [3]; **EHV** = Extra High Voltage, **HV** = High Voltage, **MV** = Medium Voltage, **LV** = Low Voltage

Due to the minor consumption of the local loads in rural areas, in times with high solar irradiance the present distribution of installed PV capacities generate an overproduction of electricity in the rural low voltage grids.

Therefore the load flow direction in the grid is inverted, i.e instead of consumption in those rural areas there is a negative net load and power flows back to the Medium Voltage grid and with increasing regularity it reaches the High Voltage layer of the electrical grid. In these situations the initial design of the electical grid as a one way road is obsolete. The inverted load flow causes voltage rises on the connection points of the PV plants. Due to the local weather conditions (e.g. clouds, fog) the power production of the PV plants fluctuates within short term periods and as a result the power flow in the grid changes direction frequently leading to voltage fluctuations. The power and thus the voltage fluctuations are transferred to the upper layers of the grid and more often the Distribution System Operators (DSO) and Transmission System Operators (TSO) have to take control for the security of supply and thus need to adjust, i.e. reduce the feed-in power of the volatile generation [2, Fig. 17]. To take proper actions it is important for the DSO to know the state of the grid, therefore the installation of measurement equipment in the local distribution grids is subject to high priority. The acquired data then can be used to identify the state of the grid. In case of transmission or acquiring errors, a state estimation enables the interpolation of missing and incorrect values. In a later section of this paper we describe an application for measured grid data in a state estimation in a rural Low Voltage grid with high photovoltaic penetration.

The increase of voltages on the installation points of the PV is conventionally resolved by grid extension arrangements like additional cables or transformers. These arrangements are expensive, inflexible and are not capable to control the load flow. In order to manage the fluctuating load flow in the distribution grid and to avoid inflexible extensions, so-called smart grid components are introduced. In addition to regulated transformers, electrical energy storage systems are a key enabling technology to meet local energy production and demand. Storage systems – even though being expensive – are more flexible as they can be used to shave short term photovoltaic production peaks and later feed-in the power in times of underproduction. This enables conserving electrical energy within the local grid, preventing transport losses and regulating energy exchange with higher voltage levels. Furthermore storages can help to relieve network capacities in regions with less elaborated grid infrastructures and can also deliver system services in the electrical grid. Later in this paper we point out the ability of decentralised storage to participate in the German primary frequency response market and show preliminary simulation results.

An electrical energy supply that consists of an increasing share of renewable energy sources and especially photovoltaics faces many challenges. Storage systems vary in their suitability for use in current and future scenarios. Therefore, different types of storage systems are compared in the project ”Smart Grid Solar”. Here, we provide a list of storage technologies that were implemented in the northern Bavarian region and are operated in the context of the research project.

A. *Types of storage systems*

The storage systems mentioned in the next sections have been installed on a test centre as well as in selected households. The electrical and communicational structure of the test centre is shown in Fig. 3. The test centre consists of a photovoltaic plant with a power of 42 kWp as well as two types of electrical storage systems. The PV plant is monitored with respect to the feed-in and lifetime behaviour of the modules and produces power for the operation of the storage systems. One storage system is a PEM-Electrolyser (Proton Exchange Membran) with a peak power of 75 kW that is currently operated as controlled load. The hydrogen system will be supplemented with a prototype LOHC-storage system (Liquid Organic Hydrogen Carrier) and a fuel cell by the end of 2015. With 2016, the hydrogen system will also serve as electricity source. The other storage system installed on the test centre is a Vanadium Redox-Flow system with a peak power of 90 kVA and a capacity of 390 kWh. It is used to shift energy produced by the PV plant to hours with less generation. The test centre is connected to the local Low Voltage grid at the Low Voltage Main Distribution (LVMD), so energy can be consumed or fed-in. The connected electricity consumers were encouraged to install small, customary lead battery systems and smart meters for monitoring purposes. Further, also the remaining costumers, with and without rooftop PV systems, were encouraged to install smart meters that measure with a high resolution, synchronised timestamps and thus enable a comprehensive evaluation of the state of the grid. All the information are collected and evaluated on the server in the control room of the test centre. The storage systems are slightly oversized in order to be able to influence the Low Voltage local distribution grid based on the measured values.

At a second site, which is characterised by a high number (about 300 kWp) of rooftop PV plants, a proximity storage with a peak power of 72 kVA and a usable capacity of 330 kWh was installed. The present control strategy of the

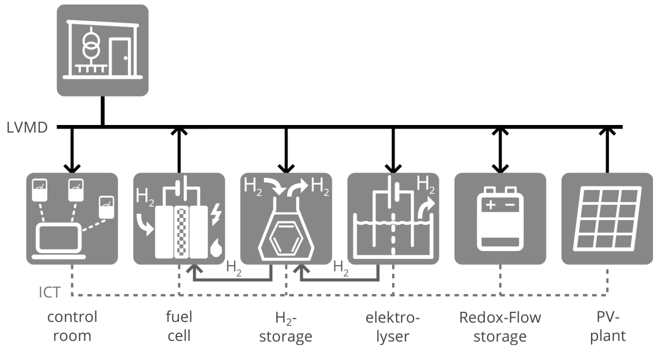

Fig. 3. Electrical and communicational structure of the test centre; **LVMD** = Low Voltage Main Distribution, **ICT** = Information- and Communication Technology

proximity storage is to limit voltage rise at times of solar peak production. To gather the state of the grid and the impact of the storage operation, smart meters were installed to the households attached to local grid. Here we want to further analyse a virtual participation in energy markets and characterisation of restrictions arising from the local grid.

B. Strategies for Storage Systems

In contrast to other components in an electrical grid – where feasibility and profitability basically is a result of proper dimensioning and positioning – for storage systems the operation strategy is of crucial importance. In this context we focus on the following applications:

1) Voltage regulation
2) Reactive power management
3) Regulation by market signals
4) Peak-shaving resp. short-term synchronisation of generation and consumption
5) Enhancement of autarky and self-consumption resp. long-term synchronisation of generation and consumption

Market signals, mentioned under point 3, can thereby arise from two different origins. On the one hand side storage systems can shift energy in time, i.e. they can be used to draw profit from arbitrage on the energy exchange. On the other hand storages can participate in the primary control market with a minimum power of 1 MW that can be pooled by multiple assets. The scenarios 4 and 5 differ from the spatial and temporal extent. While variant 4 is focused on a single unit or house and a time horizon of about one day, variant 5 refers to a wider scope of balance, e.g. to balance generation and consumption in a low-voltage line or subnet in a weekly or seasonal cycle.

The storage systems deployed in the project can be categorised as follows:

- Battery storages in households
- Proximity lead storage at the end of a LV line
- Redox-Flow-Storage as part of the test centre
- Hydrogen storage as part of the test centre

Not every application is appropriate for the mentioned storage systems because of their different specific characteristics. Therefore Table I gives a short overview for the different storages and the degree of applicability:

TABLE I
ASSESMENT FOR APPLICATION WITH DIFFERENT TYPES OF STORAGES; (+) HIGH, (O) MEDIUM, (+) LOW

Variant	**1**	**2**	**3**	**4**	**5**
Household	-	o	-	+	-
Proximity	+	+	o	o	o
Redox-Flow	o	o	+	+	o
H_2-storage	-	-	+	+	+

In principle storage systems can be operated simultaneously with different strategies. Storage systems of different types could be combined to fulfil different operation scenarios at one time, e.g. an electrolyser could consume a constant power level while the Redox-Flow storage is compensating short-term power fluctuations from the PV generation or the main supply. These operation strategies have to be developed and will be tested in real-life. In a later part of the paper we describe how the optimisation of the operation strategy in our project is modelled.

II. CHALLENGES USING MASS PRODUCTS

The products deployed in the households and at the test centre as well as the proximity lead storage all are products provided by various manufacturers as they are available on market. Being designed for different purposes their communication interfaces and their control structures are also varying. As we provide a generic approach, we had to develop a flexible way to connect those diverse systems to the central acquisition platform. This section describes the challenges we had to cope with by deploying all devices.

A. Proprietary Protocols

For data acquisition of power generation, weather and current AC levels as well as controlling the storage devices we are using the default protocol each device comes with. The hardware protocols we came across, when establishing the information and communication structure, are Modbus over RS485, PakBus and Modbus over TCP/IP, CAN as well as HTTP and FTP over TCP/IP. Furthermore, we observed different endianness. As the storage components only allow for setting few variables like current charge and discharge power, an easy and standardised protocol would be a great benefit in the future. In addition, each component uses proprietary data structures for gathering the provided measurement values.

B. Lack of Generic Control Systems

Each component comes with its own software that can be used to control the system. For example, the photovoltaics measurement unit provides a website showing the current power production and the electrolyser was shipped with a LabVIEW[2] based and well designed GUI. As each system has its own pros and cons, we want to demonstrate advantages in having a combined usage. This task can only be accomplished by having all measurement values available in a central place, locally taking a global decision and control the systems by need. In this context, openMUC[3], Mango

[2]http://www.ni.com/labview/ accessed August, 19th 2015
[3]http://www.openmuc.org/ accessed August 19th, 2015

Automation[4], MyOpenLab[5] and AggreGate[6] do provide flexible configuration and development of new interfaces to the deployed systems as well as mechanisms to control these systems. Nevertheless the controlling techniques provided by these platforms only comprise the automation and management, that is not building closed-loop controls as formerly known from PLCs. Furthermore, the mentioned platforms do neither provide easy access to other programming languages nor enable to swap complex tasks to other processes. LabVIEW does provide mechanisms to build closed-loop controls but suffers from high effort to be spent on attaching and configuring diverse systems.

C. Data Provision

As the explored systems may run in standalone mode, each unit is equipped with its own measurement and control unit. For example, the Redox-Flow system can be used for increasing self-consumption of locally produced electricity. Only one system provides all of the following requirements arising from our application scenario. First, time synchronisation is necessary when evaluating measurement values from different sources. Second, the update rate of measurement values has to be high enough to set up closed-loop controls. The violation of both requirements leads to inaccuracies in reaching the global goal. The weather station based on a Campbell Scientific datalogger[7] meets both requirements. The components using Modbus RTU are build in a too simplistic way in order to fulfil both of the two requirements, as described in the next section.

III. Data Acquisition

Data quality, namely density, accuracy and pertinence of available data, is crucial both to an *a posteriori* evaluation of electrical infrastructures including operation strategies and for online IT-based command control. In our approach, the continuously collected data falls roughly into four categories, each covering a separate dimension for decision making in a smart grid infrastructure:

1) Live data from the end nodes of the distribution grids,
2) Measurements from the various installations at our test centre,
3) Live weather conditions both from on-site acquisition through the meteorological sensors implemented at the test centre and from open web-based resources, and
4) Stock exchange prices from major energy markets as available through open, web-based access (EEX, EPEXSpot, Regelleistung.net)

Due to principal reasons, not all data can be collected in real time, however timestamps enable correlation of synchronous events during evaluation.

In the process of implementing the data acquisition system we face two intrinsic challenges due to novel requirements. First, currently available measuring, logging and control hardware, though normally being fitted with sufficiently precise measuring equipment, does not meet the demands of frequent, multi-dimensional data collection and communication on the IT side. Rather, the internal computing hardware is constructed for a temporal resolution of at most 15 minutes and features constrained processing power, very little volatile memory, and virtually no persistence. Second, existing communication carriers either lack in bandwidth or struggle with substantial interruptions in service, practically prohibiting real-time command control. End-to-end communication at consumer side is instead laid out for infrequent bursts of high bandwidth communication.

Both issues are appropriately illustrated in the task of distribution grid data acquisition. The layout requires collecting voltage, current, and phase angle at high frequency at the interface point between distribution grid and private household and transmitting these values in near real time to the data centre. Due to the involvement of private housholds, the acquisition system must be non-intrusive, reliable (accurate as well as low maintenance), and provide sensible privacy protection. Hardware had to be approved by the grid operator and for legal reasons requires another standard meter for the energy bill of the participating households. The communication must rely on a readily available carrier, as the installation of a new, dedicated, carrier at the appropriate bandwidth proves too expensive for the duration of the project.

To consolidate these competing requirements, the chosen meters are assembled with additional, external, on-site computation and communication hardware that complements the capabilities of the meters and provides storage capacity capable of holding the entire body of measurements throughout the project duration. By accessing the meters directly through their internal system bus, the devices manage synchronisation of the measurements, high temporal resolution (15-seconds-intervals), continuous buffering, and lossless, minimum latency, transmission including appropriate privacy protection, without interfering with the meters' functionality to collect data for the energy bill. A single computing device can manage up to four meters.

As communication carrier, the following options were studied.

a) Cable bound communication: While probably the best choice in terms of bandwidth, reliability, and suitability for IP-based communication, solutions such as DSL, coaxial, or fibre cable were dismissed as their installation required too many resources in time and funds. As the requirements entail a low profile, the use of existing cable bound communication available at the households was not considered.

b) Power-line: Broad band power-line communication requires a dense network of relay stations. However, the topology of the distribution grids considered in the project are roughly linear. Small band power-line communication is only suitable for limited control tasks and the bandwidth is insufficient for data acquisition.

c) Dedicated radio: There are a several IP-based solutions available that use dedicated radio as carrier. Unfortunately either costs and overhead of managing available frequencies are very high or the bandwidth is not sufficient for data acquisition.

d) Cellular phone network: The use of the cellular phone network for smart metering is widespread. However,

[4]http://infiniteautomation.com/ accessed August 19th, 2015
[5]http://www.myopenlab.de/ accessed August 19th, 2015
[6]http://aggregate.tibbo.com/ accessed August 19th, 2015
[7]https://www.campbellsci.com/cr1000-specifications accessed August 19th, 2015

the data volume that is continuously transmitted in the project exceeds the design of the current network.

Ultimately, cellular network communication was selected. The same computing devices that manage the data collection and buffering from the meters handle encryption and transmission of the data. Hence frequent breaks in the cellular connections – which is not built for continuous data streams – lead to high latency.

The observation that the requirements of smart grid data acquisition and communication do not match well with currently available hardware and infrastructure is by no means limited to the area of distribution grids. Data acquisition at the test centre faces very similar issues. For example, the collection of 1108 variables from the electrolyser, three redox-flow batteries, four Rogowsky coils into 16 files at one second intervals (amounting to 1.012.987 B, *i. e.*, roughly 1 MB every 15 minutes) exceeds the capability within the controller hardware. As all equipment in this setting is closely collocated, data transmission is not an issue, nevertheless the persistence layer bottleneck constrained the data acquisition intervals to 5 second periods at a minimum. The approach to separate measuring and computing hardware into a modular system as implemented in the distribution grid proves to be a necessity. Further, experience shows that decisions inside a smart grid must not be escalated beyond necessity, the command control design should instead strictly adhere to the subsidiary principle.

IV. Common Platform for Data Analysis

In order to enable our interdisciplinary team to extensively analyse relevant data from the described distinct sources we implemented a common platform based on statistical computing environment R [4] and a server-based version of RStudio [5]. The server-based infrastructure further allows users with different levels and fields of expertise to work together on a common basis of data and tools for analysis. In the following sections we showcase some of our applications that make use of our platform and the data we are collecting. First we present some preliminary results of a simulated battery energy storage system (BESS) participating in the German Primary Frequency Responce (PFR) market which is implemented in R only and uses data collected from the four German Transmission System Operators (TSOs). Then we present a method of so-called state-estimation that makes extensive use of several data-sources to derive consistent approximations of the different characteristics of an electrical grid. Finally we describe our mathematical optimisation framework which uses several interfaces to our R platform and can be used to compute optimal (dis-) charge schedules, i.e. a strategy to control the operational state of a grid. The selected applications represent respective expertise in the economy, physical and strategic global control of BESS in a smart grid. Combining these fields on a common platform helps to derive a detailed understanding and common model of the overall system.

A. BESS participating in German PFR Market

For the integration of fluctuating renewable energy sources into the German electrical energy market, an inceasing amount of Load-Frequency Control reserves is needed. Furthermore the number of conventional power plants is decreasing and large nuclear power plants will be shut down. At the same time regulatory changes concerning the control reserve market have led to a wider accessibility to this market, e.g. for battery energy storage systems (BESS). The following analysis focus on the participation of such BESS in the German Primary Frequency Response (PFR) market.

In the PFR market the load is adjusted according to the mains frequency that is measured locally but is almost synchronous for the european electricity grid.

Here our preliminary results for the year 2014 are summarised and evaluated with regard to technical feasibility and economic profitability. We show that the participation of a BESS in the PFR market is possible when the state of charge is controlled by means of intraday-trading at the European Spot Market for electrical energy. With a battery system based on Li-Ion technologies we show a high economical potential even though this method of charge management goes with high expenses.

The analysis features a hypothetical BESS with a net (dis-) charging power of 1 MW, which represents the minimal amount of system power that is allowed to participate in the German PFR market. The BESS is considered to operate within a round-trip-efficiency of 90 %, which is a realistic value for modern Li-Ion technologies. Due to the relatively high power-to-energy ratio of Li-Ion systems the capacity of those systems is rather limited. In order to keep the state-of-charge (SOC) within a technically reasonable range of roughly 1 MWh it is crucial to implement respective control mechanisms. Hence the four German Transmission System Operators (TSOs) have granted certain degrees of freedom in operation for systems with limited storage capacity – especially battery systems – to participate in the PFR market [6], [7], [8]. Therefor it is allowed to virtually increase or decrease the power available for PFR regulation via short-term trading in the Intraday-Electricity-Market which can be used to control the SOC of a BESS. Furthermore very small deviations not exceeding 10 mHz from the nominal value of the mains frequency can be ignored in order to support SOC management.

Fig. 4 depicts the scheme used in the analysis.

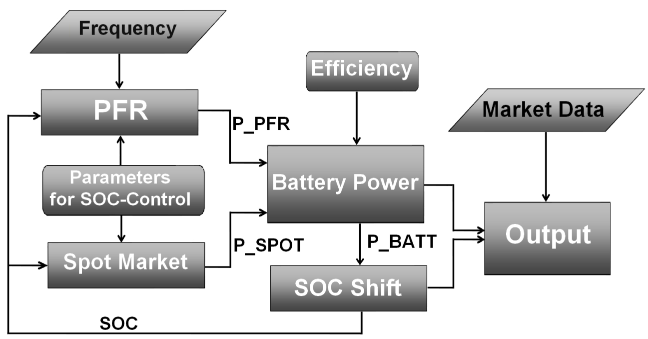

Fig. 4. Simplified simulation scheme

In order to save computing resources we initially aggregate the european mains frequency of the year 2014 – recorded in 1-second intervals by the TSOs – to 30-second interval average values. In the block named PFR the deviation of the mains frequency from the nominal value of 50 Hz is directly being transformed to the respective primary control power of the BESS. The following linear characteristic curve is used in order to meet the specifications of PFR, which is basically a proportional controller. The dotted line in the region from 49,99 Hz to 50,01 Hz indicates the above mentioned option to ignore PFR power demand if it is supporting the SOC management. This means, if the SOC is below or above a certain threshold parameter the resulting PFR power can be set to zero.

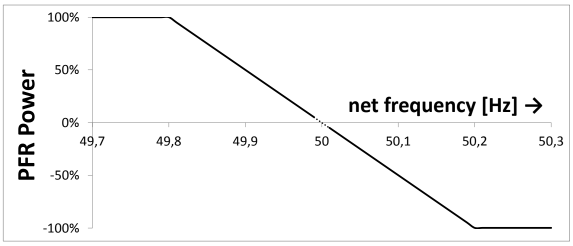

Fig. 5. Characteristic Curve for calculating PFR Power Demand

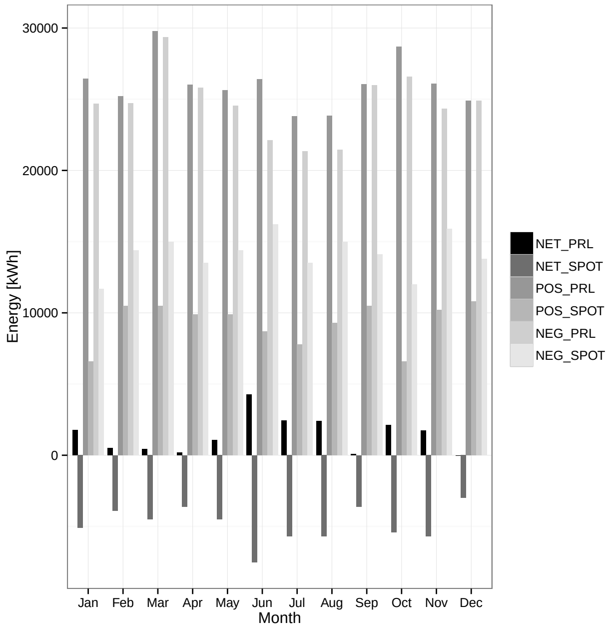

Fig. 6. Monthly aggregated simulation results

Besides this threshold, which indicates the desired SOC, certain other parameters have to be given in order to implement battery management via spot market trading. These parameters include a lower and an upper bound for the SOC as well as a parameter to determine for how long a violation of these bounds is tolerated. In the block called Spot Market the SOC is tested for these violations and if so, a trading contract is announced to the spot market and the corresponding TSO. Further the type of contract (one hour or 15 minutes) and the trading volume must be specified a priori. Then the current PFR power is combined with trading businesses that may be active simultaneously and the net (DC-)battery power is computed considering the (dis-) charge efficiency. The resulting change in the BESS's SOC is applied to the current state, which is the basis for the evaluaton of the next step of the analysis. Finally the output is computed where intraday electricity prices obtained from the European Power Exchange (EPEX SPOT SE) are used to generate financial estimates.

Fig. 6 contains some of the preliminary results generated by the analysis for the year 2014.

The total amount of energy used for PFR exceeds the energy traded on the spot market. Due to losses in the BESS the net energy traded on the spot market is higher than the net energy used for PFR. Although both PFR and spot market trading were executed simultaneously the absolute value of the DC-battery-power remains below the maximum of 1 MW. The required storage capacity of 948 kWh is below 1 MWh, which corresponds to the capacity requested by the TSOs. The BESS operated 424 full-cycles (complete charge and discharge), which is a relatively high number with regard to a long calendarical lifetime. Hence depending on the particular battery technology the lifetime may be less than 20 years. In total the energy contributed to the power grid sums up to 313 MWh, whereas a total of 296 MWh drawn from the grid. A bit less than half (≈ 45 %) of the energy accounts for energy traded on the spot market. These spot market trades result in total cost of more than 26.000 Euro. Here it is worth mentioning that trading energy also includes a significant amount of fees and taxes both for charging and discharging. Hence costs may be decreased significantly if those fees and taxes would be applied to the net value of (dis-)charge. But the overall net win is still above 156.000 Euro, despite the high operational costs.

Depending on investment costs and income return plans this earnings could lead to economically feasible strategies. Especially in view of decreasing specific energy storage costs of Li-Ion battery systems, the economy of participation in the PFR market may further improve.

B. State Estimation

The goal of a network data acquisition system is to monitor and subsequently to control the grid. However issues like missing measurement points in the network and incorrect data due to the finite accuracy of the measurement devices can reduce the applicability of the system. The purpose of a state estimation in electrical power grids is to determine a consistent, error-corrected operating state of the network. The intended result is the voltage magnitude and phasor at every bus, the so called state vector, to enable a comprehensive view of the given network at a given point in time. To approximate the state and to filter incorrect data, a network model as well as a redundant set of measurement data is needed. Common input data is voltage magnitude, active and reactive power, but also current and phasor measurements can be used. The minimum number n of data to perform state estimation is 2k-1, where k represents the number of busses of the given grid. Though, especially in the low voltage level with a large number of busses, it is not possible to equip every bus with measurement devices due to high costs. Also temporary or complete failure of measurement devices is possible. That, however, means that in most cases observability of the grid is not given, because of an insufficient number of measurement data available. Before state estimation can be performed, observability of the (low voltage) network needs to be restored by completing the data with so called pseudo measurements to form the measurement vector. Therefore, in the wider sense the purpose of the state estimation is not only to perform adjustment calculation based on a redundant set of data but also to compensate missing measurements in the grid. The procedure of the state estimation is illustrated in Fig. 7.

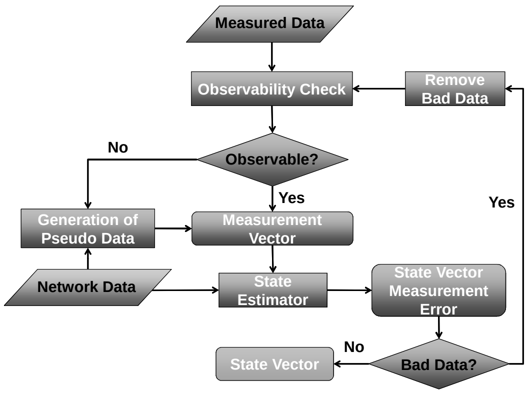

Fig. 7. Procedure of a State Estimation with compensation of missing measurements

1) Pseudo measurements: Pseudo measurements can be created in various ways depending on the available data and on the type of bus or element. The first task is to determine values for active and reactive power at all loads and PV feeds of the grid. Especially for loads it is difficult to develop data suitable for state estimation because of the wide range and stochastic distribution of the power values. One way of developing data is to generate mean values of all measured loads of the same type or of historic measurements (if devices failed temporarily or completely) at the given point in time. A very similar approach is to use standard load profiles, which also consist of means of measured data from similar load types. From the season, the day of the week and the daytime, the active power of a household can be given by those curves. In the next step, assuming an empirical value for the power factor, the reactive power can be calculated. Another, more advanced possibility to generate data is to simulate active and reactive power for house connections. These simulations can be based on standard load profiles as well as measured data. Besides that, simulations can also take into account specific information about particular loads like special equipment or extraordinary profiles based on measurements. For the control of the grid and therefore for the state estimation PV feeds are more important. In case of missing data at those facilities, pseudo measurements with high accuracies need to be generated in order to avoid undetected voltage or equipment load problems. One option is to genate pseudo data on measured data of nearby PV facilities. Assuming similar solar radiation for all PV feeds in the same area, a mean value of all PVs ratios of measured power to installed power is calculated. With that mean ratio of the considered area, pseudo data can be estimated knowing the installed power of the PV facilities in question. This method can be extended by using historic measurements, weather conditions, the facilities orientation as well as type or age of the facilities modules and inverters as input to simulate active and reactive power. After the first determination of the active and reactive power of all components, a power flow calculation can be performed to adjust these values based on measured voltage magnitudes in the grid. At the same time, the power flow calculation is used to determine pseudo measurements for the missing voltage values at the busses. With the complete set of data, consisting of measured values and pseudo measurements, the state estimation can be performed. The resulting measurement errors are checked for unrealistic errors (in case of real data) or for high deviations from the predefined values (for pseudo measurements), so called bad data. In the latter case the pseudo measurements are adjusted to fit the results of the state estimation. In case of real measurements, the data is replaced by pseudo values. That way, observability of the network is restored, state estimation is performed again (see Fig. 7).

2) Requirements to Pseudo Measurements for Smart Grids: The requirements to the pseudo measurements regarding accuracy and time interval severely depend on the purpose of the associated state estimation. The demanded temporal resolution of the state estimation and therefore of the pseudo measurements is the result of the necessary response time for network control by e.g. storage devices, transformers, converters or switches. The accuracy of the pseudo measurements has a direct influence on the precision of the state estimation. Especially the values of the PV facilities – high installed powers in particular – are important considering that the lower voltage levels were originally not designed for reverse power flows which can therefore cause critical states. However, also high loads have a big influence on the state of the network. The achievable accuracy of the state estimation again has high influence on the necessary number of measurement points in the grid. In the light of cost reduction, a low number of measurement devices are desired. Dependening on the given state estimation algorithm and the quality of pseudo data, the goal is to find the minimum required number and optimal placement of the measurement devices while ensuring the desired state estimation accuracy. That in turn means that the number of necessary measurement devices can be reduced by raising the pseudo data accuracy. In conclusion, the necessary time interval as well as accuracy of the pseudo measurements depends on network topology, safety margins, type of controllable components as well as on the control strategy. In general it is particularly important to generate pseudo data with high accuracy at PV facilities as well as high loads.

C. Mathematical Optimisation of BESS

In general mathematical optimisation uses well-studied mathematical concepts to describe complex problems and find solutions with proven optimality. Here linear constraints are frequently used to describe (relaxations of) the body of feasible solutions for a given problem, e.g. rates of (dis-)charge for an BESS. In our model these constraints are used to limit (dis-)charge rates according to storage capacities, maximum (dis-)charge rates, available residual loads and conservation of energy between steps in time. The last class of constraints is similar to equalities known from kirchhoff's circuit laws and is called flow-conservation contraints (cf. Fig 8).

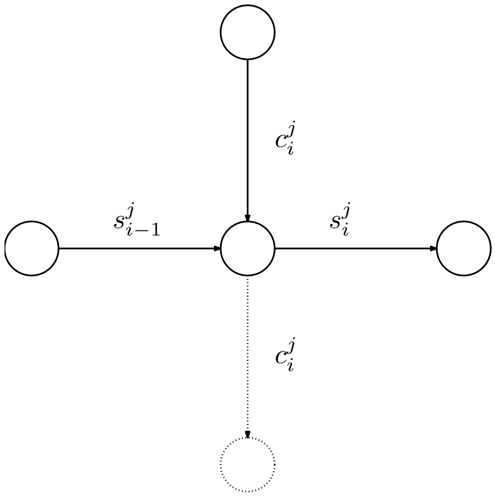

Fig. 8. Basic schematics of the flow model

In our model, flow-conservation constraints are relaxed to account for the self-discharge ϵ^s and charge efficiency ϵ^c:

$$(1-\epsilon^s)s_{i-1}^j + (1-\epsilon^c)c_i^j d_i^j - s_i^j \quad = \quad 0$$

Here s_{i-1}^j and s_i^j represent the SOC of a BESS j in consecutive timesteps $i-1$ and i and $c_i^j d_i^j$ accounts for the respective (dis-)charge energy, i.e. the product of power and duration, of the same BESS.

With respect to given residual loads the objectives of optimisation are maximisation of self-consumption and minimisation of peaks loads. Additional objectives include costs of investment and profits from trading with energy.

The mathematical optimisation is implemented using the python [9] library of gurobi [10] and it uses interfaces to our R environment to load input data e.g. residual loads or properties of the BESS. Furthermore we implemented an interface based on R that can be used to access our model with R programming language. Hence our optimisation can be used seemlessly for both artificial and real-world data.

Due to these interfaces it is also possible to use optimisation in a more interactive way, i.e. to find optimal (dis-)charge schedules for different temporal resolutions, use previously computed cost and profit values or e.g. compute the maximum self-consumption with respect to a previously computed minimum peak load.

The optimisation model is currently being extended with respect to more realistic non-linear capacity constraints and stochastic residual loads that may arise from predictions, discretisation or linearisation.

V. Conclusions

For the German energy transition towards renewable production of electricity we may conclude that fundamental technologies like photovoltaic and wind generators are well-suited to meet the German demand. Due to the historic evolution of our power distribution system we still need to adapt to fluctuating and decentralised electricity production. We summarised different storage systems and their desired applications in a power distribution system as they are used in the research project "Smart Grid Solar". We discussed practical challenges with regard to interoperability, centralised evaluation and control of the standard components applied in the project. The operation of such a diverse variety of components serves a mass of data available for evaluation. Here we summarised fundamental concepts of our data acquisition and design choices. From this practical experiences we conclude that the chances of centralised control strategies in a smart grid are very limited. Nevertheless an evaluation of synchronised data is needed to derive models and decentralised control strategies.

The collected data can now be used to derive precise mathematical models, that represent technical, political and economical limits in a reasonable detail. These models enable the development of optimal control strategies that can be applied to the components of the test centre. To do so, a control platform will be developed which is capable of executing the control strategies in short runtime cycles. As the components in the test centre are applied to real life, effects on the local distribution grid can be observed and the measured values can be revalidated. The close coupling between acquisition, analysis and control allows for short iterations of development and validation.

Acknowledgment

The research project "Smart Grid Solar" is co-financed by the European Union through the European Regional Development Fund and by the Free State of Bavaria.

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