Intelligent monitoring of power networks – system architecture and communication network infrastructure

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Abstract. The paper presents the system architecture and communication network infrastructure of the Intelligent Monitoring of POwer NETworks (IMPONET) project. The main objectives of the project were development of a communication platform for handling network devices with bidirectional communication and real-time management of the energy data together with new services to control the quality of electric signals. The IMPONET platform was validated through acquisition and processing of the energy-data experimental scenarios. The obtained results show that the proposed platform is capable of real-time data exchange and raw-energy data processing from multiple data concentrator devices and smart metering devices.

Key words: smart grids, intelligent power network monitoring, system architecture, communication infrastructure, communication components.

Inteligentni nadzor električnih omrežij – sistemska arhitektura in omrežna komunikacijska infrastruktura

Članek predstavlja sistemsko arhitekturo in komunikacijsko infrastrukturo IMPONET platforme za inteligentni nadzor električnih omrežij. Glavni cilji projekta so bili razvoj komunikacijske platforme za obvladovanje omrežnih naprav z dvosmerno komunikacijo za upravljanje podatkov iz pametnih števcev v realnem času ter novih storitev za nadzor kvalitete električne energije. IMPONET platforma je bila ovrednotena z eksperimentalnimi scenariji zajema in obdelave podatkov merilnikov električne energije. Rezultati potrjujejo, da predlagana platforma omogoča izmenjavo in obdelavo podatkov o porabi električne energije, zajetih iz več podatkovnih koncentratorjev in pametnih števcev v realnem času.

1 INTRODUCTION

Smart Grids are the next generation power grids [1] enabling real-time two-way flows of electricity and information to create an automated and distributed advanced energy-delivery network. The fundamental component of the Smart Grid concept is a robust and dynamic communication infrastructure for real-time, two-way communications throughout the grid and interaction between producers and consumers. Nowadays, the power generation and distribution network utilities already have communication systems providing essential data and information exchange between devices. But these communication components need to evolve to support the new demand imposed on the power transmission and distribution networks.

According to [2], very complex automation, distribution and control will be needed to integrate renewable energy sources, smart meters with bidirectional communication, electric vehicles, and future storage infrastructures. The main requirement these systems should meet will be the existence of a communication network capable of responding to their needs for capacity, price, reliability, flexibility, interoperability, multi-platform ability, priority, security and development. At the same time, Smart Grids represent a huge market for the electronics industry [3].

The notable worldwide Smart Grid research activities are Open Meter, EPRI–IECSA, Meters and More, Address, OpenNode, InovGrid and INTEGRIS [4]. They cover the relevant fields, e.g. power generation and distribution networks, communications, remote management and smart metering and represent the state-of-the-art technology and concepts developed to support the Smart Grid vision.

The IMPONET project [5] is an industry-driven project focused on the strategic and technical requirements as demanded by the electricity markets worldwide regarding Smart Grids, smart metering, peak demand management, demand response and real-time monitoring. The focus of our project research and development activities was on three main areas: communication infrastructure, remote control and smart metering software platform, and power quality (PQ) services. The significance of the project was pronounced by being selected for the ITEA Award of Excellence 2013 in the category Seizing the High Grounds [6].

This paper presents the system architecture and communication infrastructure proposed and developed for the IMPONET project. In the next section, the IMPONET system architecture and functional framework are outlined. The communication network infrastructure with an emphasis on the development of the data concentrator and metering device is followed by describing the evaluation and testing scenario of the platform. Finally, in conclusion the IMPONET project testing and demonstration results are summarized.

2 IMPONET SYSTEM ARCHITECTURE

The system architecture is based on the Service-Oriented Architecture concepts [7]. It is built by using architectural elements satisfying the major functional and non-functional requirements of the system.

To achieve the main goals of the project, a platform is needed to design and implement init PQ monitoring, remote control and smart metering features. The focus is herefore on development of a new network monitoring system concept required to achieve the ambitious goals of the Smart Grids of the future. Fig. 1 shows their IT ecosystem.
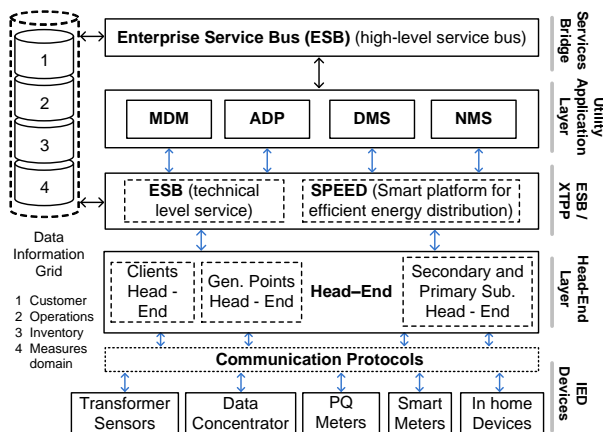

Figure 1. Smart Grid ecosystem conceptual view [7].

At the lower level of the IT ecosystem, there are different network devices and technologies together with the software components that reside in the data concentrators located at different nodes of the network, e.g. the primary and secondary substations, central processing nodes, etc. Above them, there are different communication protocols and Head-End layer. The technical-level services of the enterprise service bus (ESB) and smart platform for efficient energy distribution (SPEED) are located in the middle of the architecture. All operational and non-operational data are then transferred from the ESB-based eXtreme Transaction Processing Platform (ESB/XTPP) and services bridge level to the data information grid where there are databases from the customer, operations inventory and measurments domain. In the higher level, there are important components, such as extreme processing middlewares for providing real-time

connectivity among all the nodes present in the network and software packages that provide monitoring and control for the overall Smart Grid, such as the metering-data management (MDM), network management system (NMS), distribution management system (DMS) or the advanced devices platform (ADP). The MDM system acts as a centralized data management system to store meter readings and meter-related event data. The NMS system manages the devices, smart meters and sensor control from the grid, providing a centralized management including faults, configurations, performances, security and monitoring the device health. The advanced DMS system is designed to monitor and control the entire distribution network efficiency and reliability. The main function of ADP is controlling the life cycle of data concentrators and communication devices. It also allows to parameterize the type and policy process for each of them.

Based on the IT ecosystem concept (Fig. 1), the system architecture and functional framework of the IMPONET solution are designed (Fig. 2).
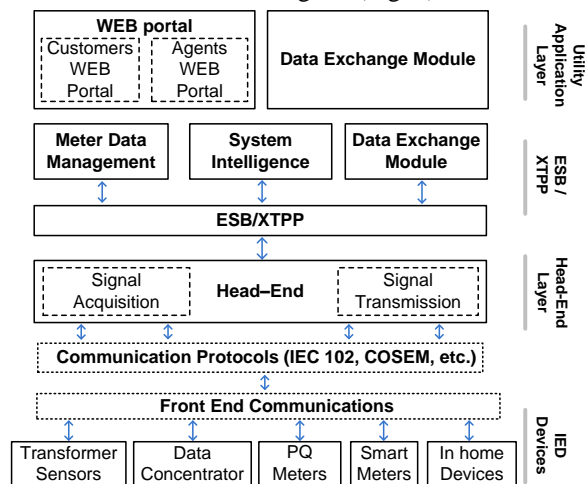

Figure 2. System architecture and functional framework [7].

The functional framework consists of the network devices (e.g. IED devices), processes to monitor the PQ and the monitoring infrastructure processed the huge amount of data [7]. The architecture of the flexible platform continously monitors the power network with real-time or quasi real-time data processing capabilities, including a wide range of devices, protocols and technologies. On the utility application level, the developed platform includes features and services enabling consumers to configure their consumption profile, to monitor its evolution (WEB portal) and to make decisions based on this information. The system architecture and fudamental framework (Fig. 2) are consistent with the concept shown in Fig. 1.

Within the project, an advanced AMI infrastructure was developed. The current AMR infrastructures mainly support generating the unit meters, high (HV) / medium voltage (MV) substation meters, MV outgoing feeder meters and transformer-level meters. These infrastructures handle a certain number of network meter
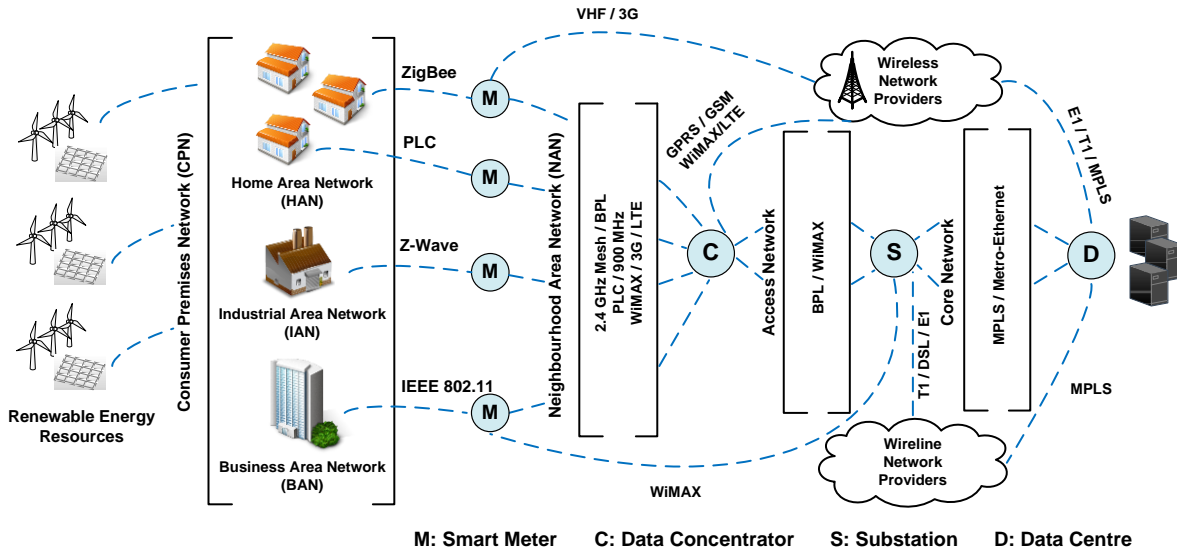
Figure 3. Communication technologies in Smart Grid [22].

points but fail to address the needs of the consumer-level smart meters. To support the large number of smart meters on the consumer level, a new type of paradigm is implemented which makes use of the latest technological advances in processing and storage technologies. An elastic cloud infrastructure [8] is designed to respond in a flexible manner to the grew amount of information generated by the smart meters in consumer premises. Depending on the current needs, new processing nodes can be added or removed from the existing deployment. The elasticity is provided by multiple points in the network capable of parallel data processing.

A PQ monitoring architectural approach [9] is designed as a set of services oriented to exploit specific PQ field data. The goal is to provide the network operators with an elaborated information of disturbances in the voltage waveforms collected by various monitoring devices, such as PQ monitors and smart meters connected through different data nodes. In fact, PQ monitoring does not require a specific infrastructure, but it can be deployed as a set of services capable of handling power events and disturbances collected by PQ instruments. Within the project, the PQ monitoring capabilities are extended towards event oriented services able to deal with short duration disturbances, such as voltage sags, swells or short duration interruptions [9].

Although the IMPONET project was mostly oriented towards developing the platform and software services, these could not be deployed without an appropriate communication infrastructure.

3 COMMUNICATION TECHNOLOGIES IN THE FUTURE POWER GRIDS

Nowadays, the power grid and communication technologies are deeply interwound. Embedding the communication technologies for efficient and reliable two-way communications in the power network environment is essential in order to provide a reliable and flexible power grid. The state-of-the-art communication technologies used for data transfer in smart metering as well as among all the Smart Grid components are briefly presented in Section 3.1.

The essential elements of the power network monitoring communication infrastructure are the data concentrators enabling data collection and supporting heterogeneous communication infrastructure.

The data concentrator is a hardware and software device that connects a number of data channels with one destination [10]. The data concentrator devices are used in the AMR and AMI architecture to collect information and data from multiple meters via wired and wireless communication technologies supporting different protocols before forwarding them to the utility.

In the power grid, there are several strategic locations where operational (currents, voltages, active and reactive power, etc.) and non-operational (faults, power grid fluctuations, voltage disturbances, etc.) data are gathered. An example of these strategic interface locations are the MV substation units with data concentrators installed in most cases. These locations are important for being placed right between the MV and LV level. From this point of view, the power distribution parameters as well as the user power consumption data on the LV level can be measured.

According to the proposed basic guidelines for the IMPONET global system architecture [7] and communication infrastructure requirements [11], [12] the data concentrator and smart metering device hardware architectures were developed to meet the IMPONET platform demands [7]. Both architectures and their features are presented in Sections 3.2 and 3.3, respectively.

3.1 Communication technologies – state-of-the-art

The communication technologies currently used in various levels of Smart Grid are presented in Fig. 3

highlighting two important sections significant for collection of the operational and non-operational energy data.

The first section is the location of the data concentrators (C) between the access network (usually at an MV substation) and the neighbourhood area network (usually at a low-voltage (LV) level). The data concentrators (C) collect data from smart meters (M) and forward it to the data centre (D). To provide connectivity and interoperability of the communication technologies, such as PLC, BPL, WiFi, optical fibre, etc., the data concentrators must enable data transfer by supporting the applicable standards, e.g. IEEE 1901, IEEE 802.11x, IEEE 802.15.4, LTE, WiMAX, GSM/GPRS, etc, and protocols such as ZigBee, Z-Wave, etc.

The second section is the location of the smart meter devices (M) between the consumer premises network (CPN) and the neighbourhood area network (NAN). CPNs contain the connected devices and smart meters from the business area networks (BAN), industrial area networks (IAN) and home area networks (HAN). The smart metering devices communicate with the data concentrators via different communication technologies, e.g. PLC, optical fibres, Ethernet, WiFi, etc.

In general, selection of an appropriate communication technology and standards depends on the parameters, such as local availability of the communication technology, required data transfer rate, latency, security and cost. Based on a close study of the technologies used for communication in the power grid [4], [12] selection of an appropriate technology also depends on the field of application and communication media supported. For example, communications between the utility centre and substations are usually connected via fibre optics, Ethernet or wireless link (supporting IEC 61850, DNP3, IEC 60870-5, etc.). From here on, the substation data concentrators in most cases communicate with metering devices over the power-line communications (PLC) or wireless channels (supporting DLMS/COSEM, IEC 61334-5, PRIME, etc.) [13].

The currently best practice solutions on the market for data transfer between the smart meters and the data concentrators in the LV networks are broadband PLC (e.g. IEEE 1901) and wireless channels (e.g. GPRS) for upstream communication to the remote management system supporting the above mentioned communication standards and protocols [4], [7]. Therefore, the broadband PLC and wireless channels are considered as key communication technologies supporting the IMPONET bidirectional real-time communication infrastructure.

3.2 Data concentrator device specification

Before developing the new advanced data concentrator, the basic architecture, features and functionality were well defined. For this purpose the leading manufacturers of the data concentrators were evaluated with respect to the relevant features, such as the system architecture,

performance, processor type, operation system, communication interfaces, number of the smart-meters-supported and data storage available for meter readings.

The proposed data concentrator specification is comparable with other available data concentrators. However, it has a higher processing power and supports connection of a larger number of IOMs (Input Output Module). The architecture of the developed data concentrator is shown in Fig. 4.
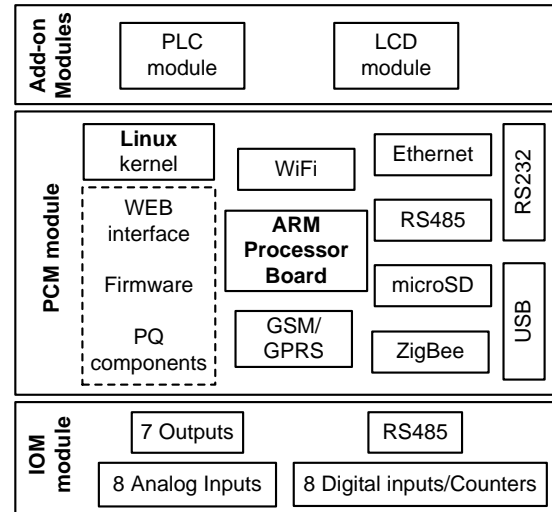

Figure 4. IMPONET data concentrator conceptual architecture.

The device is composed of two main modules: PCM (Processing and Communication Module) and IOM module. The PCM module supports the Freescale processing systems iMX25 ARM 9, iMX28 ARM 9 and iMX53 Cortex A8. This powerful processing unit with embedded Linux kernel 2.6 OS enables implementation of the IMPONET software platform [7]. To store data, the microSD cards are used and the available storage space can be up to 32 GB. The data concentrator supports GSM/GPRS, ZigBee, WiFi, RS485, RS232, 100 MB Ethernet and PLC communication interfaces.

PLC being standardised, the advanced, reliable and affordable communication technology [14] data concentrators can also transfer data trough power lines. According to the feasibility study in [12], the available PLC modules were evaluated based on their specifications, standardization, data rate, communication distance and dimensional limitations. The Maxim 2992 system-on-chip was proposed as a viable solution for hardware implementation.

Data concentrator connectivity with other devices is effected through four IOM modules containing eight analogue 16-bits inputs (0 – 12.5 V), eight digital counter inputs (0.1 – 2.5 kHz) and seven on/off outputs (12 V, up to 1 A) each to control different devices. Furthermore, the data concentrator prototype developed by the LNL Technology has a built-in polarity, lightning and ESD protection.

3.3 Metering device

The metering device is a cost-efficient communication and control device that can communicate with the existing smart meters, concentrators, grid, in-home displays, IED devices, and smart-home systems. Its architecture is depicted in Fig. 5.

A low-power microprocessor from Cypress with analogue and digital interfaces and enough computation power to handle the required interface communications is used in the metering device. The main communication interfaces of the metering device for the last-mile solution are PLC, GSM/GPRS and ZigBee. The RS485/Optical IEC 62056 interface is used for reading the metering data from the existing utility meters.
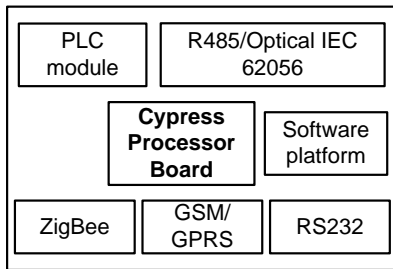

Figure 5. IMPONET metering device architecture.

4 IMPONET COMMUNICATION INFRASTRUCTURE

The communication infrastructure being a vital part of the IMPONET service-oriented concept is given in Fig. 6. The grid includes two main components: data concentrator and metering device. The major part of the communication infrastructure is the interface at the last mile related to the costumers. The required functions are not limited to the reading metering information but also allow interfacing with intelligent devices in smart homes and buildings, handling energy positive buildings and sensing some critical parameters such as LV PQ.

Fig. 6 shows that the metering devices are two-way communication devices relaying measuring data and messages to in-home devices and sending information about smart meters and other critical parameters to the higher level services through the data concentrator devices which are interim data gathering and evaluation points representing a bridge between the local and the grid level data network. The data concentrator communicates with the metering devices via the PLC standards or ZigBee/6LowPan. The metering devices communicate with in-home devices enabling collection and visualization of consumption information gathered from sensors and intelligent devices. The collected energy data are forwarded by the data concentrator to the grid-management system through the IP-based GPRS or Ethernet backbone network. The grid management system ensures communication between other data concentrators installed in the power grid.
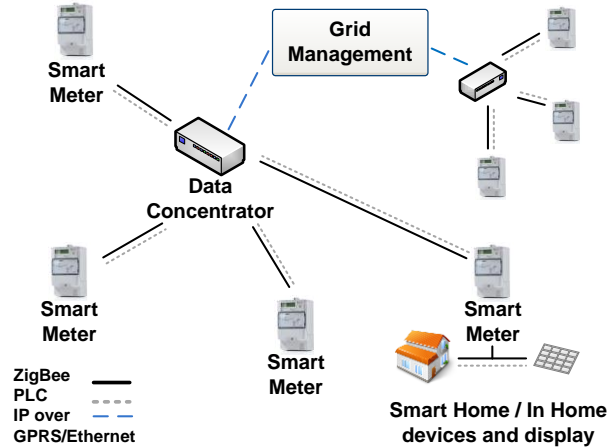

Figure 6. Communication component placement [7].

5 IMPONET PLATFORM INTEGRATION

IMPONET developed a flexible platform that allows for continuous monitoring of the power network with real-time data processing and configuration of the costumer consumption profile to monitor its evolution and to make decisions based on its information. The achieved results are reflected in a series of demonstration experiments conducted during the system integration and testing phase of the project [15].

The most relevant demonstration scenario, i.e. the acquisition, processing and availability of energy-data scenario, is presented in Fig. 7. The set-up shows the data flow defined in the IMPONET infrastructure, starting with the data concentrator, ending with the visualisation of the validated values designed for different exploitation purposes and considering the utility, retailer and customer points of view.
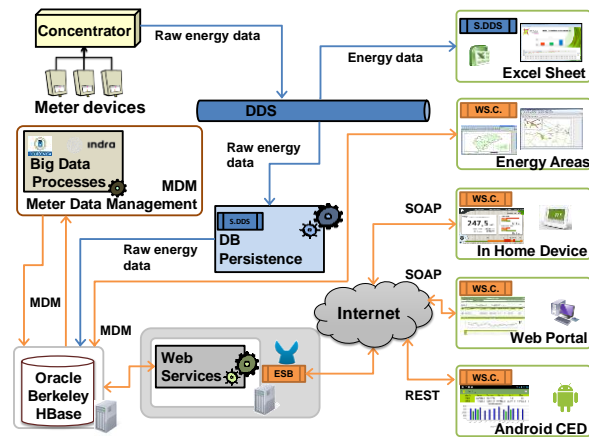

Figure 7. Acquisition, processing and availability of the energy data scenario [15].

Within the infrastructure (Fig. 7), three data concentrators collect the energy data from the real metering devices and publish them to the DDS (data distribution services) platform in real-time. The data concentrator device performance shows that it is possible to support up to 2000 metering devices at 15-minute meter reading intervals. Reducing the number of

the metering devices to 200 reduces the meter reading interval to 30 seconds [16].

The DDS bus serves as a coordinator for the rest of the platform modules ensuring real-time capabilities. The big data processing is performed by using the Hadoop [17] and Oracle Berkeley DB Non-SQL database [18]. This implementation was validated by using different scenarios. The results obtained for storing and processing of some 150 million measurements in less than three hours are promising [19].

The results of processing the energy data were visible in different platforms for the customers, distributors and retailers [19]. The raw energy data are visualized through the Web portal for distributors and retailers [20]. For customers, the raw and optimal energy data are demonstrated in the In-Home device, Web portal and Android application for mobile devices. The IMPONET platform is mutually complemented by the architecture developed within the NEMO&CODED [21] project.

6 CONCLUSIONS

The IMPONET system architecture addresses the problem of processing large amounts of information in real-time while maintaining bidirectional communications by using several communication technologies and common standards.

The paper presents the system architecture and communication network infrastructure of the developed concept. The main advantage of the proposed architecture is the use of the state-of-the-art techniques and technologies for collecting, storing and processing the residential metering data. The focus is particularly placed on the real-time extreme processing middleware and storage architecture. To meet the necessary acquisition, processing and communication demands, a prototype data concentrator and a metering device are developed. The data concentrator has high processing power and storage capabilities and can host an appropriate middleware for real-time bidirectional communications.

The advanced metering platform for the residential consumer and the powerful framework for PQ monitoring together with the communication infrastructure were tested and validated in a series of demonstration experiments performed in a real power grid.

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