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Architectures for Optimized Interactions between TSOs and DSOs: Experiences and learnings from SmartNet

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Abstract

Increased levels of Distributed Energy Resources (DERs) and their participation in provision of Ancillary Services (AS) at both transmission and distribution levels, call for a more advanced dispatching management of distribution networks to transform distribution from a “passive” into an “active” system. Moreover, new market architectures must be developed to enable participation of DERs in energy and AS markets. New operational and trading arrangements will also affect the interface between transmission and distribution networks, which will have to be managed in a coordinated manner between TSOs and DSOs in order to ensure the highest efficiency, effectiveness and security.

Evaluation and validation of the proposed schemes has been carried out both via simulations which have modelled market operation under different TSO-DSOs interactions, as well as in the laboratory and pilot project settings. This paper present experiences and learnings obtained during development and testing of the market clearing algorithm and simulator, including bidding by market participants and aggregation to provide flexibility used for ancillary services. It also discusses how solutions proposed in the SmartNet align with the present national and European policy goals and positions of the key industrial stakeholders, and also elaborate on the final guidelines and regulatory recommendations that result from the SmartNet project

Introduction

To realize low-carbon electricity networks we need to increase levels of Renewable Energy Resources (RESs) connections, which then brings higher levels of generation uncertainty. Intermittency and variability of renewable generation, however, calls for additional instruments to increase flexibility of system operation so to facilitate integration of these resources. Thus, due to renewable generators' variable power outputs that are not easy to predict even for the next day, such resources are far from being "plug and play".

High penetration of renewables brings higher levels of generation uncertainty and, because of a need to balance demand and supply at any instant in time, will require additional support. New technology which can provide additional flexibility, with energy storage (including electric vehicles) and active demand participation are regarded as two major ways to provide this. They could be introduced at all voltage levels, but due to costs and available technologies, this is often considered at distribution levels, where larger number of smaller renewable generators, active demand side participation of smaller customers (e.g. commercial or domes-tic) and energy storage (including electric vehicles) are expected to be connected. These distributed devices are typically referred to as Distributed Energy Resources (DERs).

Since considerable share of RESs are connected at the distribution systems, it changes the nature of their operation whereby such networks are becoming more active, with possible changes in directions of power flows. One of the key approaches to help harness RESs in an efficient and cost-effective way is to utilize flexibility which can be provided by DERs. Some of the main aspects of the transition towards low-carbon energy systems envisioned by new European regulation and roadmaps [3] include market based provision of ancillary services by DERs that need to be give a level playing field to participate in all electricity/energy and ancillary services markets, at both transmission and distribution networks.

Therefore, procurement and activation of resources from distribution network for ancillary services, such as congestion management and voltage regulation, will require new grid organisation for ensuring and improving interaction between TSOs and DSOs, and defining their roles and responsibility under new operation regimes. In addition, operation of systems with high levels of DERs as well as design and operation of associated energy and ancillary services markets will need new tools and underpinning regulation and codes.

This paper discuses some of the regulatory aspects analysed within the EU H2020 project SmartNet [1] proposes five different architectures or coordination schemes (CSs) that each present a different way of organizing the coordination between transmission and distribution system operators (TSOs and DSOs), when distributed resources (production, storage or demand) are used for ancillary services [2]. Each coordination scheme is characterized by a specific set of roles, taken up by system operators and a detailed market design. These different schemes span from the situation of a complete centralized control over AS market to the creation of different local markets run by DSOs and one AS market run by the TSO.

SmartNet in a Nutshell

This section briefly outlines the project - a set of coordination schemes, assumptions which were made for their implementation and the simulator used to assess and compare of these CSs.

SmartNet coordination schemes

SmartNet evaluates five coordination schemes (CSs), each presenting a different way of organizing the coordination between transmission and distribution system operators (TSOs and DSOs), when DERs participate in provision of ASs. Here, only a brief outline for each of the CSs is provided, while their detailed descriptions are provided and discussed in [2], while market aspects of the CSs are discussed in [4]. Each of the CSs is characterized by a specific set of roles assigned to TSOs and DSOs with a comprehensive operational rules and market designs. The main differences between different CSs are related to how, and by whom, coordination of DERs' participation in AS markets or local markets is managed.

The five proposed CSs, developed within the SmartNet, are as follows:

- *Centralized AS (CS-A) market model* where the TSO operates a market for resources connected both at transmission and distribution levels, without involvement of the DSO and without receiving any real-time information on distribution network status.
- *Local AS (CS-B) market model* where the DSO organizes a local market for resources connected at the DSO-grid and, after resolving local grid constraints, offers the remaining flexibility bids to the TSO for participation in AS markets.
- *Shared balancing responsibility (CS-C) model* where balancing and congestion management responsibilities are divided between TSO and DSO according to a predefined schedule. The DSO organizes a local market while respecting a schedule agreed with the TSO This does the same for the transmission grid.
- *Common TSO-DSO AS market (CS-D) model* where the TSO and the DSO have a common objective to decrease costs to satisfy the needs for resources by both the TSO and the DSO. This mutual objective could be realized by the joint operation of a common market operated by the TSO and the DSOs.
- *Integrated flexibility market (CS-E) model* where the market is open for both regulated and non- regulated market parties, having each a different goal to achieve (non-regulates parties would see this market as an extension of the intraday market, whereas the grid operators would procure services for the network). This scheme as not simulated because it was recognized it would pose a lot of problems (technical and regulatory) to work properly.

SmartNet simulator

To evaluate proposed Coordination Schemes (CSs), a large-scale simulator has been developed to realistically model the behavior of complex systems which include transmission and distribution networks, bidding and market processes, as well as fundamental physics behind each flexible device connected to the system. As illustrated in Figure 1, the SmartNet simulator comprises of three main layers:

- *The Market layer*: is an optimization algorithm responsible for simulating the real-time balancing market clearing process and includes network representation, market products and arbitrage opportunities between day-ahead, intraday and ancillary services markets. It is designed to manage large optimization problems including the constraints of all the networks and the different TSO-DSO interaction models
- *The Bidding and dispatch layer*: It is assumed that a large number of relatively small dispatchable devices will participate in the market via third party aggregators, whose role is to aggregate devices and submit aggregated bid for participating in the ancillary services markets, and the to carry out a disaggregation process which depends on the results of the market clearing and sends activation/instruction signal to each of the participating devices. Bids for each of the devices should reflect flexibility costs and other constraints of particular technologies while also taking into account the potential arbitrage between different markets
- *The Physical layer*: The basis of the entire simulator is represented by the physics of the system components. The complex behaviour/characteristics of each network (transmission and distribution), loads, generators and flexible devices (storage, electric vehicles etc.) are simulated together with the automatic processes directed by grid operators (state estimation/forecasting, network asset management etc.). The processes include voltage regulation, reactive compensation, aFRR and network protections.

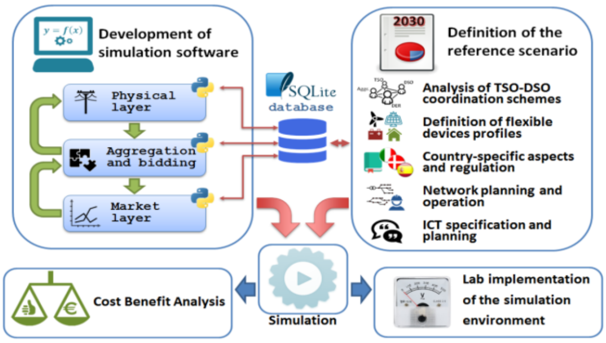

Figure 1 - Structure of the SmartNet simulation platform [5]

Implementation and Pilot Projects

In order to evaluate practical implementation of the concepts developed within SmartNet, in particular, regarding the different coordination schemes and the market models developed these were tested in three technological pilot projects, namely in Italy, Denmark and Spain. Each of the pilots is seeking to evaluate different parts/aspects of the TSO-DSO coordination value chain, as summarised in Table I [8].

Regulatory Analysis: Where does SmartNet Project fit and What does it Address

Two main aspects regarding regulatory analysis have been considered (i) how does a work carried out in the SmartNet fit within the current and emerging EC and national regulation, roadmaps and position papers of various stakeholders, and (ii) what important aspects should be considered when developing and implementing practical TSO-DSO coordination schemes, and how these issues have been addressed in the SmartNet project.

Table I – Summary of Technological Pilots

	Pilot A	Pilot B	Pilot C
Country	Italy	Denmark	Spain
Coordination scheme	Centralised Ancillary Services market	Common TSO-DSO Ancillary Services market	Shared balancing responsibility
Services to be gathered by TSO/DSO	- Aggregation of information for TSO - Voltage control for TSO - Frequency control for TSO	- DSO Congestion management - Frequency control for TSO	- DSO Congestion management - Frequency control for DSO
DER providing flexibility	Run-of-river hydro power plants	Impulsion pumps for heat water for indoor swimming pools in rental houses	Back-up batteries for radio base stations used in mobile phone communications
Main focus of the pilot	- TSO-DSO communication - TSO control - Assessment of DER capability to participate in markets	- Price-signals from aggregators to obtain DER flexibility - Communication chain from market to DER through aggregators	- Monitoring of distribution network - Creation and operation of local flexibility markets - Assessment of base station capability to provide services for grid support

The first question regarding current regulation, road maps and position papers has been addressed by firstly identifying main and critical issues that are associated with SmartNet models, assumptions and solutions. Then, comprehensive screening studies were carried out to evaluate how those issues fared in over 40 different documents that included legislation/regulation (EU Directives, Network guidelines, national regulatory Decisions), position papers, strategies, roadmaps, etc. Detail findings from these analyses are presented in [6].

In addition, similar approach has been used to gather learnings related to the similar critical issues associated with SmartNet models, assumptions and solutions used in the coordination schemes and in the simulators [7].

The following is a sample of these issues and associated analysis.

Market modelling and timelines

In the SmatNet market, the model developed and implemented sought to enable mechanisms which will help DERs trade their electric power and energy in ancillary services. Depending on the adopted coordination schemes, these services can be provided to TSO and/or DSO, and the simulator, and its market design, have been developed to handle DERs' trades with both TSO and DSO. The simulator is based on a hierarchical design formulated as standard constrained optimization problem that clears the market based on bids submitted by market participants [4].

Due to the nature of the market and trades, i.e. intraday market for flexibility, as well as technical characteristics of the DERs, the following aspects of the market design and operation are important to consider:

- **Time step:** Considered time granularity for the market clearing. Activation decisions are made for each time step and the behaviour of the system and the flexibility assets inside each time step are considered constant at their average value.
- **Time horizon:** Overall time period considered for the market operation and clearing. The time horizon can be equal to or greater than the time step. However, it will typically be a multiple of the time step in order to model intertemporal constraints and to clear the market with some anticipation on the future time steps.
- **Frequency of clearing:** Defines how often the market is cleared. From a network balancing perspective, the market needs to be cleared sufficiently often in order to take into account the latest updated data from the system state. From an algorithmic perspective, the frequency of clearing needs to be sufficiently low, so that the optimization algorithm used to clear the market can generate (near) optimal solutions within the allowed time. If a higher frequency is required, e.g., for security reasons, an economically sub-optimal solution can be acceptable.

In the SmartNet simulator, time steps, time horizon and frequency of market clearing are parameters that are controlled by the user, providing necessary flexibility to adjust market operation and clearing for the particular conditions that will typically be dependent on regulatory settings.

Above explained screening analysis of various documents revealed a need for an overall harmonisation process across Europe. In addition, from 1st January 2025, the imbalance settlement period should be 15 minutes in all control areas. Since Market Operators (MOs) on the Day-ahead Market (DAM) and Intra-Day Market (IDM) shall provide the opportunity to trade energy in time intervals which are at least as short as the imbalance settlement, energy will be traded in at least 15min period from 2025. Finally, the trade should be moved as close as possible to operation, while it is important to ensure non-discriminatory access to the markets and creation of level-playing field.

Accounting for technical DER constraints in a market design

When deciding on modelling technical capabilities and responses from different DERs, it is important to consider how to include these into the market model. Thus, it is necessary to decide which constrains should be included in the market model, and how market participants should account for technical constraints of different DER technologies.

In SmartNet, five technology specific aggregation models, aimed at separate DER categories, have been used in order to reflect physical constraints of the devices being aggregated, as summarized in Table 2 (with more details provided in [9]. The physical approach (bottom-up) includes the physical constraints of each aggregated technology in the aggregation models, and assumes that that the aggregator knows the parameters of each individual device and its real time status. As indicated, in Table 2, the physical i.e. bottom-up, approach has been selected as the preferred aggregation option in the SmartNet market design [9]. Other aggregation approaches have been used only in two of the models due to physical characteristics of the aggregated devices, the number of the individual devices being aggregated and the availability of data. For example, in the case of atomic loads, which use load profiles and associated costs, rather than directly defined constraints, traces aggregation approach has been used, while justified approximation (hybrid) approach, which represents the entire population of aggregated devices by a single or a limited number of virtual devices has also been used for aggregation of TCLs.

Table 5 - Aggregation approaches, types of bids and units used for aggregation of different DERs [10, 9]

Models	Aggregation approach	Type of bid	Units used
Atomic Loads	• Traces	• Non-curtailable UNIT bid	• P [W], t [min], C [€]
Combined Heat and Power (CHP) Units	• Physical	• STEP curtailable Q-bid	• P [kW], t [h], C [€]
Thermostatically Controlled Loads (TCLs)	• Physical • Justified	• STEP non-curtailable Q-bid • STEP non-curtailable Qt-bid	• P [W], T [˚C], E [J], t [s], C [€]
Electric Energy Storage (EES) Units	• Physical	• STEP curtailable Q-bid • STEP curtailable Qt-bid	• P [kW], E [kWh], t [h], C [€]
Curtailable Generation and Curtailable Loads	• Physical	• STEP curtailable Q-bid	• P [kW], t [h], C [€]

It is also important to note that the way in which technical constraints of DERs are accounted for in the market design will directly influence the definition of bids, i.e. products, used by market participants, and in particular aggregators.

No present legal requirements for inclusion of device-related constraints, however, proposal for inclusion of certain requirements on portfolio-level are advanced by a number of stakeholders.

Management of voltage constraints

Voltage control is formally defined as non-frequency ancillary service [8] and thus shall be allowed to be procured by DSOs in market-based manner (both active and reactive power can be used for voltage control). According to common reports TSOs and DSOs should agree on voltage control parameters at the border of the networks.

Voltage control is one of the key aspects in managing power system stability, and it is becoming more challenging at the distribution level with the increase levels of DERs. In the SmartNet project, voltage management is considered one of the key aspects, with the DERs participating in provision of this service [2] both to DSO and to support the voltage at transmission network. Within SmartNet coordination schemes, this service is delivered in several coordination schemes: The Local AS market, Shared Balancing Responsibility, and Common TSO-DSO AS market.

Therefore, in addition to technical constrains of DERs, it is also important to include limitations of the power network into the market model. This, however, requires utilization of full AC network flow models, which introduce non-linear constraints, making optimization (i.e. market clearing), computationally challenging task, especially in the presence of binary variables. To enable utilization of existing solvers and provide computational tractability, modelling of the distribution network in the SmartNet simulator is based on Dist-flow model [4]. This has enabled inclusion of realistic physical models of the distribution system networks into a market clearing algorithm, providing more accurate market clearing solutions that respect physical constraints of networks and DERs .On the other hand, for transmission network linearized DC model is applied as it provide sufficient accuracy for those networks.

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Learnings from the SmartNet project

All the schemes of TSO-DSO coordination that have been assessed within the SmartNet project assume significantly higher levels of DSOs involvement and responsibility, in particular for the management of congestion and voltage constraints using DERs flexibility. This is in line with the EC package Clean Energy for All Europeans, which seeks to allow customers to provide become more actively engaged and also provide flexibility services at the level playing field with the participants connected to transmission networks (but, subject to secure system operation) However, this will require significant investments in monitoring and control systems, as well as good TSO-DSO coordination. To succeed, roles and responsibilities of both TSOs and DSOs should also be well defined.

Looking at the question of whether distribution constraints management should be shallow or deep, it is important to acknowledge the state and the capacity of the network. Traditional TSO-centric schemes could stay optimal if distribution networks don't show significant congestion. However, distribution grid planning was (and still is) affected by the fit-and-forget reinforcements policy, which may cause system operation issues.

More advanced centralized schemes incorporating distribution constraints show higher economic performances but their performance could be undermined by big forecasting errors: it is important that the gate closure is shifted as much as possible toward real time, market clearing frequency is increased and forecasting techniques are improved. However, although intraday markets should bring gate closure as close as possible to real time. It is not feasible to overlap a real-time session of intra-day market with a services market (CS-E): this solution would create uncertainty in the operators (TSO and DSO) in charge of purchasing network services because they would be no longer sure of how many resources are needed (i.e. the real amount of congestion and imbalance). This is a significant shortcoming of this coordination scheme.

Ensuring level playing field in the participation of distributed resources in the tertiary market will make it necessary to allow bidding, and thus market products, that will be able to reflect some of their technical characteristics, otherwise these technologies may be prevented from participating in the market. This could imply to enable complex bids or other sophisticated products.

Scarcity of liquidity, and potential impact of local market power (not investigated in SmartNet), along with extra constraints introduced to avoid counteracting actions between local congestion market and balancing market (e.g. increasing system imbalance while solving local congestion) furthermore negatively affect economic efficiency of decentralized schemes.

Local congestion markets should have a “reasonable” size and guarantee a sufficient number of actors are in competition in order to prevent scarcity of liquidity and exercise of local market power. Small DSOs may need to pool-up.

Reaction to commands coming from TSO or DSO in real time of the control loops which were initially planned for real time services provision can be too slow. So, a testing is needed to ensure compatibility with requested reaction times.

ICT is nearly never an issue: whatsoever TSO-DSO coordination scheme is implemented, the economic performance depends by wide and large on operational costs, being ICT costs mutually comparable between different CS and, in any case, one order of magnitude lower than operational costs (in our simulations: maximum 5% over operational costs).

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