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Software-driven active customer interface for DER integration

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Jan Ringelstein[1] ✉, Mohamed Shalaby[2], Mihai Sanduleac[3], Lola Alacreu[4], João Martins[5], Vasco Delgado-Gomes[5]

[1]*Fraunhofer IWES, Division Systems Engineering and Distribution Grids, Kassel, Germany*
[2]*DERlab e.V., Kassel, Germany*
[3]*Exenir SRL, Bucharest, Romania*
[4]*ETRA I+D, Department of Technology, Valencia, Spain*
[5]*Centre of Technology and Systems Uninova, FCT Nova, Caparica, Portugal*
✉ *E-mail: jan.ringelstein@iwes.fraunhofer.de*

Abstract: The Nobel Grid project is developing information technology to integrate and fully utilise flexibility potentials of demand response and end-customer operated distributed energy resources (DERs) in the electric energy system. As key part of an according technical solution, the authors develop the 'smart meter extension (SMX)' for rapid development and deployment of new functionalities at end-customer premises. The document at hand reports the project results achieved so far. After summarising their approach, they introduce the Nobel Grid architecture. They then detail the architecture focusing on the SMX. Finally, they show how the SMX can be used to implement two example smart grid functions, highlighting the SMX's capabilities as a modular interface for software-driven DER integration.

1 Introduction

The conventional electric energy system is continuously undergoing a fundamental transition toward an increased share of distributed energy resources (DERs) – including electricity loads, storages and variable renewable generators – which makes grid control a challenge [1]. In recent years, research demonstrated that end-customer DER control and demand response (DR) can significantly contribute to reliable, save and economically optimal operation of networks with high shares of renewables [2]. Appropriate information technologies (ITs) at all system levels are considered a key enabler to control the future energy system [3]. In recent years, a vast number of consumer-level 'smart IT' solutions which may be used for this have become available as off-the-shelf products [4]. Also, the emergence of smart metering in many European countries is a strong driver for energy service-related IT deployment. However, when it comes to using end-customer's load and DER flexibilities for advanced smart grid applications, there has been no breakthrough in mass-scale application.

2 Problem statement

The 'Smart Grid' as defined by the American National Institute of Standards and Technology [5] introduces new advanced functionalities to different stakeholders in the electric network, e.g. the distribution system operator (DSO). Example functionalities are voltage control, grid congestion management, real-time balancing as well as self-healing, optimisation of reliability and real-time pricing [6].

However, despite successful demonstrations in research, the high potential for such applications remains greatly unused. Barriers for market breakthrough generally include legislative, regulative, business model and technological barriers, part of which are specific to the country in question. IT solutions at the customer side need to integrate into existing energy systems at the full process and value range, from enterprise down to customers. They need to seamlessly interface with state-of-the-art technology – billing, asset management, supervisory control and data acquisition (SCADA) systems, even smart homes and building automation, to only name a few. Complexity and cost of such a solution must be adequate. Adaptation to different country policies and compliance to standards and data security requirements is mandatory. Finally, the higher-level energy systems are in constant change. Hence, smart grid IT solutions at the customer must be highly configurable, flexible and extendable by functionalities that cannot even be seen today. Even more, smart grid systems at end customers may also provide applications from the area of Internet of things, new media and building automation, which are overlapping on a technological and functional level [4].

All in all, such IT solutions are exposed to much higher dynamics than components in the classical energy world. Even if functionalities are limited to the smart grid area, this basically calls for software-driven systems that enable for rapid development and deployment of new functionalities within a high security IT infrastructure.

3 Approach

Addressing named barriers, the Horizon 2020 project Nobel Grid was set up to develop the next level of tools and IT services for integration of active customers and producers (aka. 'prosumers') in the smart grid. Nobel Grid defines an architecture including all domains of the smart grid reference architecture model (SGAM) from commission for european normalization (CEN)–comité européen de normalisation electrotechnique (CENELEC)–european telecommunications standards institute (ETSI) by a use case driven approach as proposed by the European Mandate M/490.

It combines three central components operated by unbundled market actors (Fig. 1):

(i) Grid management and maintenance master framework (G3M).
(ii) Energy monitoring and analysis app (EMA).
(iii) DR flexible market (DRFM) cockpit.

The G3M framework allows DSOs to control and manage the distribution network including DER. The EMA app provides

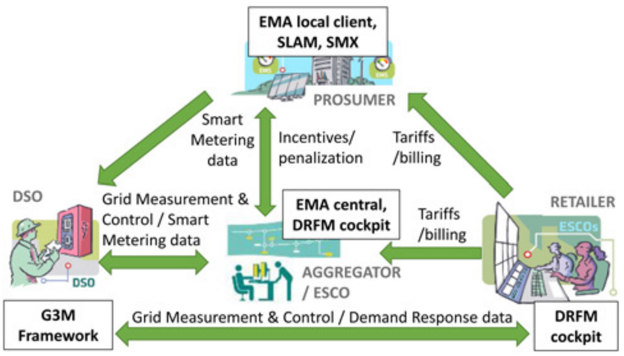

Fig. 1 *Nobel Grid actor relations*

prosumers with a mobile and web tool to analyse data concerning electricity consumption and production in real time. The DRFM cockpit bridges demand side and DER flexibility with the distribution grid actors to provide services to the DSO, which support network stability and security. The DRFM is used by aggregators and retailers. At the customer sites, flexibility of kW-scale DER is utilised by the central components through a new smart low-cost advanced meter (SLAM) which combines a classical smart metrology meter (SMM) and a smart meter extension (SMX). The SMX (Figs. 2 and 3) is acting as a residential gateway and communicates with the smart home environment through a radio interface. All the tools developed in Nobel Grid communicate with each other through a secure IT infrastructure.

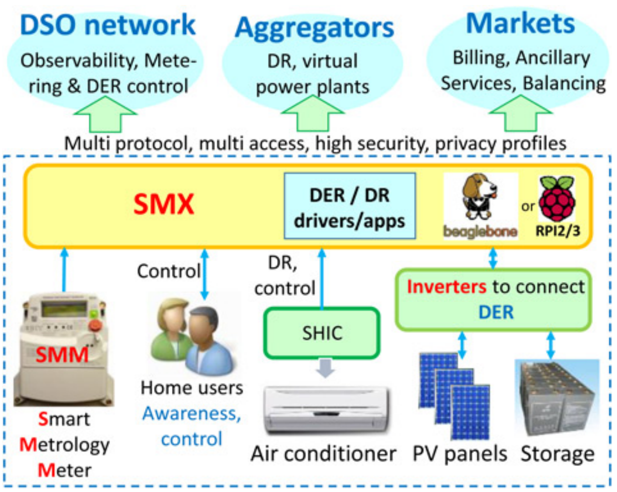

Fig. 2 *Smart Meter Extension*

4 Nobel Grid architecture

On the basis of project goals, requirements and a set of high-level, primary and secondary use cases, the architecture was detailed using the SGAM toolbox as collaborative modelling tool. It relies on state-of-the-art communication protocol and data modelling standards.

The business actor definition of Nobel Grid at the *SGAM business layer* corresponds to a subset of the unified smart energy framework. It includes business actors named above, where additional services are provided by energy service companies and third parties which act as external entities. The actors realise their goals through three main business use cases: provision of flexibility services, maximisation of power reliability and detection and quick resolving of blackouts. The prosumer/consumer is operating DER which oftentimes offer flexibility in operation, e.g. enabled through energy storages. With the business goal of optimising energy usage, the prosumer/consumer provides flexibility toward the aggregator, which bundles and again sells the flexibility, for example, to the DSO for grid capacity management. Part of the realised profits are delivered back from the aggregator to the prosumer/consumer. This delivery is implemented through the retailer, which takes the role of an energy supplier, managing financial interactions between the other actors.

At the *SGAM component layer*, G3M components at the DSO operation centre, DRFM and EMA central components at the aggregator/retailer premises and SMX/SLAM at the customer/prosumer home are defined as main software-driven components. Fig. 3 shows these components arranged around the SMX. The components inside the SMX are referred to in the following sections.

The SMX continuously exchanges supervision and control information with the G3M, DRFM and EMA centrals utilising communication drivers, which are labelled 'D' in Fig. 3. The connection between G3M/EMA and DRFM is used for organising DR campaigns. G3M, DRFM and EMA use three software modules:

(i) the data acquisition and control frontend (DACF), a repository of drivers and services covering all the communication protocols that are required,
(ii) the actor specific data repository, providing a real-time database (RTDB) and a middleware interoperability service and providing policy and security enforcement and
(iii) the actor specific big data repository, a database for holding historical measures that are related to the smart grid.

Also sketched in Fig. 3 is an enterprise service bus (ESB) which is used at each control centre along the DACF for organisation of information transfer. The three modules share a common code base, but are – in line with the principle of market unbundling – installed as independent instances in each of the actor's control centres.

The SGAM *communication layer* defines communication protocols for information exchange. They have been drawn from those recommended by CEN, CENELEC and ETSI. Controllable

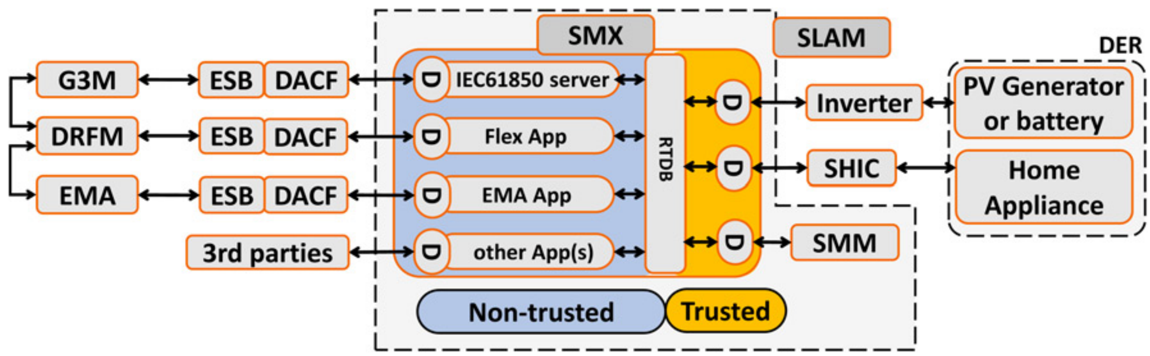

Fig. 3 *Simplified SMX-centric architecture*

kW-scale home appliances and DER are supervised and controlled by smart home intelligent controllers (SHICs). Local area network communication between SHIC and SMX uses IEEE 802.15.4-based 6LowPan as physical layer and internet protocol for smart objects (IPSO) objects as application layer. SMX and SMM, whose hardware can be bundled as SLAM, communicate through distribution line message specification (DLMS)/companian specification for energy metering (COSEM). Also, the SMX may communicate to local photovoltaic (PV) and battery inverters through MODBUS/transmission control protocol (TCP). For wide area network information exchange from or to the SMX, DLMS/COSEM is used for billing relevant metering data, tariff data, load profiles, meter instrumentation values, power quality data and events. IEC 61850 is used for SCADA and other smart grid related activities including DER monitoring and control by the G3M. automated demand response (OpenADR) profile V2.0b is used to support DR activities by the DRFM. Finally, message queue telemetry transport (MQTT) is used for implementation of energy services.

At the SGAM *information layer*, data models associated to DLMS/COSEM, IEC61850 and OpenADR are used. In addition, we use the common information model data model for exchange of information between different components at the DSO premises.

5 Smart Meter Extension

As can be seen from the architecture, the SMX acts as a kind of pivot point in the Nobel Grid system, providing data hub and firewall functionality. It has been developed as highly modularised interface between DER and central systems, connecting the consumer/prosumer private premises at one side with the control centres at the other side, and fully integrates into process and communication chains. Our SMX implementation relies on off-the-shelf low-cost embedded systems such as Raspberry Pi and BeagleBone Black and open source software. It uses a Linux operating system with customised scheduler; its internal architecture relies on strict separation of trusted and non-trusted zones at the operating system level. Both zones share access to a RTDB (RTDB, cp. Fig. 3) which offers a secure, role-based access model. The data model used at the RTDB is an extension of the COSEM data model. Real-time data is accessed through MQTT, while persistently stored data is accessed through representational state transfer. At the trusted zone, communication drivers interfacing to the local area networks are placed. At the non-trusted zone, functionalities with communication to wide area networks – and thus the Nobel Grid control centres – are implemented in virtual machine sandboxes. We use Docker as software solution for this. The concept allows third party applications to be installed at the non-trusted zone, hence making the SMX an open and modular software-driven smart grid component. The SMM can be an existing smart meter with local communication interface, resulting in a cost effective and highly adaptable smart grid key enabler that can be certified for use throughout Europe.

5.1 Basic functionality

The SMX acts as a meter gateway which at the same time enables complex functionalities and support for:

- Smart grid – by delivering Real-time data in a traditional or synchro-SCADA mode [7].
- Power quality – by allowing essential assessment on continuity of supply and on voltage level [8, 9].
- Energy services – by supporting recording of energy load profiles down to 1 min resolution combined with appropriate recorded events, in order to properly record services such as DR [10].
- Dynamic energy markets – by allowing real-time interaction between the market and the prosumer.
- Local production and storage control – by allowing to host specialised software agents which can control and optimise use of these local resources.
- Security and privacy – by providing a single communication endpoint for the remote control centres and acting as a firewall for the prosumer/consumer premises.

5.2 Software stack

The SMX software stack is built around the RTDB with role-based access control system featuring external actor individual privacy policy, which is a combination of country specific rules and prosumer preferences. The system is strictly dividing trusted and non-trusted software zones. Drivers for the SMM, SHIC and inverters at the local area networks are located at the trusted zone, while third party apps connecting to the Internet and central components are located in sandboxes at the non-trusted zone and executed within Docker environments (cp. Fig. 3).

Owing to the database-centric architecture, strict control of data access is possible. This means that data cannot be generally exchanged between different applications, because they can have different access rights. Any access to the data is made by interaction with the RTDB, through javascript object notation (JSON) messages which can be well filtered by role-based access control. Also, trusted and non-trusted drivers are interacting with the database only, and any application consuming this data needs to interact separately with the same database, with its specific access rights.

Since being exposed to the Internet, cyber security needs to be treated at highest level, because the SMX stores energy data convertible in billing data, thus in money, and it supports the smart grid ecosystem. To address this, each external actor can communicate with the SMX only through its own virtual private network, with its own credentials and in its sandboxed environment. With this strategy, external interaction can happen only within controlled environments, thus drastically reducing the risk of cyber attacks. Correct implementation of this approach removes any open input ports to be accessed from the outside, the SMX having the initiative for any connection being made by the local virtual private network client.

Appliance operation is automated by the generic SHIC. The SMX bundles local and wide area communication standards and protocols, and it can host functionalities from different manufacturers.

5.3 Rapid development of smart grid applications

For implementation of SMX functionalities at the untrusted zone as ‘sandboxed’ apps, Nobel Grid aims to provide rapid development tools. One possible basis for this is the open gateway energy management (OGEMA) framework, an advanced middleware for energy management provided by Fraunhofer institute for wind energy and energy system technology (IWES) (cp. www.ogema.org). It provides a platform where an arbitrary number of concurrently running applications can carry out energy management and building automation functions. OGEMA defines data resources representing real-world physical entities, units or devices which follow a standardised object oriented, unambiguous data model. It provides various core services for apps which allow for secure resource access, provision of web interfaces, and event-based functionality implementation. With support from Nobel Grid, an OGEMA Java software development kit (SDK) was created providing plugins for the commonly used Eclipse integrated development environment. It is currently used in order to implement the core SMX functionality of providing and activating flexibility of PV and battery systems toward the DRFM.

6 Software-driven applications

6.1 Integration of grid supporting inverters

This section describes a PV inverter-based solution with combined PV production and local storage, as an all-in-on solution for grid connection. Combining production and storage, it acts as a hybrid resource where storage can be used for both storing unused PV energy and also surplus energy from the network. Advanced grid services are enabled through connecting the inverter to the SMX.

In the Nobel Grid project, we use a quasi-z-source inverter due to its advantage on reducing component rating and constant DC current from the power source. Moreover, the inverter can boost the input voltage in single stage by introducing a special shoot through switching state.

The PV power interface is controlled to support the grid regarding unbalancing currents. If the load current is unbalanced, the PV system AC currents amplitude will also be unbalanced in order to balance the grid currents [11]. The reference of the amplitude of the PV AC currents is defined to compensate the imposed unbalance on the grid demanded currents. In case the power injected by the PV system is bigger than the power demand by the on-site loads, the PV inverter interface can supply the grid or send the excess power to the storage device.

To control the PV power interface, several functions were defined and implemented to measure values and to define set points. The measurement values include active and reactive powers, phase shift, battery voltage, current and state of charge. The control functions allow to set active and reactive powers, phase shift, operation mode and constraints. Functions implemented at the non-trusted zone of the SMX may access the inverter values and functions through the RTDB and an inverter driver placed at the trusted zone. The driver places measurement data received from the inverter through MODBUS/TCP at the RTDB, ready to be read by non-trusted zone apps which are equipped with appropriate access rights. These apps may again write power set points, operation modes or constraints to the RTDB, where they are read by the driver and translated to MODBUS/TCP commands, which are exchanged with the inverter. This design exposes the inverter's functions at the non-trusted zone, where, e.g. an IEC 61850 server could be placed with an according wide area network driver for connection with the G3M (cp. Fig. 3). This would be an example for an SMX low-level function which does include data receival, storage, translation and sending, but does not involve data processing at the SMX.

6.2 DER flexibility usage

As an example for a high-level SMX function which includes data processing and analysis at the SMX, we take another look at the flexibility ('flex') app as shown in Fig. 3. This app is designed to supervise the operation of PV generators and batteries, and to calculate and predict the amount of flexibility that can be provided by changing the DER operation modes, e.g. storing residual PV generation into the battery instead of feeding it into the grid or derating the PV generator. The flexibility information is prepared and exchanged on request with the DRFM control centre using OpenADR messages. The flex app utilises a solar irradiation forecast as external information from a third party, fetched by yet another app, to predict the PV generation and calculate future flexibilities. Control of the PV-battery system and activation of the flexibility potential on request by the DRFM central station is a task carried out by an additional app which is communicating to the RTDB only (not shown in Fig. 3). In Nobel Grid, we implement named apps in a single Docker sandbox using the OGEMA SDK. This high-level function highlights the SMX capabilities of providing software-driven smart grid functions in a secure environment.

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