ADVANCED SYSTEM ARCHITECTURE AND ALGORITHMS FOR SMART DISTRIBUTION GRIDS: THE SUSTAINABLE APPROACH

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ABSTRACT

In order to allow large scale integration of Distributed Energy Resources in a secure and efficient way, the EU Project SuSTAINABLE designed a reference architecture for management and control of the distribution system as a whole. This novel architecture is based on the hierarchical architecture already deployed in the InovGrid test site in Évora, Portugal – InovCity. This will require the development of specific algorithms and tools to support distribution system operation that are able to exploit distributed intelligence in several network components. These advanced control functionalities are summarily described and include: state estimation, load and renewable energy forecasting and voltage control.

INTRODUCTION

The Smart Grid paradigm enables the active management of Distributed Energy Resources (DER) available in the distribution grid and fosters energy efficiency, operational efficiency, Renewable Energy Sources (RES) and electric vehicles (EV) integration. In this context, proper control architecture with advanced management functionalities is required.

An advanced control architecture has been proposed within the framework of EU project SuSTAINABLE aiming at enabling a coordinated and efficient control of the whole electrical distribution system, taking advantage of its own resources in order to support network operation [1]. It must be stressed that these DER that can be located at the LV level or at the MV level, may be either the property of the Distribution System Operator (DSO) or be owned by individual customers/entities. Therefore, in the latter case, the use of these resources for supporting network operation has to be ensured through adequate means of remuneration for instance in the framework of a market structure.

Furthermore, future distribution systems will be composed of active networks (at the HV, MV and even LV levels) with several controllable and non-controllable DER, which will result in large volumes of data to be exchanged. Consequently, the proposed control architecture incorporates several control layers and enables some form of automated local actions in order to overcome technical problems in network operation on the several voltage levels.

The main objective of the architecture, according to the SuSTAINABLE concept, concerns the operational part of distribution system. Therefore, a control and management architecture is proposed based on the hierarchical architecture already implemented in the InovGrid test site in Évora, Portugal (InovCity) [2]. However, in order to achieve an efficient coordinated control of the distribution system, it is necessary to develop specific advanced control and management functionalities. These functionalities, under the control of the DSO, aim at exploiting local resources whenever possible in order to overcome technical problems that may occur in the distribution network especially in scenarios with high integration of RES.

This is particularly important as it is now essential that the problems that may arise at the distribution level are not passed to the upstream transmission level and translate into an uncertainty seen by the transmission system. In this regard, the distribution system should not be seen as a burden to the transmission and use its own resources to manage technical difficulties that may occur.

Consequently, a set of advanced control and management functionalities are being developed aim at: (a) ensuring an increased knowledge of the distribution system and (b) effectively acting on the available DER to solve technical problems.

This paper describes the general framework adopted in the project, as well as the main functionalities:

- State Estimation at the MV level;
- Load and RES Forecasting at the MV level;
- Voltage Control at the MV, LV and field level.

ARCHITECTURE AND CONTROL LAYERS

Overall Framework

A general framework for the data flow model of the SuSTAINABLE concept is presented in Figure 1. This framework comprises two different types of information: commercial (related to billing) and technical (related to operation).

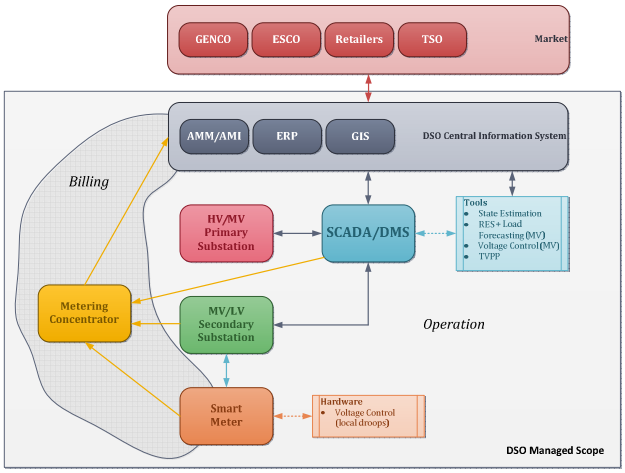

Figure 1 – Overall SuSTAINABLE Framework and Data Flow Model.

At the top level is the DSO Central Information System, which includes Advanced Metering Management (AMM) / Advanced Metering Infrastructure (AMI), Enterprise Resource Planning (ERP) / Asset Management (AM) and Geographic Information Systems (GIS).

All the billing information from the customers down to the LV level, transmitted by the Metering Concentrator, must be processed in an AMM/AMI module located at the central information system level. Also, since several control algorithms that may be envisaged (such as forecasting functions, load flow analysis, state estimation routines) require the knowledge of the exact position of the DER, it will be necessary to have GIS at the central information system level that should not be local but cover all the territories that the DSO is responsible for. Therefore, every Supervisory Control and Data Acquisition / Distribution Management System (SCADA/DMS) should be able to communicate with this system. Moreover, a similar situation occurs for the technical characteristics of the lines, substations, transformers or smart meters. These characteristics are usually recorded in a central database (ERP/AM) as well all the subcomponents (e.g., current/voltage transformers, etc.) and their history (i.e., replace of a current transformer with a new one with a different ratio).

Finally, the DSO will have to handle market data (e.g., prices, costs, etc.) concerning fuel costs or tariffs and interact with other market actors (e.g., GENeration Companies – GENCO, Energy Service COmpanies – ESCO, retailers, Transmission System Operator – TSO, aggregators, etc.). Ancillary services offered by retail companies must also be taken into account since it is not realistic that they will communicate directly with each SCADA/DMS.

Control and Management Architecture

The proposed control and management architecture, illustrated in Figure 2, is organized in three main layers:

- The upper control level with the SCADA/DMS located at the control centre of the distribution system (i.e., dispatch level). This layer is under the responsibility of the DSO for managing the whole distribution network and ensures the interface with the upstream transmission grid.
- An intermediate control level located at the HV/MV primary substation – the Smart Substation Controller (SSC) – which is in charge of each MV network and incorporates a set of advanced control functionalities that allow a coordinated and efficient operation of the MV system exploiting the resources that may be available at this level through set-points, namely storage systems (STOR MV in Figure 2), controllable loads under Demand Side Management (DSM) action (CL MV in Figure 2), Distributed Generation units (DG in Figure 2), On-Load Tap Changing (OLTC) transformers (OLTC in Figure 2) and capacitor banks (CAP MV in Figure 2).
- A lower control level located at the MV/LV secondary substation – the Distribution Transformer Controller (DTC) – which is responsible for a single LV network. This control layer is used to serve as a gateway of data to the upstream systems but will also incorporate some basic control functionalities in order to efficiently respond to technical problems that may occur at the LV network level by communicating set-points to the several smart meters and corresponding DER under its control as well as for MV/LV On-Load Tap Changer (OLTC) transformers and storage devices (property of the DSO) that may be located at the secondary substation.
- A field control level located at the customer premises in which the smart meter will serve as a gateway to control its associated resources, namely microgeneration (µG in Figure 2), controllable loads under DSM actions (CL LV in Figure 2), storage devices (STOR LV in Figure 2), and Electric Vehicles (EV in Figure 2).

This architecture is expected to evolve to a future version in the medium/long run where a Home Energy Manager

(HEM) at the LV customer will be installed, which will be in charge of managing all the resources of domestic clients including controllable loads (appliances), microgeneration units, EV and storage devices (if they exist) following a request from the upstream control structure (i.e., the DSO). In this case, there will be a coordinated management of all resources regardless of their nature, requiring only a single smart meter that will serve as a gateway to communicate with the HEM.

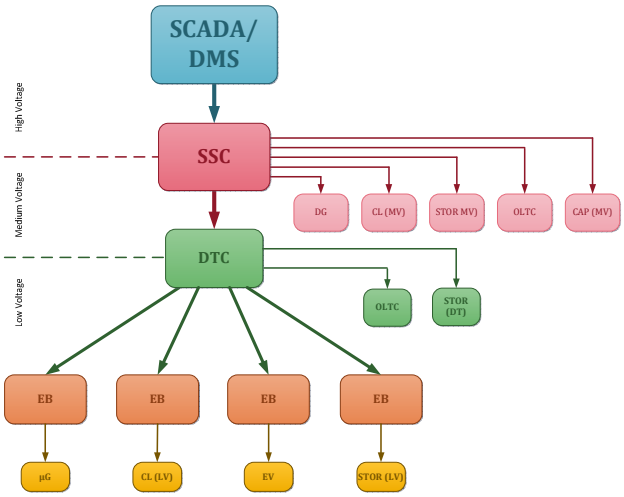

Figure 2 – Proposed SuSTAINABLE Architecture and Control Layers.

Advanced Control Functions

Future distribution systems will be composed of active networks (at the HV, MV and even LV levels) with several controllable and non-controllable DER, which will result in large volumes of data to be exchanged. Consequently, the proposed control architecture incorporates several control layers previously identified and enables some form of automated local actions in order to overcome technical problems in network operation on the several voltage levels.

In order to achieve an efficient coordinated control of the distribution system, it is necessary to develop specific advanced control and management functionalities that explore local resources whenever possible in order to solve technical problems.

Consequently, a set of advanced control and management functionalities will be developed that will aim at: a) ensuring an increased knowledge of the distribution system and b) effectively acting on the available DER to solve technical problems. The main functionalities identified are the following:

- State Estimation at the MV level;
- Load and RES Forecasting at the MV level;
- Network Planning at the MV level;
- Voltage Control at the MV, LV and field level.

Depending on whether these functionalities reside physically at the DMS or SSC level, two different architectures can be envisaged:

- *Data processed at the SCADA/DMS level*: parallel processing of each SSC data on separate CPUs of a computer cluster or a multi-core processor, which constitutes a hierarchical structure;
- *Data processed at the SSC level*: decentralized algorithm based on geographically distributed computers physically located at different SSC, provided an appropriate communication infrastructure is available.

At a first stage, it is assumed that these functionalities may reside physically at the central system's level (SCADA/DMS), since they will require data from different MV networks (i.e., different SSC), according to the hierarchical structure presented previously.

Nevertheless, in the medium/long-term, it is expected that the architecture may evolve to a really distributed one provided that other communication solutions (such as General Packet Radio Service, fiber, etc.) are employed.

The different control layers, their physical levels as well as the functionalities identified are shown in Figure 3.

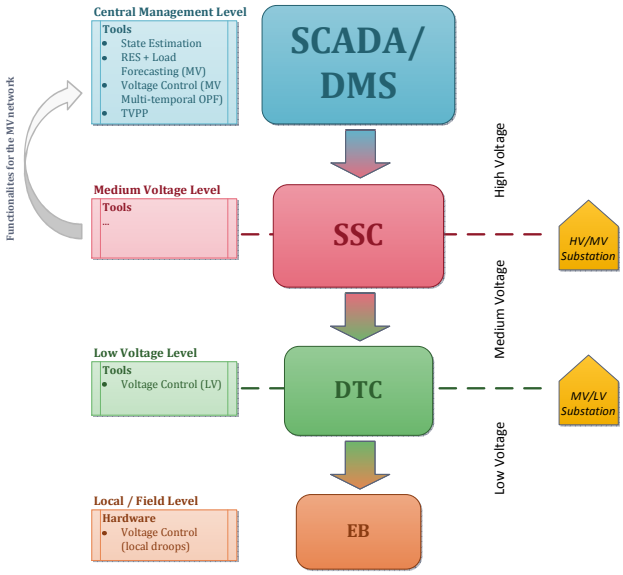

Figure 3 – Proposed Functionalities and Control Layers.

STATE ESTIMATION (MV LEVEL)

The main objective of the state estimation functionality is to find the values for a set of variables (states) that adjust in a more adequate way to a set of network values (measurements) that is available in real-time. The state variables are such that all the other network variables can be evaluated from them, and the operation state is obtained. The calculation of state variables considers the

physical laws directing the operation of electrical networks and is typically done adopting some criteria.

The Distribution State Estimation (DSE) is implemented at the functional level of the HV/MV primary substation, and only MV level state variables are calculated. It is assumed that this functionality will be installed at the central management level, i.e., at the SCADA/DMS.

In order to derive consistent and qualified state estimates, it is necessary to use all the information available for the network and not only real-time measurements because their availability is very limited. Therefore, the DSE functionality includes information coming from different sources, namely: AMI, DTC acting as Remote Terminal Units (RTUs), and Phasor Measurement Units (PMUs) synchronized by the Global Position System (GPS) signal, if available. Smart meters (EBs) connected to LV nodes can make time-synchronized measurements of active (P) and reactive (Q) loads, as well as voltage magnitudes, at predefined time intervals (usually every 15 minutes). These measurements are transmitted to a database server periodically (for instance, daily). This ensures that the DSE will have, at least, measurements from the previous day of all the loads.

Based on these measurements, a set of pseudo-measurements will be generated and used, together with near real-time information, for instance from DG, to make the network fully observable and guarantee an adequate degree of redundancy for running the state estimator. This can be accomplished by an autoregressive load estimation model, which utilizes previous day metered LV consumption data as well as same day explanatory variables, such as temperature, day structure, humidity, etc. The upstream MV/LV substation P/Q load will be estimated by will aggregating all the downstream LV loads. This will be done using an expert system trained specifically for this purpose. This expert system will be located at the central management level, where historical information is available.

The MV/LV substations that require these pseudo-measurements generation are the ones with virtual DTC or substations where the transmission of real time DTC measurements has failed. When the MV/LV substation has a DTC with measurements available in real-time, the generation of pseudo-measurements is not necessary.

LOAD AND RES FORECASTING (MV LEVEL)

Figure 4 depicts the framework of the RES (wind and solar power) and load forecasting systems for the MV level. Both systems are installed at the central management level, in the DMS. Although installed in the DMS, the forecasting systems can be virtually distributed by HV/MV substation, but using information from DTC connected to different HV/MV substations.

The load forecast takes as inputs the load time series of each DTC, which means that the forecasts are produced for the total load of each MV/LV substation. The load consumption of medium/large consumers directly connected to the MV network is individually forecasted.

Similarly to the load forecast system, RES forecasts are also produced for each DTC and for DG units connected to the MV network. In order to capture the impact of clouds in solar power for the very short-term forecast horizon (i.e., up to six hours ahead) the measurements from the EB with solar power are included as explanatory variables in the model [3]. Thus, the RES forecasting system can use two alternative sources of information:

- RES generation time series aggregated by DTC and which decreases the volume of transmitted data from the DTC to the DMS;
- Aggregated generation by DTC plus time series data from the EB; this solution increases the volume of transmitted data.

It must be stressed that although currently the communication between the DTC and the EB is in many cases based on PLC communication, other technologies are expected to become widely available in the future. For these technologies all the data will be collected in a central point and not in each substation separately.

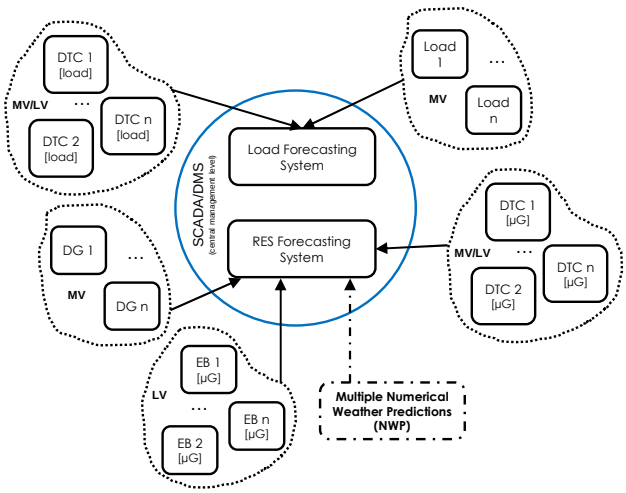

Figure 4 – Framework of the Load and RES Forecasting Systems.

Numerical Weather Predictions (NWP) for multiple coordinates in one region can be included in the RES forecasting system in order to produce forecasts for longer time horizons (e.g., up to 72 hours ahead) with lower forecast error compared to a model that only uses measured information [4].

The forecast is updated every 60 minutes and it is constrained by the communication requirements related

with the transmission of time series data from all EBs to the DMS. The time resolution varies with the decision-making problem that uses the forecasts. For steady-state analysis (e.g., voltage control) it is foreseen a time resolution of 30 or 60 minutes.

VOLTAGE CONTROL (MV AND LV LEVEL)

The objective of the coordinated voltage control functionality developed in the SuSTAINABLE project is a manifold one. The maximization of the integration of energy from variable RES is a first target. Other significant objectives include optimization of voltage regulation, reduction of energy losses and minimization of RES curtailments. In order to achieve this, it is necessary to develop a methodology to control voltage throughout the network by coordinating all available regulation devices, DG active and reactive output power, storage and controllable loads [4]. This strategy will be implemented at the level of the HV/MV primary substation (SSC), while a secondary controller will also exist at the level of the MV/LV substations (DTC).

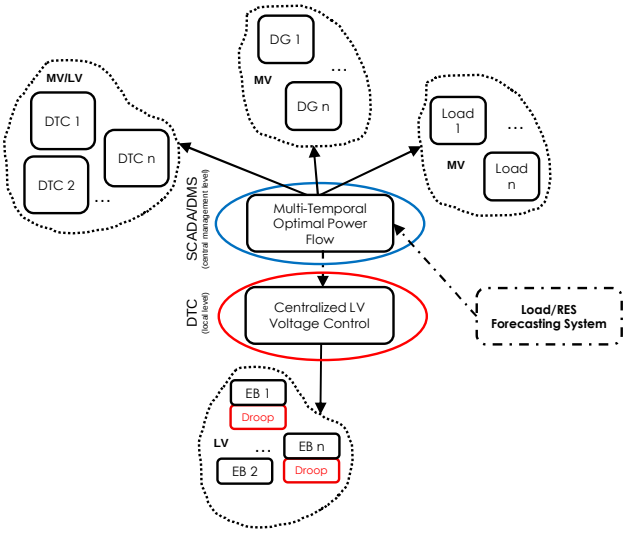

Figure 5 – Proposed Approach for the Voltage Control.

Such a methodology, illustrated in Figure 5, exploits two different levels of control:

- *At the MV level* – using a multi-temporal Optimal Power Flow (OPF) at the functional level of the SSC to coordinate the several MV control means (DER, storage, loads, OLTC, capacitor banks etc.) in order to avoid technical problems by satisfying the constraints and minimizing a single or a multi-objective function. Furthermore, in real time operation, the multi-temporal OPF may be augmented by practical rule-based control, which will address potential regulation issues (e.g. unforeseen load/DER power variations, voltage violations);
- *At the LV level* – centralized controller housed in the DTC, which will send set-points to DER located within the specific LV network (i.e., controllable loads, microgeneration, storage devices) in order to observe the requirements imposed by the SSC or by responding independently to a set of voltage alarms obtained from the EB; using local droop functionalities implemented in some inverters interfacing the DER and a centralized voltage control algorithm housed in the DTC to remotely update the parameters of the droops based on a set of rules.

CONCLUSIONS

The architecture described in this paper contains the main information flows foreseen concerning data between the several control layers and identifies control signals between the several network devices. The functionalities residing at each control layer and equipment requirements are also detailed and specified.

The SuSTAINABLE project is also exploring the Technical Virtual Power Plant (TVPP) concept, applied to distribution networks, bearing in mind the reduction of the impact on the transmission network of variable generation in distribution systems under very high penetration of RES. Moreover, this will open new perspectives towards improving the coordination between the DSO and the TSO and the way how the distribution system is presented at the transmission grid boundaries.

Acknowledgments

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