GRIDBOX – AN OPEN PLATFORM FOR MONITORING AND ACTIVE CONTROL OF DISTRIBUTION GRIDS

Marco MANGANI
ewz – Switzerland
marco.mangani@ewz.ch

Dr. Florian KIENZLE
ewz – Switzerland
florian.kienzle@ewz.ch

Marc EISENREICH
BKW – Switzerland
marc.eisenreich@bkw.ch

Yamshid FARHAT QUINONES
BKW – Switzerland
yamshid.farhat@bkw.ch

Dr. Rainer BACHER
Bacher Energie AG – Switzerland
rainer.bacher@bacherenergie.ch

Alain BRENZIKOFER
SCS – Switzerland
alain.brenzikofer@scs.ch

ABSTRACT

GridBox is an open platform for monitoring and active control of distribution grids. It is based on an innovative concept that comprehensively addresses the challenges DSOs will be exposed to in the context of increasing amounts of decentralized and often fluctuating generation as well as the electrification of the heat and transportation sector. In this paper, we outline the principles of the GridBox concept, we describe its key elements in terms of hardware and software and we specify functionalities and applications. The practical implementation of the concept is illustrated by presenting an overview and first results from field tests in two different regions in Switzerland – one in an urban grid area in the city of Zurich and one in a rural grid area in the canton of Bern.

MOTIVATION

With the increasing amount of decentralized and often fluctuating generation and the electrification of the heat and transportation sector, the planning and operation of distribution grids has to be adapted. DSOs will have to balance their investment in new network infrastructure and in smart technology for active network management to ensure a stable operation of the grid in a cost-efficient way. In addition, the regulatory requirements for distribution system operators necessitate more and more detailed documentation of reliability of supply and power quality. Therefore, DSOs will need better information and control of the state of their distribution grids especially on the medium- and low-voltage level. On these two voltage levels, the usage of monitoring and control devices is currently very limited. As a consequence, the observability and controllability of the distribution grids on these voltage levels is typically low. This represents a big challenge for DSOs as most of the new generation capacities such as photovoltaic (PV) or wind power plants are connected to these voltage levels.

Several studies show the potential impact of distributed generation (DG) capacities on the needs for distribution grid reinforcements and extensions [1], [2]. These studies come to the conclusion that the costs for DG grid integration can be significantly reduced by adopting innovative grid components as well as information and communication technologies. It is exactly these issues which the GridBox concept addresses.

THE GRIDBOX CONCEPT

The GridBox concept represents an open platform which provides solutions to the challenges mentioned above. At the core of the GridBox concept is a highly distributed network of real-time measurement devices synchronized by GPS. All devices within this network measure voltage and current phasors with a high accuracy in real time and communicate the measurement data to hierarchically layered masters. Thus, in contrast to purely decentralized control approaches, the GridBox concept allows for an optimal balance between local control functions and centralized functions being activated by the GridBox master. The centralized monitoring and control is enabled by a continuous grid state estimation carried out by the GridBox master. The state estimation uses the real-time phasor measurements communicated by all GridBox devices in the network. In this way, appropriate control signals can be sent to the actuators of components that are controllable by the GridBox devices in the case of a critical grid state. Examples for grid components that can be controlled in such a way are low voltage regulation systems for controlling the voltage in an individual distribution feeder or controllable local grid transformers with on-load tap-changers. Distributed generators such as PV plants, controllable loads such as hot water boilers or storage devices such as battery energy storage systems can also be controlled by the GridBox devices. Thus, the GridBox platform aims at integrating any type of controllable power generation, load, storage and intelligent building technology and offers a flexible framework for grid monitoring and optimizing algorithms. In this way, the GridBox concept enables an active network management by DSOs. This endows DSOs with the opportunity to optimally balance the use of Smart Grid technologies with conventional grid development measures in the short-, medium- and long-term. Furthermore, the open platform principle shall guarantee interoperability and the seamless integration of third party applications.

KEY ELEMENTS OF THE GRIDBOX CONCEPT

The GridBox devices are the basic components of the concept. They measure voltage phasors at the nodes where they are installed as well as current phasors for all lines attached to that node.

The form of the GridBox is chosen to fit distribution cabins. PCB[1]-based Rogowski current sensors have been developed to fit in smaller house connections boxes.
The GridBox base module measures voltage on 3 phases and current on 4 phases. Additional current modules are attached for each line to be measured. Figure 1 shows the hardware setup for a cable distribution cabinet, to be extended according the number of feeders present.

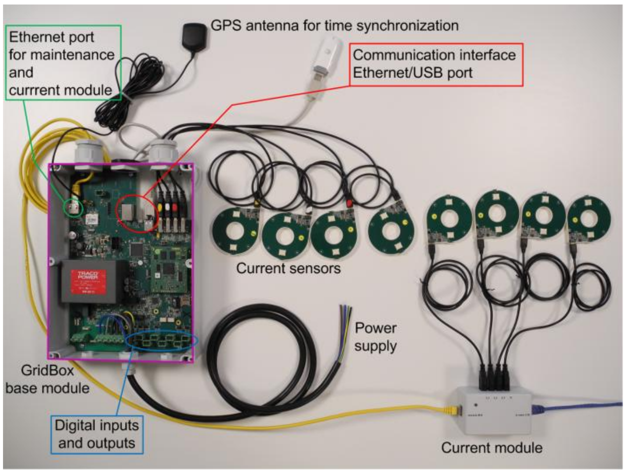

Figure 1. GridBox base module, current module and Rogowski sensors.

Apart from measuring voltage and current, the GridBox devices can interface low-voltage relays, DG inverters or storage devices to be able to control load and generation at the grid nodes. Thus, the GridBox devices represent the local physical components of the grid management system.

Another crucial component of the GridBox system is the communication network. GridBox supports several low-bandwidth communication channels to minimize operational cost. For the two pilot grids, three communication types are implemented: fibre optics, broadband powerline (BPL) as well as GPRS/UMTS. First experiences have shown that GPRS/UMTS solutions are not suitable for future applications because of their high cost to handle high data volumes. Nowadays, fibre optics are not yet widely available. BPL has a good potential for future application, but is quite power-hungry and it is restricted by law to grids consisting only of underground cables. Further possibilities are RF-transmission in multi-hop mesh networks or narrowband powerline communication (PLC).
Instead of using standardized, generic protocols like IEC 61850, a custom communication protocol based on SCTP needed to be developed to reduce overhead and minimize bandwidth as well as data volume. This protocol is optimized for the transfer of GridBox measurements in intervals of one second and time-limited prioritized retransmission to enforce configurable delay limits and for sending commands to controllable grid components. As an extension, GridBox is designed to allow for protocol tunnelling for third party devices.

Each grid region is managed by a GridBox master that collects and processes all the data. A real-time state estimation is performed, followed by an optimal power flow algorithm. Those algorithms are described in subsequent chapters.

The decentralized approach has several advantages. Data and control is kept as local as possible. This increases robustness and also reduces data security and privacy violation risks.
On the other hand, purely local control of grid-connected devices based on local voltage measurements has the disadvantage that it can suffer from stability problems as soon as many such controllers are deployed. When tap-changing transformers or reactive-power-controlled inverters are present, the local voltage level is often an insufficient indicator of the severity of the grid state. A GridBox Master employs regional control based on state estimation of the entire sub-grid to overcome this problem.

FUNCTIONALITIES AND APPLICATIONS

The core functionality, which has been demonstrated with a few GridBoxes in summer of 2014, consists of sampling every second the measurement data of each GridBox device and collecting this information in quasi real-time on a GridBox Master. Based on this functionality, two types of applications are possible. On the one hand, real-time applications are executed with the set of information available every second. On the other hand, ex post applications that require archived measurement data can be run.

The elementary real-time application consists of a linear state estimator capable of detecting and treating bad data such as measurement deviations and to handle missing data. Missing data can be of temporary nature in case of communication interruption. However, more relevant are nodes that are not measured at all. Besides technical reasons such as inaccessible cable junctions in the ground, it is also an economical motivation to deploy only as many GridBoxes as necessary. In both pilot

1 Printed Circuit Board

networks, all accessible nodes are equipped with a GridBox device in order to be able to evaluate the confidence metric of the state estimator by deliberately considering only a subset of the available measurement points. One outcome of this project will be the optimal number and position of measurement points in the network. The state estimation associates to each node estimated values and confidence intervals for current and voltage.

Automated topology identification is a subsequent application which will be tested during the pilot project. The objective is to draw a connectivity graph, i.e. to determine which nodes are connected with each other. Therefore, an algorithm matches node currents on both sides of a line. Especially in a meshed distribution network, the connectivity graph may be subject to frequent changes by switching operations. Even though a distribution system operator normally possesses at least one network diagram for planning and operation purposes, the automated identification can replace manual interventions for the initial input of network data or updates in the case of topology switches. Adding node voltages to the current phasor data used in the topology identification, the electrical parameters of the lines can be obtained so that load flow calculations can be performed.

Based either on the automatically identified topology or on a manually given one, further functionalities such as monitoring and optimization can be implemented. Therefore, the actual state of the distribution network is calculated and evaluated against the permissible operational limits at every instant. The results are displayed by means of traffic lights (red, yellow, green) for the nodes and lines of the system. Another evaluation criterion can be the compliance with power quality according to corresponding standards.

In case of yellow or red traffic light, an optimization algorithm becomes active. It evaluates the effect of modifications applied to the state of the grid by controlling available actors before executing the one with the highest potential for optimisation. These actions can happen for example by setting a set-point voltage of regulated distribution transformers or line voltage regulators, by requesting a defined active and reactive power balance from grid-connected inverters of generators or storage devices, or by direct or indirect load shifting. Further goals could be a general loss minimization or an individual incentive/penalty for participation. With that, the user will be able to choose several objective functions,

The second major set of possible functionalities can be seen as a by-product of the aforementioned real-time applications. An archive with measured values and the outputs of the real-time algorithms, like estimated values, switching states and optimizer set-point values, can be used to develop machine-learning algorithms. One possible stakeholder today is the DSO's asset management service to use loading and voltage profiles for a more efficient network planning.

These functionalities will be implemented and tested during 2015. Furthermore, the capability of the GridBox to measure synchronized phasors would allow the implementation of innovative future applications such as fault detection (i.e. locate the exact place where a fault has appeared), transient analysis, detection of unintentional islanding or management and operation of micro-grids (i.e. reconnect a part of the grid without injecting disturbances).

The GridBox platform will be designed as open as possible in order to be able to address future questions that are not yet foreseeable today or that require long-term data.

DEVELOPMENT PROJECT AND FIELD TESTS

The GridBox system is developed within a 3-years research project by the project partners BKW (DSO in the Swiss cantons of Bern and Jura), ewz (DSO of the city of Zurich and part of the Grisons), Supercomputing Systems (development service provider), Bacher Energie (consulting and project support) and co-funded by the Swiss Federal Office of Energy [3]. The GridBox system will be tested in two pilot installations: one in an urban low-voltage grid area in the city of Zurich and one in a rural medium- and low-voltage area in the canton of Bern. In total, roughly 200 GridBox devices will be installed by March 2015. ewz has identified a low-voltage grid area in the periphery of Zurich (district Affoltern) for the project. This pilot grid is illustrated in Figure 2.

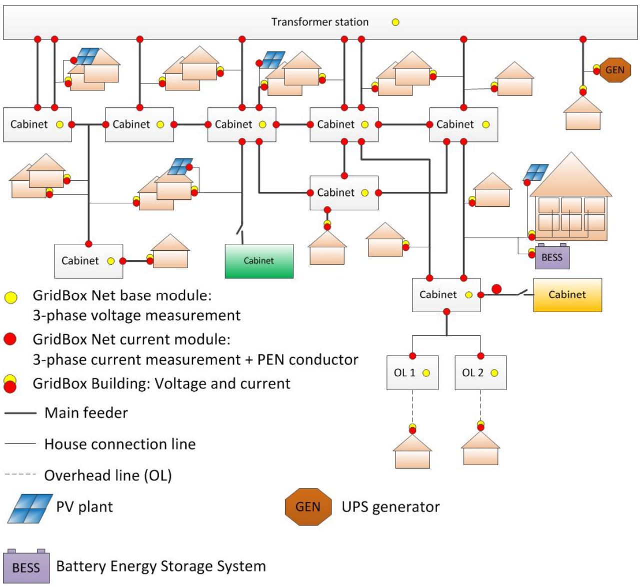

Figure 2. Urban pilot grid in the city of Zurich (ewz).

The chosen area provides opportunities for numerous tests. The goal in the field test is to install GridBox measuring instruments with a complete coverage of all nodes in the network area in order to be able to extensively and reliably validate the concept. In a second step analyses will be done about the number of GridBoxes that bring added value for consistent information about the state and control of grid stability. As illustrated in Figure 2, there are several controllable loads and PV plants with controllable inverters in the ewz pilot grid area. This allows for changing different parameters by means of the GridBox devices. For example, the GridBox devices can send control signals to the PV inverters so that they provide reactive power for voltage control. Furthermore, tests for active power curtailment of the PV plants will be carried out. In addition, there is a battery energy storage system (BESS) installation in the pilot grid area with a power rating of 120 kW and a nominal capacity of 720 kWh.

Most of the GridBox devices are placed within the ewz distribution grid, either in transformer stations or in distribution cabinets. Some GridBox devices are installed next to house connection boxes. Data security is a crucial issue. The handling of the measured data has to be considered carefully, especially where the GridBoxes are installed at house connection boxes and the measurement data could be attributed to individuals. Therefore, adequate measures for guaranteeing the protection of customers' privacy have been adopted.

The BKW pilot network is located in a rural area of the canton of Bern. It comprises a part of the medium voltage network as well as an entire low voltage network (see Figure 3).

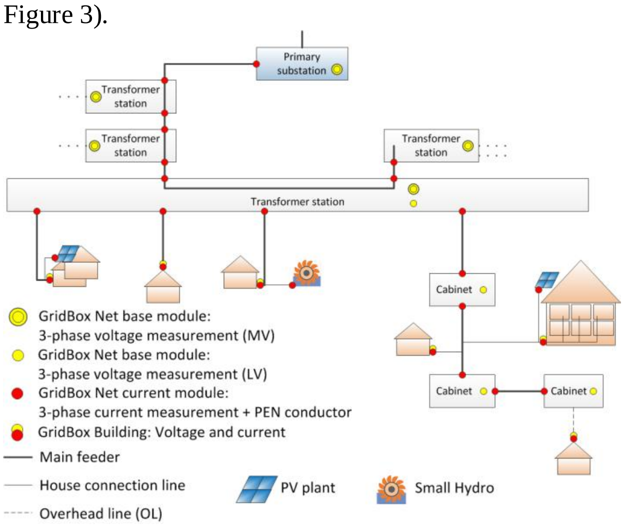

Figure 3. Rural pilot grid in the canton of Bern (BKW).

In the low-voltage network, the aim is to install a GridBox at every accessible point, i.e. on the low-voltage feeders of the transformer stations, the cable distribution cabinets in the streets, and the house connection boxes of the end customers. In the medium-voltage network, GridBoxes will be installed in selected transformer stations along one substation feeder. While the GridBox base modules can be connected directly to the LV connection points for voltage measurement and power supply, the MV switchgears have been equipped additionally with sensored cable terminations, housing a resistive voltage sensor and a Rogowski-type current sensor.

At BKW, both voltage levels (MV and LV) are characterized by a radial structure. In accordance with a considerable share of overhead lines and pole-mounted transformers, this network was chosen as it is typical for rural areas. Furthermore several DG units, here photovoltaic systems and one small hydro plant, and controllable loads like warm water boilers are available. Due to the low customer density in the chosen grid area, the technical options for high volume data communication are very limited. The choice was between the landline DSL and the mobile phone network. In order to be as independent as possible from end customers and because this communication channel is already in use inside the company for remote meter reading, data will be sent via the mobile phone network of Switzerland's biggest telecom operator.

As the success of a pilot project in the low voltage level is expected to depend on the acceptance or at least the toleration of the end customers, particular attention is dedicated to the non-technical aspect of data protection and privacy. As a proof-of-concept for hard- and software, four GridBoxes were put into service in summer 2014 in transformer stations and cable distribution cabinets.

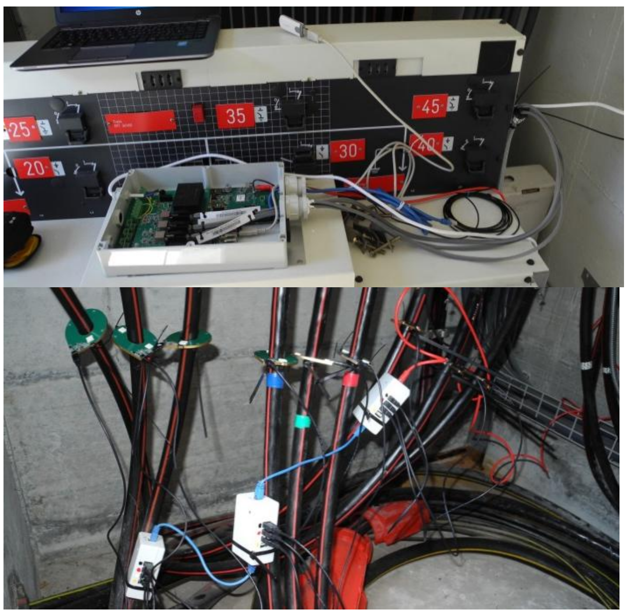
Figure 4. GridBox installation in a transformer station (BKW).

Figure 4 shows the first GridBox installation in a transformer station. The handling of the devices, the signal processing on the base module as well as the data communication via the mobile phone network towards a virtual server inside the IT landscape of the company met the expectations. The synchronously time-stamped instantaneous values of frequency, voltage and current (magnitude and angle) and power can be displayed on a time axis.

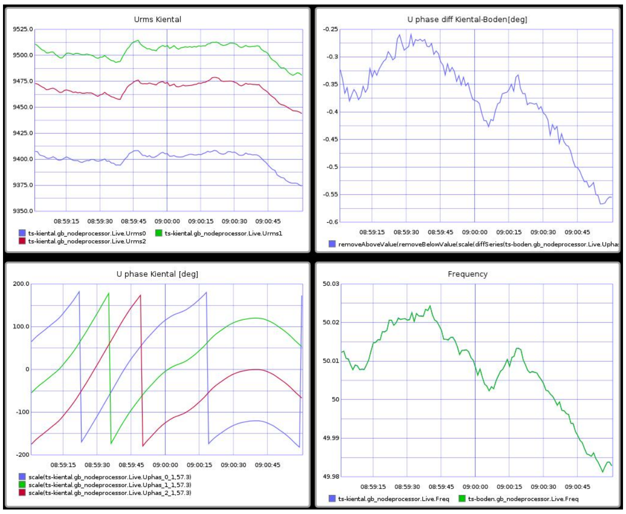

Figure 5. Voltage magnitude and angle, angle difference between two neighbouring transformer stations and frequency during two minutes.

Figure 5 on the left shows voltage magnitude and angle at one of the transformer stations for the three phases respectively. On the right on top, it can be seen that the phase angle difference to the neighbouring transformer stations is far below one degree as expected. On the right at the bottom, the frequency at both transformer stations is reported identically.

Accuracy for all measurement channels was verified by means of a laboratory installation with defined frequency, voltage, current and harmonics content. It can be highlighted that the total vector error for the voltage phasor measurement at nominal frequency and nominal voltage is in the range of 0.04 %, dominated by the magnitude error. For the actual rollout in early 2015, only minor adaptations were necessary.

CONCLUSIONS AND OUTLOOK

The GridBox system is a novel approach for monitoring and active control of distribution grids which addresses a whole set of challenges faced by DSOs in the near future. The GridBox concept represents an open platform where the hardware and software elements are specifically developed for covering the practical needs of a DSO. The platform is designed such that it can flexibly integrate a broad set of applications in the future. In order to test the applications under typical circumstances, two different pilot regions in the distribution grids of ewz and BKW were chosen.

A preliminary proof of concept phase has shown positive results. The GridBoxes, which have been installed in the medium and low voltage network, measure and send real-time measurements to the GridBox Master. Also, the accuracy of GridBoxes has been tested in the lab using an adjustable signal source. Especially the synchronized phasors have shown high accuracy. This performance allows the future development of innovative applications for the distribution networks.

Several measurement campaigns will be carried out to demonstrate the potential functionalities in addition to the continuous recording of all nodes with a resolution of one second. These additional applications include linear state estimation, topology detection, grid monitoring and power quality, real time optimization and network planning. The project will run until March 2016.

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