

## TESTING TSO-DSO INTERACTION SCHEMES FOR THE PARTICIPATION OF DISTRIBUTION ENERGY RESOURCES IN THE BALANCING MARKET: THE SMARTNET SIMULATOR

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### ABSTRACT

Many projections of near-future electricity system foresee a constantly increasing necessity of power flexibility services. In particular, thanks to the growing presence of renewable generation and innovative load technologies, distribution resources are becoming attractive products in ancillary services markets. In order to open the market gates to distribution flexibility, constant interactions between transmission and distribution system operators are required and the European project SmartNet is investigating in detail the possible coordination schemes among these two actors. The paper describes the SmartNet simulator, one of the main tools developed within the project, which precisely estimates the impact of TSO-DSO coordination schemes from the bidding and market clearing perspective, taking into account the consequent effects on the network physics at both transmission and distribution level.

### INTRODUCTION

Nowadays, distribution networks are facing a significant revolution, particularly thanks to the government incentives in favour of renewable energy which, for its diffuse nature, can be principally gathered through distributed generation. According to the current trends, it can be likely expected that large portions of the generation mix, as well as the volumes of the reserves aimed at guaranteeing the stability of the entire electricity system, will be located at distribution level. Of course, this transformation will have a relevant impact on the interactions between transmission and distribution systems, with new possible roles for their operators. The SmartNet project aims at investigating the potential Coordination Schemes (CSs) between the Transmission System Operator (TSO) and the Distribution System

Operator (DSO) and the related technical and regulatory challenges behind these interactions.

SmartNet has identified five possible TSO-DSO coordination models [1] and, each of them represents a possible evolution of the current way of organizing ancillary services provision and activations. Depending on the requested flexibility, different coordination schemes can be applied. SmartNet investigations focused on the activation of manual Frequency Restoration Reserve (mFRR) for the following services:

- balancing, requested by the TSO in order to restore the power exchange with the border countries and/or match load and generation;
- congestion management at transmission level, requested by the TSO in order to avoid overloading on network bottlenecks;
- congestion management at distribution level, requested by the DSO in order to avoid overloading/voltage issues on the distribution grid.

These three services (and related responsible actors) are the ones considered by SmartNet for all the coordination schemes. In particular, the role of the DSO is the one with the highest evolution potential and, in one case (CS C), the DSO also shares the balancing responsibility with the TSO [1], determining a complete revolution of the current network operators' roles. However, this paper presents the results only related to

- CS A, where the DSO cannot acquire services on the flexibility market (congestion management at distribution level is operated outside of the market);
- CS D, where the DSO can access to the flexibility market for the acquisition of distribution services (congestion management).

In particular, the application of CS A corresponds to a scenario in which the roles of network operators are not evolving with respect to the current situation. CS D, instead, represents a situation in which both TSO and

DSO can acquire services with the same priority. In the following sections the numerical results of these two coordination schemes are reported for a forecasted electricity scenario of Spain in the near future, illustrating the benefits of extending ancillary services market to the DSO. The outcomes of the other coordination schemes, in which the DSO assumes additional roles and/or responsibilities, are detailed in [2].

## CONSIDERED SCENARIO

The SmartNet project investigates the effects of TSO-DSO coordination on three European regions: Northern Italy, Continental Denmark and Spain. Figure 1 reports a possible 2030 energy scenario for Spain, from which it is possible to notice:

- an increase of photovoltaic and wind generation (mostly distributed), which results comparable to the total power capacity of conventional power plants;
- thanks to the spread of electric vehicles, storage-base technology represents a significant portion of flexibility, even where large storage power plants (pumped hydroelectric units) cannot be hosted.

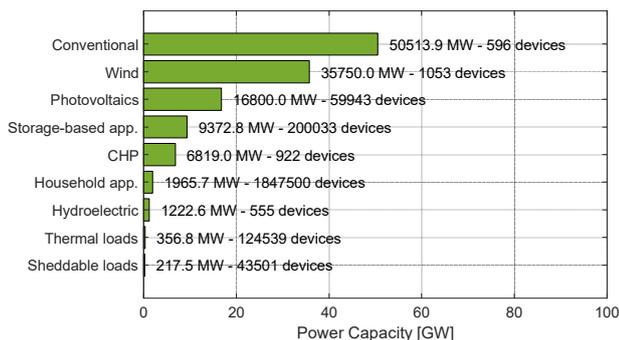


Figure 1. Hypothesized flexibility mix for 2030 in Spain

The main information related to this high-level scenarios are detailed in [3]. Further analyses have been conducted in order to precisely locate every single source of flexibility on the considered territories. Later, thanks to the reconstructed electrical maps of the transmission and distribution power systems, devices and flexibility providers have been connected to the grid nodes [2].

In addition to the network model and the position of all the flexible units, the baseline profile of each simulated device as well as the energy prices have been computed. These inputs are generated by running a day-ahead market session, having considered the generation mix, forecasted load and the energy price of border countries. Figure 2 reports the results of the day-ahead market processed for a typical Spanish summer day, sunny and averagely windy [2].

Two other typical days of the Spanish scenario, featuring different load and generation profiles, have been simulated. The results of their simulation, together with the ones related to the other two regions, are detailed in [2].

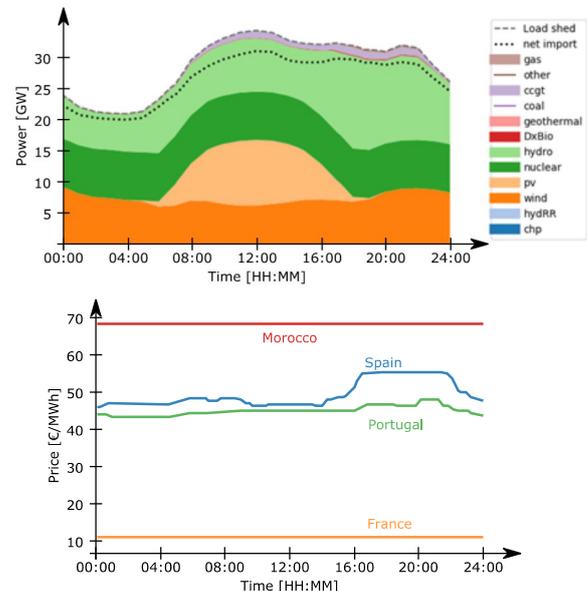


Figure 2. Results of the simulated day-ahead market session

## STRUCTURE OF THE SIMULATOR

In order to compare the performance of the investigated CSs, SmartNet relies on the results provided by a large-scale simulator, able to realistically mimic the behaviour of complex systems. Its structure is based on the combination of three layers which are sequentially processed in a continuous loop (Figure 3):

- **Bidding and dispatching layer**, which integrates the software routines responsible of aggregating and disaggregating the power flexibility provided by the different controlled devices.
- **Market layer**, which runs the market clearing routines aimed at optimizing the activations of the bids submitted by the previous layer for the selected ancillary services.
- **Physical layer**, which simulates the physics behind transmission + distribution network and each connected flexible device (together with the automatic controllers aimed at maintaining the grid within the stability margins).

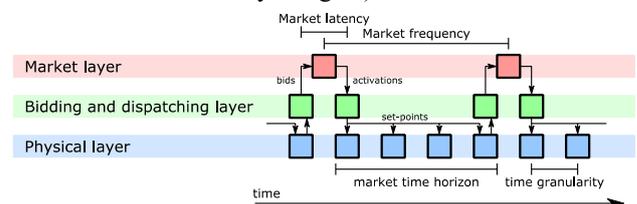


Figure 3. Sequence diagram of the SmartNet simulator blocks

### Bidding and Dispatching Layer

The bidding and dispatching layer incorporates the algorithms used by the market player participants in order to convert the power flexibility of electrical resources in bids for the ancillary services market. After the clearing, the disaggregators decompose the market layer results into the individual power set-points to be sent to all the controlled units.

SmartNet simulations considered eight different categories of flexible devices, which are grouped into six aggregation models on the basis of their technology similarities [4]. Because of the complexity of the flexibility, additional dimensions (such as rebound effect, all-or-nothing, all-time-steps-or-nothing, etc.) have been added to the conventional quantity-price bids [5].

### Conventional generators model

SmartNet simulator considers a traditional bidding routine for managing the flexibility of conventional power plants. Power and ramps limits are included within the bidding and dispatching process, having considered the operational and fuel costs related to the offered flexibility.

### Atomic loads model

It aggregates flexibility offered by loads, which have a fixed consumption profile that can be shifted in time and/or replaced by an alternative fixed profile. Once started, atomic loads cannot be paused or interrupted. Flexibility (which is mostly consisting in domestic appliances) is aggregated by solving an optimization problem and its price is calculated by comparing the cost of activating the alternative profile with the baseline one. For this technology the bid is built in order to be all-or-nothing accepted and to include also the information on the rebound effects.

### Combined heat and power units model

It aggregates the flexibility of combined heat-power units by adopting a model based on the physics of the controlled devices. The aggregator monitors the internal variables of each unit and proposes a bid taking into account the current working point with respect to the operational constraints (e.g. ramp-up/down, thermal demand limits, rebound effect).

### Thermostatically controlled loads model

Heat pumps, air conditioning systems, water heaters flexibilities are submitted to the market by a dedicated aggregator which monitors the internal variables of each controlled device (physical approach) and calculate the discomfort cost of deviating from the baseline profile. As demonstrated by the results plotted in Figure 4, for this technology the bids also include information on the rebound effect caused by the flexibility activation (all-time-steps-or-nothing bid dimension concept) [6].

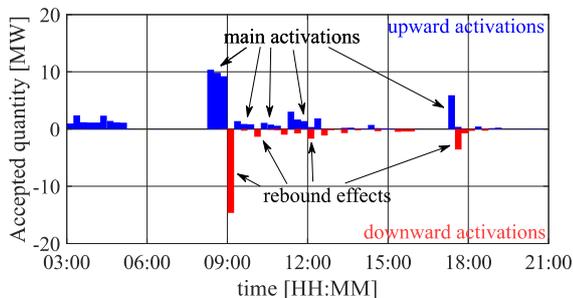


Figure 4. Accepted flexibility of thermostatically controlled loads

### Electric energy storage units model

All storage-based technologies are aggregated by a single

algorithm which, thanks to the introduction of the “availability” concept, is capable of managing both stationary (such as pumped hydroelectric units) and mobile storage (electric vehicles).

Even in this case, the aggregator monitors the physical variables of the controlled units and bid the flexibility by solving an optimization function which maximises the profit of the storage owners taking into account the efficiency of each single unit and the cost of deviating from the baseline profile. This deviation, particularly for mobile storage, produces a rebound effect which depends on the requested state-of-charge at the end of the availability periods (early morning and late afternoon according to Figure 5).

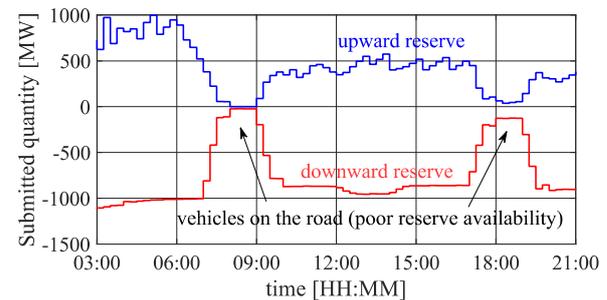


Figure 5. Offered flexibility from storage units

### Curtable generation and loads model

An aggregation algorithm is dedicated to photovoltaic, wind, small-scale hydroelectric generation and to all the loads that can be curtailed without any rebound effect. This guarantees the adoption of a conventional bidding structure (without logical constraints and rebound information), with the possibility of adding information on ramp and power flexibility margins.

When this flexibility is represented by distributed generation, it can be noticed that its activation is very dependent on the coordination scheme. In fact, Figure 6 demonstrates that higher downward regulation is requested to photovoltaic power plants when the DSO is acquiring congestion management services (CS D).

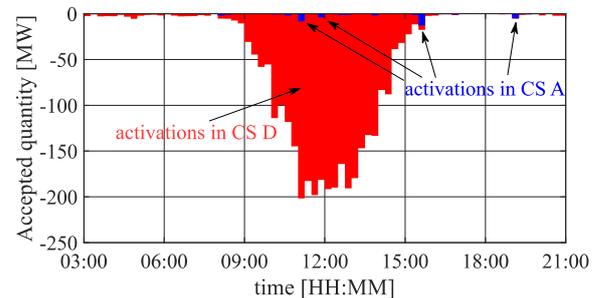


Figure 6. Accepted flexibility of curtable generation (comparison between CS A and CS D)

### Market Layer

The market layer implements the clearing routines aimed at optimizing the activations which solve balancing and network congestions. Depending on the coordination scheme, these two services are limited to transmission network (CS A) or extended to distribution too (especially congestion management – CS D).

The market clearing routine selects which bids have to be

partially/totally activated and at which price, by solving an optimization function (e.g. costs minimization) while satisfying the relevant constraints. The design of the market simulator has been carried out by considering the following five main aspects [5].

### Network constraints

Transmission and distribution grid models are coded within the market clearing algorithm in order to solve the predicted congestions and to avoid the occurrence of new ones while balancing.

Because of the different characteristics of transmission and distribution networks (i.e. topology, line impedance, etc.) two distinct models have been adopted. Having investigated the best trade-off between accuracy and practicality, transmission grid has been modelled with a traditional DC linear approximation. Distribution grid, instead, has been represented by means of a *DistFlow* model, capable of modelling radial grids physics [5].

### Timing

The simulated market integrates the possibility of acting on several timing parameters: time horizon (i.e. period for which aggregators trade their flexibility within one market session), time granularity (i.e. time resolution of the market products) and market clearing frequency have been particularly investigated within SmartNet. The simulations have been carried out by assuming a market clearing session per hour, with a time horizon of 60-minutes and a 15-minutes time granularity.

### Bidding

As anticipated above, the structure of the bidding has been designed in order to allow a technology-neutral catalogue of market products. In addition to the conventional quantity-price pairs, additional information has been added, such as time-dependent limitations (e.g. ramping, minimum duration, integral constraints) and logical variables (e.g. exclusive constraints between bids).

### Clearing

The objective function of the market clearing routine consists of minimizing the activation costs for the system operators. Welfare maximization strategies has been hypothesized as well but then discarded since it leads to unnecessary activations (zero-sum selection of opposite bids).

### Pricing

The pay-as-clear approach has been adopted for the pricing of the activated bids. In order to remunerate the effective contribution of the selected flexibilities, the locational marginal price approach is chosen as a pricing scheme. This strategy attribute to each node of the controlled system a price dependent on the local flexibility and the presence of network bottlenecks in the area.

Looking at the mFRR activations returned by the market layer (Figure 7), it is already possible to notice some peculiar differences between CS A and CS D. In the first case, the TSO is activating flexibility resources regardless of distribution network constraints and no downward distribution flexibility is activated (distribution downward flexibility is more expensive than transmission

one). In the second case, the participation of the DSO to the market is evident: about 0.9 GWh of photovoltaic curtailment bids are acquired for congestion management, and the market rebalance them by increasing upward flexibility at transmission level.

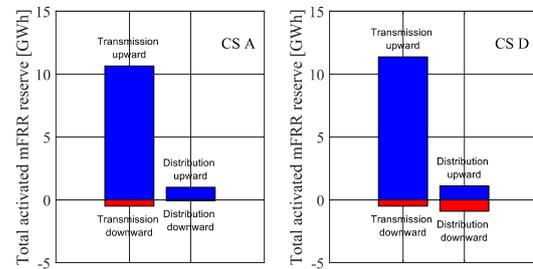


Figure 7. Total accepted mFRR during the simulated day (comparison between CS A and CS D)

According to this, the same net amount of mFRR is activated in both the CSs, however CS D leads to larger amounts of activations with a negative impact on the mFRR costs, but with the benefits of an optimized management of distribution networks (which is beneficial from the physical layer perspective).

### Physical Layer

Finally, the effectiveness of the bidding, market clearing and dispatching can be evaluated by analysing their impact on the actual network behaviour. For this reason, a layer of the simulator is entirely dedicated to the simulation of the physics behind the flexible devices and the evolution of the network quantities which is the consequence of the selected activations.

### Power exchanged by flexible units

The first step processed by this layer consists of updating the state of each controlled device. Depending on the technology, the set-point provided by the aggregator is computed through a zero-order or first-order dynamic models, which returns the total power exchange of the flexible unit. These models also include stochastic variables, which introduce the effect of forecasting error due to the noise naturally present on non-controllable variables.

### Network variables

Once the power of the flexible units is available, the network state can be calculated by running a conventional AC power flow. However, since the simulated market is dealing only with balancing and congestion management, other fundamental services (such as voltage regulation) have to be simulated in order to maintain the network stable. For this reason, the asset which is not interfering with market decisions and products (e.g. reactive power of generators, phase-shifting/tap-changing transformers, etc.) are controlled by dedicated optimization functions.

### Unwanted measures

Since the market is processing the activation of flexibility on the basis of a predicted network situation, the forecasting error might lead to unforeseen congestions that have to be promptly managed by the network operators. These situations often cannot be solved without interfering with the market activations and, when

mFRR reserve is used, the related actions are named *unwanted measures*. They consist of a re-dispatch of flexible resources which, normally, is manually managed by network operators. This process is simulated by running an optimal power function which minimizes the re-dispatch of mFRR devices (in conjunction with grid assets) in case of network congestion.

Network congestions are frequently happening on distribution networks characterized by large penetration of renewables. These violations can be efficiently managed by CS D thanks to the acquisition of flexibility on the market by the DSO. On the contrary, CS A implies their solution by applying manual re-dispatch (Figure 8).

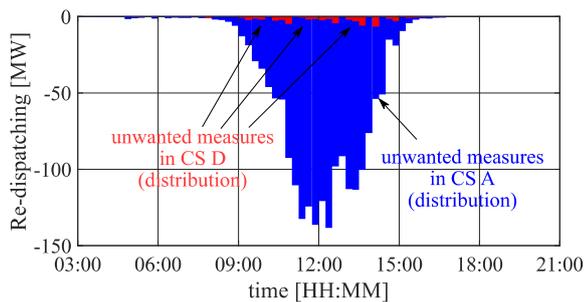


Figure 8. Unwanted measures occurring at distribution level during the simulated day (comparison between CS A and CS D)

### Automatic Frequency Restoration

Finally, the simulated forecasting errors and unwanted measures determine a residual imbalance which, on real electricity systems, is compensated by accessing to the automatic Frequency Restoration Reserve (aFRR). This service consists of (and is simulated as) a closed-loop control which is designed to keep the system constantly balanced by modulating the aFRR active power. According to [7], the devices capable of providing this service are the same selected for mFRR (except for atomic loads which power cannot be modulated continuously). For this reason, aFRR is assumed to be a fixed (small) portion of the available active power flexibility. In addition, since this fixed portion is limiting the opportunity of flexible resources in bidding to other markets (often leading to economic losses), normally aFRR is more expensive than the same volume of mFRR.

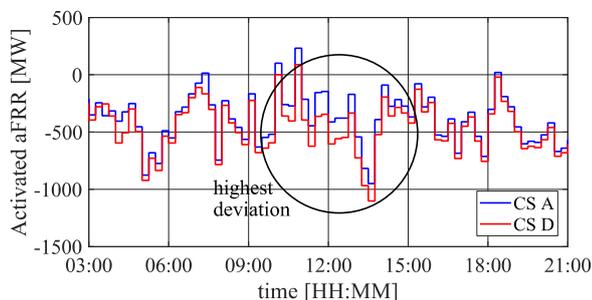


Figure 9. Total activated aFRR during the simulated day (comparison between CS A and CS D)

As it can be noticed in Figure 9, the effects of the unwanted measures on the residual imbalance (and aFRR) is evident. In particular, aFRR profile in CS A is resulting shifted upward of the manually curtailed 0.9 GWh (see Figure 8) with respect to CS D. Of course, this is resulting in an extra cost for network operators.

## CONCLUSION

The SmartNet simulator demonstrated to be a powerful tool for the practical comparison of TSO-DSO coordination schemes in different energy scenarios. In particular, the paper demonstrated a successful comparison between two distinct CSs: one in which the DSO is not participating to the market (CS A) and one in which the DSO manages it together with the TSO.

The simulation results related to the activation of mFRR reserve for both transmission and distribution services have been presented for one hypothetical energy scenario of Spain in 2030. The analysis of them demonstrated how the access of the DSO to distribution flexibility can improve the activation of existing reserves, limiting the residual imbalance and the procurement of additional aFRR.

In order to complete the evaluation of these coordination schemes (together with the other proposed CSs), SmartNet has carried out a dedicated cost-benefit analysis [8][9]. Thanks to these investigations, a complete picture of the CS costs (including mFRR, aFRR, unwanted measures and ICT) has been defined for the selection of the best TSO-DSO interaction model for each considered scenario.

## Acknowledgments

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