MACROSCOPIC ANALYSIS OF INTERACTION MODELS FOR THE PROVISION OF FLEXIBILITY IN DISTRIBUTION SYSTEMS

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ABSTRACT

To ease the transition towards the future of distribution grid management, regulators must revise the current interaction model, that is, the set of rules guiding the interactions between all the parties of the system. Five interaction models are proposed, three of them considering active network management. This paper evaluates the economic efficiency of each model using macroscopic representation of the system, by opposition to more techniques requiring a complete picture of the system. The interaction models are simulated on the horizon 2015-2030. Results show that for the first five years all the models provide similar economic efficiency. For the remaining ten years, interaction models implementing active network management provide up to a 10% higher economic efficiency.

INTRODUCTION

Distribution systems were typically designed to face peak consumption or production without considering any coordinated control action on the production or on the consumption side. However, increasing the amount of renewable generation in distribution networks using the same design rules may lead to large network capacity upgrade costs. Active network management (ANM) is an alternative that could allow to postpone or avoid these upgrade costs [1]. However, adapting the regulatory framework is necessary to ease the transition between the current situation and the future of distribution grid management. An appropriate regulatory framework is essential to optimize the benefits within a deregulated environment [2].

An *interaction model* is a set of rules in a regulatory framework that guides the interactions between all the parties of the system. Although the methodology applied in this paper is general, we define and study five interaction models among the numerous possible candidates. In the first two interaction models, the distribution system operator (DSO) does not use ANM and either restricts or not the access to its network to the grid users. The three remaining models are focused on flexibility service usage for ANM. In model 3, the DSO may restrain the users without providing any financial compensation except for the imbalance created by its request. In model 4, the grid user is compensated financially for the activation request of the DSO. In the last model, the DSO places no access restriction on to the grid users and relies on voluntary remunerated flexibility services to operate its network.

Several attempts to define interaction models for the exchange of flexibility within a distribution system are proposed in the literature. An example of specifications to exchange flexibility services is proposed in [3], which streamlines the relevant business interactions and illustrates the concept on a low-voltage transformer overload case study. Another framework to coordinate the flexibility usage on a low-voltage feeder based on flexibility margins imposed to controllable resources is proposed in [4]. Benefits of tariff based flexibility services directly controlled by the DSO is investigated in [5]. The business case from the DSO perspective of dynamic line rating, demand side management and network reinforcement on a MV-grid use case is elaborated in [6].

This paper evaluates the economic efficiency of each model using a macroscopic representation of the system, by opposition to more complex techniques that require a complete picture of the system [7], [8]. In particular, the analysis uses data that can be easily obtained for each quarter of the year, such as the total production and consumption in the distribution network. These productions and consumptions provide an approximation of the flexibility needs of the DSO for each quarter of the year. Depending on the interaction model, these flexibility needs can be matched either by shedding production/consumption, restraining the grid users or activating flexibility services. Using approximation of the different prices, we evaluate the costs on this typical year of the DSO, the producers and the retailers. The economic efficiency of each interaction model can be estimated on the long term by repeating the process for each year of the time horizon using forecasts of the production, consumption, energy prices, etc.

The paper is organized as follows. First, we present the candidate interaction models to evaluate. Second, the procedure to evaluate quantitatively the proposed models is described. Results on a year representative of the expected trends toward the year 2025 are presented in the third section. Results of a complete simulation of the horizon 2015-2030 are presented in the fourth section.

CANDIDATE INTERACTION MODELS

An important part of ANM is devoted to the coordination for the usage of flexibility to operate a distribution system. How the flexibility services may be exchanged depends on the interaction model that the agents must follow.

Model 1. *The DSO does not use any flexibility service and does not restrict grid users.*

Model 2. *The DSO does not use any flexibility service. To ensure the safety of its system the DSO restricts the users to a safe full access range computed on a yearly basis.*

Model 3. *An access contract specifies a full access range and a wider flexible access range. These access bounds are represented in Figure 1. The grid user may produce or consume without any restriction within the full access range, which is computed on a yearly basis. The full access range is determined such that no ANM strategies are needed if all grid users are in their full access range. If necessary, the DSO may ask a grid user to restrain its production or consumption in the full access range in critical periods where the agent is in its flexible access range. This restriction does not lead to financial compensation by the DSO except for the imbalance created by the request.*

Figure 1: Visual representation of the access bounds.

Model 4. *This model is equivalent to Model 3 but the DSO pays for the activation of the flexibility of the grid users. For instance, this case allows producers to recover from the loss of the subsidies for renewable energy generation.*

Model 5. *The DSO acts as a simple flexibility user like the TSO or every BRP. The DSO does not restrict the grid-users and relies on the flexibility offered by the other agents to operate its network.*

A modulation request by the DSO to a grid user is a reduction of its production or consumption to ensure the safe operation of its system. A modulation influences the total balance of the system with respect to the announced total production and consumption. The imbalance created by a modulation is paid by some parties in the system. The choice of the parties responsible for the imbalance depends on the interaction model. In the last three interaction models we consider that the DSO is responsible for the imbalance. The economic performance of the five models is evaluated using the procedure described in the next section.

EVALUATION PROCEDURE

The evaluation of the interaction models is done by getting an approximation of the actions to take for each quarter of a typical year. To obtain a base scenario for each quarter of a typical year, the simulation is based on historical production and consumption data. The consumption data comes from the total consumption monitored in 2013 by ELIA, the Belgian transmission system operator [9]. The production curve is taken from a real wind production unit in 2013. These curves are scaled to match a given mean and maximum value on the whole year. The resulting production and consumption values for each period t of the simulated year are denoted respectively by P_t^p and P_t^c. The energy and imbalance price curves are processed alike taking as a basis the BELPEX day-ahead energy market prices of 2013 [10]. The net export from the distribution network in a period t is given by $N_t = P_t^p - P_t^c$. If this net export is greater than the capacity of the network C, actions needs to be taken do deal with the exceeding production. For the sake of conciseness, we do not consider the case where $N_t < -C$ as distribution networks are usually designed to satisfy the peak consumption. Note that in the Model 5, P_t^p is capped to C to model the safety restriction of the DSO.

The next step decides for each period t what are the quantities of flexibility activated on the production side and on the demand side and the production quantities curtailed, R_t^p. For Model 1, if $N_t > C$, then $R_t^p = N_t - C$. For the other interaction models R_t^p are the remaining exceeding quantity that could not be handled using flexibility services.

In Models 3 to 5, the DSO uses flexibility to deal with the exceeding energy $N_t - C$. Regarding the flexibility on the production side, the maximum quantity available is bounded by the total production. The cost for the DSO to use this production flexibility is equal to the imbalance price plus the flexibility cost depending on the interaction model. In Model 3, there is no flexibility cost. In Model 4, the DSO pays only for the activation and in Model 5 the DSO pays for the reservation and the activation of the flexibility. The DSO may also use flexibility from the demand side. The total amount available is computed by βP_t^c where β is the flexibility ratio of the demand side. We consider that a modulation of the demand side in one period induces an equal modulation in the opposite direction in the next period. The costs for the DSO to use the flexibility spans on two periods, the period t and the following one, $t+1$, to consider this payback effect. Therefore a modulation F_t^c modifies the consumption in the next period such that $N_{t+1} := P_{t+1}^p - P_{t+1}^c + F_t^c$. As a result, we consider that the DSO pays the imbalance created in period t and $t+1$. However, the reservation and activation is paid only for the period t. A last criterion to check before using demand side flexibility is that the payback effect does not cause problems in the period $t+1$. To remove a congestion using flexibility, the DSO chooses the cheapest option between the production and the demand side if the payback effect allows its use.

The final step is the computation for the period t of the surpluses and the costs of each actors. These surpluses and costs are computed following the interaction models directives using if needed a reservation and/or an activation price for the flexibility provided. Producers earn surpluses from selling electricity at the day-ahead energy market price and must cover their marginal production costs. Retailers buy energy to the day-ahead market and earn money from the retailing activity whose tariff is fixed for the whole year. The network management costs imputable to the DSO is given by the cost of activating flexibility. A welfare is computed as the sum of the surpluses minus the costs of each actor. A penalty term is added for the production and the consumption shed assuming a value of lost production and a value of lost load.

The whole evaluation procedure was implemented in Python and run on several scenarios as detailed in the next sections.

FOCUS ON 2025

This section shows results for a one year simulation corresponding to the expectation of 2025. The maximum capacity of the network is assumed to be 40MW. The marginal production costs of producers is fixed to −45€/MWh. This cost is negative to take into account the subsidies for renewable production. The value of lost load is fixed to 1000€/MWh and the one of lost production to 500€/MWh. The flexibility prices of the producers are 20€/MW for the reservation and 45€/MWh at the activation. For the retailers, the flexibility has a reservation cost of 5€/MW and no activation cost. Remaining parameters values can be found in Table 2 for the year 2025.

The mean expected production and consumption for the simulated year are respectively 93805 and 140525MWh or a mean by day of 257 and 385MWh. The maximum production for one hour is 76.4MWh and the maximum consumption 25.1MWh. The energy production exceeding the network capacity for each day is shown in Figure 2 and is handled as explained in the previous section.

A comparison of the models is provided in Table 1 where the figures are aggregated by day. Over the year, the mean lack of capacity is 21.9MWh which represents 5.69% of the total production. Models $3-5$ obtain identical welfares as their only difference is the remuneration of the flexibility from the DSO to the producers. The flexibility from the demand side is not used by the DSO due to the imbalance costs. This is the consequence of having imbalance prices greater than prices of the production side flexibility services. In Model 5, the flexibility of the demand side is cheaper for some hours but the payback effects prevents using it.

TRENDS TO 2030

The expected evolution of the macroscopic parameters can be obtained from [11]. This report provides the development of the EU energy system under current trends and policies in the EU27 and its Member States. An evolution of the gross wind onshore generation is forecasted for 2015, 2020, 2025 and 2030 of respectively 72, 146, 204 and 276TWh. The after tax energy prices for industry should be approximately of 92, 101, 104 and 98€/MWh. The expected electricity consumption is about 3000, 3194,3370 and 3515TWh. These expected evolutions are used to obtain the parameters of our network in the horizon 2015-2030 based on the 2015 figures. The obtained expected parameters are summarized in Table 2.

Figure 3 shows the expected evolution of a system welfare for the five interaction models and the 15 years horizon. The first three years, all the models perform similarly with a difference of welfare of less than 2%. Model 1 welfare increases until 2021 then decreases constantly due to the high necessity of production shedding. By restricting the production, Model 2 achieves reasonable welfares at about 10% of the one of Models 3 to 5 for the five last years. The cumulative welfare of Model 1 and 2 are respectively 24% and 7% smaller than the one of Models 3 to 5.

As the welfare of Models 3 to 5 are identical, selecting one of these models should be based on other criteria. The main difference is the amount that the DSO pays to the producers. These models impacts the actors costs and revenues favoring either the producers or the DSO. The active network management costs paid by the DSO for the Model 3, 4 and 5 are represented in Figure 4. Model 3 achieves the minimum cost for the DSO and comes from the payment for the imbalance created by the activation of flexibility services. On the last five years, Model 4 and 5 cost respectively around 3.5 and 4.5 times more than Model 3 to the DSO. The cumulative costs of Model 3 and 4 on the whole horizon are respectively 21% and 76% of the cumulative costs of Model 5.

CONCLUSION

This paper evaluates the economic efficiency of five candidate interaction models using a macroscopic system representation. In two interaction models, DSO does not use ANM and either restrict or not the access to its network to the grid users. The three remaining models are focused on flexibility service usage for ANM and differs only on the financial compensation for the provided flexibility services. These five models are first evaluated quantitatively using expected data for a typical network in 2025 according to the expected energy trends to 2030 [11]. The economic efficiency of each interaction model is estimated on the long term by repeating the process for each year of the

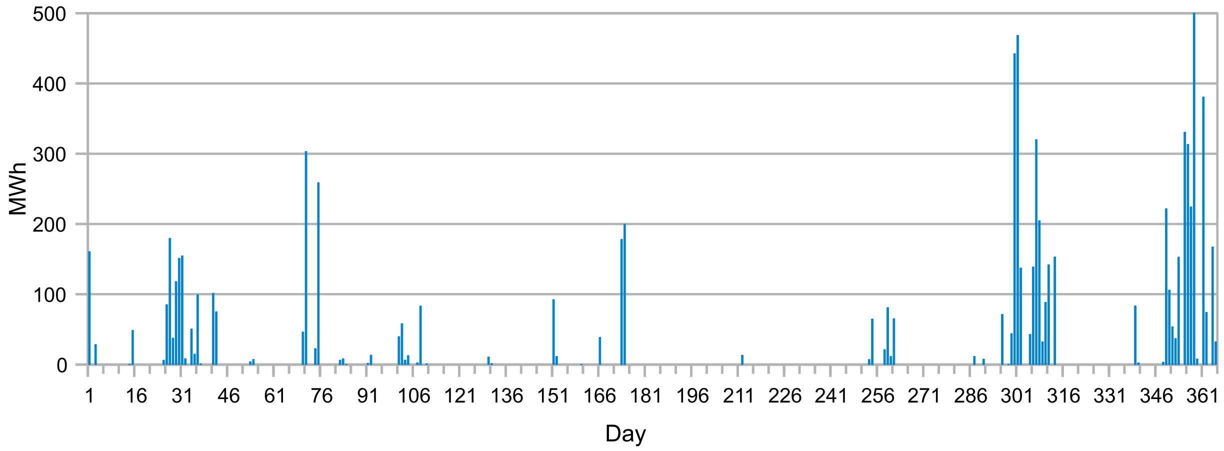

Figure 2: Simulation of the expected production exceeding the network capacity for each day in 2025.

	Model 1			Model 2			Model 3			Model 4			Model 5			
	min	*mean*	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*	
Welfare	-13903	26450	8301	-4385	34059	6221	-4385	37217	8575	-4385	37217	8575	-4385	37217	8575	€
DSO costs	0	0	0	0	0	0	-1013	389	919	-183	1358	1986	0	1789	2461	€
Producers surplus	-2031	35346	9172	-2031	32189	7070	-2031	35735	9497	-2031	36704	9957	-2031	37135	10167	€
Retailers surplus	-3347	1871	648	-3347	1871	648	-3347	1871	648	-3347	1871	648	-3347	1871	648	€
Over-capacity	0	21.5	32.9	0	0	0.5	0	21.5	32.9	0	21.5	32.9	0	21.5	32.9	Mwh
Prod. flexibility	0	0	0	0	0	0	0	21.5	32.9	0	21.5	32.9	0	21.5	32.9	Mwh
Prod. shedding	0	21.5	32.9	0	0	0.5	0	0	0	0	0	0	0	0	0	Mwh

Table 1: General hourly results for the five interaction models for the expected 2025 year.

		2015	2020	2025	2030	
Demand						
	mean	9.70	10.33	10.90	11.37	MW
	max	19.0	20.23	21.34	22.26	MW
Production						
	mean	10.0	12.84	16.04	18.68	MW
	max	40.0	51.37	64.16	74.72	MW
Electricity price						
	mean	47.45	52.09	53.64	50.54	€/MWh
	max	82.3	90.35	93.03	87.67	€/MWh
Retailing price		60.5	66.42	68.39	64.45	€/MWh

Table 2: Expected evolution of the parameters of the evaluation procedure.

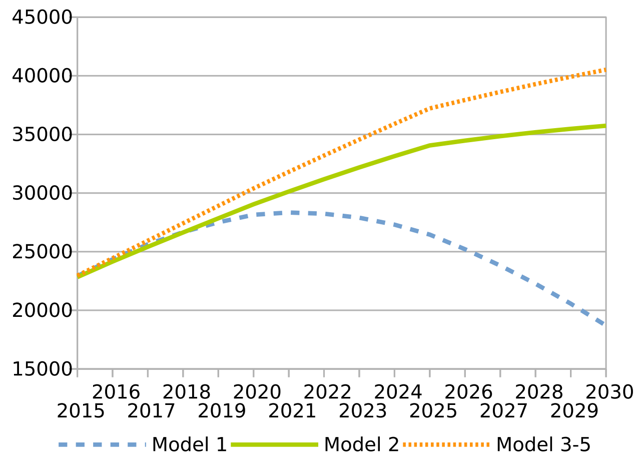

Figure 3: Mean daily welfare of the five interaction models in € for the 15 years horizon.

horizon 2015-2030 using forecasts of the evolution of the parameters of the simulation.

Results show that for the first five years, the five models provide similar economic efficiency. For the remaining ten years, active network management interaction models clearly provide higher economic efficiency. The ANM models are identical from a welfare perspective. Selecting one of these models should be based on other criteria.

These models impact the actors costs and revenue favoring either the producers or the DSO. The main difference between the models is the amount of money that the DSO pays to the producers. For instance, not remunerating the

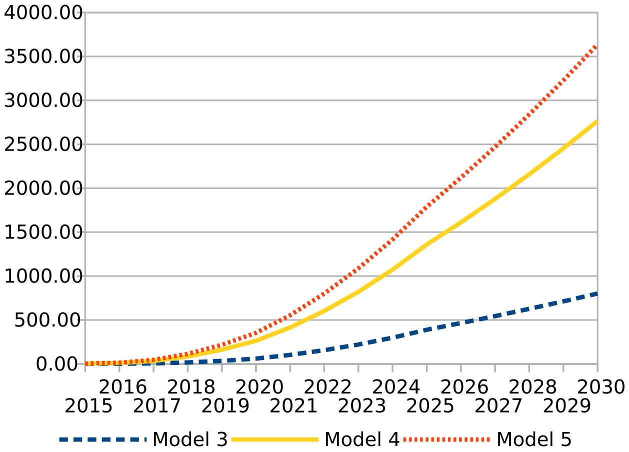

Figure 4: Mean active network management daily costs of the five interaction models in € for the 15 years horizon.

producer for the subsidies' loss due to the curtailment of a renewable generation may discourage future investments in renewable generation in distribution networks.

This quantitative analysis could be extended along several lines. The results should be put with regard to investments planning [12]. An additional study could arbitrate if putting in place the infrastructure for ANM is economically efficient. To do so, the cost of setting up this infrastructure should be evaluated. If ANM solutions are still cost efficient considering the set up cost, an additional study could obtain the best number of years to delay network reinforcement considering active network management. Finally, a more detailed investigation of the models could be considered to confirm that every party of the system behaves as expected given a set of rules. Such simulation would model the behavior of each actor individually in a specific interaction model as it is done in [8]. This detailed analysis is the object of an additional paper [13].

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