Control algorithms for micro-grid local controllers

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List of acronyms

DER	Distributed Energy Resources
DG	Distributed Generator
DMS	Distribution Management System
DSO	Distribution System Operator
EMS	Energy Management System
ICT	Information and Communication Technology
PV	Photovoltaic
RES	Renewable Energy Resources
MDMR	Meter Data Management Repository
MG	Micro-Grid
LAN	Local Area Network
IAN	Industrial Area Network
BAN	Building Area Network
HAN	Home Area Network
WAN	Wide Area Network
FAN	Field Area Network
SA	Substation Automation
HEM	Home Energy Management
IED	Intelligent Electronic Devices
ESS	Energy Storage Systems
MV	Medium Voltage
LV	Low Voltage
DNO	Distribution network operator

1. INTRODUCTION

This report is a part of European project "micro to Mega – Grid" (m2M) funded by the ERA – Net Smart Grid Plus Initiative. The main target of the m2M-Grid project is to enhance the interaction between micro–grids (MGs) (both physical and commercial), which increases the overall benefits for both customers and DSOs.

To accomplish the abovementioned target, four distinct objectives can be identified:

- Development of an interface between the control system of the distribution network and the individual control system of the MGs.
- Development of an interface for the interaction of the MGs with the market.
- Enhancement of the network planning process by considering the deployment of multiple MGs.
- Identification of the functional requirements that are needed for the interoperability of the MGs before the physical tests at the demonstration sites.

In Work Package 4 of the m2M-Grid project, the interface for the physical MGs has been developed. Base on the functional requirements defined in Work Package 2, the control and coordination algorithm for physical MG interface is developed, along with the validation in laboratory environments and facility preparation for onsite demonstrations.

The main objective of task 4.1 is to enhance communication capability of the voltage controller box developed by CEA in the PARADISE project.

1.1 BACKGROUND

The future world, energy point of view, will be a less carbon world for two reasons. There are fewer and fewer major discoveries and the operating costs will be more and more important for new areas. However, an increasing number of scenarios of the future energy development estimates that the electricity will go with the digital era. Electricity is one of the major levers of policy, economic and social development. This is what makes it possible to affirm that the future is electric. In addition, the steady growth of new kinds of the load as an electric vehicle, heat pumps, and storage will encourage the penetration of renewable energy as environmentally friendly, cleaner and renewable.

In order to improve the electricity supply and power quality for the end user, the electricity production brings closer to the customer for the simple reason: bound the infrastructure investment in the transport and distribution grid and reduce the power losses. MG concepts emerge as a promising solution to enable optimized management of the distributed units essentially based on renewable energy generation, loads and storage [1].

Conceptually, a MG is a (relatively small) group of Distributed Generators (DG), Energy Storage Systems (ESS) and flexible loads that are electrically interconnected. Another particularity of the MG, besides its size is its ability to continue operating while being disconnected from the main network [2]. Independence and autonomy are therefore the major assets of the MG.

In terms of size, we define:

- Micro-grid: from 1 MW to 50 MW. (An island, rural area or a district)
- Nano-grid: from 100 kW to 1 MW. (A group of building)
- Pico-grid: less than 100 kW. (A tertiary building, a small community of houses)

MGs are smaller (and therefore involve more local areas) than traditional grids but can be arranged and designed in different ways. We consider three types:

- Off-grid MGs: they include islands, temporary sites, this type of MGs are not connected to the main network.

- Campus MGs: fully interconnected and able to disconnect when needed. Highly requested by the military, universities, hospitals.
- Community MGs: which are part of the network, this kind of MGs are in the steady increase. Community MGs encompasses neighborhoods, districts, and cities.

The MGs combine multiple production units (micro-turbines, fuel cells, small diesel generators, photovoltaic panels, mini-wind turbines, and small hydro), consumer installations, storage. Supervision and control tools are necessary for optimization and efficient management. As we can see in Figure 1, a communication network zone represents the ICT infrastructure and is responsible for transmitting/ receiving signal and exchange information between different components and between components zone and control zone.

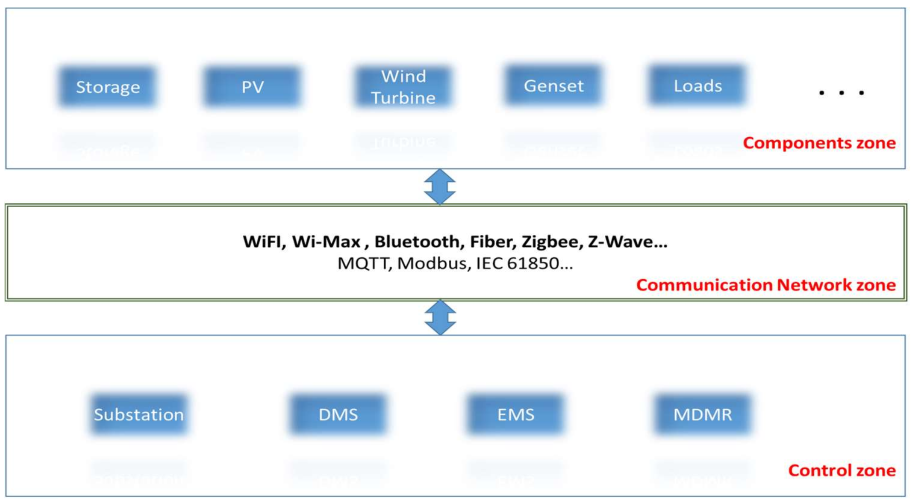


Figure 1. MG zones

1.2 OBJECTIVES OF THE REPORT

The aim of the report is to present the local voltage controller box developed by CEA in the PARADISE project. The designing and the efficiency of this toolbox is indicated along with the real implementation in a distribution network operated by the French DSO partner SOREA. A cloud-based communication for Solar PV inverter created in the EU FP7 project, INCREASE will also be demonstrated to create the communication ability for CEA's toolbox. This will help to solve not only local voltage issues but also coupling effectively with the hierarchical control system within a MG.

The remainder of this report is organized as follows:

- The first section introduces the concept of a physical MG and the objectives.
- Sections 2 to 6 present the state-of-the-art of communication systems in MGs.
- Section 7 presents the local voltage controller developed by CEA.
- Section 8 demonstrates an example of the application of the cloud-based communication for controlling the PV inverters in MGs.
- Section 9 reports a real implementation of the local voltage controller developed by CEA in SOREA network.
- Sections 10 describes a proposal for enhancing the communication capability of local controllers of PV inverters in combination with a hierarchical control in order to coordinate the inverter performance.
- Section 11 concludes the report with summarizing remarks.

1.3 HIERARCHICAL APPROACH

There are two distinct approaches to MG control: centralized and decentralized. With a centralized approach, all the data will be gathered and calculated at a single point, with the communication between each control unit. On the other hand, with a decentralized approach, each control unit only bases on local measurement. In reality, the fully centralized approach is not feasible because there will be a huge amount of data and computation at the central controller. Similarly, fully decentralized is not possible because using only local measurement is not enough for the operation of the MG. Therefore, we need a compromise between these two approaches, which can be done by hierarchical control schemes [1].

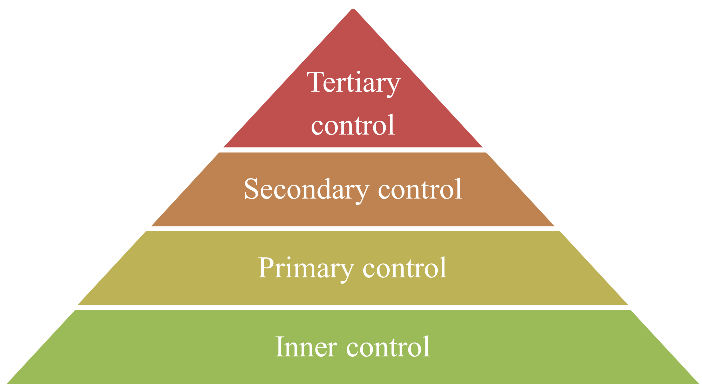


Figure 2. Hierarchical control diagram

1.3.1 Inner control

The function of this layer is to determine the operating state of DER units. Typical inner control consists of an outer loop for voltage regulation and the inner loop for current control, which is called Cascaded method [2].

1.3.2 Primary control

Primary control aims at dealing with controlling and sharing power between DERs. Primary control will send the setting values for inner control. There are two main methods for primary control: droop – based methods and non–droop–based methods [3]. Droop – based methods mimic the behaviour of synchronous generators in the power system. That is, the deviation in frequency appears when there is an imbalance between the input mechanical power and its output electric active power, the similarity with voltage and reactive power.

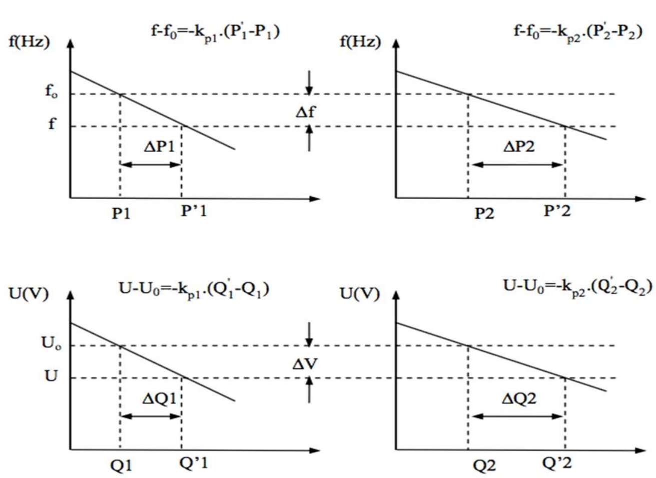


Figure 3. Conventional droop characteristics

From Figure 3, f_0 and U_0 are the reference values and k_{p1} and k_{p2} are droop coefficients which are determined based on steady-state performance criteria [4]. This method bases only on local measurement, which avoids the need for communication.

On the other hand, non–droop based method focus on a centralized perspective. Master-slave is a typical example of this method [3].

1.3.3 Secondary control

The author in [3] illustrates that secondary control has responsibilities for both the reliable and economical operation of the MG. However, in [1], the function of secondary control is only to eliminate the deviations of frequency and voltage amplitude created by primary control. Figure 4 shows the secondary control for frequency.

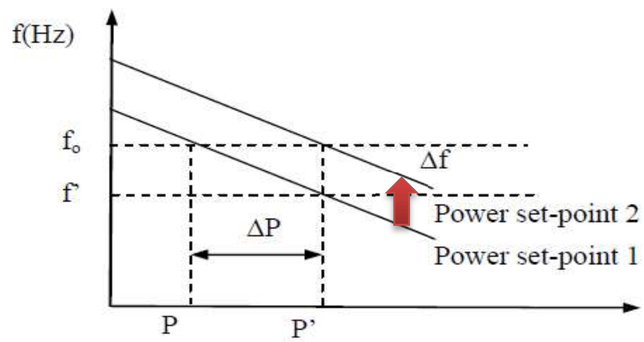


Figure 4. Secondary control for frequency

1.3.4 Tertiary control

The tertiary control is more related to economic optimization, based on energy prices and electricity market and it decides the import or export of energy for the MG.

2. ARCHITECTURES AND REQUIREMENTS OF MG COMMUNICATION SYSTEM

2.1 ARCHITECTURES

MG involves integrating advanced communication infrastructure. A typical MG architecture consists of three main layers (from bottom to top): the power layer, the communication layer, and the information layer, as shown in Figure 5 [5]. The power layer consists of the physical system of power generation, transmission, distribution, and customer premises. The communication layer represents the backbone of MG systems by providing interconnection among all of the devices. The information layer contains computing platforms, operational systems, business applications and business services. Generally, the communication systems with ICT consist of smart meters, communication modules plus software and distributed computers [6].

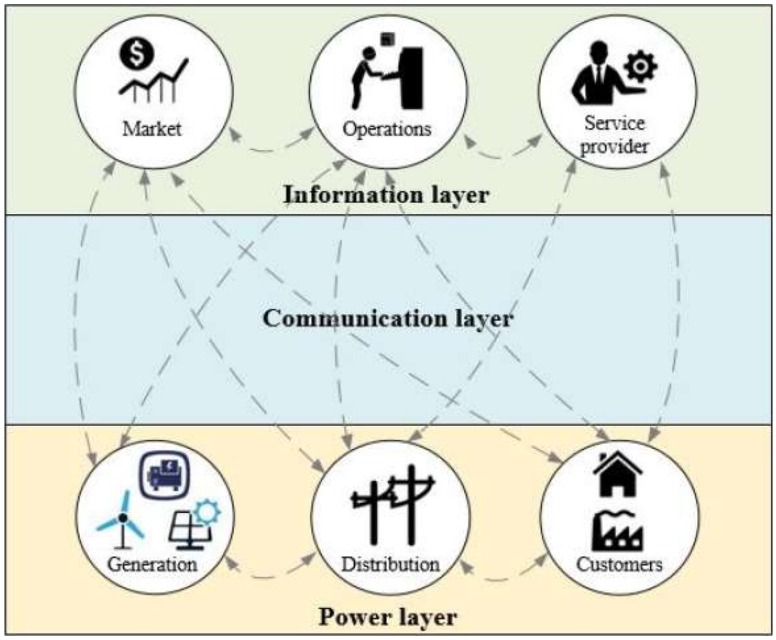


Figure 5. Layers of MG architecture

The communication layer performs a critical function in overall MG control and operation. Presence of the communication layer allows the information about performance condition of all MG components to be collected and subsequently used for control, monitoring and maintenance purposes. For example, with an efficient communication architecture, proper monitor and control actions can be quickly performed to mitigate problems occurring in the power layer. The communication architecture in a MG can be centralized or decentralized, according to the architecture of the control system in a MG [7]. In the case of the centralized control, a central controller makes decisions of MG operation, and the local controllers follow the instructions of the central controller [8].

The central controllers have to receive and process numerous messages from all local controllers. Thus, the communication between the central controller and all local controllers are required [8]. For decentralized architecture, each local controller is capable of making decisions and taking actions [8] by utilizing locally measured data and information exchanged with neighbouring nodes [9]. Therefore, a small piece of information is sent to the higher control level, imposing the modest requirement of communication systems [8]. The MG communication systems can be also of a hierarchical structure, including the Local Area Network (LAN), Field Area Network (FAN), and Wide Area Network (WAN) [10]. As the lowest level, the LAN provides bidirectional communications between local network segments, such as smart meters, and the electrical devices at customers' premise. The LAN involves integrating Home Area Network (HAN), Building Area Network (BAN), and Industrial Area Network (IAN) [9], [10].

Thus, the LAN facilitates the state estimation and control of the customers' devices. The FAN, or Neighbourhood Area Network (NAN), provides two-way communications between multiple LANs and control stations deployed in a MG [9]. Moreover, such a network also enables a medium of communication between sensors and actuators used in MG for the monitoring and control of MG equipment (e.g., DG and ESS units, and circuit breakers) [10]. Advanced Metering Infrastructure (AMI) networks play an important role in the FAN because they permit the smart meters to exchange information with the data aggregators and MG control stations [10]. The FAN, therefore, supports the monitoring and control of MGs in distribution networks. The WAN, as the highest level of hierarchical communication structure, enables bi-directional communications of MGs to control centers of the upstream distribution network over long distances [11]. This bidirectional communication empowers the network operators with more interaction with the customers and network subsystems. The MG communication architecture can utilize either a public or private network [5]. The wide availability of public communication networks, for instance, the Internet, provides a communication mean for the remote control and monitoring of the power system at relatively low cost. However, using the public communication network in MG may lead to the concerns of security and quality of services [5].

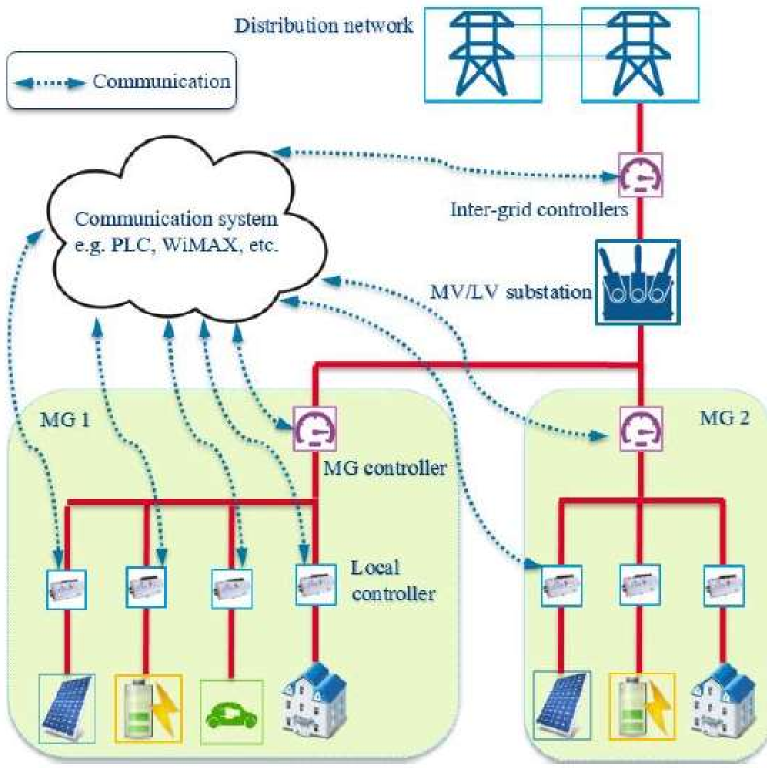


Figure 6. Example of communication architecture in a MG

A private communication network that is dedicated to MG communication purposes can offer an improved reliability and more secured communication channels, although it requires a higher operation and maintenance cost. Therefore, during the design phase of a MG, a detailed cost-benefit analysis should be conducted to evaluate the application of public versus private networks [5]. Figure 6 illustrates an example of communication architecture typically used in MGs.

2.2 REQUIREMENTS

Since the performance of the communication systems has a decisive effect on the control, monitoring of MG, the requirements of communication need to be satisfied. In [10], the requirements of MG communication systems embodies the latency, data rate, reliability, scalability, interoperability, flexibility, and security. Moreover, frequency range [5] and bandwidth [12] were included as important parameters for the communication requirements.

Table 1. Requirements of MG communication systems [5], [12]

Application	Latency	Data rate	Reliability	Security
SA	15-200 ms	9.6-56 kbps	High	High
DA	20-200 ms	9.6-56 kbps	High	High
DG and EES	300-2000 ms	9.6-100 kbps	High	High
HEM	300-2000 ms	9.6-56 kbps	High	High
AMI	2000 ms	10-100 kbps per node, 500 kbps for a backhaul	Medium	High
Meter data management	2000ms	56 kbps	High	High
WASA	15-200 ms	600-1500 kbps	High	High
Demand response	500 ms - several minutes	14-100 kbps per node	High	High

Table 1 briefly shows the communication requirements for several subsystems of a MG. Some important requirements of MG communication systems are listed below:

- Latency: Latency is the time delay of transferring data between MG devices. Different MG functions have different requirements for latency. Some critical functions are not tolerant of latency when it requires the data to be promptly transmitted [5]. For instance, the transmission of data from intelligent electronic devices (IED) installed in the substation to the data collectors must be within 4 ms in Substation Automation (SA) systems [10]. Meanwhile, other less time-critical applications can be tolerant of latency, such as AMI and Home Energy Management (HEM) [5]. For example, the latency for AMI based real-time metering should be around 12–20 ms [5]. The choosing process of ICT must examine the specific latency requirements of MG functions.
- Data rate: Data rate describes the speed of data transmission from a MG device to another [5]. The requirement of data rate varies among MG applications. Some MG applications, such as Wide-Area Situational Awareness System (WASA), necessitate employing the communication links with high data rate (600-1500 kbps) to attain fast and accurate data transmission [5]. In contrast, for other MG applications like DG and EES, and Distribution Automation (DA), the data rate requirements are lower (9.6-56 kbps) [5]. The design of the communication system needs to take into account the data rate requirements of each MG application.
- Flexibility: Communication infrastructure comprises a large number of devices to fulfill various MG functions. Consequently, flexibility is one of the essential requirements for such an infrastructure. Flexibility, on one hand, signifies the ability of communication architecture to assist the provision of various MG functions which impose various requirements of reliability [10]. On the other hand, flexibility denotes the ability of the communication system to accommodate different communication modes [10]. MG communication infrastructure ought to possess the flexibility and self-adaptability to satisfy the heterogeneous operational requirements.

3. AVAILABLE TECHNOLOGIES FOR MG COMMUNICATION SYSTEM

The adoption of communication technologies in MGs depends on the communication architecture. For example with the hierarchical architecture, the use of ICT for WAN, FAN, and LAN differ from each other. Moreover, the communication technologies for MGs can also be categorized as wired and wireless ones [13]. Wired communications refer to optical communication, DSL, and PLC. On the other hand, wireless communications represent cellular (i.e., GSM, GPRS, and 3G/4G), Wi-Fi, satellite, and WiMAX. Recently wireless communication has been attracting an extensive research interest. For instance, in [14] the application of wireless communication is proposed to collect data on total output power generation of all DG units for MG stability enhancement. In [15], wireless communication systems composed of a local Wi-Fi network, a cloud-based program, and MQTT protocol is utilized for MG control. Wi-Fi network is also widely used in residential houses [15]. Adopting the Wi-Fi network eases the deployment of communication systems in MG consisting of residential scale DG units and household loads. More details of various wired and wireless technologies are presented in [7], [10], [12], [16] with the data rate, coverage range, advantages, and disadvantages. Three major factors that affect the choice of communication technologies are the needs for reliability, security, and availability of the technologies [12]. Multiple ICT, such as PLC, wireless and Ethernet, can be employed to build communication infrastructure in MGs.

3.1 COMMUNICATION OF LAN

LAN supports the bidirectional low-bandwidth communications between electrical devices at customers' premise and smart meters [5]. Consequently, consumers are able to monitor the cost of electricity usage and adjust their electricity consumption by controlling their smart home appliances. In LAN, there is no need for urgent needs and fast response of the control actions. Thus, the communication architecture of LAN accepts low-bandwidth (10-100 kbps), low-speed, and high latency [5]. Moreover, low energy consumption, low cost, simplicity and secure communication are examples of the main communication requirements for LAN [17]. The candidates for communication technologies in LAN consist of ZigBee, Wi-Fi, HomePlug, Z-wave, M-Bus [5], Optical fibre [17], Digital Subscriber Line (DSL), 6LoWPAN, cellular (i.e., 3G/4G) and Power Line Communication (PLC) [11]. For instance, ZigBee is a wireless communication protocol for the personal area based on the IEEE 802.15.4 standard [17]. Its maximum coverage distance ranges from 100 meters (ZigBee) to 1600 meters (ZigBee Pro). ZigBee, therefore, is widely used for the communication in HAN and BAN [17]. ZigBee is advantageous for low energy consumption [5], cost-effectiveness, high efficiency and security [17]. However, a major disadvantage of ZigBee is that it may suffer from significant interferences by another communication protocol (e.g. Wi-Fi) sharing the same the channel [17]. Z-wave, in contrast, is another wireless communication protocol that is free of interference [5]. Originally, Z-wave is designed with the aims of remotely controlling the lighting and appliances in residential and small commercial domains. It is characterized by reliable, low-power, low-cost and short communication range [17]. As a result, it becomes a suitable candidate for HAN communication.

3.2 COMMUNICATION OF FAN

FAN or NAN represents a communication network for electricity distribution areas. FAN involves distribution automation systems and control equipment, that communicate with each other and are located in between the backhaul points to the power utilities and customer connection points [5]. In other words, FAN plays a role of an overpass between the power substations and customer network with the access points, data concentrators, and collectors [5]. FAN can cover urban, suburban and rural areas with distances up to 10 km [5]. Accordingly, the communication infrastructure of FAN calls for the communication technologies with high data rate and large coverage distances. Nevertheless, FAN accepts low bandwidth channels as robust means for reliable performance of the communication systems [5]. As mentioned in the previous section, AMI provides a considerable support for FAN. In FAN or NAN, the most applied communication technologies are WiMAX [11], Wi-Fi, PLC, DSL, cellular (i.e., GSM, GPRS), and Optical fibre [11]. In [18] a combination of HAN and PLC is proposed to develop the communication systems for urban MGs. The selection of communication technologies for FAN depends on the communication requirement of MG applications. For instance, Fibre-optical communication is suggested for the application with the requirement of low latency and robust communication performance [5]. While WiMAX is preferred in case of the need for larger coverage distance [17]. More specifically, WiMAX is a 4G wireless communication technology based on the IEEE 802.16 standards [17]. WiMAX is designed to strengthen the quality of services and to provide the network nodes with real-time bidirectional communication at a high data rate and long transmission distance [17]. Additionally, with one station, WiMAX is capable of offering services to hundreds of users [17]. These characteristics make WiMAX a good option for MG communication application.

3.3 COMMUNICATION OF WAN

WAN is the highest hierarchical level of the communication structure and acts as the backbone of the communication network [5]. WAN communication network is characterized by high bandwidth and long transmission distance and is equipped with advanced monitoring and sensing functions [5]. To fulfill WAN's functionalities, its communication requirements contain a significant data rate and long distance of data transmission (up to 100 km) [17]. WAN allows the power utilities to interact with the network subsystems (i.e., power substations). In addition, WAN supports two-way communication between automation and distribution purposes like SCADA, Phasor Measurement Unit and Remote Terminal Unit [17]. SA, Demand Response, and field devices automation are examples of the applications that are supported by WAN [17]. Suitable communication technologies for WAN include PLC, Optical fibre [5], cellular (i.e., GSM, GPRS, and 3G/4G), satellite, and WiMAX [17]. For example in [19], WiMAX is used as a communication link between control centers to the substation on the field for remote control of on-load-tap-changer setting. The most broadly used technologies for WAN communication links between the utility control centers and the substation is optical fibre because of its low latency and remarkable capacity [17]. With high data speed and wide coverage range, cellular and WiMAX are also good candidates for WAN [17]. Specifically, the cellular network uses radio frequencies and a significant number of transmitters to exchange the data [17]. Cellular technologies are divided into four main generations namely 1G, 2G (GSM), 3G (UMTS), and 4G (WiMAX and LTE), and two intermediate groups of 2.5G (GPRS and EDGE) and 3.5G (HSPA). Cellular networks can assist the implementation of smart metering over the wide network areas. For example, it can support the communication between the utility control centers and smart meters, and among the network nodes [17]. Thus, employing the existing cellular communication infrastructure can facilitate the rapid establishment and cost-effectiveness of MG communication architectures [17]. However, since the mobile services also share the cellular networks, MG communication systems using cellular network may suffer from the congestion and degradation of overall performance [17]. On the other hand, PLC is a wired communication technology utilizing the power line to transmit data. PLC is being widely used for a large number of command actions, such as smart metering, energy management, and HVAC control [17]. PLC is considered as one of the most cost-effective options for MG communication due to the use of existing power infrastructure. However, some drawbacks to the use of PLC for MG communication mean are a distortion of the signal, increased noise and security vulnerabilities [17]. Notwithstanding these drawbacks, PLC is regarded as the most suitable option for MGs in rural regions, where power lines are available, but other communication infrastructures are not [17].

3.4 COMMUNICATION OF DA AND SA

The choice of communication technologies in MGs is also determined according to MG applications like DA and SA. DA and SA are vital functions in MGs. DA introduces the capability of automatically and remotely monitoring, controlling and coordinating the distributed elements (e.g. feeder switches, feeder reclosers, and capacitors) in real-time [17]. SA is described as the ability to remotely and automatically monitor, control and protect the devices involved in the power substations [17]. Communication links act as the most important factor to achieve the desired functionalities of DA and SA. These DA and SA are the critical applications in MGs, then require reliable, secure and scalable communication systems [17]. For example, in DA, the latency of communication among network points should be less than 1s for alarm information, 15ms for control signals and 100ms for more detailed information [17]. PLC, Optical fibre, WiMax, cellular are the communication technologies that can be employed for SA and DA [17]. Particularly, cellular infrastructure can be adopted to remotely monitor the substation devices [17]. Regarding DA in MGs, the wireless LAN can be used for information exchange between Distributed Energy Resources (DERs), and between DERs and the substation, for instance, using GPRS [17] or Wi-Fi [15]. In terms of the used standards, IEC 61850 is the widely used one for SA in MG environment and currently the trend in DA [17]. IEC 61850 proposes an object-oriented description of the power substation by splitting its functions into monitoring, control, and protection [17]. IEC 61850 enables IEDs to better interoperate and communicate with each other [17].

Furthermore, using IEC 61850 satisfies the needs of MG applications. For instance, the adoption of IEC 61850 protocol in FAN allows the latency around 3-10 ms for the transmission of essential data [17]. The comparison of the data rate and coverage distance of different communication technologies for MG is demonstrated in Table 2. The summary of communication technologies used in various MG applications is shown in Table 3. More detailed description of aforementioned communication methods with a review of different ICT methods and network topologies are reported in [9], [11], [14], [17], [20].

Table 2. Comparison of MG ICT [13]

Communication Technologies	Standard/ Protocol	Data rate	Coverage distance
Wired Communication Technologies			
Optical fibre	PON	155 Mbps-2.5 Gbps	up to 60 km
	WDM	40 Gbps	up to 100 km
	SONET/SDH	10 Gbps	up to 100 km
DSL	ADSL	1-8 Mbps	up to 100 km
	HDSL	2 Mbps	up to 3.6 km
	VDSL	15-100 Mbps	up to 1.5 km
PLC	HomePlug	14-200 Mbps	up to 200 m
	Narrowband	10-500 kbps	up to 3 km
Wireless Communication Technologies			
ZigBee	ZigBee	250 kbps	up to 100 km
	ZigBee Pro	250 kbps	up to 1,600 km
WLAN	802.11x	2-600 Mbps	up to 100 m
Z-Wave	Z-Wave	40 kbps	up to 30 m

WiMAX	802.16	75 Mbps	up to 50 km
Cellular	2G	14.4 kbps	up to 50 km
	2.5G	144 kbps	
	3G	2 Mbps	
	3.5G	14 Mbps	
	4G	100 Mbps	
Satellite	Satellite Internet	1 Mbps	100-6,000 km

Table 3. ICT Technologies for MGs [10]

Application	**Information and Communication technologies**	
	Wired	***Wireless***
AMI	PLC, Optical fibre, DSL	ISO/IEC 18000-7, WPAN (6LoWPAN, ZigBee, WirelessHART), Wi-Fi, WiMAX, Cellular network (GSM, GPRS, 3G/4G)
HAN	Broadband-PLC	ISO/IEC 18000-7, WPAN (6LoWPAN, Bluetooth, ZigBee, WirelessHART), Wi-Fi, Cellular network (3G/4G)
FAN	Narrowband-PLC, DSL, Optical fibre	Wi-Fi, WiMAX, Cellular network (GSM, GPRS)
WAN	Narrowband-PLC, Optical fibre	WiMAX, Cellular network (GSM, GPRS, 3G/4G), Satellite
DG and EES		ISO/IEC 18000-7, Wi-Fi, WiMAX, Cellular network (GSM, GPRS, 3G/4G)
SA and DA, and Protection	PLC, Optical fibre	ISO/IEC 18000-7, Wi-Fi, WiMAX, Cellular network (GSM, GPRS, 3G/4G)
Standards/ Protocols	- NB-PLC: ISO/IEC 14908-3, ISO/IEC 14543-3-5, CEA-600.31, IEC 61334-3-1, IEC 61334-5, Insteon, X10, G3-PLC, PRIME - BB-PLC: TIA-1113, IEEE 1901, ITU-T G.hn, HomePlug AV/Extended, HomePlug Green PHY, HD-PLC - Optical fibre: IEEE 802.3ah, ITU-T G.983, ITU-T G.984, IEEE 1901 - DSL: ITU G.991.1, ITU G.992.1, ITU G.992.3, ITU G.992.5, ITU G.993.1	- ISO/IEC 18000-7: DASH 7 - WPAN: IEEE 802.15.4/IP (6LoWPAN), IEEE 802.15.1 (Bluetooth), IEEE 802.15.4 (ZigBee, WirelessHART), ISO 100.11a - Wi-Fi: IEEE 802.11e, IEEE 802.11n, IEEE 802.11s IEEE 802.11p - WiMAX: IEEE 802.16, IEEE 802.16j, IEEE 802.16m - Cellular Network: EDGE, GSM, GPRS, 3G (UMTS), 4G (LTE, LTE-Advanced) - Satellite: LEO (Iridium, Globalstar), MEO (New ICO), GEO (Inmarsat, BGAN, Swift, MPDS)

4. INTEROPERABILITY ISSUES

Different manufacturers, utilities, and customers can employ different ICT solutions for their devices and systems. This results in numerous kinds of ICT, devices, and networking protocols in MG communication systems. As a result, guaranteeing the interoperability between those different communication components becomes an essential task [10]. The interoperability is the ability of the network components, or applications to interact and communicate in an effective, seamless manner. The interoperability can be described as a multi-faceted issue including physical network interoperability and application interoperability [10]. Moreover, the interoperability is regarded as the desired characteristic within an MG, between multiple MGs, and between MG and upstream distribution network. Standardization of the related communication requirements is one way to realize the interoperability of MG communication technologies. Institute of Electrical and Electronics Engineers (IEEE) and International Electrotechnical Commission (IEC) are main organizations making the efforts to develop a standardized framework. Several issued communication standards are IEEE C37.1, IEEE 1379, IEEE 1547, IEC 60870, IEC 61850, IEC 61968, IEC 61970 and IEC 62351. More detailed discussion of various communication standards is included in [9], [11], [13], [21]. Additionally, [22] presents a review of communication standards and protocols for The Internet Protocol Suite, Modbus, and Distributed Network Protocol (DNP3). The interoperability of agent-based communication systems using IEC 61850 is examined in [23]. A summary of communication standards used in MGs is included in Table III. An additional way to support the interoperability involves integrating the network elements that function as translation services between different communication standards [10]. For instance, network gateways are employed to transmit packets of data between different systems using different protocols [10]. In [24], a hybrid cloud-based SCADA architecture is proposed to achieve the interoperability between multiple MGs. For this architecture, Common Information Model(CIM/XML/RDF) is selected as a model for information exchange and is mapped with OPC Unified Architecture (OPC UA) [24].

5. RELIABILITY ISSUES

Reliability represents the reliable degree that the communication system executes the data transfer [24], measured in total outage period shorter than one second per year [24]. All MG components need to send and receive critical messages to maintain proper operation and control. The communication nodes and paths must reliably perform to maintain the continuity of the overall communication system. Some mission-critical application like SA and DA requires a high level of reliability (up to 99.99%) to achieve its performance goals [24]. Meanwhile, some other applications accept lower reliability with some data transmission outages. There are three main failures causing the communication system to be not reliable, including time-out failure, network failure, and resource failure [21]. For instance, experiments on Dutch field trials reported that using the public communication for the monitoring and control purpose showed an unreliable performance [19]. This can lead to improper control and operation of MGs. Hence, it is essential to evaluate the reliability of the communication systems during its design process and seek suitable solutions to enhance the reliability.

6. SECURITY ISSUES

The security issue is one of the major challenges of MG communication systems. The huge number of connected devices and applications involved pose a great risk of information security threats to communication systems. Failure to address such security threats will reduce the reliability of the MG. Security implies the ability of the communication systems to defend the communication component against physical and cyber security attack [24]. Authors in [25] emphasize that almost all MG applications regard the end-to-end security as the highest priority. The communication systems must be capable of securing its metering information against any unauthorized access [24]. Furthermore, the communication system must protect the sensitive data from being modified when it is transferred within the network [24]. Likewise, the communication system has to be secure enough to cope with cyber-attacks, which intend interrupting the communication services to cripple the electricity provision [10]. Potential problems with cyber-security and their solutions have been analyzed in [25]. It has been highlighted that using ICT involves risks of cyber security attack, inducing the communication system to be vulnerable to cyber-attacks. In [26], a survey of communication vulnerabilities and threat models is provided for the implementation of a secure MG control system. In order to assist the MG communication system in realizing and alleviating such cyber-attacks, it is important to implement the security schemes. Some examples of such security schemes are authentication, encryption, trust management and intrusion detection [25]. In [27], a communication architecture with higher security level is proposed to support MG operation and control. The work involves defining security model and developing security protocol for real-time communication of MG.

7. LOCAL VOLTAGE CONTROLLER

7.1 INTRODUCTION

The LV distribution networks across Europe are experiencing a notable increase in integrated MGs. In MG context, there is an increasing share of photovoltaic (PV) systems, mainly driven by environmental concerns, installation cost reduction, and new energy policies. Despite supplying environment-friendly energy, the growing penetration of PV systems in the LV networks presents a series of operational and power quality challenges, e.g., congestions and overvoltage [15].

Therefore, this section focuses on voltage control in distribution networks with a local innovative regulator developed for DGs. First, it presents the French Distribution Network Operator (DNO) requirements and the equipment used to control voltage inside its contractual values. Then, the DGs impact on actual control is reminded. Finally, the section describes the voltage regulator developed by the GIE IDEA in Grenoble [28] and it focuses on various simulation results.

7.2 CONTEXT

Today, probable voltage constraint violations in distribution networks are solved during the connection studies. Before the connection to the grid, the DNO checks and verifies with a deterministic approach, that the voltage values can be maintained within the contractual limits everywhere on the network regardless of the operating conditions. Thus, the DNO defines the kind of control for DG (constant reactive power (Q), Q control or V control). However in the future, with a continuously increasing penetration of DGs in the network, DGs will have a more active contribution to voltage control. This section presents a local, intelligent and adaptive voltage regulator.

7.2.1 Grid requirements

The voltage supplies to MV and LV customers must conform to contractual laws. DNO controls the root mean square voltage and its contractual rule concerns the average value on ten minutes points. In France for example, contractual obligations on MV networks consist to maintain the voltage in the range 20 kV ± 5% and between 230V [+6%, -10%] on LV networks.

7.2.2 DGs requirements

Today in France, the voltage level for the grid connection of a generating plant depends on its size. Concerning DG contribution to voltage control and reactive power, the requirements are defined in the French ministerial order [29] and in the [30]. At the present time, a voltage control system is required only for DGs bigger than 10MW.

7.2.3 DNO Facilities of control

Today, the DNO controls the network voltage with two main voltage setting devices.

- The HV/MV transformer On-Load-Tap-Changer (OLTC) which changes the transformation ratio according to a voltage set point
- The MV/LV transformer off-load tap-changers are equipped with three tapping steps of 2.5% around the nominal ratio.

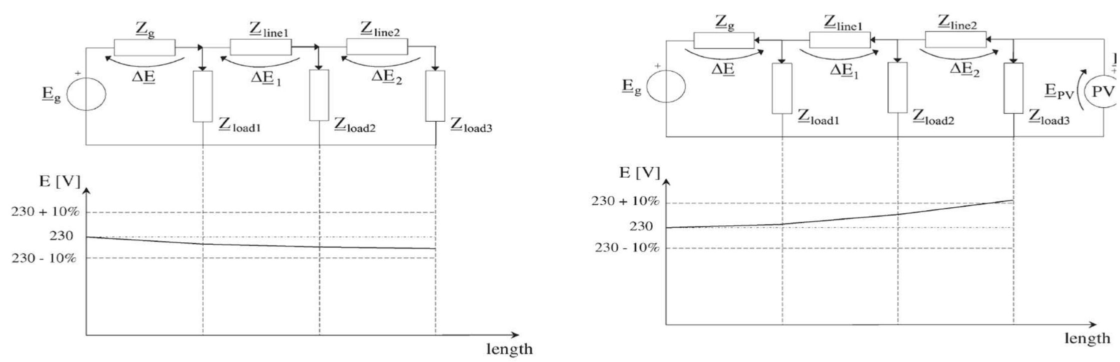
Capacitor banks are also installed on HV/MV bus to compensate reactive power demand.

7.2.4 The negative impacts of DGs on the voltage profile in the system

The connection of a DG unit modifies the voltage profile on the grid due to the change in the active and reactive power flows in the network impedances. Usually, the voltage increases at the connection point and on the feeder. DGs connection effects are presented in paper [30], [31]. The most prominent ones are:

- Fast voltage fluctuation at the connection point due to variants of PV or Wind production.
- Injection of harmonics due to the use of electronic devices.
- Voltage rise and unbalances between the phases.
- Leakage current
- DG connection creates overvoltage during minimum load times.
- Undervoltages could also occur during peak load times when generation is not connected.
- Usually, DGs optimize voltage settings at the HV/MV substation, particularly when the allocation of generation is not homogeneous between the different feeders.

From all the issues above, the most noticeable drawback remains on the voltage profile. To ensure the safety of the end users and system components, the voltage profiles must be held within the predefined limits set by the rules of electrical network operation (e.g. European EN50610). It is witnessed that the rising in voltage profile not only appears in high DGs penetration situation but also occurs when the MG has long transmission lines, which is totally opposite to traditional grid.



Voltage profile relative to distance with no DGs (a)

Voltage profile relative to distance with DGs (b)

Figure 7. Voltage profile in the Low Voltage systems

In order to maintain transformer saturation limits and to preserve a good operation of industrial or domestic devices, the voltage limit must not be violated.

There are some possible solutions to deal with the voltage problems:

- Using FACTS devices (SVC, STATCOM).
- Strengthen the grid (increase conductors size).
- Using a shunt capacitor.
- Using Load Tap Changer (LTC) transformer.

However, all the solutions mentioned above are not very suitable. Firstly, FACT devices are expensive and based on electronic devices which introduce more harmonics to the grid. Increasing the conductor's size is not achievable because every time we bring new DG to the grid, we have to increase the size of conductors again. Shunt capacitors can be useful but they are limited by the amount of storage. Another way to control the voltage is using load tap change transformer (LTC) at the substation. However, as we can see in the Figure 7b, in order to reduce the voltage at load 3, if we use LTC, the customers at load 1 and 2 will have unwanted effects.

Thus, using the DGs inverter system to control the voltage profile at load 3 is the most advantageous method. Next part presents a local voltage regulator for DGs. This regulator is able to control voltage not only at the connection point but also everywhere on the grid.

7.3 THE PRINCIPLE OF THE AUTO-ADAPTIVE REGULATOR

DGs connected in the network can participate in the voltage control, however, a few questions arise:

- Who decides to change the DGs voltage set points?
- How much? (set point value appropriate to bring back the voltage within the acceptable limits)
- When and how long? (Moment of change)
- Where? (Which DG?)

The developed auto-adaptive regulator answers partly to above questions with technical but also economic advantages: local decisions based only on local measures. This avoids investments in communication systems for DNOs.

The paragraph below describes the working principle of the auto-adaptive voltage regulator.

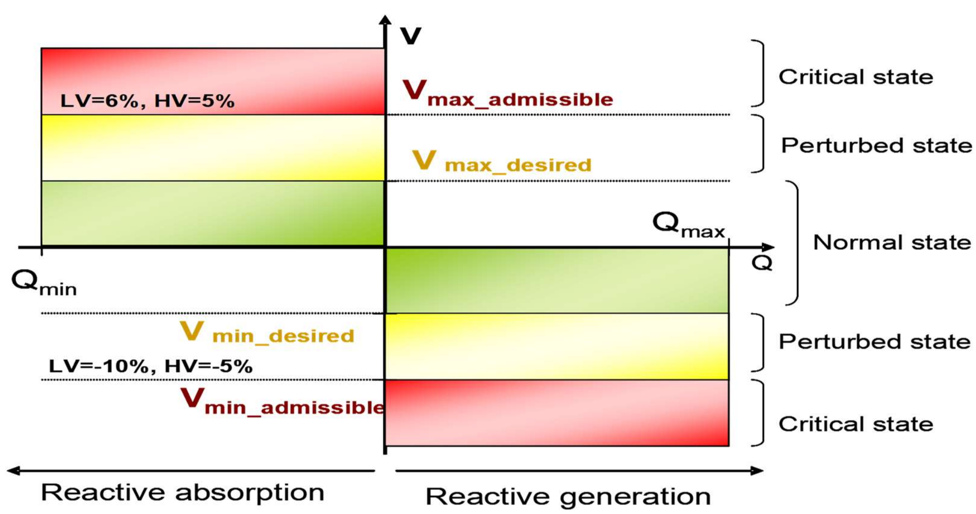


Figure 8. Principe of the auto-adaptive regulator

Three operating modes of the regulator are possible. They correspond to three possible states (Figure 8):

- Normal state: where the voltage is located inside a window of "desired" voltage (Vmin_desired ≤ V ≤ Vmax_desired). In this state, DG is in P/Q control (PF/VAR control).
- Perturbed state: where voltage leaves the desired limits (V> Vmax_desired or V< Vmin_desired). The goal of the adaptive regulator is to maintain, within the limits of the system, the voltage between these fixed values. Thus, under perturbed conditions, DG commutates in voltage regulation mode (AVR for the synchronous machines and P/V mode for sources using an inverter). Here, only reactive power is used to control voltage at the DG connection point. The voltage set point is set at Vmin_desired or Vmax_desired according to whether the network voltage profile is too low or too high. If DG is in reactive power limitation (Q=Qmin or Q=Qmax), it cannot ensure anymore the control in the desired voltage. The voltage moves and reaches a critical state when voltage admissible limits are crossed.
- Critical state: where the voltage is out of the admissible limits (V> Vmax_admissible or V< Vmin_admissible) and, as previously explained, DG cannot act anymore by compensation of reactive power. In the critical state, the regulation of active power becomes necessary. So, the DG commutates in active power regulation mode (Mode P). It means that DG changes active power generation in order to bring back the voltage in the admissible values.

In addition, automatic adjustment of desired limits allows several strategies of control. First, it is possible to use this regulator for maintaining the voltage at DG connection point only. Indeed, by setting desired limits such as Vmax_desired = Vmax_admissible and Vmin_desired = Vmin_admissible the regulator operates to maintain in priority the voltage at the connection point in the admissible values. Nevertheless, with this strategy of control, the regulator acts slightly for keeping the voltage in the adjacent buses.

Secondly, it is possible to set constraining values for the desired limits (Vmax_desired < Vmax_admissible and Vmin_desired > Vmin_admissible). With this strategy, the regulator controls first the voltage at DG connection point. Moreover, the conservation of voltage in a narrower window at the connection point (Vmin_desired <V< Vmax_desired), also regulates the voltage on the adjacent buses. But careful, for small DGs this choice is very sensitive to a reactive power limitation. Indeed, if one sets a rather low value for Vmax_desired, DG often reaches the limit of reactive power absorption. On the contrary, if the Vmin_desired value is high DG often reaches the limit of the reactive power supply. Three strategies of control are possible for these values: the fixed desired window, the controlled desired window, and the adaptive desired window.

7.3.1 Fixed desired window

The user can set these values, e.g.: Vmax_desired = 1.04 p.u. and Vmin_desired = 0.98 p.u. This choice is available for every network. The Vmin_desired value specified at 0.98 p.u. maintains a rather high voltage profile. This contributes to a decrease in the losses of the network. The Vmax_desired value specified at 1.04 p.u. helps to avoid a too high voltage profile of the network.

7.3.2 Controlled desired window

After an Optimal Power Flow (OPF) calculation the grid operator can impose desired values for each DG. OPF calculation is at least necessary for two extreme scenarios (low load scenario associated with the maximal generation plan; and full load scenario cumulated with the minimal generation plan) to determine these values. They can be modified in real time by the grid operator when a change of topology occurs on the grid for example.

7.3.3 Adaptive desired window

The regulatory changes in an adaptive way the desired voltage values, correlatively with the operation, by respecting the reactive power limits of each DG. Indeed, according to the voltage value on the connection feeder and the quantity of reactive power produced or absorbed, the Vmin_desired and Vmax_desired will be variable. Adaptive limits allow all DGs to contribute to voltage profile, even DGs located on not critical voltage feeders. In fact, the more the voltage measured is closed to 1.0 p.u. the more the voltage desired window will be narrow. This window moves according to the quantity of reactive power provided or absorbed compared with the physical limits of the DG considered. When the contribution of the reactive power is more important, the window of the voltage will increase more, while always respecting the limits: Vmin_admissible ≤ Vmin_desired ≤ Vmax_desired ≤ Vmax_admissible.

This adaptation is realized with the use of an adaptive module based on fuzzy logic (Figure 10).

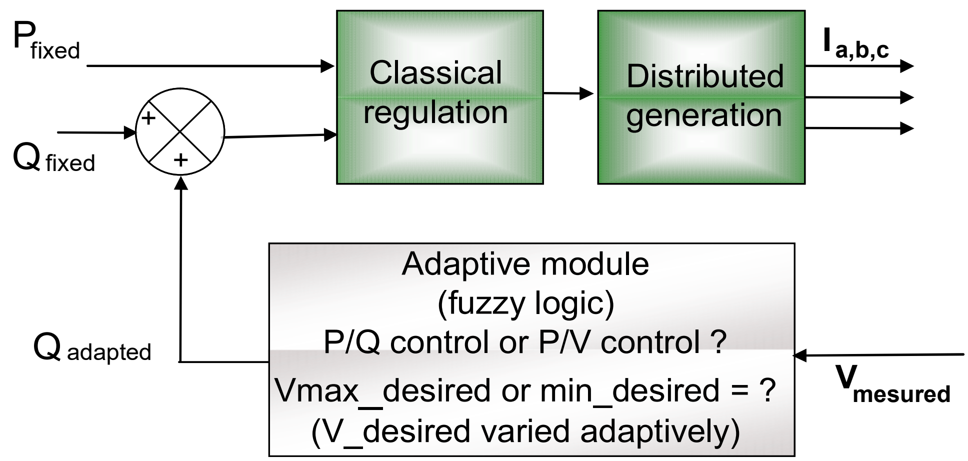


Figure 9. The functionality of auto-adaptive regulator

Fuzzy logic is chosen for its capacities of interpolation. Indeed, this logic is more precise than Boolean logic to adapt the desired voltage window according to each voltage and reactive power measured at the connection point (Figure 10).

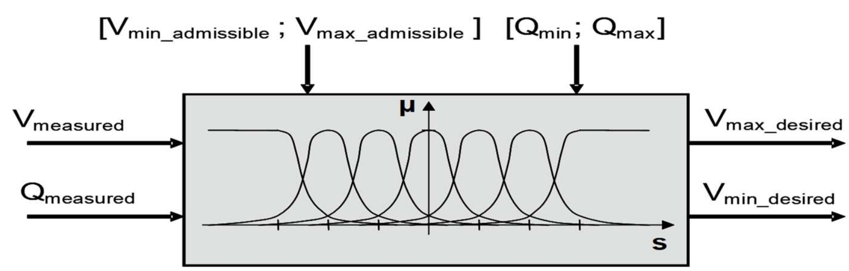


Figure 10. Determination of voltage setpoint by fuzzy logic

Three steps are necessary for fuzzy control in order to calculate the desired voltage setpoint (Figure 11).

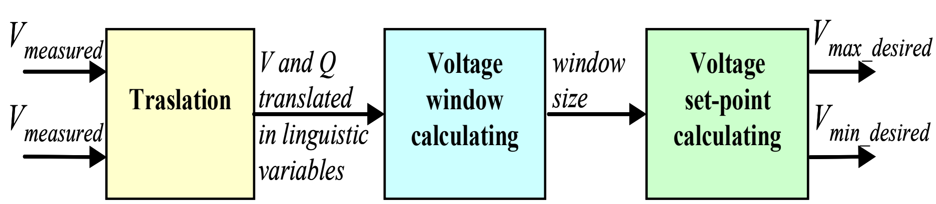


Figure 11. The principle of fuzzy control

7.4 SIMULATIONS

The following simulations complete the technical process presented in this deliverable. For this, we use the modeling of a LV network (Figure 12).

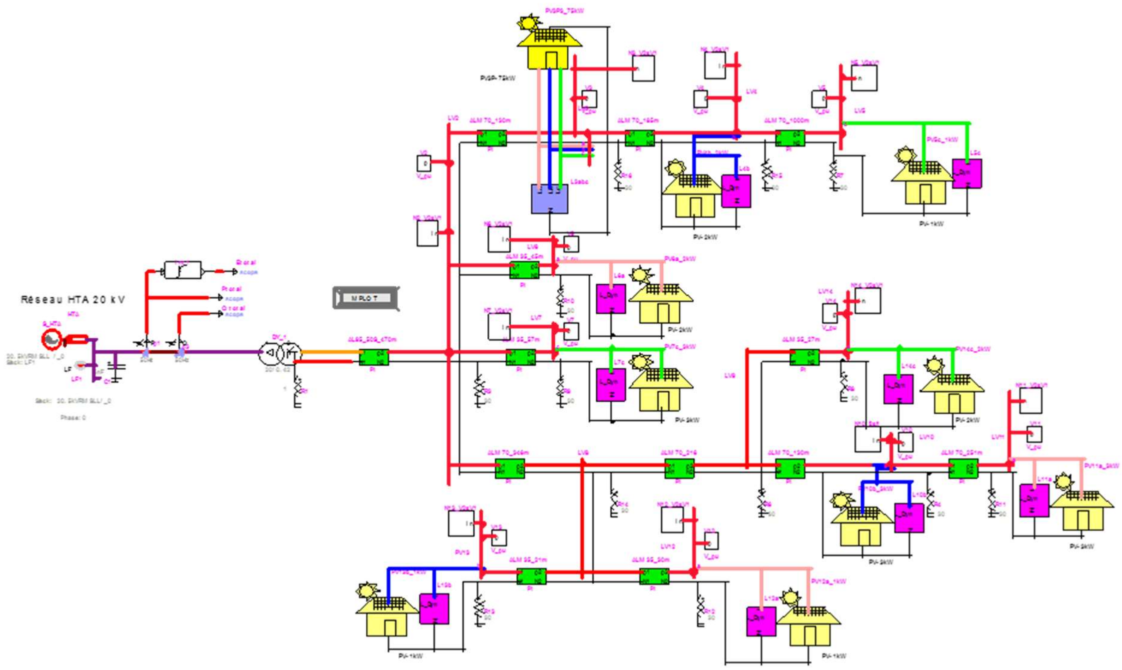


Figure 12. Studied LV network

For the connection of PV systems to this network, it is assumed that there are two types of PV generators:

- A three-phase PV system connected to node 3 (75 kWp) – commercial centre.
- Nine single-phase PV systems connected to the other nodes (1, 2 or 3 kWp).

Two types of regulation for these PV systems will be used:

- Classic P / Q regulation.
- Intelligent voltage regulation (RIV).

Two types of load are used for simulation:

- Residential load (see Figure 13).
- Commercial load (see Figure 14).

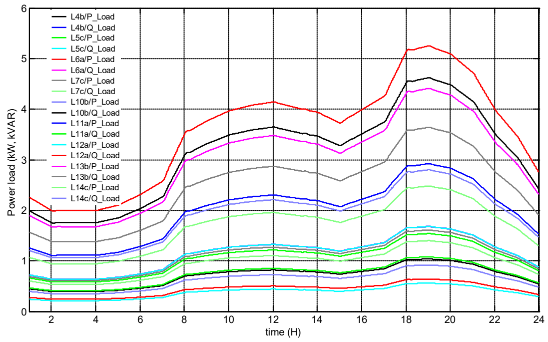


Figure 13. Variation of single-phase loads (residential loads)

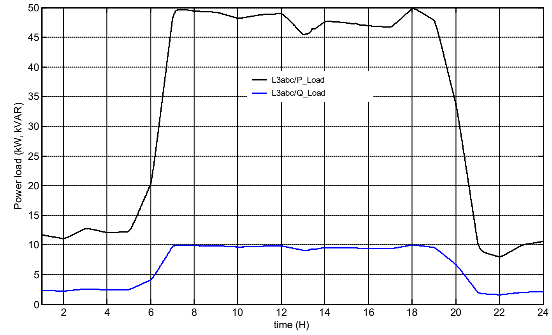


Figure 14. Variation of three-phase loads (commercial charge)

7.4.1 P/Q control

For PV inverters, when operating in P/Q control mode, the reactive power is zero (0 kVAR). PV production for a typical day is shown in Figure 15 for single-phase PV productions and Figure 16 for three-phase PV production. Figure 17 shows the variation of the voltage at the connection nodes and Figure 18 shows the power exchange between the upstream network (HV) and the studied LV network.

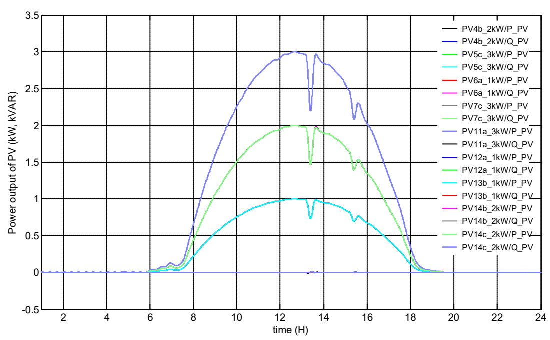


Figure 15. Power Variation of the single-phase PV installations

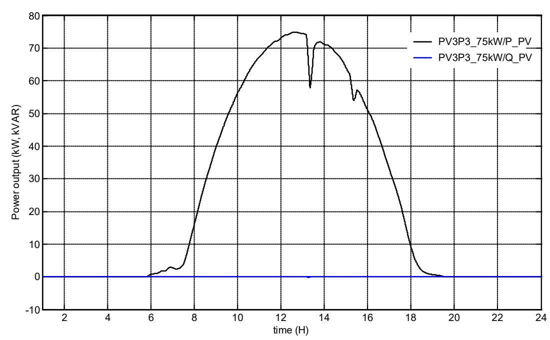


Figure 16. Power Variation of the three-phase PV installations

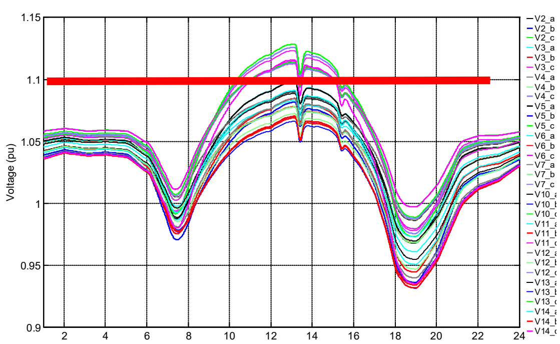


Figure 17. Voltage variations

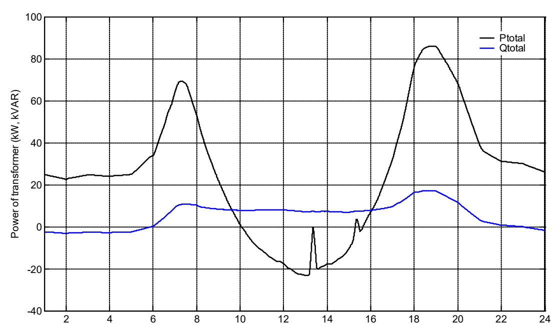


Figure 18. Power variation of the transformer

We observe that:

- On the few nodes where the PV installations are connected, there is a significant overvoltage at times of strong sunshine. The voltage exceeds the admissible voltage limit (110%); these PV installations can be disconnected by their associated protections.
- At times of high load and low PV output between 18h and 21h, there is undervoltage on most nodes; this can cause an increase in losses.
- In the case of single-phase connection, there is a voltage imbalance between the phases.
- This control mode highlights the overruns of the voltage limits (because of PV installations with regard to overvoltage problems). It shows the need for a voltage adjustment performed by intelligent regulation; this is the subject of the next point.

7.4.2 Intelligent Voltage Regulation (RIV or RAA Auto-Adaptive Control)

Under the same conditions as the previous study, the PV inverters now use a self-adaptive voltage regulator. Figure 19 and Figure 20 show the active and reactive power variation of single-phase and three-phase installations connected to node 3. Figure 21 shows the voltage variation at all connected nodes.

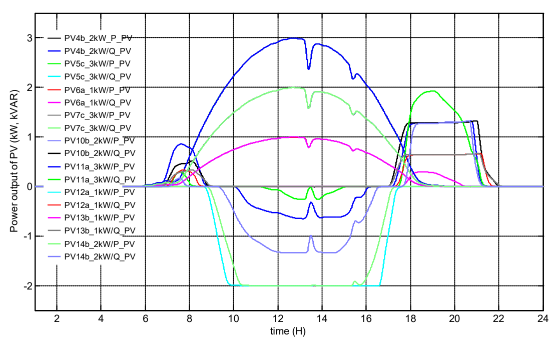


Figure 19. Power Variation of the single-phase PV installations

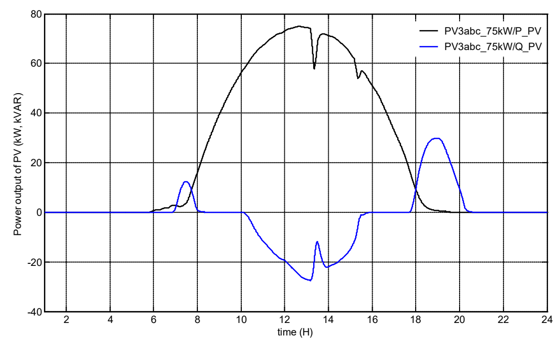


Figure 20. Power Variation of the three-phase PV installations

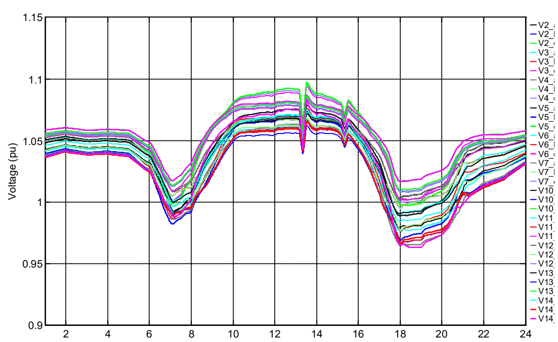


Figure 21. Voltage variation

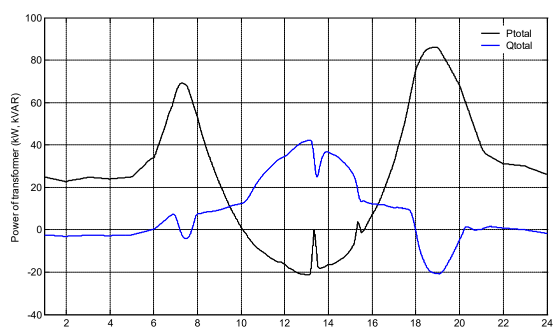


Figure 22. Power variation of the transformer

The PV inverters participate in the voltage adjustment (see the reactive powers absorbed and supplied by them) to maintain the voltage within the allowable limit (90% - 110%). In case of high production, the inverters participate in the alleviation of overvoltage by reactive power absorption in order to keep the voltage lower than the maximum permissible voltage. In case of high consumption, the inverters participate in raising the voltage profile by reactive power generation to maintain the voltage close to the nominal voltage. This participation depends on several factors, such as the power output of the inverters, the connection location, the voltage status, etc. This case demonstrates the performance and services provided by inverters equipped with self-adaptive voltage regulators.

The PV inverters participate in the voltage regulation (see the reactive power absorbed and provided by these PV inverters) to restore the voltage in the permissible window by the decoupling protections ($U \leq 1.15$ p.u. and $U \geq 0.85$ p.u.). In the event of a short-circuit, the PV inverters take part in maintaining a fairly high voltage level by reactive power generation in order to keep the voltage above the limit voltage (0.85 p.u.) which prevents disconnection of the PV systems. This participation depends on several factors such as the power output of the PV inverters, the connection point, the voltage status, etc. The results in Section 9 show the performances provided by the inverters equipped with the proposed self-adaptive voltage regulator.

<u>Remarks</u>

The proposed self-adaptive voltage regulator has the following advantages:

- This regulator maintains the voltage within the desired limits and avoids unjustified disconnection of PV systems in the event of an uncomfortable short circuit on an adjacent HV feeder.
- The switching between the control modes is carried out automatically and adaptively for different operating regimes.
- It is possible to maintain the active and reactive power of the DG in its constructive limits.
- The operation of the regulator is totally automatic, it does not require specific knowledge about the characteristics of the DG for its parameterization.
- The regulator does not require additional measures or new equipment, thus reducing the cost of connection.
- This regulator increases the capacity of the DGs to penetrate the network.
- This principle can be used for DGs connected in HV or LV.

8. CLOUD-BASED COMMUNICATION CAPABILITY OF PV INVERTERS

8.1 INTRODUCTION

Task 4.1 aims at applying the communication to the local voltage controller, which CEA developed in the PARADISE project. This communication application allows the local voltage controllers to couple effectively with the hierarchical control system within a MG. The solution provided by the project of EU FP7 INCREASE is chosen in order to facilitate the increasing penetration of Renewable Energy Resources (RES) in the distribution grid, then providing the ancillary services (towards DSO, but also TSOs), in particular, voltage control and the provision of the reserve. Solar Photovoltaic (PV) system on the house rooftop is one type of RES. Along with the development of the control algorithm, the well-known WiFi (IEEE 802.11) ICT infrastructure and Intelliweb cloud-based program are proposed to be applied in Solar PV control system [15].

The benefit from using WiFi (IEEE 802.11) ICT infrastructure is that most of the houses in Europe are utilizing the Wifi connection, thus such adoption with remote monitor and control for Solar PV inverters does not require any hardware-related changes either in solar PV inverter or in the existing communication infrastructure [32]. As a result, on one hand, the adoption is very likely to be quickly implemented. On the other hand, that adoption results in the avoidance of the development of new wired ICT infrastructure which is a dedicated communication channel for Solar PV inverter interconnection. The corresponding additional investment for such communication, therefore, is avoided [32].

8.2 IMPLEMENTATION OF THE CLOUD-BASED PROGRAM

In order for the Solar PV system to be efficiently managed, it is necessary that the Solar PV inverters are capable of remote monitoring and control [33]. Furthermore, a cloud-based program which is a service on the Internet must be introduced to obtain and manage the measured data from such inverters [33]. Speaking of general principle, Solar PV inverters will be equipped with communication modules, either wired or wireless, subsequently connecting to the local communication network and a cloud-based program by using a communication protocol, for example, Message Queuing Telemetry Transport (MQTT) [33].

For the sake of explanation, the following diagram shows the architecture of a proposed cloud-based program in the EU FP7 project INCREASE with the interaction among system components.

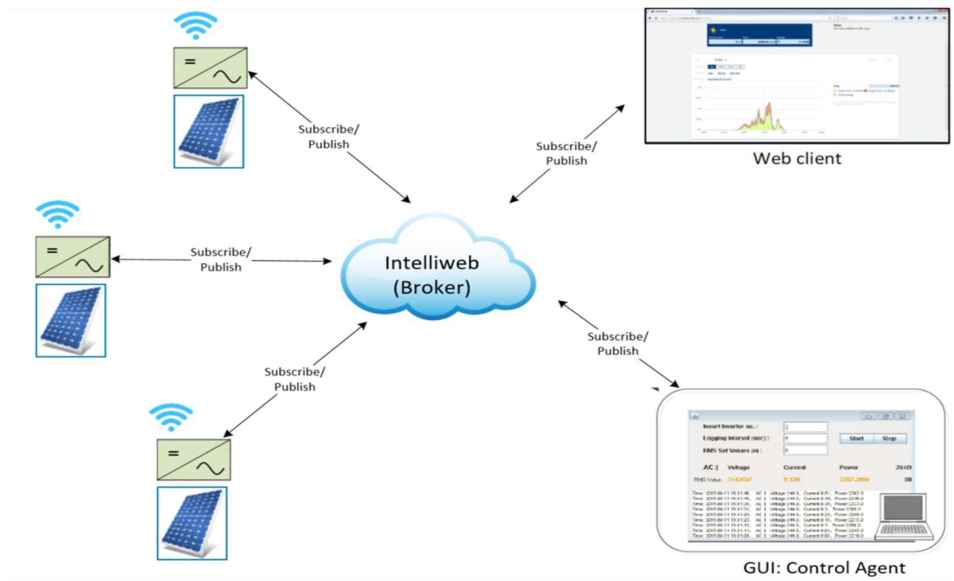


Figure 23. Intelliweb cloud-based program architecture [33]

The Solar PV inverters named MASTERVOLT Soladin with remote monitoring and control capability are equipped with Wi-Fi modules, then connected with the local Wi-Fi network and a cloud-based program [33].

8.3 INTELLIWEB

A cloud-based program called Intelliweb is offered by the MASTERVOLT manufacturer. Intelliweb cloud-based program is a vendor specific service that is compatible with MASTERVOLT inverters for the purposes of gathering and managing the measured data.

The Intelliweb (broker) acts as a data acquisition entity while the publisher and subscriber (the inverters and the Web client) serve as the data source and the data sink respectively [33]. The measurement data in Intelliweb are managed in different topics where the publisher/subscribers will send and collect the corresponding content [33]. The working principle of the Intelliweb (broker) is shown in Figure 24.

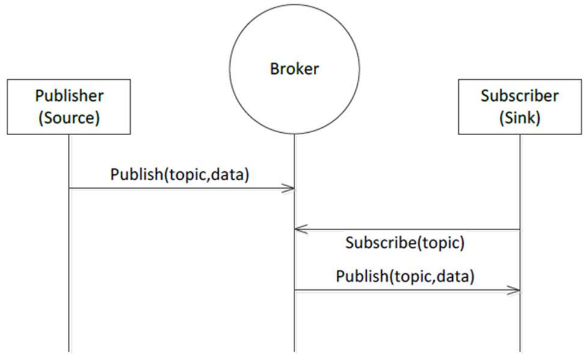


Figure 24. Intelliweb (broker) working principle [33]

- Broker: The server that receives data from the publisher and passes it to the subscribers.
- Topic: In MQTT, data are organized under different directories called topics.
- Publisher/subscribers: A publisher sends data to the broker where the data are sent to the corresponding topic. A subscriber subscribes to the desired data by subscribing to the corresponding topic. Therefore, the subscriber only receives the data of interest to it.
- Data: Data contain more information in which most of it is to manage the protocol. For the user, a part of data called payload is the desired data.

8.4 WEB CLIENT

For purpose of monitoring, measurement of these MASTERVOLT inverters can be retrieved by logging via Webclient of the Intelliweb cloud-based program. The Webclient is the web portal offered by MASTERVOLT manufacturer for the end users to log in and retrieve the measurement data from the MASTERVOLT inverters [33]. Figure 25 shows a snapshot of Web client of Intelligent.

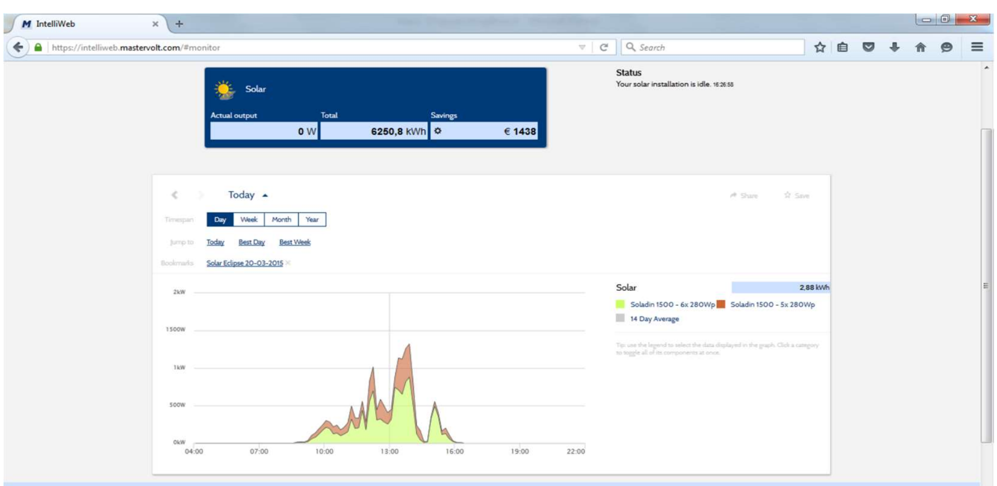


Figure 25. Snapshot of Web client of Intelligent [33]

8.5 CONTROL AGENT

The control agent is developed to monitor and control the MASTERVOLT inverters with the application of a Graphical user interface (GUI) for the visualization of the client including the Communication segment and Control Algorithm segment [33]. While the Communication segment acts as a connection and data exchange utility, the Algorithm segment performs the control function.

Since the MASTERVOLT inverter is capable of remote control, but cannot implement the droop control, the Application Programming Interface (API) is developed to enable the droop control and employ the remote controllable characteristic [33]. The APT is based on Java because of MQTT protocol usage with MASTERVOLT inverters (More description of MQTT protocol below). In addition, a Graphical user interface (GUI) is developed. After successfully connecting and subscribing to the Intelliweb (broker), the control agent monitors the voltage at the point of connection of the inverters and provides the power set point to the inverters if necessary.

8.6 COMMUNICATION PROTOCOL (MQTT)

The Message Queuing Telemetry Transport (MQTT) protocol is adopted as the standard for communication between the inverters, local Wi-Fi network and a cloud-based program [33].

Message Queuing Telemetry Transport (MQTT) is a lightweight, simple messaging protocol that is proved suitable for low bandwidth, high latency, highly unreliable networks [33]. Using MQTT enables the minimal network bandwidth and device resources required, and ensures the reliability and delivery standards of the message [33]. In reality, the MQTT has widely utilized candidate for implementing complex and data-intensive communication network for example Internet of Things (IoT). Moreover, the laboratory experiments show that the broker can deliver measurement data to the web client and the developed MQTT client simultaneously.

Since most of the houses in Europe are utilizing the Wifi connection, the proposed solution is very likely to be quickly implemented [33].

9. VALIDATION AT SOREA

The proposed solution was implemented on an Arduino microcontroller box interfaced with the inverters of the SOREA site (Figure 26). The communication between the box and the inverter is provided by Modbus RS 485.

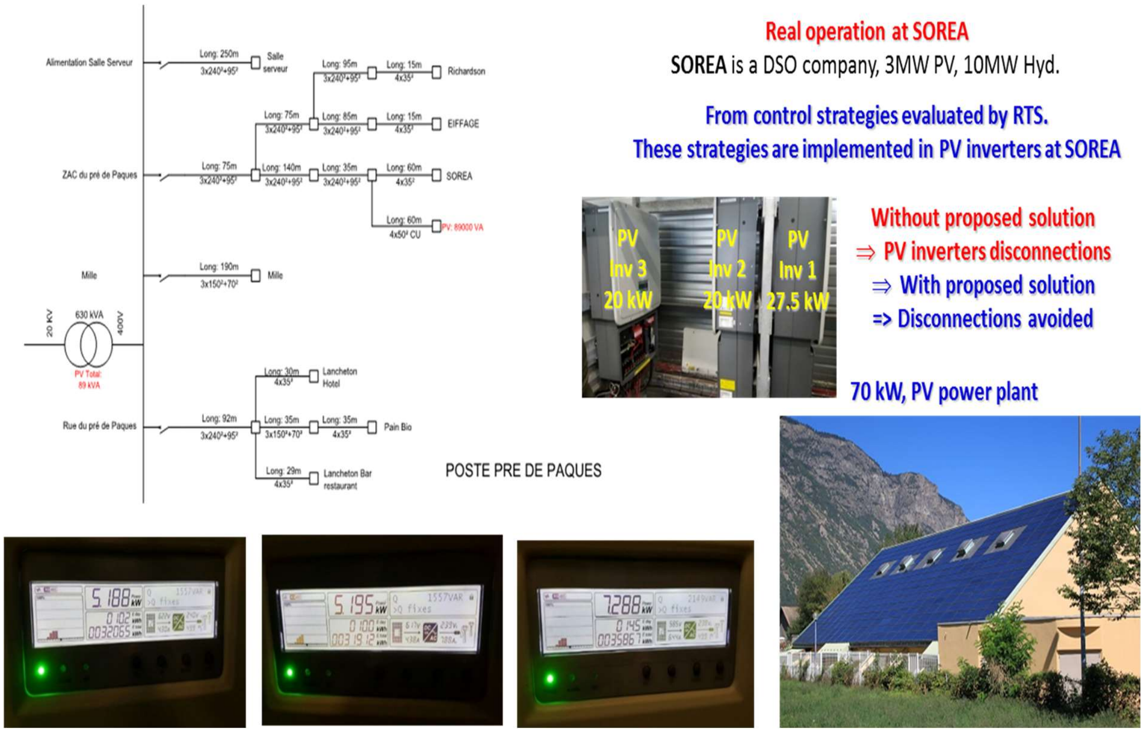


Figure 26. Validation at SOREA network

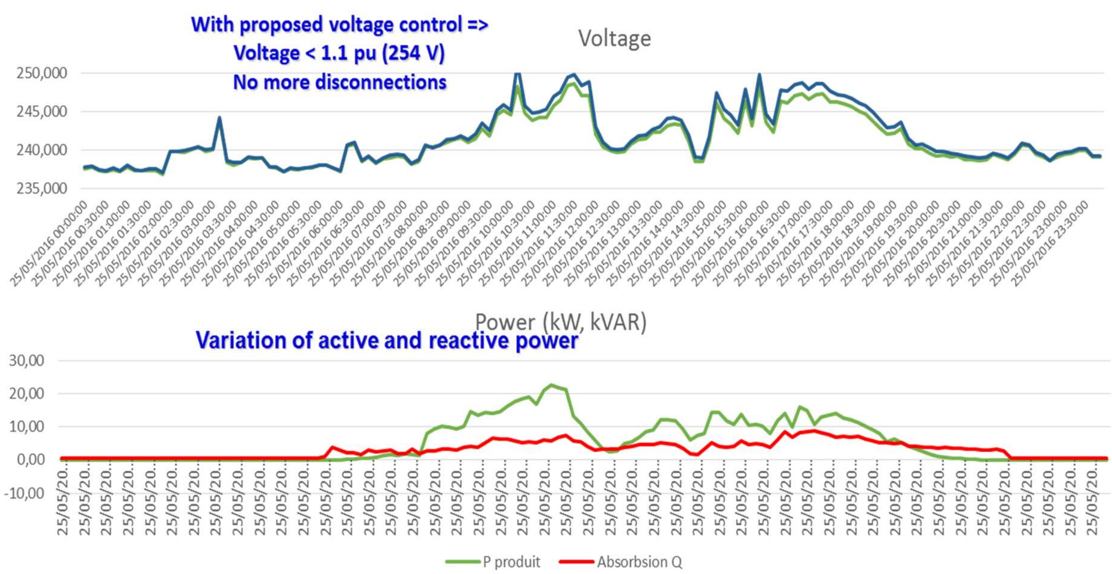


Figure 27. Variation of voltage and reactive power

Figure 27 shows the variation of voltage and active, reactive power of the inverter. Without a solution, there were UPS connections several times a day. With the proposed solution, disconnections are avoided. Voltages are maintained within the permitted limits.

10. COORDINATED CONTROL OF LOCAL VOLTAGE CONTROLLERS

Coordinated control is crucial to enable the MGs to ensure the grid reliability and security of supply. Additionally, coordinated control facilitates the capability of providing ancillary services to the upstream distribution network. Such functionalities require communications among the involved actors within a MG as well as their interactions with external stakeholders including DSOs. The communication system presents a means of exchanging data and monitoring a wide range of MG components for the purpose of control and protection.

As discussed in the above sections, one the noticeable problems related to increasing integration of PV systems in the LV networks is of the overvoltage problem. Lack of proper solutions to overvoltage mitigation results in the severe damages to electrical appliances in customers premises and an increase in PV systems tripping. Overvoltage becomes a bottleneck for the maximum power output of the inverters. Therefore, an effective control methodology is essential to mitigate overvoltage issues and maximize the power outputs. On the other hand, as the share of PV systems used in the power generation mix has been quickly rising, it is becoming necessary for PV inverters to provide the support for voltage regulation in the network.

European LV networks are generally characterized by a high ratio of R/X, making the use of reactive power absorption (RPA) alone less effective to solve overvoltage problems. Nevertheless, a proper control of the reactive power of PV inverters can still be of benefit to the overvoltage mitigation. Active power curtailment (APC) based on P – V droop control is being used widely for voltage management [34] because the active power change has a strong impact on the voltage variations. The APC approach, however, causes the loss of revenue of the PV owners from selling their surplus power. The combination of APC and RPA of PV inverters become attractive solutions to overvoltage mitigation [35], [36], especially as the share of PV systems in the power network is rapidly growing.

Therefore, inspired from the fuzzy logic of CEA toolbox, communication capability from the INCREASE project, this section describes the proposal of the coordinated control of APC and RPA of PV inverters based on a hierarchical control within a physical LV MG to solve overvoltage problems. The coordinated control aims at mitigating the overvoltage problems while minimizing the curtailed active power. The proposed mechanism is comprised of primary and secondary control layers to tackle the overvoltage problems.

10.1 COORDINATED CONTROL MECHANISM

10.1.1 Droop – based active power curtailment

P-V droop-based APC reduces the active power injection ($P_{injected}$) of the inverters to the grid in order to support the overvoltage mitigation, as expressed by [36]:

$$P_{injected} = \begin{cases} P_{MPP} & \text{if } V_{\min} < V_P \le V_{thP} \\ P_{MPP} - P_{MPP} \times \dfrac{V_P - V_{thP}}{V_{max} - V_{thP}} & \text{if } V_{thP} < V_P < V_{\max} \\ 0 & \text{if } V_P \ge V_{\max} \end{cases} \quad (1)$$

Where [V_{min} V_{max}] = [0.9 1.1] to comply with the standard EN50160. When the voltage at the point of connection (POC) (V_P) varies within the range from V_{min} to the active curtailment threshold voltage (V_{thP}), the inverters operate at the maximum power point (P_{MPP}). If V_P crosses V_{thP}, the APC is activated, thus regulating the amount of active power injection as a function of V_P.

10.1.2 Droop – based reactive power absorption (RPA)

The absorbed reactive power (absorb Q) is a function of VP as shown in the following formula.

$$Q_{absorb} = \begin{cases} Q_{max} \times \dfrac{V_P - V_{thQ}}{V_{max} - V_{thQ}} & \text{if } V_{thQ} < V_P \le V_{max} \\ 0 & \text{if } -V_{thQ} \le V_P \le V_{thQ} \end{cases} \quad (2)$$

When VP exceeds the reactive absorption threshold voltage (V_{thQ}), the RPA is accordingly triggered. The Q – V droop control then regulates the amount of absorbed Q. Q_{max} represents the maximum RPA of the inverters and is restricted by the inverter's apparent power and active power generating at a given irradiance. Moreover, Q_{max} is limited due to the power factor (PF). The European Standard EN 50438 stipulates that distributed generation units connecting to the LV network are required to operate with PF ranging from 0.9 lagging to 0.9 leading [37].

10.1.3 Proposed control approach

This part investigates the correlation and coordination of a pair of parameters, referred to as absorption threshold (V_{thQ}) and curtailment threshold (V_{thP}). A set of V_{thQ} and V_{thP} is defined for different PV inverters along the feeder in a coordinated manner using the hierarchical control. At each control time interval, the slopes of the droop are then updated according to redefined V_{thQ} and V_{thP}. Figure 28 shows the proposed coordination of Q – V and P – V droop control of the inverters to solve the overvoltage problems. Here Q – V droop control is modified that has a higher slope to reach its maximum rate at the voltage value that triggers the APC. The hierarchical control framework is composed of primary control and secondary control given the communication capability is available. Employing droop control, the primary control is locally performed at each of the inverters [37], sending measured operational data to the secondary control. Using the data from the primary control, the secondary control implemented at the central controller utilizes the multiple optimization methods to determine the new V_{thQ} and V_{thP} , and update the new droop control slope. These parameters are consequently sent back to primary control as reference values for active and reactive power control. One of the objective functions of the proposed optimization is to minimize the APC of all inverters in the physical LV MGs.

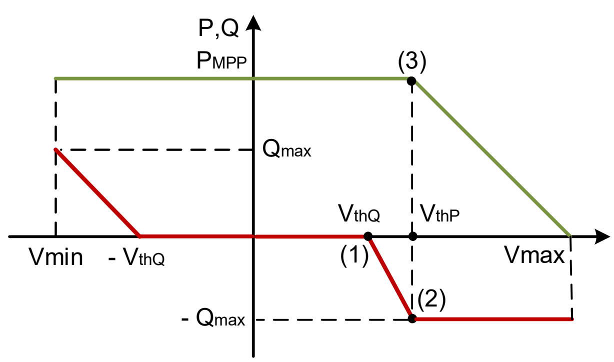


Figure 28. Proposed coordinated control for DGs inverters

From Figure 28 at the point (1), V_P surpasses V_{thQ} and the RPA is hence activated. The *Q-V* droop control then regulates the amount of Q_{absorb} . At the point (2), once V_P reaches V_{thP} , the reactive power that an inverter can absorb is capped at -$Q_{\max}$. At the same time, the coordination scheme switches from RPA mode to APC mode with *P-V* droop control after point (3). It is noticed that RPA is activated prior to the APC (i.e., $V_{thQ} < V_{thP}$).

10.1.4 Optimization objectives

The first optimization objective is the minimization of voltage magnitude deviation over the network:

$$\min\left(F_1\right)=\min\sqrt{\sum_{i=1}^{N}\left(|V_i|^2-\frac{1}{N}\sum_{i=1}^{N}|V_i|^2\right)^2} \tag{3}$$

Function (3) encourages the flat voltage profiles as it calculates the distance of the vector collecting the bus voltage magnitude $\left\{|V_i|^2\right\}_{i\in N}$ from the average value $\frac{1}{N}\sum_{i=1}^{N}|V_i|^2$.

The second optimization objective is the minimization of the curtailed active power that uses the following expression:

$$\min\left(F_2\right)=\min\sum_{i=1}^{N}\left(P_{i,MPP}-P_{PVi,opt}\right) \tag{4}$$

where $P_{i,MPP}$ is the maximum values according to the MPPT algorithm and $P_{PVi,opt}$ is the optimization variable of the active power of PV inverter at bus *i.* This optimization objective can be described as the common goal for the PV owners.

The third optimization objective is the maximization of the absorbed reactive power of the inverters, as given as follows:

$$\min\left(F_3\right) = \min\sum_{i=1}^{N}\left(|Q_{i,\max}-Q_{PVi,opt}|\right) \tag{5}$$

where $Q_{i,\max}$ is the maximum value and $Q_{PVi,opt}$ is the optimization variables of active power absorption of PV inverter at bus *i.*

The objective functions F_1 and F_2 are conflicting with each other. Specifically, minimization of voltage magnitude deviation may need more curtailed active power. The choice of objective functions is made with the different preferences. For instance, power utilities may prefer the objective function F_1 and F_3 for better voltage profile. While PV owners prefer the objective function F_2 for better revenue from selling the power produced from the PV systems. Therefore, the satisfaction of a single objective function may provoke the conflict of interest among the relevant parties The Pareto-based optimal approach is utilized to define the solutions for multiple optimization problems [38]. The weighted sum method is used to combine these three objective functions into a single function [39]. This method involves multiplying each of the objective functions with a predefined weighting factor (w_i). The weighting factors reflect the user preferences for the objective functions regarding its significance. Subsequently, all objective functions are summed up to form the single-objective function, which is formulated by:

$$F=\sum_{i=1}^{3}w_i.F_i\left(x\right) \tag{6}$$

subject to:

$$\sum_{i=1}^{3}w_i=w_1+w_2+w_3=1 \tag{7}$$

$$V_{\min} \leq |V_i| \leq V_{\max} \quad (8)$$

$$0 \leq P_{PVi} \leq P_{i,MPP} \quad (9)$$

$$-Q_{i,\max} \leq Q_{PVi} \leq Q_{i,\max} \quad (10)$$

10.2 SIMULATION AND RESULT

10.2.1 Simulation setup

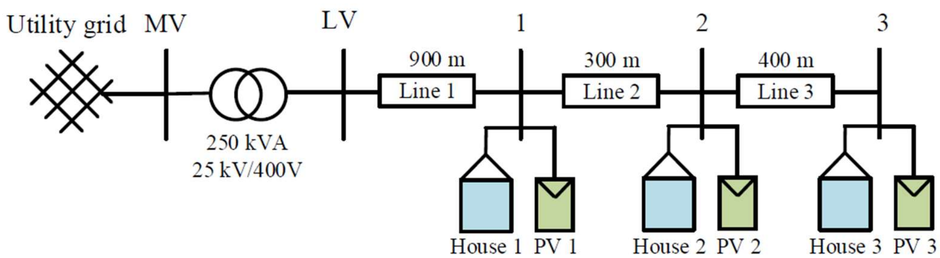


Figure 29. Proposed model for the simulation

The test system for the proposed coordinated control strategy is a simplified radial LV feeder as shown in Figure 29. The feeder accommodates three households as three-phase balanced variable PQ loads with identical load profile and three equal-sized PV systems with 28.5 kW peak generation each. All the lines are the same underground cables Al 185 mm XLPE with parameters R (Ω/ km) and X (Ω / km) of 0.182 and 0.0663 respectively. MATLAB is used to load all input data, such as household loads, irradiation and environment temperature for the PV inverters, and set the other parameters. Simulink is used to simulate the test system with defined parameters. The proposed optimization problem is solved using the MATLAB optimization toolbox.

Five cases of different control methods are involved in the simulation and its features are shown in the following tables.

Table 4. Five cases of control methods

	Case 1	***Case 2***	***Case 3***	***Case 4***	***Case 5***
Control approach	No control actions	Only APC	Combination of APC and RPA	Coordination of APC and RPA	Coordination of APC and RPA
Set points	Not applicable	Fix V_{thP} = 1.07 p.u. for all inverters	Fix V_{thP} = 1.07 p.u. and V_{thQ} = 1.06 p.u. for all inverters	Set of w_1 = 0.05, w_2 = 0.475, w_3 = 0.475 respectively to the inverters	Set of w_1 = 0.9, w_2 = 0.05, w_3 = 0.05 respectively to the inverters

10.2.2 Result

The simulation results of voltage magnitude at bus 3 in all cases are illustrated in Figure 30. It can be observed that in case 1 overvoltage appears at bus 3. In the remaining cases from case 2 to case 5, overvoltage problem is solved. It is important to note that, for a fair comparison between control cases, the control actions are activated after the first 5 minutes. More specifically, in case 2 with only APC (V_{thP} = 1.07 p.u.), the voltage at bus 3 remains constant at V_{thP} over the control time period which implies that APC keeps activated. In case 3 with both APC and RPA, the voltage at bus 3 is regulated at the lower value than V_{thP} in several last minutes because of RPA control actions. In case 4, the coordinated control of APC and RPA with higher priority of minimizing APC and lower priority of minimizing voltage deviation introduces different setpoints of V_{thP} and V_{thQ} to the PV inverters, particularly $V_{thP,1}$ =1.055 p.u., $V_{thQ,1}$ =1.045 p.u., $V_{thP,2}$ =1.067 p.u., $V_{thQ,1}$ =1.057 p.u., $V_{thP,3}$ =1.075 p.u., and $V_{thQ,1}$ =1.065 p.u. We can see that the voltage on bus 3 is properly regulated without any violation of threshold values. In case 5, with higher priority of minimizing voltage deviation, lower set points of V_{thP} and V_{thQ} are provided to the PV inverters, particularly $V_{thP,1}$ =1.052 p.u., $V_{thQ,1}$ =1.042 p.u., $V_{thP,2}$ =1.062 p.u., $V_{thQ,1}$ =1.055 p.u., $V_{thP,3}$ =1.069 p.u., $V_{thQ,1}$ =1.059 p.u. The rippling part of voltage profile at bus 3 during 14:07 to 14:13 depicts that APC is performing to regulate the voltage at bus 3 at a lower value compared to case 4.

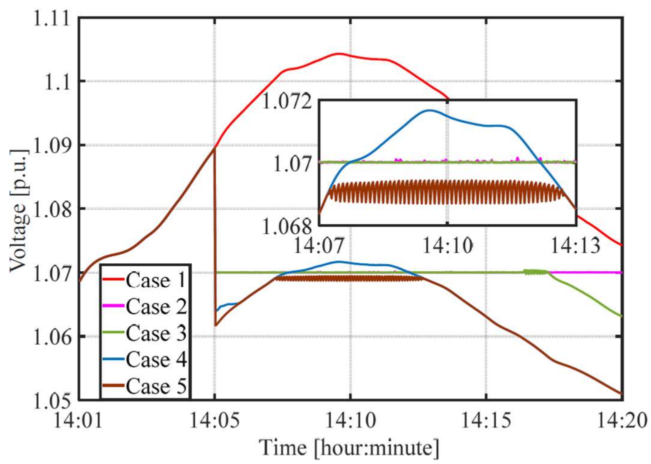


Figure 30. Injected power of PV inverter 3 in different cases

Figure 31 and Figure 32 show the active power injections and reactive power absorptions respectively of the PV inverter at bus 3 in all cases. It is evident that case 2 has the biggest amount of curtailed active power and no absorbed reactive power. In case 3, the activation of RPA leads to smaller curtailed active power. In case 4 with a high amount of absorbed reactive power, the inverter 3 does not curtail any power, resulting in injecting exact amount of active power compared to case 1.

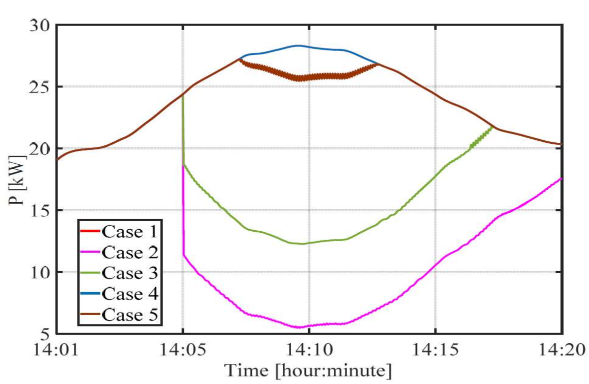


Figure 31. The voltages on bus 3 in different cases

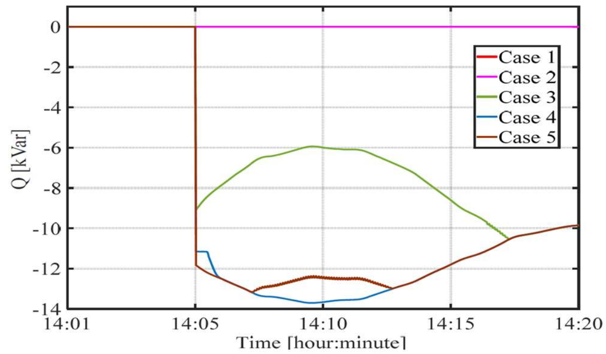


Figure 32. Absorbed power of PV inverter 3 in different cases

In comparison with case 4, case 5 results demonstrate a smaller amount of both injected active power and absorbed reactive power. It reveals that although APC and RPA control is coordinated among the inverters to alleviate overvoltage, more preferably of flat voltage requires more power curtailment.

Table 5. Results for different cases of control methods

	Case 1	***Case 2***	***Case 3***	***Case 4***	***Case 5***
P_{PV1} [kWh]	8.078	8.078	8.078	8.078	8.078
P_{PV2} [kWh]	8.078	8.078	8.078	8.078	8.078
P_{PV3} [kWh]	8.078	4.169	5.839	8.078	7.924
Total injected [kWh]	24.235	20.326	21.995	24.235	24.080

Table 5 summarizes the numerical results of the simulation. It demonstrates the ability of RPA to support overvoltage mitigation and reduce the curtailed active power. Furthermore, it can be seen from case 2 and 3 that all amount of curtailed active power is from only PV inverter 3, while the inverter 1 and 2 have zero curtailed active power. This shows the unfairness when the inverter 3 suffers a loss in revenue. Comparing all cases can conclude that coordinated control of APC and RPA is a more effective control for overvoltage mitigation while minimizing active power curtailment.

11. CONCLUSION

Being mainly driven by environmental concerns, installation cost reduction, and new energy policies, the share of PV systems in the LV networks is rapidly increasing. Consequently, such growing penetration of PV presents voltage limit violation problems. Among these problems, overvoltage is a common issue. Without a proper control solution, the overvoltage, on one hand, can cause severe damages to electrical appliances in customers premises. On the other hand, the overvoltage can become a bottleneck for the integration of PV systems in the LV network.

In the report, the control solutions to overvoltage mitigation in the LV network resulting from the growing penetration of PV have been discussed.

Firstly, the report presents a review of different approaches for ICT systems in MGs, covering architecture, requirements, available technologies, interoperability, reliability, and security. A communication system performs a critical function in overall MG control and operation. ICT with low consumption, low cost and simplicity are preferred for a communication network in customer premises. ICT with high data rate and large coverage distance are suitable for FAN/NAN communication systems. ICT with high reliability, low latency, and large capacity are requested for the communication systems in WAN. Ultimately, the choice of specific ICT mostly depends on its cost-effectiveness and ability to satisfy the requirement of the related application.

To provide an example of an ICT solution, a communication system proposed by the EU FP7 project INCREASE is included. In this communication system, the Wi-Fi (IEEE 802.11) ICT infrastructure and Intelliweb cloud-based program are applied to the control actions in PV systems. It is indicated that utilizing the Wi-Fi-based ICT infrastructure is a promising solution. That adoption takes advantage of using the well-known Wi-Fi connection in houses, thus leading to the avoidance of the development of separately dedicated ICT infrastructure for PV inverter interconnection.

The local voltage controller developed by CEA in the PARADISE project is introduced in the report. The proposed local voltage controller employs fuzzy logic and operates as an auto-adaptive regulator to solve overvoltage problems. The desired voltages provided by the fuzzy supervision are a function of the voltage measurement at the POC and reactive power output of the DG. It is reported that by using the developed auto-adaptive regulation, the overvoltage problems are solved in an optimal way. The report also presents the validation of the developed local voltage controller in the demonstration site in SOREA network.

For a purpose of introducing a control solution to overvoltage problems using the communication systems, the report proposes a coordinated control of APC and RPA. In this control approach, each local voltage controller can operate with both APC and RPA and communicate with the MG central controller via the communication system. A hierarchical control is utilized to coordinate the local controllers to perform APC and RPA. The simulation results indicate that the overvoltage is mitigated with minimum curtailed active power and all local controllers actively contribute to the overvoltage mitigation.

In the future, the real-time evaluation of the developed control scheme of the project will be performed in the laboratory environments in TU/e. This will safely and efficiently reveal the prospective issues before the demonstration. Accordingly, the real-time demonstrations at the sites will be implemented to test the developed control scheme.

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