Small or medium-scale focused research project (STREP)

Energy Demand-Aware Open Services for Smart Grid Intelligent Automation

SmartHG

EU FP7 Project #317761

Deliverable D4.3.1

Third Year Design of Grid Intelligent Automation Services

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Contents

List of Acronyms

API Application Programming Interface

CIM Common Information Model

DAPP Demand Aware Price Policies

DAPP-H Demand Aware Price Policies for Homes

DAPP-K Demand Aware Price Policies for Substation-Level Energy Storage Control

DB&A Database and Analytics

DBService Database Service

DLC Direct Load Control

DR Demand Response

DSM Demand Side Management

DSO Distribution System Operator

DSSE Distribution System State Estimation

EBR Energy Bill Reduction

EDN Electric Distribution Network

ESS Energy Storage System

EUMF Energy Usage Modelling and Forecasting

EUMF-K Energy Usage Modelling and Forecasting for Control

EVT EDN Virtual Tomography

GIAS Grid Intelligent Automation Service

HECH Home Energy Controlling Hub

HIAS Home Intelligent Automation Service

IAS Intelligent Automation Service

JWT JSON Web Token

LV Low Voltage

MILP Mixed-Integer Linear Programming

MV Medium Voltage

PEV Plug-in Electric Vehicle

PPSV Price Policy Safety Verification

SCADA Supervisory Control And Data Acquisition

SEP2 Smart Energy Profile version 2

SE State Estimation

SMC SmartHG Market Controller

T&D Transmission and Distribution

UML Unified Modeling Language

URL Unified Resource Location

XML eXtended Markup Language

CIM Common Information Model

Dbservice Database Service

DSO Distribution System Operator

DSSE Distribution System State Estimation

EKF Extended Kalman Filter

EKF-R Extended Kalman Filter - Robust

HV High Voltage

LV Low Voltage

MV Medium Voltage

NARX Non-linear Auto-Regressive eXogenous

SCADA Supervisory Control And Data Acquisition

SE State Estimation

WLAV Weighted Least Average Value

WLS Weighted Least Squares

WLS-R Weighted Least Squares - Robust

JWT JSON Web Token

OAuth2 OAuth 2.0

API Application Programming Interface

LV Low Voltage

EMS Energy Management Systems

CCAPl Control Center API

UML Unified Modeling Language

EA Enterprise Architect

ESB Enterprise Service Bus

Executive Summary

Objectives The main objective of the SmartHG project is to develop effective Intelligent Automation Services (IASs) to minimise users energy bill for end residential users while optimising operation on the grid for Distribution System Operators (DSOs). This deliverable describes the third year SmartHG activities in WP4, that focuses on the Grid Intelligent Automation Services (GIASs) that are those services working on the DSO side. Since GIASs output must be directly available to DSOs, direct communication between GIASs and DSOs has been designed and established.

Retrospect The activities in the project first year resulted in building a prototype version of all the GIAS and in defining their dependencies, outputs, and functional specifications. The Database and Analytics (DB&A) service worked as a communication channel between different IAS and between home devices and IASs. In the second year the DB&A has been re-designed to accommodate for the new services, of which Database Service (DBService) primarily provides measurement data for third party service providers and SmartHG Market Controller (SMC) is responsible for the delegation of access. Demand Aware Price Policies (DAPP) has been re-designed to include two different services, to be employed in two different scenarios for DSOs. The Price Policy Safety Verification (PPSV) service has been re-designed so as to enable both a safety verification (by performing a sort of robustness analysis) and an economic evaluation of effect of individualised price policies output by DAPP. EDN Virtual Tomography (EVT) has been improved so as to include a fully-functional State Estimation (SE) system developed based on detailed recordings from the Kalundborg test site Electric Distribution Network (EDN). In their second year version, EVT, DAPP and PPSV offered an integrated approach for improving EDN usage, by exploiting the EDN hierarchy induced by EDN substations interconnection. Finally, we introduced a methodology for evaluating the performance of Smart Energy Profile version 2 (SEP2) communication protocol along with a Demand Response (DR) strategy for the communication between DSO and IASs.

Achievements During the SmartHG third year, the WP4 activities have been mainly focused on the DAPP and EVT services. As for DAPP we further clarified the business model we employ: all residential homes using DAPP will also have both an Energy Storage System (ESS) and the Energy Bill Reduction (EBR) Home Intelligent Automation Service (HIAS) installed. The expense will have to be entirely covered by the DSO/retailer. As we show in Deliverable D5.3.1, the DSO/retailer actually has a revenue in doing this.

Furthermore, the achievements this year iteration have been a major re-factoring of code for enabling testing and adding additional business logic to the Application Programming Interface (API) for more efficient data extraction. Much work has put into ensuring that the output is correct.

Moreover, demand forecasting models to support advanced EVT service functions have been developd along with a number of scenarios designed to demonstrate the benefits of

EVT and other GIAS services to the DSO. The models for the interaction of EVT with the other GIAS services and the DSO network monitoring and control systems have been proposed.

Finally, Common Information Model (CIM) has been identified as a powerful overall integration framework, which is historically grown and continuously improved in order to meet the last requirements. Therefore, CIM models have been developed to handle the communications between DSOs and IASs in a standard manner. The model follows IEC 61968 standard and shows the data and message exchange models.

Impact

The DB&A is built on open source software and can potentially be reused as a reference model in other smart grid projects. The design of the data model ensures flexibility and scalability.

DAPP can be used by DSOs/retailers to actually and effectively perform load shifting on EDN substations, thus lowering down Transmission and Distribution (T&D) investment deferral costs. In this setting, PPSV can be effectively used to estimate if the theoretical load shifting promised by DAPP is still achieved under probabilistic residential users deviations.

The demand forecasting models and Distribution System State Estimation (DSSE) algorithms that are developed to support advanced EVT service functions can be readily applied in the planning and operation of distribution power networks. The work conducted in this work package attracted the attention of academic audiences and a number of journal and conference papers have resulted from this work.

The designed Common Information Model (CIM) enables a standard data exchange not only between IASs and the energy utility companies but also allows other applications in the power systems domain.

Chapter 1

Retrospect

In this section we briefly recall the main achievements of the first two years of the SmartHG Grid Intelligent Automation Services (GIASs) design, which was described in Deliverables D4.1.1 and D4.2.1.

The activities in the project first year resulted in building a prototype version of all the GIAS and in defining their dependencies, outputs, and functional specifications. The Database and Analytics (DB&A) service works as a communication channel between different Intelligent Automation Service (IAS) and between home devices and IASs. The goal of the Demand Aware Price Policies (DAPP) service is to compute individualised power profiles for residential users, so that they obtain together with retailer and Distribution System Operator (DSO) economic benefits. The Price Policy Safety Verification (PPSV) service is in charge of checking the safety of Electric Distribution Network (EDN) substations in case residential users follow or not (on a probabilistic basis) the given individualised price policies. The EDN Virtual Tomography (EVT) service is tailored to estimate the state of the EDN and all the related physical quantities. As for communication between DSO and IASs, a common database and an open protocol were designed.

The main achievements of the second year iteration are the following. DB&A has been re-designed to accommodate for the new services, of which Database Service (DBService) primarily provides measurement data for third party service providers and SmartHG Market Controller (SMC) is responsible for the delegation of access. Demand Aware Price Policies (DAPP) has been re-designed to include two different services, to be employed in two different scenarios for DSOs. In the first scenario, the DSO does not aim at changing the configuration of EDN substations, and instead aims at shifting user demand. In the second scenario, the DSO aims at fulfilling users demand as it is, by counteracting demand peaks with Energy Storage System (ESS) installed at each EDN substation. The PPSV service has been re-designed so as to enable both a safety verification (by performing a sort of robustness analysis) and an economic evaluation of effect of individualised price policies output by Demand Aware Price Policies for Homes (DAPP-H). EVT now includes a fully-functional State Estimation (SE) system developed based on detailed recordings from the Kalundborg test site EDN. Demand forecasting techniques have been developed in order to forecast electricity demand profiles at the distribution substation level. Such demand forecasts are important as an input to the SE, and also for the EVT to provide early warning of potential network issues, and generate recommendations and advices for the DSO. EVT, DAPP and PPSV offer now an integrated approach for improving EDN usage, by exploiting the EDN hierarchy induced by EDN substations interconnection. The previous year iteration has introduced a methodology for evaluating the performance of Smart Energy Profile version 2 (SEP2) protocol along with a Demand Response (DR) strategy for the communication between DSO and IAS.

The challenges identified for the third year were the following.

1. Third year design of DB&A (Task T4.1) must focus on enforcing data access policies for the residential users and the DSO in the Database Service (Dbservice),design and implementation of the SMC for managing the communication between services and improvement the reliability of Dbservice.

2. Third year design of DAPP (Task T4.2) must focus on further clarifying the business model for the residential users and the DSO.

3. Third year design of EVT (Task T4.3) must concentrate on improving the performance of the demand forecasting and network state estimation services and their integration with other SmartHG services.

4. Third year design of PPSV (Task T4.4) must work in synergy with the third year versions of the DAPP and PPSV services

5. Third year design of open protocol for DSO–IAS communication (Task T4.5) must work on further investigation for using Common Information Model (CIM) to handle the data exchange in a standard manner is still needed.

Chapter 2

Introduction

Work Package 4 (WP4) is in charge of the design of the SmartHG Grid Intelligent Automation Services (GIASs). Such services are oriented to power network operators, primarily Distribution System Operators (DSOs) and energy retailers with an aim to improve the overall Electric Distribution Network (EDN) usage and performance. From the functional point of view, GIAS control loops are the outer loops of the overall SmartHG functional schema, see highlighted part of Figure 2.1. From the architectural point of view, GIASs are those highlighted in the overall architectural schema of Figure 2.2. In the second year iteration of WP4, we re-designed the SmartHG GIASs. Such new design for SmartHG GIASs is described in this deliverable. The (Web-based) implementation of GIAS prototypes, based on the design described here, is described in Deliverable D4.2.2. Such prototypes are then used for the evaluation phase described in D5.2.1.

In the second year's iteration, the SmartHG Market Controller (SMC) service was co-located within the internal report of the Database and Analytics (DB&A). Since the SMC service is responsible for the communication between Intelligent Automation Services (IASs) and delegating access to the Database Service (Dbservice), the design of the SMC service has be placed in IR 3.2.3.1 this year's iteration.

In the third year iteration, the focus was on fine tuning the already developed designs of Demand Aware Price Policies (DAPP), EDN Virtual Tomography (EVT) and Price Policy Safety Verification (PPSV), their integration with the final beneficiary and their evaluation. The proposed service architecture remains the same as previously proposed and is shown in Figure 2.3.

This iteration of the SmartHG system has improved the portability and the integration with other services, while ensuring having an access control system. Furthermore, this iteration has focused on increasing the robustness of the Dbservice such that every analytic function has a unit test. This will not only help the robustness of the development, but also the correctness of the functionality. In general, the Common Information Model (CIM) is used for two major use cases: Message exchange based on eXtended Markup Language (XML) serializations and exchange of power grid topologies serialized with resource description framework.

This deliverable reports about the design progress for the services mentioned above, and performed in Tasks T4.1, T4.2, T4.3, T4.4 and T4.5 of WP4.

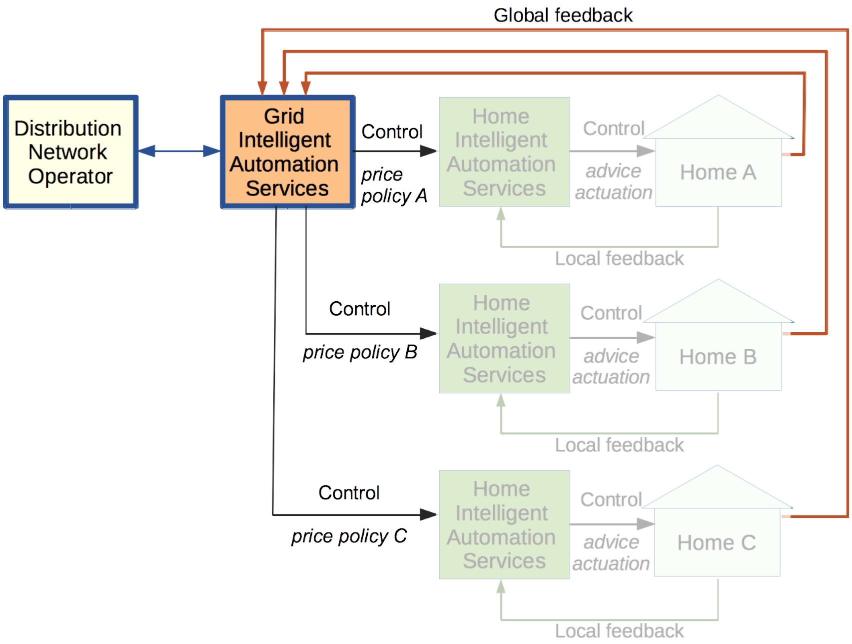

Figure 2.1: Functional schema of SmartHG GIASs.

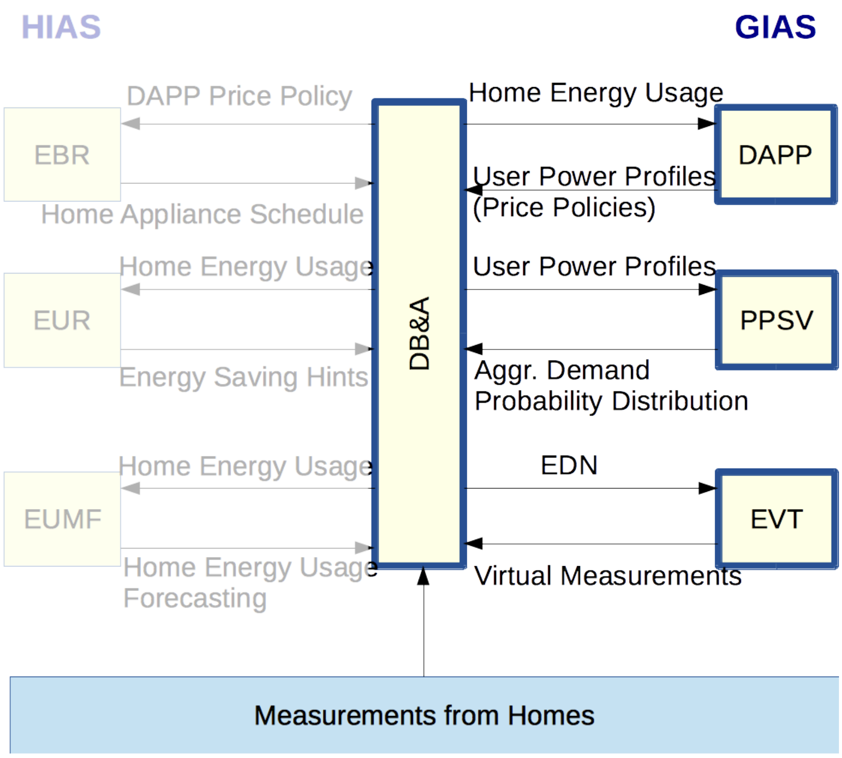

Figure 2.2: SmartHG GIASs architecture.

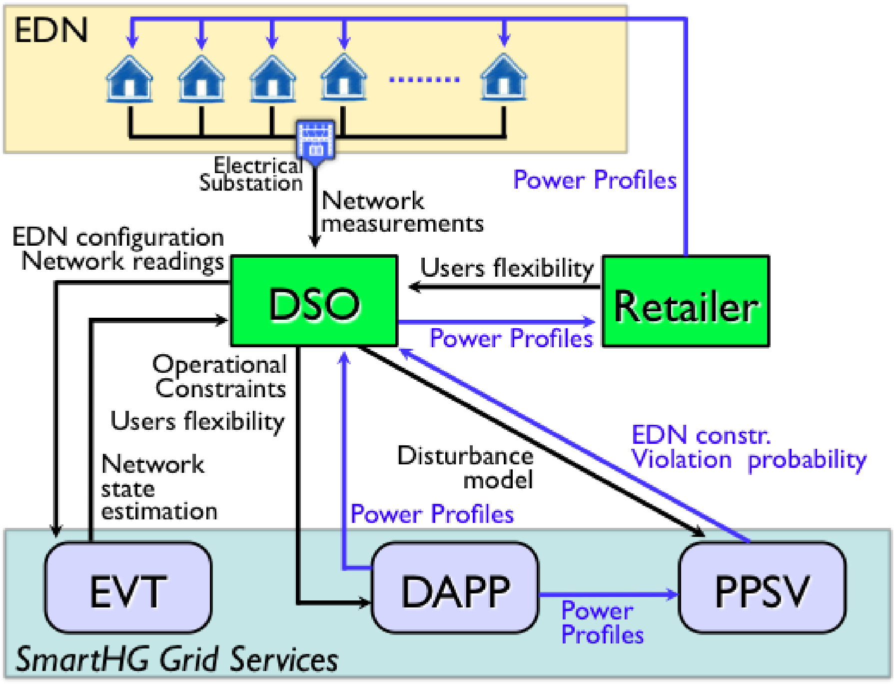

Figure 2.3: The proposed services architecture.

2.1 Motivation

The main motivations for developing our second year version of Grid Intelligent Automation Services (GIASs) are the following.

Storage system for meter data An essential part of the future smart grid systems is the storage system for meter data. The Dbservice is envisioned to provide the storage capabilities for saving the meter data securely and reliably in the SmartHG project. Furthermore, it is envisioned to provide business logic for the other IASs, such that common calculations and views of datasets can be provided directly, instead of each service has to calculate these by themselves.

Residential Users Load Shifting In order to optimise EDN substations (feeders) usage, residential user power demand should be mostly flat throughout the day. On the contrary, typically residential user power demand is very low during night, morning and early afternoon, and has very high peaks during late afternoon and evening. To this aim, DSOs try to either force (Direct Load Control (DLC) methods) or motivate (Demand Response (DR) methods) users to shift their power demand. However, DLC methods are typically not accepted by users (as they require the DSO to see how they use their own home appliances), and DR methods are not enough to motivate users to shift their loads. Inclusion of Energy Storage Systems (ESSs) into the scheme is also essential as future trends indicate their usage will increase at the residential homes level.

Probabilistic Models for Residential Users Power Demand Residential users behaviour (i.e., aggregated power demand) is typically not exactly predictable, and only probabilistic models may be used. Basing on probabilistic models of residential users, DSOs need a service able to evaluate both safety of the EDN feeders (to check that very high peaks in user demand are unlikely) and variations in the economic gain.

Active Management of EDN All relevant studies suggest that such trends towards more actively-managed distribution systems are set to continue, and that the integration of these technologies will lead to more frequent occurrences of problems in the distribution network, such as congestions and excessive voltage variations [1, 2]. This has led to interest in adapting network management techniques, previously only used at the transmission level to distribution systems, such as state estimation and short-term operational planning [3, 4, 5, 6]. Given this context, EVT activities should focus on developing services and tools aimed at assisting the network operator (DSO) in the operation and management of active distribution networks.

Communication Protocols for DR Methods To build a standard data model to exchange messages between EVT and utility energy company.

2.2 Objectives

With respect to the motivations in Section 2.1, the main goals to be obtained by the third year version of GIAS are the following.

- Goals DB&A To mature the Dbservice for production and allow for further integration with the other services in the SmartHG project. This includes Application Programming Interface (API) improvements and version control for enabling asynchronous development between the Dbservice and the other service. Also, to include a new virtual energy port concept to provide energy measurements based on current, voltage, and power factor sensor data. The objective has also been to change the access control system to be compliant with the SMC service using JSON Web Tokens (JWTs) in the authorization procedure in the OAuth 2.0 (OAuth2) protocol.
- The DAPP service must be designed to make DLC methods acceptable by the residential users. To this aim, it must yield an economic saving for the DSO which must be enough to cover the additional software (in our case, the Energy Bill Reduction (EBR) service) and hardware (in our case, an ESS or a Plug-in Electric Vehicle (PEV), in addition to smart meters) required to actually put DAPP into work on an EDN substation.
- The PPSV service should be designed so as to be a support service for the proposed schema, consisting in proposing individualised profiles to residential users. To this aim, it must provide both a safety verification and an economic evaluation.
- Regarding the EVT the main objectives for the third year were to improve demand forecasting techniques to support the service in the generation of intelligent warnings, alarms and recommendations for the DSO, to improve the algorithms for bad input data detection and increase the robustness of the Distribution System State Estimation (DSSE) solver, to integrate the EVT service more closely with the other GIAS services, namely DAPP and PPSV and to demonstrate, where possible, the benefits of these services to the DSO, using data from the SmartHG test site electricity networks.
- Study CIM models to handle the communications between DSOs and IASs in a standard manner.

2.3 Achievements

The main achievements of the third year iteration are the following.

DB&A The source code has been re-factored for enabling unit testing and adding additional functionality to the RESTful API for more efficient data extraction. Much work has put into ensuring that the output is correct. Moreover, the Dbservice now supports self-containing JWT tokens which are compliant with the service integration mechanism.

DAPP The DAPP service has been re-designed so as to propose an integrated methodology with EVT and PPSV services on the grid side and with the EBR service on the home side. Namely DAPP works in synergy with:

- the EVT service. Namely, the EVT service provides part of the input of DAPP, i.e., the desired limits for the aggregated demand to be enforced on the EDN substations.
- the PPSV service. Namely, PPSV uses part of the output of DAPP, i.e., the *collaborative* profiles computed by DAPP for each of the residential users, when they have to follow the power profiles output by DAPP itself.
- the EBR service. In this year iteration, we assume each residential home to be equipped with the EBR service running on the Home Energy Controlling Hub (HECH), as well as with either an ESS, a PEV or both. This allows us to leverage the residential users from the responsibility to follow the DAPP output power profile. Furthermore, in our exploitation scenario the DSO will provide and install all the necessary hardware (ESS) and software (EBR) to residential users. Thus, the DSO must obtain a saving by using DAPP and EBR, also considering that all installation costs must be covered. This will be shown in Deliverable D5.3.1.

PPSV As for PPSV, the second year version already fulfils all desired goals for this service. In Annex we recall the second year design of PPSV.

EVT

- Developed demand forecasting models to support advanced EVT service functions, such as the generation of intelligent warnings, alarms and recommendations for the DSO, and implemented several improvements to the DSSE algorithms to improve the robustness and accuracy of the estimator.
- Developed a number of scenarios designed to demonstrate the benefits of EVT and other GIAS services to the DSO.
- Designed models for the interaction of EVT with the other GIAS services and the Dbservice, and proposed a suitable CIM for the communication between EVT service and the DSO network monitoring and control systems.

DSO-IAS protocol In this final iteration, the focus was on CIM development. Therefore, CIM models have been studied to depict the communications between DSOs and IASs in a standard manner and the adopted model followed the IEC 61968 standard.

Table 2.1: Mapping between SmartHG tasks inside WP4 to chapters of this deliverable

Task	Task Name	Chapters
T4.1	Design and Development of the DB&A service	Chapter 3
T4.2	Design and Development of the DAPP service	Chapter 5
T4.3	Design and Development of the EVT service	Chapter 4
T4.4	Design and Development of the PPSV service	see of Deliverable D4.3.1
T4.5	Design and Development of Open Standard Internet based communication between DSO and IASs	Chapter 6

GIASs Integrated Methodology EVT, DAPP and PPSV offer now an integrated approach for improving EDN usage, by exploiting the EDN hierarchy induced by EDN substations interconnection (see Figure 2.3).

Other Achievements Finally, the user-friendly Web interfaces for DAPP, PPSV and EVT, as well as the corresponding RESTful APIs, have been improved and finalised. (see Deliverable D4.2.2).

2.4 Outline

This deliverable is organised as follows. Chapters 3, 5 and 4 describe the advances in the design of DB&A, DAPP and EVT, respectively. Furthermore, Chapter 6 describes the communication protocols between DSOs and SmartHG GIASs. The overall results of this deliverable are summarised in Chapter 7. Moreover, Section 7 describes in detail the advance of third year year in GIASs design and discusses their impact on the global project objectives. Finally, Table 2.1 shows the correspondence between SmartHG tasks inside WP4 and sections of this deliverable.

Chapter 3

DB&A Service Design Description

3.1 RESTful API Improvements

The RESTful Application Programming Interface (API) of the Database Service (Dbservice) is the main interface for its clients. Its composition and implemented business logic determines its flexibility. A higher flexibility requires fewer queries for the clients to extract specific data sets. This will give better performance and utilization of the service. The added business logic will not provide backward compatibility since clients will often ignore added functionality. However, a change in the composition and API will often break backward compatibility, since this is the "address" for client to obtain their requested resource.

In this third year iteration, the Dbservice has been extended with API versioning, such that clients can be requested to upgrade their services gracefully. The old API will be maintained for a period, but the new API will be recommend. At some point the old API will be declared obsolete. This enables the Dbservice to be extended without breaking compatibility of its clients. Moreover, to support the querying process, the Dbservice has been added Unified Resource Location (URL) traversing.

3.2 Virtual Energy

A vital addition to this third year's iteration is the implementation of the concept of virtual measurements. The virtual measurements represent inferred information based on a number of assumptions about the system. More concretely, the test-bed in Svebølle have been equipped with current sensors. These current sensors are clammed to conductors for appliances and measures only current flow. However, to deduce the energy consumption or production from this data, it is necessary to know the voltage and the power factor as well.

The fixed value meter ports set a fixed value on a meter port. Fixed values can, in some cases, be a valid estimate for a measurement that cannot be measured. For instance, this could be an estimation of the voltage level in the Low Voltage (LV) network in Denmark (which is very close to 230V generally).

3.2.1 Virtual Energy Measurements

A virtual energy measurement is defined to be an accumulated consumption value within a time frame. It represents the energy consumption (or production) for an appliance where only current measurements are present. For instance, this could be Panoramic Power's noninvasive and self-powered current sensors that are put on a single conductor. With this information, it is possible to get a good estimate of the power consumed, assuming the voltage level and power factor are constant. However, when information about the voltage and power factor are present, it is possible to improve the precision, especially when the appliance is an inductive load (e.g., an inductive stove). Furthermore, if the main energy consumption of the house is available, this can be included as reference in a presentation of a virtual energy measurement. The administrative interface of the Dbservice (`/admin`) (which is considered the entry point of the Distribution System Operator (DSO)), has therefore been extended to combine meter ports that are relevant for creating a virtual energy port.

The improvements have been based on a continuous discussion with the partners in the SmartHG project to find a trade off between accuracy and the number of generated measurements. Concept #3 illustrated in Fig. 3.1 has been implemented in the third year iteration of the Dbservice and tested with test cases presented in Section 3.3.

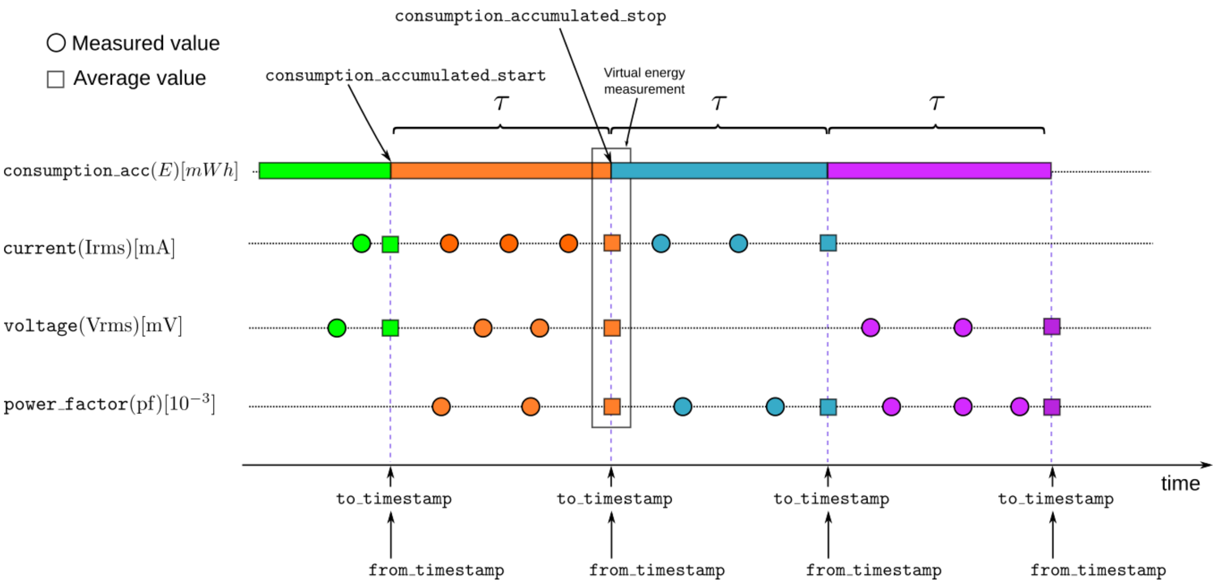

Figure 3.1: Concept #3 of generating a virtual energy measurement.

3.2.2 Fixed Value Meter Ports

In some cases, virtual energy ports cannot be constructed because of the lack of measurement types, e.g., voltage or power factor. In such cases a fixed value meter port can be generated. A fixed value meter port delivers a static value with a given resolution to simulate a real source. For the integration of other services, this is useful to get a coherent API.

The DSO can go through the administrative interface of the Dbservice and add a fixed value meter port for a customer. Typically, after this is done, the fixed value meter port can be associated with a virtual energy port such that it can generate a virtual energy measurement with a certain configuration.

3.3 Unit Testing

The Dbservice project includes a number of test cases to show that the functionality of each part works appropriately. Not only does this ensure verification of the functional parts, e.g., access control, aggregation algorithms and condensing of data, but also helps the developer to find bugs early in the development cycle. Moreover, it provides a living documentation of the implementation itself, such that clients to the Dbservice can see an example of an interaction with the Dbservice.

The test cases are focused around the access control policies and the functionality provided for other services. In particular, these test cases are made:

- `AccessControlFilteringTestCase`
- `FixedValueMeterPortTestCase`
- `VirtualEnergyMeasurementsTestCase`
- `TemperatureMeasurementsTestCase`
- `AggregationTestCase`

The test cases follow the unit testing framework[1] accompanying the Python standard library. The Django web framework supports this by default. It supports test automation for all apps in the project, where tests can share setup and shutdown code before and after executing the tests. Furthermore, it include a reporting framework that gives an overview of results. The module supply functions for creating users and objects in the database, as well as an `APIRequestFactory` class for simulating communication directly with the API.

[1] https://docs.python.org/3/library/unittest.html

Chapter 4

EVT Service Design Description

4.1 Introduction

This section describes the design of demand forecasting and state estimation tools which support critical functions of the EDN Virtual Tomography (EVT) service, including the Distribution System State Estimation (DSSE) solver, and the generation of warnings, alarms and recommendations for the Distribution System Operator (DSO).

Also, the performance of various different DSSE methods, using field data taken from the Kalundborg Medium Voltage (MV) network is compared. The performance of each method is assessed in terms of its solution accuracy, robustness to noise and input measurement uncertainty, and ability to identify bad data and network topology errors.

4.2 Demand Forecasting Tools to Support EVT

Short-term demand forecasting refers to the prediction of electrical demand over periods from several hours to a week ahead. The forecasting of electrical demand is considered to be critical for power system operation, particularly for energy balancing, management of network congestions and contingencies. Most of the previous literature in demand forecasting area to date focuses on large-scale aggregated loads, such as the aggregated electricity demands for entire countries, or regions, for transmission system applications. However, recent developments such as active distribution networks and the large-scale integration of distributed energy resources have led to significant interest in forecasting demands at a more local, disaggregated level. A number of authors have investigated the forecasting of demand at each substation in the network, or even at the individual feeder or end-user level [5, 7, 8, 9, 10, 11, 12, 13]. Moreover, the recent availability of smart metering data provides much more detailed information on electricity end-use than was available before.

Before carrying out any modelling, an assessment of the correlations between electrical demand and the variables which influence it was carried out at various levels of load aggregation. This assessment was carried out using data from the Kalundborg test site. Smart meter demand data was available from 1,600 customers for a continuous period of 24 months during 2012-2014, at a resolution of 1 hour. The corresponding local weather forecast data (including typical 24-hour ahead forecast errors) were obtained by request from the Danish Meteorological Institute [14].

The analysis on an annual basis shows strong correlations with the temperature (negatively correlated) and the previous 24 hour average demand. The influence of the aggregation level on the correlation between the demand and the above-mentioned variables is analysed.

In order to carry out demand forecasting, a model of the electrical demand is created using some or all of the variables discussed above. Several approaches using linear and non-linear predictive techniques were applied: Naive Model, Load Shape Model, Linear Autoregressive Models and Non-Linear Autoregressive Models.

Demand Forecasting Model Selection The results in Fig. 4.1 show that at the Primary (High Voltage (HV)/MV) and Secondary (MV/Low Voltage (LV)) substations, the Non-linear Auto-Regressive eXogenous (NARX) model shows the best performance. At the most local levels (LV feeders and individual users), none of the demand forecasting models 2-4 offer any clear improvement over the Naive Model (1), indicating that the demand forecast models do not have any significant predictive capability at these levels of aggregation. Given these results, the NARX model was selected for forecasting demands at the Primary (HV/MV) and Secondary (MV/LV) substation level in the EVT service.

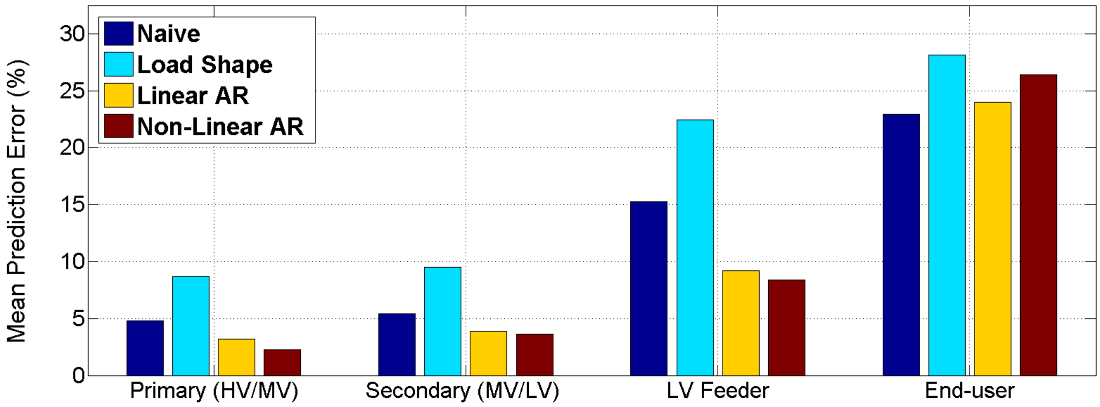

Figure 4.1: Comparison of demand forecasting model mean prediction errors, at various levels of load aggregation: (i): Primary HV/MV substations (hundreds to thousands of customers); (ii) Secondary MV/LV substations (few hundreds of customers); (iii) LV feeder level (few to tens of customers); (iv) End-user level (single customer)

4.3 Advanced State Estimation Methods

In the analysis, five different State Estimation (SE) solvers are applied to the MV distribution network case study: 1) Weighted Least Average Value (WLAV)); 2) Weighted Least Squares (WLS); 3) Weighted Least Squares - Robust (WLS-R); (4) Extended Kalman Filter (EKF); 5) Extended Kalman Filter - Robust (EKF-R). The performance of each SE is assessed based on estimation accuracy, robustness to noise and gross input data errors, ability to detect network topology errors, and computation time.

In order to select a suitable SE solution method for the EVT, each of the SEs 1-5 outlined above were tested using a detailed model of the Kalundborg network, along with real data recorded from the Supervisory Control And Data Acquisition (SCADA) and smart metering systems in this network. This Kalundborg test site network is a suburban/rural 10kV system with a weakly-meshed structure. The network has a peak demand of 3.2 MW, which is made up primarily of suburban/rural residential customers

(77% of the total annual demand), with the remaining demand comprising factory, district heating and street lighting loads. There are around 1,600 customers located at 46 MV nodes, where each MV node corresponds to a secondary transformer substation (10:0.4 kV).

The following criteria were used to select the most suitable method: SE Solution Accuracy, Noise Performance Tests,Robustness Test,Bad Data Identification,Handling of Network Topological Errors and Computation Times.

Final Selection of Estimator for EVT The analysis of the performance of each DSSE approach allowed the specification of an appropriate solution for the EVT service. It was shown that each SE has advantages and drawbacks in terms of different aspects of its performance, such as noise suppression, bad data detection, robustness, etc. The WLS-R estimator was eventually selected for this application since it gave sufficient performance in terms of solution accuracy and bad data detection, and also since the "robustness" (define here as the ability of the SE to find a solution in the presence of extreme outlying error values) was a very important design criteria. In addition, the computation time (average solution time of around 62.4ms for the Kalundborg Electric Distribution Network (EDN)) is sufficient for this type of static SE e.g. calculating and updating the network state at intervals of few to tens of minutes.

4.4 Integration of EVT with other GIAS Services and DSO Systems

The proposed architecture for the Grid Intelligent Automation Service (GIAS) services is illustrated in Fig. 2.3, taken from [15]. The main role of the EVT is to use all of the available measurements and sensor data from the EDN to provide an accurate estimate of the system state. This is designed to improve the DSO visibility of the MV part of the network, through providing "virtual" measurements even in parts of the network where no sensor data is available. This is achieved through computer modelling of EDN and using the forecasting and state estimation techniques outlined in Sections 4.2 and 4.3 of this report.

The EVT is also used to support the other GIAS services by computing the EDN operational constraints, which are a required input to the Demand Aware Price Policies (DAPP) service, and by verifying (in combination with the Price Policy Safety Verification (PPSV) service) that the proposed price policies do not cause adverse effects in the EDN. The interaction between the EVT and the other GIAS services is illustrated through the analysis of scenarios using data the Kalundborg test site in the Evaluation Internal Report (IR 5.5.3.1).

For exchange of all EDN parameters such as bus and branch information, the Common Information Model (CIM) from the standard IEC-61970: Common Information Model/Energy Management [16], the relevant standard for exchange of information in power network. Another standard, IEC-61850 deals with the design of electrical substation automation [17], and is a part of the reference architecture for electric power systems. The abstract data models defined in IEC-61850 can be mapped to a number of protocols. This architecture includes a data model for warning and alarm messages for the operator in a DSO control centre.

Chapter 5

The DAPP Service

The main goal of Demand Aware Price Policies (DAPP) is to optimise Electric Distribution Network (EDN) operation at substation level, by avoiding peaks (*peak shaving*). In order to do this, for each EDN substation s, DAPP computes *individualised power profiles* for each of the homes connected to s, so that the operational constraints on s (namely, lower and upper bounds for the aggregated power demand resulting on s) suggested by the EDN Virtual Tomography (EVT) service are met. More in detail, as the individualised power profile for residential user u defines lower and an upper bounds for the power demand of u, if user u is able to keep the power demand inside such bounds, then the aggregated demand resulting on the substation s meets the constraints suggested by the EVT service. To meet such objectives, the last year version of DAPP has strengthened the synergy with the Energy Bill Reduction (EBR) Home Intelligent Automation Service (HIAS) (described in Deliverable D3.2.1). Namely, it is assumed that each of the residential users connected to s will be provided with the EBR service and an Energy Storage System (ESS) (both payed by the Distribution System Operator (DSO)). Thus, differently from the second year version of DAPP, the EBR service instances running on each home will be responsible of keeping residential users demand inside the bounds defined by DAPP. On the other hand, differently from the second year version of DAPP, residential users will never be required to change their habits, nor they have to sustain the expense of the ESS and EBR. In Deliverable D5.3.1 (and Deliverable D7.3.1) we will show that this market model is indeed convenient for the DSO.

Finally, w.r.t. the second year version of DAPP, here we focus on the Demand Aware Price Policies for Homes (DAPP-H) service only, as the Demand Aware Price Policies for Substation-Level Energy Storage Control (DAPP-K) service was proven not economically convenient in the second year evaluation. For the sake of simplicity, we will refer to DAPP-H as DAPP.

5.1 DAPP Overview

As outlined above, DAPP computes an individualised power profile for each residential user connected to a given substation. We note that, in the first and second year version of DAPP, such power profiles were not the final output of DAPP. Instead, they were used to build *individualised power profiles*, where a low [high] tariff was applied if the user was inside [outside] the power profile bounds. This was motivated by the fact that price policies were used by the DSO as an indirect mechanism (as in Demand Response (DR)) to steer each user demand as to follow a specific (individualised) power profile. Instead, in this last year we assume that each residential home will be equipped (at the DSO/retailer expense) with an ESS and the EBR HIAS service. This will allow residential users to seamlessly follow the power profiles output by DAPP.

More in detail, each power profile output by DAPP for a user u is defined by power usage lower ($P_u^-(t)$) and upper ($P_u^+(t) > P_u^-(t)$) bounds for each time-slot t (typically lasting one hour) of a set of future contiguous time-slots. Then, the EBR service suitably drives real-time ESS charge/discharge in order to keep the overall average power of user u within the interval $[P_u^-(t), P_u^+(t)]$, for each t. Note that this results in a direct mechanism (Direct Load Control (DLC)-like) at the level of the single household. However, traditional DLC approaches are typically not accepted by residential users because:

- the DSO/retailer needs to monitor and control single household appliances (typically, the most power-eager ones);
- the control actuation typically consists in turning an appliance off, thus changing residential users habits.

Our approach overcomes both such issues, since:

- the DSO/retailer only needs to know, one day later, the overall household power demand (in order to compute the output individualised power profiles);
- the control actuation performed by EBR only consists in driving an ESS in such a way that the residential user habits are not changed.

Note that different users may have very different power demands, thus different ESS sizes (in terms of capacities and power rates) are needed. In our approach, the DSO/retailer uses a variant of the EBR service in order to determine once and for all the optimal ESS size of each residential user (see Deliverable D3.3.1). Such ESS sizes are then passed as an input to the DAPP services, and are interpreted as the users *flexibility* w.r.t. shifting their demands. Note that this is different from the second year version of DAPP, which was designed to output such sizes instead.

As for nominal usage, DAPP should be called once a day (or every few days). The computed individualised price policies will be applied the next day (resp. the next few days). Households power usage predictions for the next day (resp. next few days) are provided either by the Energy Usage Modelling and Forecasting (EUMF) HIAS (see Deliverable D3.2.1) or by looking at the power demand of the last two weeks.

5.2 DAPP Specification

In this section we describe the input-output behaviour of DAPP.

We first define the notation we use. T is a finite set of contiguous time-slots, all having the same duration. A *power profile* is a function $P : T \to \mathbb{R}$ (being $\mathbb{R}$ the set of real numbers). A *power profile tube* (or *region*) is a pair of power profiles (P_l, P_h) defined over the same set of time-slots T, such that $P_l(t) \leq P_h(t)$ for all $t \in T$. A power profile P *follows* a power profile tube (P_l, P_h) if and only if $P_l(t) \leq P(t) \leq P_h(t)$ for all $t \in T$.

Finally, we define the *flexibility* of a user u as a pair of real numbers (Q_u, R_u), where Q_u is an ideal (i.e., without energy losses) ESS capacity (in kWh) and R_u is an ideal ESS power rate (in kW). As an example, Figure 5.1 shows the individualised power profile $\tilde{P}_u$

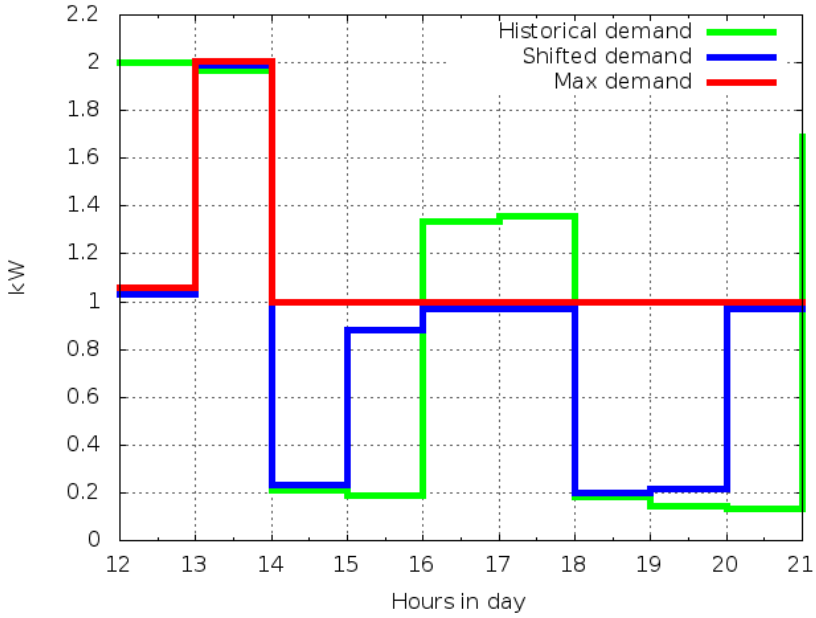

Figure 5.1: Historical demand compared to power profile output by DAPP for a single home on a given day.

(red curve, only the upper bound is shown) together with the actual power demand P_u (green curve) for a user u connected to a selected substation s in the reference scenario we use in our experiments. In the time-slots t_1 from 4PM to 5PM, the user is outside the individualised power profile (i.e., $P_u(t_1) > P_u^+(t_1)$), whilst in the preceding time-slot t_2 the user is inside. In order to stay inside the individualised power profile also in t_1, the user should be *flexible* and, as an example, move approximately 0.3 kW of power demand (i.e., $P_u(t_1) - P_u^+(t_1)$) from t_1 to t_2 (*load shifting*). To this aim, it is sufficient to have $Q_u = 0.3$ kWh and $R_u = 0.3$ kW. Of course, the ESS should have been charged during time-slot t_2 (from 3PM to 4PM, where the user needs less power than the one allowed in the individualised power profile), and then discharged during time-slot t_1 (from 4PM to 5PM, where instead the user needs more power than the one allowed). Instead, in order to be able to stay inside the individualised power profile of Figure 5.1 for all the displayed 9 hours (from 12PM to 9PM), the user flexibility required is $Q_u = 1$ kWh, with a power rate $R_u = 1$ kW, since the user is 1kW outside the individualised power profile in the time-slot from 12PM to 1PM. A possible shifted demand w.r.t. a (1 kWh, 1 kW) flexibility, which is always inside the individualised power profile, is shown in the blue curve in Figure 5.1.

5.2.1 DAPP: Input and Output

Here we describe in detail input and output for DAPP (for a high-level view, see Figure 5.2). DAPP requires the following input:

- a set of homes U connected to a substation s;
- a set of contiguous time-slots T (with a time span one day in the future);

- the desired power profile region (P_s^-, P_s^+) on T for the substation s, as decided by the DSO on the basis of EVT output;
- for each user $u \in U$, a power profile d_u on the (say, $k > 0$) days preceding T, representing the power demand (i.e., consumption minus production) in the given period;
- for each user $u \in U$, the contract C_u for electricity consumption and production (e.g., 3 or 6 kW);
- for each user $u \in U$, the flexibility of u, as a pair (Q_u, R_u) where Q_u is the ESS capacity (in kWh) and R_u is the ESS power rate (in kW).

The main output of DAPP is a set of *individualised power profiles*, as described above.

5.2.2 DAPP: Algorithm

The main idea underlying DAPP algorithm is to directly model the ESS on each home and try to drive it in order to fulfil the requirements at the substation level (i.e., to steer aggregated demand so that it is in the substation desired bounds decided by the EVT. In this way, load shifting is performed by accumulating energy during off-peak periods and using accumulated energy in on-peak periods. Hence, DAPP also outputs an actual plan for accumulating energy/using stored energy (*DAPP collaborative profile*). Note that this is used as input by the Price Policy Safety Verification (PPSV) service.

More in detail, the input-output behaviour described in Section 5.2.1 is achieved by setting up a Mixed-Integer Linear Programming (MILP) problem. Such MILP problem is based on a forecast of the demand of each residential user for the future time-slots in T. Such forecast is computed using the second year Energy Usage Modelling and Forecasting for Control (EUMF-K) service, basing on the most recent demand data available for each residential user (typically, we whole day preceding DAPP execution). Thus, the MILP problem is defined so as to minimise the energy which results to be outside the substation lower and upper bounds P_s^-, P_s^+ under the following constraints, for each of the future time-slots in T:

- at any time-slot, the energy stored in the ESS must not be used to send energy to the substation (that is, the ESS may be discharged only if there is a positive demand which is greater than the discharge);
- the DAPP collaborative profiles, which result from applying to the forecast of the demand the plan for the charge/discharge actions of the ESS, must always stay within the corresponding energy contract limits;
- the energy outside the lower and upper bounds P_s^-, P_s^+ is computed by checking, for each future time-slot $t \in T$, if the aggregation on t of all DAPP collaborative profiles results to be outside $[P_s^-(t), P_s^+(t)]$;
- for each user, the starting and the ending capacity of the ESS must be the same.

Once the MILP problem has been created, it is solved by means of a MILP solver (either CPLEX of GLPK). Then, since the required charge/discharge action at time t for the ESS is a decision variable in the MILP problem, the value for such action is extracted

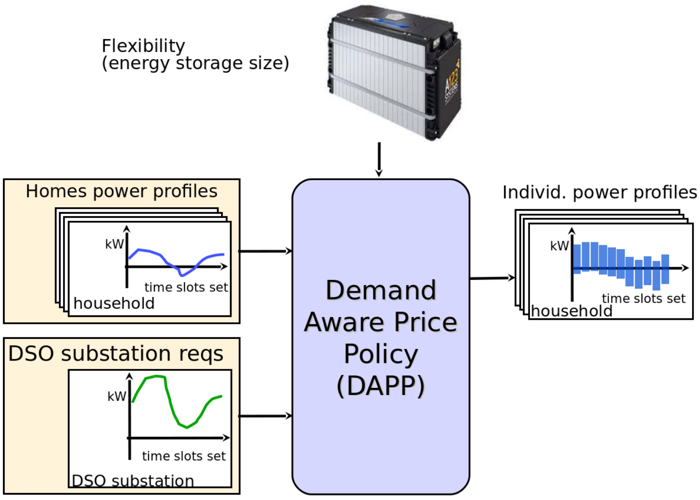

Figure 5.2: DAPP input and output.

from the solution of the MILP problem returned by the MILP solver. Finally, the upper and lower bounds of the output individualised power profile for a user u are defined as follows. As for the upper bound, for a given $t \in T$, if the aggregation of all DAPP collaborative profile on t is outside the substation desired bound $P_s^+(t)$, then the upper bound of the power profile on t coincides with the DAPP collaborative profile of u on t. Otherwise, if the aggregation is inside the substation desired bound $P_s^+(t)$ by a quantity δ (i.e., if $A(t)$ is the aggregation of the DAPP collaborative profiles, then $\delta = P_s^+(t) - A(t)$), then the upper bound of the power profile on t coincides with the DAPP collaborative profile of u on t, augmented by a quantity which is proportional to both δ and the energy contract of u. The lower bound of the power profile is computed in an analogous way.

The main goal of PPSV is to verify safety of a given substation s, when to each residential user connected to s is applied the corresponding individualised price policy computed by the DAPP-H service. Moreover, PPSV also aims to provide an *economic evaluation*. Since not all users will be able to exactly follow their proposed price policies, PPSV requires as input a *probabilistic disturbance model* describing how residential users are foreseen to deviate. Such a model may be computed from historical data on user demand. As a result, PPSV returns the probability distribution of the aggregated power demand on s (i.e., the probability that the aggregated power demand is in a given interval).

Chapter 6

Open Standard Internet-Based Communication Between Distribution System Operator (DSO) and Intelligent Automation Services (IASs)

The Common Information Model (CIM) was originally developed by the Electric Power and Research Institute (EPRI) in the midst of the 90's. In the Control Center API (CCAPl) project, the CIM was designed to solve the problem of vendor lock-ins. For that reason, it offered an internal database model for Energy Management Systems (EMS) and Supervisory Control And Data Acquisition (SCADA) systems. over the years, the CIM has outgrown its original purpose and now contains a pretty large domain ontology, which covers most topics in the power domain. Additionally it serves as an integration model and delivers interface specifications as well as data serializations.

6.1 Data Models

One of the basic parts of the CIM is the data model, which can be seen as a domain ontology for the power domain. Basically, the data model is capable of converting real power domain objects into a Unified Modeling Language (UML) data model. The data model is the lower most and basic building block. The overall data model itself is split into three subparts, which are IEC 61970-301-"CIM Base", IEC 61968-11-"Distribution Information Exchange Model" and IEC 62325-301-"Data Model for Market Extension". Each part has different UML packages with different objects and focuses.

6.2 Profiles

The next building block to be analyzed includes CIM profiles. As mentioned in Section 6.1, the basis of the CIM is a comprehensive data model. Although the extensive size of the data model providing with almost all important objects can be seen as an advantage, this size complicates the data model's application. In order to solve this problem, it is possible to define and generate profiles for specific scenarios. A CIM profile is a real subset of the original data model. It includes classes and associations required for the scenario. Furthermore, attributes of the considered classes can be defined as optional or mandatory. Finally, additional restrictions such as cardinalities of associations can be specified. Creating profiles is an established and recommended means to cope with the CIM data model. Profiles can be created individually by single users in enterprise-specific contexts or officially by working groups or other organizations.

6.3 Message exchange

XML-based message exchange is mainly described in the IEC 61968 standard series [18]. Message exchange based on CIM semantics can either be point-to-point or via Enterprise Service Bus (ESB) systems. Due to the fact that using CIM semantics in combination with or ESB systems is the more commonly used alternative, this option be focused on.

The message exchange itself can be vary in complexity. Possible applications range from simple request/reply messages to nested chain message exchange with asynchronous replies or event messages. Regardless of the complexity of the message exchange, the basic message structure is always the same and is standardized in IEC 61968-1. It is recommended by the IEC 61968-1 standard to use the following elements in order to clearly identify a message and the appropriate recipient.

- **Verb**: Identification of the type of action: limited enumeration strings like create.
- **Noun**: Identification of the type of the payload
- **Payload**: Containing the relevant data regarding the information exchange

The message structure itself is formalized as XML Schema and is depicted in Figure 6.1. The header is mandatory for all messages (except for fault response messages) and uses a common structure for all service interfaces. The optional request parts define commonly used parameters, which are required to qualify requests and identify specific objects for actions like delete or cancel. Reply is only required for response messages to indicate details on the success, failure or error. The payload is often required and is used to convey the message information as a consequence of the verb and noun from the message header. All introduced elements include further objects and the appropriate formalized XML schema can be found in [18]. Due to the standardized message structure, the focus of development is on the message's payload. The IEC 61968-9 application integration at electric utilities-System interfaces for distribution management-Part 9: Interface for meter reading and control" standard is one of the few standards, which specify standardized payloads for the CIM.

6.4 Tooling

Several available CIM modelling tools have been studied and the principal ones are mentioned here.

The CIM is directly modelled using the UML tool Enterprise Architect (EA) provided by Sparx systems [19], which thus is one of the most influencing CIM-related tools. Besides, providing the capability to browse the UML model, it also offers the functionality to use specialized Add-Inns, which are mainly created by the CIM community.

CIMbaT is an EA Add-on that can be used to create OPC UA Address Space. In combination with SDKs provided by the OPC UA Foundation, OPC UA server applications being based on CIM semantics can be created.

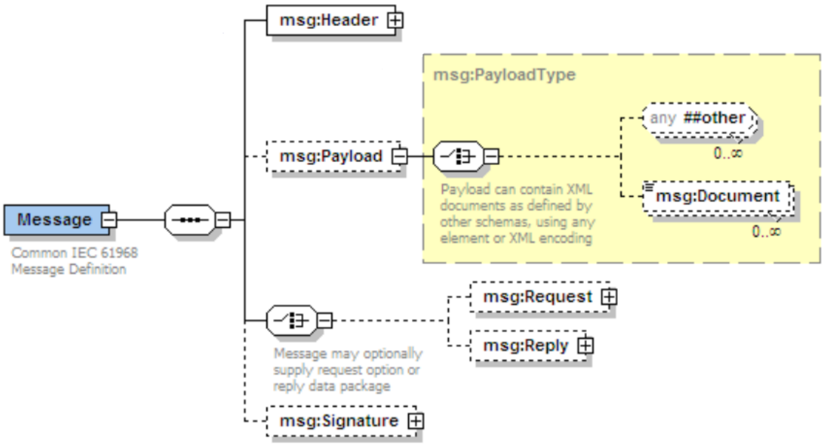

Figure 6.1: XML Schema of the basic CIM message structure

For message exchange, Altova XMLSpy is the industry's XML editor for modelling, editing, transforming, and debugging XML-related technologies. It offers the world's leading graphical schema designer, a code generator, file converters, debuggers, profilers, full database integration, support for XSLT, XPath, XQuery, WSDL, SOAP, XBRL, JSON, and Office Open XML, plus Visual Studio and Eclipse integration.

Chapter 7

Conclusions

In this deliverable the third year version of the design of all SmartHG Grid Intelligent Automation Services (GIASs), i.e., of the SmartHG services which work on the Distribution System Operator (DSO) side is described. Prototypes of such services are described in Deliverable D4.3.2.

A storage system for smart grid which depends on consumer acceptance and third party service development can be implemented using the Database and Analytics (DB&A). It allows other Intelligent Automation Services (IASs) to work together and can bring substantial benefits for both the consumers and third party developers. The objective of the DB&A has been to store consumer-specific data and provide reliable business logic for other services in the SmartHG project without compromising the residential consumers security and privacy. The final design of the DB&A has accomplished that.

The Demand Aware Price Policies (DAPP) service final third year design is able to compute a suitable load shifting in order to improve Electric Distribution Network (EDN) substations loading. This allows to lower down Transmission and Distribution (T&D) investment deferral costs, by avoiding overload of transformers and usage of peak power plants. In this setting, the Price Policy Safety Verification (PPSV) is able to compute the probability that the theoretical load shifting promised by DAPP is still achieved under probabilistic residential users deviations.

Demand forecasting models to support advanced EDN Virtual Tomography (EVT) service functions have been developed and several improvements to the Distribution System State Estimation (DSSE) algorithms have been made in order to improve the robustness and accuracy of the estimator. Models have been designed for the interaction of EVT with the other GIAS services and the Database Service (Dbservice), and proposed a suitable Common Information Model (CIM) for the communication between EVT service and the DSO network monitoring and control systems. Finally, a number of journal and conference papers have resulted from this work, 2 international journal papers: (one published [12] in IEEE Transactions on Smart Grid, and one currently in review) and 4 international conference papers: one on demand forecasting approaches [20], one on DSSE techniques [21], and 2 joint papers on EVT and the other GIAS services (to be presented).

CIM models have been studied and presented to pave the way to build data models to handle the communications between DSOs and IASs in a standard manner. The developed models are described in IR4.5.3.2 Prototype of DNO-IAS Protocol.

In addition to this, a joint paper, outlining the potential benefits of EVT and the other GIAS services, namely DAPP and PPSV is in preparation for submission to IEEE

Transactions on Smart Grid at the time of writing. This paper is intended to demonstrate the applicability of the “individualised price policy" concept introduced in the SmartHG project in a real-world context. It discusses several scenarios, which demonstrate the coordination of the GIAS services, and compares the solution proposed in SmartHG to Demand Side Management (DSM) approaches with the traditional global price policy, quantifying the potential benefits to the DSO.

7.1 Impact

The main impact the third year iteration of GIAS are the following.

DB&A The DB&A is built on open source software and can potentially be reused as a reference model in other smart grid projects. The design of the data model ensures flexibility and scalability. Furthermore, it supports and captures typical practical scenarios occurring in the monitoring process in a smart grid setup. The logical separation of the resource server (Dbservice) and authorization server (SmartHG Market Controller (SMC) service) gives significantly advantages, since it allows for other actors than the DSO to host such a service. For instance, the authorization server could be hosted by a cooperation between DSOs in a country, thus providing a single point of access for the residential consumers. The individual DSO will still be responsible for the consumers' data and be able to benefit from it using the IASs. From residential consumer's side, the authentication and authorization of services will remain the same, even if the residential consumer switched DSO, thus increasing the usability.

DAPP DAPP can be used by DSOs/retailers to actually and effectively perform load shifting on EDN substations, thus lowering down T&D investment deferral costs. In this setting, PPSV can be effectively used to estimate if the theoretical load shifting promised by DAPP is still achieved under probabilistic residential users deviations.

EVT The demand forecasting models and DSSE algorithms that are developed to support advanced EVT service functions can be readily applied in the planning and operation of distribution power networks. Several DSO operators in Spain have already expressed their interest in the developed algorithms. Also, the techno-economic studies demonstrated the benefits of EVT applied together with and other GIAS services to provide a novel alternative to the Demand Response (DR) schemes. By using the interaction models developed the EVT service can communicate with other GIAS services, Dbservice, and DSO. The work conducted in this work package attracted the attention of academic audiences and a number of journal and conference papers have resulted from this work, 2 international journal papers: (one published [12] in IEEE Transactions on Smart Grid, and one currently in review) and 4 international conference papers: one on demand forecasting approaches [20], one on DSSE techniques [21], and 2 joint papers on EVT and the other GIAS services (to be presented).

DSO-IAS protocol The use of Common Information Model (CIM) models will enable a standard data exchange not only between IASs and the energy utility companies but also with any other application in the power systems domain.

GIASs Integrated Methodology Finally, the GIASs integrated methodology that we set up as a final product of WP4 may turn out to be acually useful to DSOs to lower down EDN operation costs. This is achieved thanks to the interoperability and communication protocols we set up in the chain EVT (detect EDN overloaded substations) – DAPP (for each EDN substation, compute individualised power profiles to perform peak shaving via load shifting) – PPSV (check the robustness of DAPP power profiles under residential users probabilistic deviations). We also point out that the GIAS integrated methodology is synergic with the Home Intelligent Automation Services (HIASs), and most notably with the Energy Bill Reduction (EBR) service, which allows DAPP power profiles to be actuated on each home (see Deliverable D3.3.1).

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