SMART GRID ARCHITECTURES: FROM USE CASES TO ICT REQUIREMENTS

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ABSTRACT

The scope of this paper is to address the evolution of distribution grid architectures following the widespread introduction of renewable energy sources. The increasing connection of distributed resources has a strong impact on the topology and the control functionality of the current distribution grids requiring the development of new Information and Communication Technology (ICT) solutions with various degrees of adaptation of the monitoring, communication and control technologies. The costs of ICT based solutions need however to be taken into account, hence it is desirable to work with existing communication networks. The objective of the European FP7 project SmartC2Net in this regard is to enable robust smart grid control utilizing heterogeneous third party communication infrastructures.

1 INTRODUCTION

Nowadays the generation, transmission and distribution domains are monitored through private, dedicated communication infrastructures that are normally closed to external access. Novel scenarios require to massively extending the ICT deployment down to medium and low voltage areas, which were unobserved and uncontrolled so far. To avoid the exploding costs, the deployment of existing communication infrastructures is envisaged, but this requires an enhanced security protection, and mechanisms to monitor and maintain quality of service in the network. In this respect, the robustness of the smart grid system, given the stochastic behavior of commercial communication services, is one of the main goals of the SmartC2Net project [1]. Within SmartC2Net, smart grid scenarios expected in the near future have been analyzed covering different control layers of active distribution grids. Four use cases have been specified addressing the evolution of medium and low voltage distribution grids [2].

In this paper the main control components and information flows of the selected use cases are addressed. The paper describes the overall system architecture integrating the power grid and ICT network architectures of the particular use cases and summarizes the main Key Performance Indicators (KPI) raised by the use case requirements. Hereby, a short description of the four use cases is provided together with a high level view of their integrated architecture and sample KPIs driving the development of advance control infrastructures.

2. USE CASE ICT ARCHITECTURES

Following the guidelines on the analysis and harmonization of smart grid use cases provided by the committee Sustainable Processes of the CEN/CENELEC/ETSI Smart Grid Coordination Group[3], the following four use cases are analyzed:

- Voltage Control in Medium Voltage Grids
- External Generation Site
- Automated Meter Reading (AMR) and Customer Energy Management Systems (CEMS)
- Electrical Vehicle Charging in Low Voltage Grids.

Addressing different levels of the distribution grid, these use-cases provide a good coverage of the applications characterizing the evolution of European smart grids in the near future. Besides the normal operation, the use cases focus on abnormal behavior caused by disrupted communications in presence of malicious attacks or accidental faults. Due to space limitations, we describe in the following sections the main functionalities of each use case together with an outline of their normal/critical control scenarios. More details about the use cases can be found in the Annex B of [2] including their full IEC TC8 templates.

2.1 Voltage Control in Medium Voltage Grids

The connection of DERs (Distributed Energy Resource) to medium voltage grids can influence the power grid state, affecting the capacity of the DSO (Distribution System Operator) to comply with the contracted terms with the TSO (Transmission System Operator) and can impact directly the quality of service of their neighbor grids. In order to maintain stable voltages in the distribution grids the Voltage Control (VC) function is introduced to monitor the grid status from field measurements and to compute optimized set points for available flexible assets such as DERs, flexible loads and power equipment deployed in HV/MV substations. The VC function (cf. Figure 1) is performed by the MVGC (Medium Voltage Grid Controller) on a node of a HV/MV substation control network. In order to compute an optimized voltage profile, the algorithm needs to communicate both with components inside the DSO area, and with systems outside the DSO domain. The TSO Control Center interacts via a permanent link (between the TSO Control Network and the DSO Enterprise Network) with the Distribution Management System (DMS) in order to send the signals triggering the execution of the voltage control optimization cycle. The Aggregator provides the market prices and DER operation costs to the DMS via the DSO Enterprise Network. Also the Load and Generation forecast interact with the DMS through the DSO Enterprise Network. The DMS forwards this information to the MVGC. The DMS sends /receives information to/from the MVGC through the DSO Communication Network. The MVGC is connected through the Substation Automation System with the Capacitor Bank and with the OLTC in the substation network. DERs and flexible loads communicate with the MVGC via the DER /Flexible loads Communication Network, possibly deploying heterogeneous communication technologies available in different geographical areas. The main control steps related to this use case are listed in Table 1, whilst the specific focus on communication security is reflected in its KPIs reported in Table 5.

Table 1: MVC - Normal and Critical Scenarios

Step Name	Prim. Actor	Triggering Event	Pre-Condition	Post-Condition
Information acquisition	DMS	Periodic / Asynch.	TSO signal/ load/gen forecast or data	MVGC obtains input for the control algorithm
Grid measurement dispatch	DER / Grid device	Periodic	Field/DER dispatches new measurements	MVGC obtains new measurements
Forward of grid monitoring data	MVGC	Periodic	SAS has new SCADA and DER monitoring data	DMS receives new monitoring data
Execution of control voltage algorithm	MVGC	Values out of range	The state is not acceptable	Computation of new setpoints
Set setpoints	SAS / MVGC	New setpoint	New setpoints computed	Devices change their settings
DER /MVGC DoS attack	DER/ MVGC	Attacker launches an attack		Loss of measurements
Fake DER setpoint	DER	Attacker intercept and modify or create a new setpoint message		Wrong setpoint

2.2 External Generation Site

This use case aims to demonstrate the feasibility of controlling flexible loads and renewable energy resources in MV and LV grids over an imperfect communication network. The flexibility provided by LV grids by enabling controllability at secondary substation level for upper hierarchical control levels is also investigated. The use case addresses control scenarios on the grid operation itself under normal network conditions (base case) and when the network does not perform as expected. Here the focus is on the actual control of assets, which is divided into three sub-control functions:

- ***Energy balance***, with focus on MV grid operation, and LV grids offering flexibility to the MV grid;
- ***MV operation***, where focus is on voltage profiles and loss optimization as well as energy costs on MV grids using active and reactive power;
- ***LV grid operation***, where focus is to control the voltage profile on LV grids using reactive power capabilities offered by micro and intermediate DERs, flexible consumption and production at household or enterprise level.

Table 2 includes the main scenarios for this use case considering normal or perturbed states.

Table 2: EGS - Normal and Critical Scenarios

Step Name	Prim. Actor	Triggering Event	Pre-Condition	Post-Condition
Base Case	MV and LV grid control	No events in WAN/AN	Normal Operation	Normal operation
Network Performance Changed	AN Provider	Change in AN network performance	Normal Operation	Performance variation
Network Congestion	AN Provider	Congestion in AN network	Normal Operation	Congestion
Lost Network Connectivity	WAN/AN Provider	Network connection loss	Normal Operation	Loss of connectivity

2.3 Customer Energy Management Systems

This use case describes two basic functionalities for enabling future distribution grids for load balancing and integration of decentralized and distributed (renewable) energy resources. Therefore, Automated Meter Reading (AMR) is an enabling technology, which is capable of generating precise multi-sector metering data and aggregate them on local grid operator side for large-area and in-house analysis of current energy consumptions as well as grid load conditions. Additionally, current efforts in the context of the Internet of Things aim to connect more devices in the household to create a more intelligent Home Area Network (HAN), including components of Customer Energy Management Systems (CEMS) like DERs and storages, demand side management, private electric vehicle charging and user interaction. In the context of AMR, this adds an additional way of home building automation by combining the energy consumption of accordant components with the current status of the energy grid to improve its stability by shifting loads balanced with the neighborhood area network. All in-house components assume to be connected to a CEMS via a dedicated wired or wireless HAM (e.g. narrowband PLC, broadband PLC, bus systems, ZigBee, W-MBus, etc.) or a shared medium provided by the consumers in-house networks (e.g. wireless LAN, broadband PLC, etc.). At least one access technology (at least cellular networks), but potentially more communication means, depending on the existing possibilities, e.g. power line, 3G or fiber (if already installed in the household) and telco operators, may differ between households. Different operation could be performed in CEMS and AMR contest: Table 3 summarizes some of them considered in the analysis.

Table 3: CEMS - Normal and Critical Scenarios

Step Name	Prim. Actor	Triggering Event	Pre-Condition	Post-Condition
Obtain remote meter reading	Actor A	Actor A decides he wants a meter read	SM and communications operating	Actor A has the read he requested
Set parameter in the Smart Meter (SM)	Actor A	Actor A wants to set a parameter	All actors are connected	The parameter is received by the SM
Configure and monitor power quality parameters	Timer	Actor A wants to configure and monitor power quality parameters	Communication OK Valid contract between Actor A and the consumer	Power quality parameters are received by the SM
Appliance has end-decision about its load adjustment	Actor A or Actor B	Actor A or Actor B wants to send a load management command to the market	Communication OK Devices configured Information on consumption is available in the CEMS	The Smart Appliance executed the load management command and Actor A/B received a load curve
Information regarding individual appliances and total power generation/consumption	Smart Meter	New consumption /generation information is available in the Smart Meter	Communication connection between all actors is established	(forecasted) consumption/generation information is received by actor A /B and/or display

The ICT infrastructure needs to meet different KPIs in terms of availability of services, reliability and data integrity of metering data and control data flows as well as maintainability of the infrastructure. A selection of the KPIs specified within the project is outlined in Table 5, whereas a complete list is provided in [2].

2.4 Electrical Vehicle Charging

We distinguish between two environments for electric vehicle charging: charging at home, in which the vehicle is one of the appliances managed by the CEMS, and public EV charging at one of the charging points (CP) under the management of a charging station (CS) controller. In the latter case, we assume that the energy demand and the estimated arrival and departure time to the charging station can be learned by the charging station in advance, e.g. when the vehicle is still under way, using a reservation protocol. This information allows a better energy planning in cooperation with the low voltage grid controller and the energy aggregator which acts on the energy market for the whole region. A recent approach for energy management applied in this case of flexible loads is the exchange of flexibility information [4]. Divided into energy and power flexibility, the information defines for a certain time horizon ahead the maximum and minimum values of energy consumed by the charging process of one EV. This information is being aggregated for the whole charging station and is used both by the aggregator for acquiring the energy, and by the control algorithm in the DSO Low Voltage Grid Controller to correct the load plan, in case the voltage limits would be violated. The charging station controller has the objectives to schedule the charging of plugged-in and expected EVs in a fair way, and follow the power set points defined by the DSO. In the home environment scenario, the environment is much more heterogeneous: it consists of flexible loads such HVACs (Heating, Ventilation and Air Conditioning) and the EV, non-flexible household loads, and generation (PV). The charging plan is influenced by household objectives such as maximizing the use of own generated energy, mobility demand and eventual demand restrictions imposed on the household (only in under- and overload situations).

Table 4: EVC – Normal and Critical Scenarios

Step Name	Prim. Actor	Triggering Event	Pre-Condition	Post-Condition
EV Charging	EV owner	EV owner seeks a charging station	EV and owner are valid (credentials)	EV owner has a valid reservation at a certain charging station and successfully received desired charge
Energy & Power Management	DSO	Periodical update or change in available power resources	Data Links are OK, agreements CS and energy providers to enable control	No alarms, i.e. the grid power quality is maintained and energy resources are available for future power management
Energy Market	Energy Providers, Aggregators and CS	Periodic, based on types of market	Business relations primary actors and a market platform	Price agreements and billing closed.
Plugged in Charging aborted	EV owner	Plugin Event	Reservation OK	Power alarm, no or partial charging, plugout, leave
EV demand control disrupted	CS	Detection of Comm failure	Actuation LVGC - CS interrupted	Ramp down charging
Data flow to LVGC disrupted	CS	Detection of missing data	Grid state is OK	Continue charging on basis of flexibility

The novel part of the use case describes how the CS and

CEMS must react when the various communication network paths are disrupted. The general idea is first to try to reconfigure and repair the communication network, and if this does not succeed, to use the communicated flexibility to gracefully degrade the service.

3 INTEGRATED ARCHITECTURE AND KPI

The integrated, hierarchical high level architecture of the four use cases is depicted in Figure 1, where the assets and control components are connected to the corresponding communication networks and logical interfaces. Starting from this high level architecture, the KPIs represent the main criteria for the evaluation of the success of the solutions proposed by SmartC2Net.

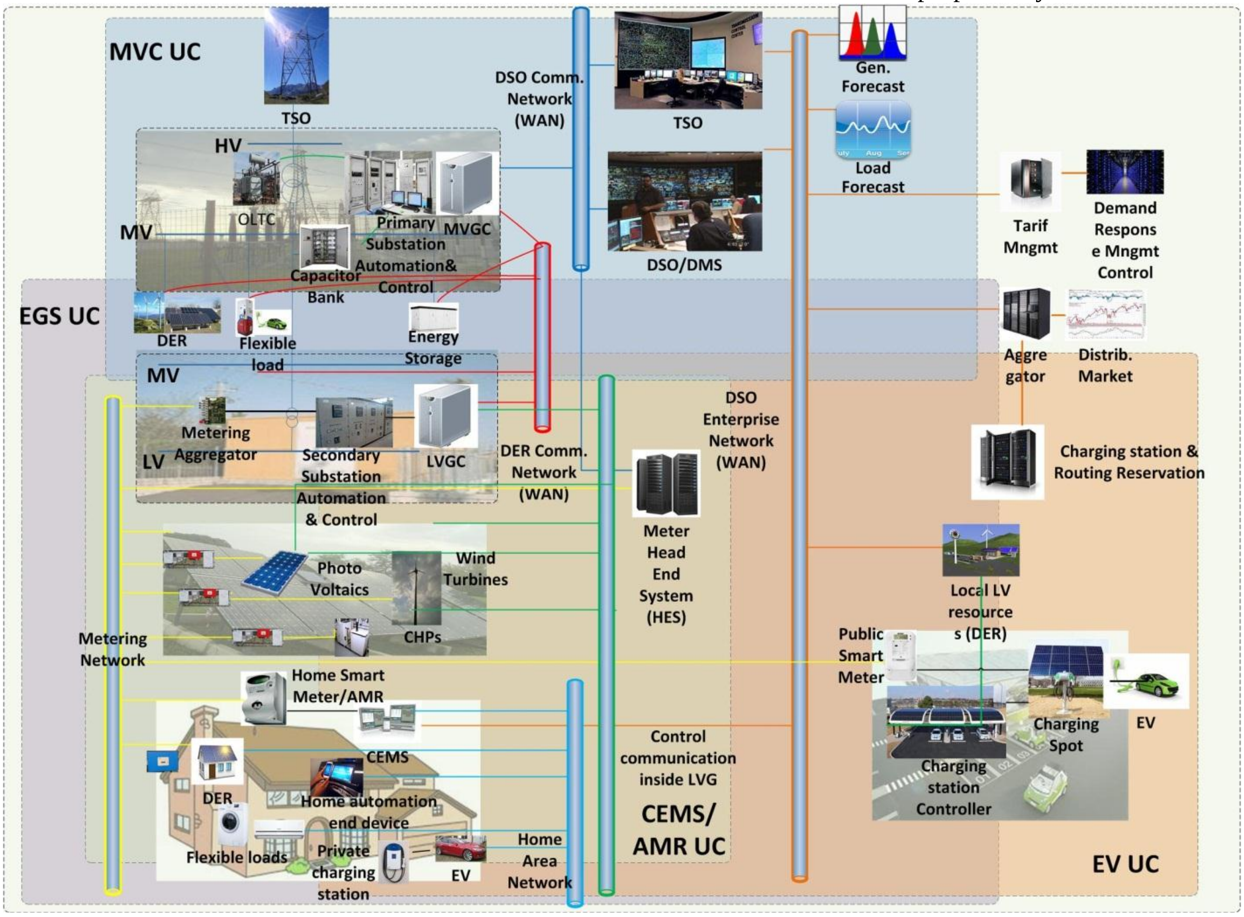

Figure 1: SmartC2Net Use Case Architecture

An extensive set of KPIs are identified in [2] from the analysis of the four use cases functionalities. More than two thirds from the total number of these KPIs are DSO oriented as shown in Figure 2.

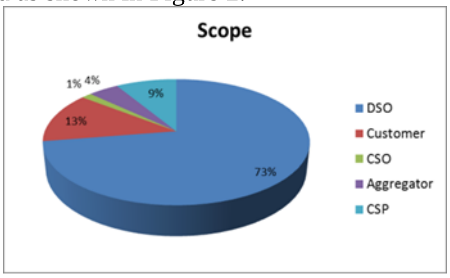

Figure 2: Scope of Use Case KPIs

It is also important to notice that most of these KPIs (i.e. 78%) are addressing technical aspects in both the communication network and power grid domain (see **Figure 3**). This is a clear indication that the SmartC2net project equally addresses both domains.

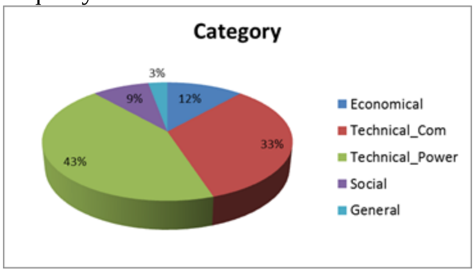

Figure 3: Categories of Use Case KPIs

Specifically the KPIs presented in Table 5 have been identified from the use case requirements as the most relevant for evaluating the SmartC2Net functionalities through system simulations, model-based analysis, as well as experimental tests.

Table 5: Selection of Key Performance Indicators [2]

KPI_id	UC	KPI name	Definition	Category	Scope	Unit	Goal
KPI_011	VC	Attack Awareness	Attack detection time	Technical_Com.	DSO	s	Min
KPI_024	VC	Security gain_setpoints	# wrong setpoints received without security / # wrong setpoints received with security	Technical_Com.	DSO	num	Max
KPI_030	VC	Security_delay	# delay with security / # delay without security	Technical_Com.	DSO	num	Min
KPI_031/ KPI_032	VC	Security gain_voltage deviation	# Overvoltage without security / # Overvoltage with security	Technical_Power	DSO	num	Max
KPI_201	EV	User satisfaction – Availability of Service	Number of served users/number of users requesting service	Social	Customer	%	100
KPI_204	EV	Number of Grid Events	Amount of grid events and type	Technical_Power	DSO	num	0
KPI_209	EV	Degradation of power quality without meter data	Degradation criteria if meter data network is disrupted	Technical_Com.	DSO	%time	Min
KPI_210	EV	Degradation of power quality if LVGC - charging station fails	Degradation criteria if charging station actuation signal from the LV controller is disrupted	Technical_Com.	DSO	%time	Min
KPI_405	EGS	Access network packet loss limit	The application layer packet loss probability shall be low enough to allow the LVGC to adhere to its voltage limits	Technical_Com.	CSP	%	N/A
KPI_406	EGS	Wide area network packet loss limit	The application layer packet loss probability shall be low enough to allow the MVGC to adhere to its voltage limits	Technical_Com.	CSP	%	N/A
KPI_407	EGS	Access network delay limit	The application layer packet delay shall be low enough to allow the LVGC to adhere to its voltage limits	Technical_Com.	CSP	ms	N/A
KPI_408	EGS	Wide area network delay limit	The application layer packet delay shall be low enough to allow the MVGC to adhere to its voltage limits	Technical_Com.	CSP	ms	N/A
KPI_602	AMR / CEMS	Availability of Service	Availability of the Service, i.e. downtimes / failures	Technical_Com.	CSP	%	100%
KPI_610	AMR / CEMS	Successful transmissions of metering data	Ration of successful metering data transmissions to failed transmissions (i.e. necessary retransmissions)	Technical_Com.	CSP	%	100%
KPI_612	AMR / CEMS	Correctness of customer feedback system and metering data	Correctness of energy usage and tariff data displayed to the customer and metering data send to the HES	Technical_Com.	DSO	Δ	Max
KPI_615	AMR / CEMS	Maintainability	Ease of deploying Soft- and Hardware upgrades	Technical_Com.	DSO	€/day	Max

4 CONCLUSIONS

The reference architecture as well as the use cases considered in the SmartC2net project are used as a basis for the assessment of robust grid control solutions utilizing heterogeneous third party communication infrastructures. These solutions allow adaptive monitoring and information access mechanisms interacting with the multilayered control architecture of smart grids under different realistic scenarios. The selected KPIs are used to determine the boundaries of stable and secure operation of smart grids as well as in benchmarking the existing technologies.

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