A Simulation of Market-based Non-frequency Ancillary Service Procurement Based on Demand Flexibility

Ricardo Faia, Fernando Lezama, Tiago Pinto, Pedro Faria, Zita Vale, José Manuel Terras, and Susete Albuquerque

***Abstract*—This paper proposes a novel approach for the provision of non-frequency ancillary service (AS) by consumers connected to low-voltage distribution networks. The proposed approach considers an asymmetric pool-based local market for AS negotiation, allowing consumers to set a flexibility quantity and desired price to trade. A case study with 98 consumers illustrates the proposed market-based non-frequency AS provision approach. Also, three different strategies of consumers' participation are implemented and tested in a real low-voltage distribution network with radial topology. It is shown that consumers can make a profit from the sale of their flexibility while contributing to keeping the network power losses, voltage, and current within pre-defined limits. Ultimately, the results demonstrate the value of AS coming directly from end-users.**

***Index Terms*—Demand flexibility, local electricity market, ancillary service, low-volatge distribution network.**

NOMENCLATURE

A. Indices and Sets

Ω_V	Set of voltage buses
Ω_I	Set of current lines
Ω_P	Set of power loss lines
c	Costumer
l	Line
t	Period

B. Parameters

B	Number of buses
b	Intersection with the Y-axis for linear reduction dependent strategy
C	Number of costumers
Cp_l	Unit cost of power loss
$I_{\max}$	Upper bound of current
L	Number of lines
m	Slope of the linear expression for linear reduction dependent strategy
Min^{Red}	Lower bound for reduction amount
Max^{Red}	Upper bound for reduction amount
Min^{Price}	Lower bound for reduction price
Max^{Price}	Upper bound for reduction price
$Offer^{W}_{c,t}$	Offer quantity of costumer offer c at period t
$Offer^{P}_{c,t}$	Offer price of costumer offer c at period t
$r_{c,t}$	Consumer behavior parameter for intelligent price reaction at period t
$r_{\min}$	Lower bound for consumer behavior parameter
$r_{\max}$	Upper bound for consumer behavior parameter
T	Number of periods
$V_{\min}$	Lower bound of voltage magnitude
$V_{\max}$	Upper bound of voltage magnitude

C. Variables

α_t	Number of accepted offers at period t
$AggC_t$	Aggregator costs at period t
$BonusC_t$	Bonus costs at period t
$Clearing^{price}_t$	Clearing price at period t
$C(PG)$	Production cost of thermometric generator
$FlexC_t$	Flexibility acquisition costs at period t
$I_{l,t}$	Current value in line l at period t
LC_t	Loss costs at period t
LMC_t	Local market costs at period t
OC^{DSO}	DSO operation costs
$Offer^{bin}_{c,t}$	Binary variable representing the acceptance status of costumer offer c at period t

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$P_{l,t}$	Loss value of line l at period t
$V_{b,t}$	Voltage value in bus b at period t
$WL_{l,t}$	Energy loss of line l at period t

D. Functions

$Auction(\cdot)$	Function to execute the market clearing, returning the $Clearing_t^{price}$ and the $Offer_{c,t}^{bin}$ vector
$PF(\cdot)$	Function to execute the power flow, returning Ω_V, Ω_I, and Ω_P
X~unif$(\cdot)$	Function to obtain a uniform value between two bounds

I. INTRODUCTION

NOWADAYS, renewable energy sources (RESs) connected to the distribution network are changing the system operation towards a decentralized and market-based paradigm. At the same time, the stochastic nature of RES production, which is often higher at periods of low consumption, is increasing the reserve requirements of power and energy systems, usually guaranteed by ancillary service (AS) provision. This situation results in new opportunities for the implementation of flexibility services, for instance, those related to the trading of available energy into local electricity markets (LEMs) [1], [2].

Directive 2012/27/EU (48, Art. 2) [3] defines AS as essentials for the operation of transmission and distribution systems, including frequency (frequency regulation) and non-frequency (e.g., voltage control, black start capabilities, and reactive power compensation) services. Furthermore, the definition of AS has been moving forward, also including balancing [3] and congestion management [4] services. In other words, AS can be defined as the services that support network operators to keep the electric power system at the levels that guarantee a secure operation mode.

Several initiatives are currently searching for innovative means of exploiting the flexibility of end-users, focusing on the development of full-scale demonstrators that take advantage of smart grid technologies [5], [6] and the flexibility of consumers at the local level of the distribution grid [7], [8]. In the case of Europe, financial support is currently given to the projects aiming at developing the European electricity grid through the program H2020-EU.3.3.4—a single, smart European electricity grid [9]. In fact, taking into account current regulation provided by public authorities in Europe in context of AS, we identified the following aspects as a motivation for this work: ① the Strategic Energy Technology Plan from the European Commission (EC) [10] stating that the energy consumers (and not aggregators) are envisioned at the center of the future energy power system; ② the Directive of the European Parliament and the Council on the internal market for electricity (recast) [11] proposing rules for transmission system operator (TSO) and distribution system operator (DSO) procurement of AS considering demand response (DR) providers and independent aggregators, in a non-discriminatory way; and ③ the 2030 framework for climate and energy policies from the EC [12] targeting a reduction of 40% of greenhouse gases and a 27% increase of shared RES efficiency by 2030. Also, the large penetration of Internet of Things (IoTs) devices in the electrical system provides network operators with a more suitable perception of the resources available in the distribution network. While several ASs are currently adopted at the transmission level for an effective operation of the system [13], market approaches at the distribution level are rather limited, usually leading to unfair contracting conditions for the end-users.

Thus, new market approaches need to be developed to make possible a competitive and fair acquisition of flexibility resources at the distribution level. In this work, we propose a local non-frequency AS market mechanism to support network operators (i. e., DSOs), keeping bus voltages and line currents within acceptable levels for the proper grid operation. We assume that the DSO (as the network operator of a distribution grid) procures non-frequency AS from consumers. An aggregator acting as a local market operator is still in place, but consumers can actively participate in the market putting flexibility offers according to their own interests. To this end, an asymmetric pool auction model is used for non-frequency AS negotiation considering consumers' flexibility offers. The article also explores different market participation strategies of consumers in the newly defined AS marketplace. The main contributions of this article are as follows.

1) A non-frequency AS market for small consumers and prosumers where they can actively participate offering their flexibility. The aggregator plays the role of the market operator, gathering the flexibility offers without the limitations of the amount offered.

2) A mechanism directed to the DSO aiming at keeping grid voltage and current limits within acceptable levels of operation using AS and a market-based approach.

3) The definition of three innovative market participation strategies for consumers and prosumers in the AS market.

4) The validation of the non-frequency AS market through simulation considering network constraints and a case study with 96 end-users (consumers and prosumers) connected to a low-voltage distribution network.

The remainder of this work is organized as follows. Section II presents the background and a literature review of related work. Section III presents the proposed methodology and the mathematical formulation. Section IV provides the details of the case study used in this work. Section V presents the main results and discussion of the findings. Finally, Section VI draws the main conclusions of the work.

II. BACKGROUND AND LITERATURE REVIEW

In traditional and vertically integrated power systems, large-size central power plants generally provide the AS necessary to maintain the power system security and stability. Network operators should have AS reserves for providing additional generation to meet the demand during contingencies. The rapid growth of distributed generation (DG) with intermittent characteristics brings new challenges to such an operation model. Therefore, this section presents an overview of different AS acquisition methods at the distribution level.

As pointed in [14], the term distributed AS refers to the

AS delivered by local resources in a distributed way. Thus, the imbalance between generation and demand can be mitigated at the distribution level (i.e., the distribution network) with distributed AS. Furthermore, this prevents the spread of issues to upstream power networks, ensuring the control and stability of the system [15].

The AS acquisition option considering the aggregator as a market operator and not in a central role is also in line with the motivations behind this work. Since the DSO procures AS from users connected to the distribution network, it is assumed that those end-users are equipped with the required technologies to execute demand-side management [16], [17]. DSO can use the AS for its own purpose and with different objectives. For instance, [18] considers the use of AS by the DSO for the control and operation of a micro-network. In [19], ASs are used from the supply side combining wind/battery power plant operation. We propose the use of demand side to offer AS at the local level. This attribute is in line with the future research directions of AS acquisitions, and it is an initiative that empowers end-users.

Also, the resources used for AS participation vary depending on the context and applications. For instance, buildings participating in AS markets is proposed in [20], using the AS to reduce the overall energy building costs. The use of heating and ventilation air conditioning (HVAC) system as flexibility resource is explored in [21]-[23]. AS provision by storage systems is proposed in [14], [24]-[26] while the utilization of electric vehicles (EVs) for supporting network operation is proposed in [25]. References [26] and [27] also considers EV for AS provision, but including battery degradation cost and estimating the safe amount of power that EVs can supply. In [24] and [28], PV generation is explored as a resource for AS. The PV inverters in [28] are used for reactive power and harmonic current compensation based on different control strategies applied to single-phase and three-phase PV inverters. Similarly, wind generation is used as a base for AS provision in [19], [29]. References [21], [28] and [30] also consider the acquisition of AS at a domestic level using a specific appliance, e.g., a fridge-freezer. An island operation capability AS implementation is presented in [31], which considers the modification of network topology, allowing the energy supply from distribution energy resources (DERs). This kind of approach requires installing advanced smart grid technologies, which are generally not included in conventional networks, requiring large investments to implement the solutions into practice.

Considering the literature analysis, we can classify the AS negotiation into pre-qualified auctions [20], [21], [24], incentive-based [25], [26], [30], penalized tariff as an incentive [14], voluntary participation [32], and price-signal-based [27]. In the presented work, a voluntary participation considering an action-based market is considered. Considering voluntary participation, costumers may choose to participate or not at certain times for different reasons, e.g., monetary or discomfort. Considering the voltage and current control, the following relevant works can be found in the literature [33]-[36]. A voltage regulation strategy with thermostatically controlled loads is presented in [33]; in this work, it is assumed that the aggregator directly controls the specific loads installed in the houses. This type of approach can present problems from the point of view of cybersecurity (in contrast, the presented approach does not allow direct control of any user's asset). In fact, analyzing the works covered, almost none of the methods consider a local market or similar approach to carry out the control of current. Voltage bus and line current are proposed in this work as the control variables. In fact, the control of line current was not presented in any of the referenced works.

Addressing the problem at the distribution level makes the proposed work more attractive for the participation of users, as it gives them greater freedom of participation. From the literature review, we can identify a gap related to the lack of models for implementing competitive markets localized at consumers level to trade AS. The purpose of this work is to provide a contribution to overcome the identified gap.

Table I presents a list of works related to AS acquisition at local level classifying the asset used to provide AS, the AS product, the AS type, the AS variable, and the AS negotion. References [14], [19], [24]-[29] consider DERs as an asset for AS provision. Besides, [15], [32] and [37] provide AS from the ideal operation of the system as a whole. The AS product can be divided into two major categories: frequency restoration reserve (FRR) and non-frequency. The FRR product can have two subcategories: automatic FRR (aFRR) and manual FRR (mFRR) [38].

Table I presents twelve applications for AS FRR products and 9 for the AS non-frequency products. The AS related to control reserve is classified as primary control reserve (PCR), secondary control reserve (SCR), and tertiary control reserve (TCR). This classification is not consensual among the market operators, so each can use its own. However, the classification is directly related to the time of operation and the order of reserve activation. With the analysis of the respective column in Table I, three works are identified as PCR and SCR and one as TCR. The AS variable column identifies the system variable controlled with the use of AS. The work classified with FRR in column AS product must have a frequency as AS variable. Twelve works have a frequency as AS variable and also have reactive power [28], voltage control [14], [15], [33], [34], ramping support [32], and spinning reserve [30]. Regarding the AS negotiation, the literature analysis considers four different mechanisms based on pre-qualified action, incentives, voluntary, and penalized tariff.

In addition to the simulation approaches listed in Table I, some works have explored the use of game-theory techniques [39]-[41] and bidding methods [42]-[44] for the acquisition of AS.

Reference [39] proposes a tri-layer multi-type AS market framework. Compared with the scope of the proposed work, this work does not consider the use of DSM and the AS should be procured in a non-discriminatory way. Reference [40] considers a game-theoretic planning problem for the integrated energy system (gas and electricity), considering the possibility of participation in AS. The work is conducted in a transmission network, and the participation of small electricity end-users is not allowed.

TABLE I
AS Acquisition at Local Level

Reference	Asset	AS product	AS type	AS variable	AS negotiation
[20]	Commercial building	aFRR	SCR	Frequency	Pre-qualified actions
[24]	Distributed solar batteries	FRR	PCR	Frequency	Pre-qualified actions
[25]	EV	aFRR	PCR, SCR, TCR	Frequency	Incentives
[37]	DC community	Non-frequency		Reactive power	
[28]	PV inverters	Non-frequency		Reactive power, harmonic current compensation	
[21]	HVAC systems	FRR	SCR	Frequency	Pre-qualified actions
[30]	Domestic fridge-freezer	Non-frequency		Spinning reserve	Incentives
[32]	Microgrid optimal scheduling	Non-frequency, FRR		Ramping support, frequency regulation	Voluntary
[29]	Wind farms	FRR		Frequency	
[22]	HVAC systems	FRR		Frequency	
[14]	Battery storage systems	Non-frequency, FRR		Power factor, voltage profile frequency	Penalized tariff
[15]	AC meshed MG	Non-frequency, FRR		Frequency voltage control	
[23]	Air-conditioning	FRR	PCR	Frequency	
[26]	EV	FRR		Frequency	Incentives
[27]	EV smart charging				Price signals
[19]	Wind and battery power plants	FRR		Frequency	
[31]	Network reconfiguration	Non-frequency		Generation reserve	
[33]	Thermostatically controlled loads	Non-frequency		Voltage control	
This paper	Bulk demand	Non-frequency		Voltage control and current control	Voluntary auction

A market mechanism for the real-time reactive power AS market is presented in [41]. For this work, the market is designed considering the participation of generation companies with large generation capacity, unlike the proposed approach where the market is aimed at small players, small prosumers, and consumers. Reference [42] presents a nonlinear optimization model for participation in the German primary balancing market. The problem is solved with a two-stage approach by decomposing into a nonlinear bidding problem and a mixed-integer linear scheduling problem. Due to the nonlinearity of the problem, some challenges remain open such as execution time and computation burden.

Optimal bidding strategies are considered in [43], [44]. Both works consider the participation of wind power plants and pumped storage plants in the day-ahead energy and AS markets. However, these works only consider bids on the generation side and do not include participation in the down-regulation services, unlike the proposed approach that allows the participation on the demand-side bids.

The precision in interaction protocols is required by game theory whereas in the real world they are often ambiguous. The game theory frequently offers a large number of equilibria with no method to select from them; it is unable to explain how people respond to competing theories in dynamic interactions. The idea is unable to explain how a given game's rules came to be as they are [45].

III. Proposed Methodology and Mathematical Formunlation

This section presents the proposed methodology that focuses on using the non-frequency AS market, considering the coordination between DSO and an aggregator. The DSO will use non-frequency AS to operate the distribution network within rated parameters, acting as a network operator. Issues can appear in the network operation where the operation parameters overreach the limits; in this case, we consider a violation of the network operation parameters. The aggregator is responsible for organizing the selection of resources (consumers providing DR) in the non-frequency AS procurement process.

Figure 1 presents the sequential diagram of the proposed methodology. Three different players and their interactions are identified in Fig. 1. Such interactions between players do not exist when flexibility is not required. The two different algorithms are referenced in the sequential diagram, one for day-ahead, and the other for real-time.

Algorithm 1 consists of a day-ahead analysis and non-frequency AS procurement, which consists of selecting potential consumers to reduce their consumption, according to the forecasted operation parameters. Algorithm 2 describes the process of real-time non-frequency AS activation, where the selected consumers are notified to reduce their consumption. Thus, Algorithm 1 is a process repeated each day.

Algorithm 1 starts with the available forecast of energy consumption for the next 24 hours, which can be performed by DSO, or contracted to other entity. With the forecasts of demand and generation, DSO runs the power flow (*Step 2*). Considering the power flow results, the DSO identifies the periods when problems with the control parameters can occur (*Step 3*). For each period when it is the identified violation, the DSO requests the pre-acquisition of non-frequency AS in the market (*Step 5*). The aggregator (working as market operator) selects the offers according to an asymmetric pool auction procedure (*Step 7*).

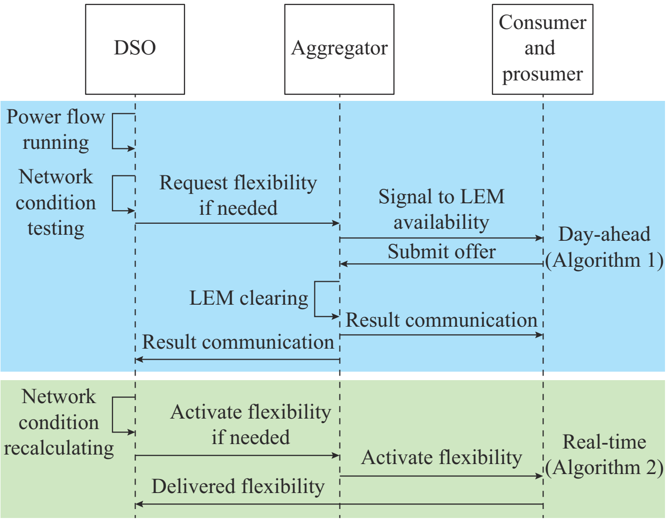


Fig. 1. Sequential diagram of proposed methodology.

Algorithm 1: day-ahead analysis and non-frequency AS procurement

```
1:  Available forecasts of energy consumption for the next 24 hours
2:  DSO, based on forecasts, runs power flow of the distribution network
3:  DSO checks control parameters
4:  If control parameters are unbounded then
5:      Request the pre-acquisition of non-frequency AS in the market
6:      Aggregator performs auction qualifications for each necessary period
7:      Procedure asymmetric pool auction
8:          Connected users submit offers of flexibility
9:          Accepted offers determine non-frequency response
10:     Aggregator communicates to DSO the results of the pre-auction
11: Else
12:     Request is not performed
```

When the non-frequency AS providers present their offers, each offer is composed of an amount of amount flexibility (for energy reduction in context of DR) and a price. The aggregator (the entity responsible for the process with non-discriminatory functioning) organizes the bids using a merit order procedure, starting with the lowest price and moving up. The non-frequency AS providers reveal their offers to set up the reduction in their consumption. Once the aggregator knows the request from the DSO, it accepts as many offer bids as needed to fulfil the request, starting from the lowest price. After the pre-acquisition process, the aggregator will communicate the offers' selection results to the DSO.

This process is repeated each day for the 24 hours of the following day, as shown in Algorithm 2.

Algorithm 2 is executed period by period and starts with the updated forecasts (*Step 1*). This process is necessary due to the accuracy of the forecasting methods. Forecasting errors can influence the activation of the non-frequency AS, as they can create a variation in load and production that is initially expected. DSO re-executes the power flow analysis and checks the control parameters of the system (*Step 2*).

Algorithm 2: real-time non-frequency AS activation

```
1: Updated forecasts for next period
2: In real time, DSO re-executes power flow analysis
3: If control variables are unbounded then
4:     DSO sends the non-frequency AS activation signal to the aggregator
5:     Aggregator activates the non-frequency AS
6:     Providers deliver the non-frequency AS
7: Else
8:     Non-frequency AS is not activated
9: Aggregator notifies DSO about the availability and provision of non-frequency AS
```

If the violations persist, the DSO sends the non-frequency AS activation signal to the aggregator who activates the non-frequency AS among providers (*Step 4*). In a later stage, the aggregator notifies the DSO about the availability and provision of non-frequency AS to proceed with the payment of services (*Step 9*).

Equation (1) represents the DSO operation costs.

$$OC^{DSO} = \sum_{t=1}^{T} \left(LC_t + LMC_t \right) \tag{1}$$

Equation (2) represents the calculation of loss costs.

$$LC_t = \sum_{l=1}^{L} \left(WL_{l,t} \cdot Cp_l \right) \quad \forall t \in T \tag{2}$$

Equation (3) represents the local market costs at period t.

$$LMC_t = FlexC_t + AggC_t + BonusC_t \quad \forall t \in T \tag{3}$$

Equation (4) represents the cost of the pool market.

$$FlexC_t = \sum_{c=1}^{C} Offer_{c,t}^{W} \cdot Clearing_t^{price} \cdot Offer_{c,t}^{bin} \quad \forall t \in T \tag{4}$$

$Offer_{c,t}^{W}$ and $Offer_{c,t}^{P}$ are considered the inputs for the problem while $Offer_{c,t}^{bin}$ are decision variables. The decision variables are presented in (5), and are composed by a binary operator indicating the acceptance of an offer:

$$Offer_{c,t}^{bin} = \begin{cases} 1 & \text{offer is selected} \\ 0 & \text{otherwise} \end{cases} \quad \forall c \in C, \forall t \in T \tag{5}$$

where $Offer_{c,t}^{bin} = 1$ means that offer c at period t is selected for DSO and $Offer_{c,t}^{bin} = 0$ means not selected.

Variables $Offer_{c,t}^{bin}$ and $Clearing_t^{price}$ are obtained using the function presented in (6). The asymmetric pool auction model is one of the pool models applied in market trading (different to the symmetric model). In the case of the asymmetric model, only offers, i. e., players' demand, are received and there is only one buyer with a defined quantity without a defined price.

$$\left(Clearing_t^{price}, Offer_{c,t}^{bin} \right) = Auction\left(Offer_{c,t}^{W}, Offer_{c,t}^{P} \right) \tag{6}$$

The results obtained from the function described in (6) have a direct impact on the corresponding values of operation costs calculated with (1). The inputs for this function are offers with energy and price information. With this information, it is possible to obtain the flexibility amount available in each customer and new values for customers' load are available. This function $Auction(\cdot)$ (as mentioned in *Step 7*, Algorithm 1) receives the inputs and returns as outputs the clearing price and the corresponding accepted offers. In the first step, the offers are sorted in ascending considering the price, and the accumulated quantity of electricity is added. When the accumulated quantity equals the requested quantity, the clearing price is determined by the price of the offer that matches the requested quantity, and all orders below this quantity are accepted. In this particular case, the required quantity is determined iteratively until the restrictions are met.

Equation (7) represents the remuneration of the aggregator.

$$AggC_t = 0.05 \times FlexC_t \quad \forall t \in T \tag{7}$$

With (7), the remuneration for the aggregator corresponds to the percentage of the total amount paid considering the offers accepted [46]. Equation (8) presents the bonus remuneration for the players' participation.

$$BonusC_t = a^{\frac{\alpha_t}{b}} C\left(PG_t\right) \quad \forall t \in T \tag{8}$$

where $a=0.5$; $b=6$; α corresponds to the number of accepted offers; and $C\left(PG_t\right) = 2b_{chp}\sqrt{PG}_t$ with $b_{chp}=0.2$ €/kWh corresponds to the thermometric generator's production cost to generate the equivalent energy to aggregator request [47]. The bonus calculation equation is an additional mechanism to encourage players to make better offers. The total bonus amount is obtained depending on the number of offers accepted. The greater the number of offers accepted, the lower the bonus amount. So, this mechanism can lead players to perform better offers with the intention of receiving a larger amount in this component.

The local market mechanism is used if the conditions of (9) and (10) are violated. Equation (9) represents the conditions imposing bus voltage magnitude limits, and (10) represents the condition that imposes the upper bound for current of lines.

$$V_{\min} \le V_{b,t} \le V_{\max} \quad \forall b \in B, \forall t \in T \tag{9}$$

$$I_{l,t} \le I_{\max} \quad \forall l \in L, \forall t \in T \tag{10}$$

To verify the conditions imposed, it is necessary to obtain the $\Omega_V = \left[V_{b,t}\right]$ and $\Omega_I = \left[I_{l,t}\right]$. For this, the forecast of customers load is updated considering the accepted offer, after applying (11). We assume that a power flow function is available to validate the network state (i. e., network constraints) at any moment. Therefore, a power flow function is defined as [48] shown in (11), which has been mentioned in *Step 2* of Algorithm 1.

$$\left(\Omega_V, \Omega_I, \Omega_P\right) = PF(\cdot) \tag{11}$$

$PF(\cdot)$ receives the information of load consumption and grid information (lines, buses, transformers, generators), and returns $\Omega_V = \left[V_{1,t}, V_{2,t}, \ldots, V_{B,t}\right]$, $\Omega_I = \left[I_{1,t}, I_{2,t}, \ldots, I_{L,t}\right]$, and $\Omega_P = \left[P_{1,t}, P_{2,t}, \ldots, P_{L,t}\right]$. This function is used to validate the network status at each time $\forall t \in T$. With the information returned by the power flow function, (9) and (10) can be validated. To run the $PF(\cdot)$ function, pandapower.runpp module from the pandapower [48] package installed in the Python software is used. The pandapower package can be installed and used on every platform with an installation of Python 2.7 or higher. The pandapower.runpp model allows to obtain a balanced AC power flow with different algorithms. For this work, the "bfsw" backward/forward sweep algorithm is used since it is recommended for distribution networks. For instance, [49] also uses the pandapower package to obtain power flow results and validate results.

IV. CASE STUDY

In the simulation process, we consider 24 periods with 1 hour of duration, the voltage limits are set to be $V_{\min}=0.95$ and $V_{\max}=1.05$, $I_{\max}$ is specific for each line, and Cp_l is 0.02 €/kWh. We consider consumers (households) complying with the actual Portuguese legislation, which allows a small amount of generation (consumers with local generation) to be used for their own energy needs and brings excess energy to the power grid. Each one of the consumers is equipped with controllable loads that can be used to reduce the total energy consumption when needed. According to the actual EU targets [12] regarding the increase in electricity production by renewable sources, we decide to create two different scenarios as follows.

1) Scenario A corresponds to the simulation considering the real configuration of the distribution network with 2 DG units.

2) Scenario B corresponds to the same network configuration of scenario A, but considers the inclusion of more 31 DG units corresponding to 33 DG units based on PV generation.

These scenarios are used to test the influence of DG in the presence of a violation of network operation limits. While the location of DG has an impact on the operation costs, the optimal location of DGs is out of the scope of this work and opens an interesting line for future research. Figure 2 presents the accumulated consumption and generation profiles used in the experiments.

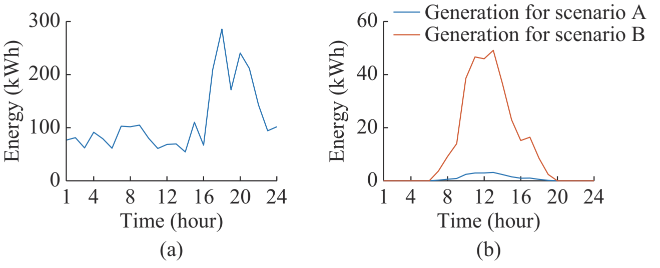


Fig. 2. Consumption and generation. (a) Accumulated consumption. (b) Accumulated generation.

In Fig. 2(a), the consumption profile presents a peak of 285 kWh at 18:00. Figure 2(b) presents two different electricity profiles generated, one for scenario A and the other for scenario B. The increment of generation is visible in the figure when scenario B is used to perform the simulations.

A. Grid Configuration

The proposed methodology is simulated using the data from a real low-voltage distribution network presented in [50]. The network is connected to a medium-voltage distribution network, rated 50 Hz of frequency, operating in radial topology.

The network contains 237 buses in total, from which 236 are at low-voltage level (0.4 kV) and 1 is at medium-voltage level (20 kV). All 98 loads at low-voltage level are considered resistive loads.

The network also has 2 distributed generators located at buses 79 and 226, based on PV technology. The number of lines is 235 (with a total of 3146 m). The transformer presented between bus 0 and bus 1 is rated 0.4 MVA, 20 kV/0.4 kV. We consider the external source bus 0 as the reference for simulation tests.

B. Offer Definition

The consumer offers used for participating in the local non-frequency AS provision are composed by the amount of load reduction (kWh) and a price (€/kWh). We consider that each consumer connected to the distribution network can reduce 30% of their total consumption in each hour. To create the amount of reduction for each consumer, (12) is obtained.

$$Offer_{c,t}^{W} = X{\sim}unif\left(Min^{Red},\ Max^{Red}\right) \quad \forall c \in C, \forall t \in T \tag{12}$$

where $X{\sim}unif\left(Min^{Red}, Max^{Red}\right)$ represents a uniform distribution between Min^{Red} and Max^{Red}. In the creation of the offer, we consider $Min^{Red} = 0$ and $Max^{Red} = 0.3$ for the referred consumption.

Regarding the price, three different strategies are considered. These strategies aim to simulate the behavior of the consumer regarding the available amount of consumption reduction as follows.

1) Random Creation (Strategy 1)

This strategy considers a random creation. The consumer does not react to the energy reduction amount. The offer prices are simulated considering a uniform distribution:

$$Offer_{c,t}^{P} = X{\sim}unif\left(Min^{Price},\ Max^{Price}\right) \quad \forall c \in C,\ \forall t \in T \tag{13}$$

The value for Min^{Price} is 0 €/kWh and for Max^{Price} is 0.02239 €/kWh (the value corresponds to the mean day price of MIBEL spot market on 06/05/2020).

2) Linear Reduction Dependent (Strategy 2)

This strategy considers a consumer reaction to the amount proposed for reduction. It is considered that a higher reduction causes a higher impact on the comfort, and the reduction price should be increased. Equation (14) represents the offer price definition of strategy 2.

$$Offer_{c,t}^{P} = m \cdot Offer_{c,t}^{W} + b \quad \forall c \in C, \forall t \in T \tag{14}$$

$$m = \frac{Max^{Price} - Min^{Price}}{Max^{Red} - Min^{Red}} \tag{15}$$

3) Intelligent Price Reaction (Strategy 3)

The last strategy provides an improvement based on strategy 2. This strategy also considers a comfort impact reaction, but the consumers adapt their offer price according to their behavior. Two different behaviors are considered: the consumer accepts a reduction of the offer price (anxious), and the consumer increases the offer price (ambitious). To model this strategy, (16) is considered.

$$Offer_{c,t}^{W} = \left(m \cdot Offer_{c,t}^{W} + b\right) r_{c,t} \quad \forall c \in C, \forall t \in T \tag{16}$$

$$r_{c,t} = \begin{cases} X{\sim}unif\left(r_{\min}, 1\right) & c \text{ is anxious} \\ X{\sim}unif\left(1, r_{\max}\right) & c \text{ is ambitious} \end{cases} \quad \forall c \in C, \forall t \in T \tag{17}$$

For $r_{\min}$ and $r_{\max}$, we chose 0.7 and 1.10.

Figure 3 presents a demonstrative example to explain the mechanisms behind of the bonus attribution. The example considers 30 players with 50 kWh of flexibility needed and the production costs from a thermoelectric are equal to €2.52.

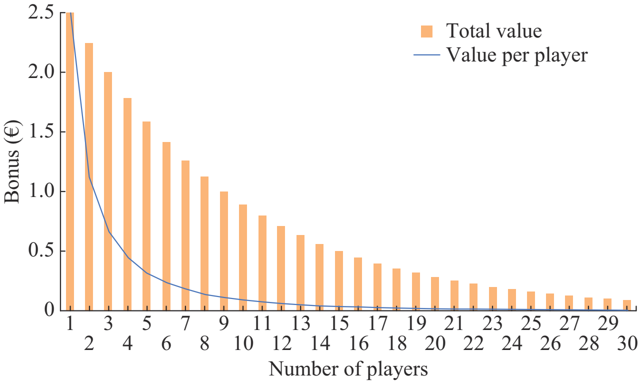


Fig. 3. Demonstrative example.

It is possible that two different results can be obtained by analyzing Fig. 3. Suppose that to achieve 50 kWh, the 30 players make reduction offers, and 15 of them together manage to reach the required value. These 15 players receive €0.5 in a total bonus, and each one receives €0.03. If the requirements are met with 7 bids, the players would receive a higher amount bonus (total: –€1.26, individual: –€0.18).

C. Simulation Parameters

Table II presents the simulations parameters used in the case study.

TABLE II
SIMULATION PARAMETERS

Parameter	Value	Reference	Parameter	Value	Reference
$V_{\min}$	0.95 p.u.	[51]	Min^{Price}	0	
$V_{\max}$	1.05 p.u.	[51]	Max^{Price}	0.02 €/kWh	[52]
$I_{\max}$			$r_{\min}$	0.70%	
Min^{Red}	0	[50]	$r_{\max}$	1.10%	
Max^{Red}	0.30%	[50]			

$I_{\max}$ bounds are specific for each line, and the lower bound of the reduction price is considered 0 €/kWh. The values of $r_{\min}$ and $r_{\max}$ to reduce or increase the price considering the player behavior are 0.7% and 1.1%, respectively. These values are chosen based on the authors' experience in the field.

V. RESULTS AND DISSCUSSION

To better organize the results, Section V-A presents the results of the day-ahead analysis where the periods with violations are identified, and the non-frequency AS procurement is made; Section V-B presents the results of the non-frequency AS activation in real time and the influence of non-frequency AS activation is analyzed; and Section V-C presents a discussion of the results using the proposed methodology.

A. Day-ahead Analysis and Non-frequency AS Procurement Results

The results of the day-ahead analysis considering the forecast for the day ahead are presented in this subsection. Table III presents the energy share results considering all 24 periods in the two scenarios.

TABLE III
ENERGY SHARE RESULTS

Categray	Scenario A			Scenario B			Difference
	Active component (kWh)	Reactive component (kvarh)	Apparent energy (kVAh)	Active component (kWh)	Reactive component (kvarh)	Apparent energy (kVAh)	
Power loss	88.32	70.07	112.74	82.93	62.85	104.05	8.69
External	2797.18	70.07	2798.05	2502.11	62.85	2502.90	295.16
DG	19.70	0	19.70	309.38	0	309.38	289.68
Total load	2728.56	0	2728.56	2728.56	0	2728.56	0
Load (average)	27.84	0	27.84	27.84	0	27.84	0

Table III presents the active component, the reactive component and the apparent energy for the losses, external supply, DG production and total load. As can be seen, all reactive power injected into the network in both scenarios is used to cover the reactive losses in the lines. In scenario B, the reactive power is lower than that in scenario A, due to the influence of DG production. We assume that loads have only active component, which results in active energy consumption in both scenarios with equal values. The average load presented in the Table II is done over the 98 loads. If we consider the total number of periods presented in the case study, each load has an average consumption of 1.16 kWh per period.

Checking the network status according to the results of power flow, the condition of (9) is violated 17 times at 18:00 for scenario A, considering that scenario B under the same condition is violated 16 times during the same period. Only one period is identified with magnitude buses with violations in both scenarios. No violations are found considering the condition of (10) for the upper bound of current limits. Considering the results of (9) for scenario A at 18:00, the buses with magnitude violation are: 215, 218, 220, 223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233, 234, 235 and 236. Regarding scenario B at 18:00, the buses with magnitude violations are the same as for scenario A except for bus 215. In buses identified with violations, buses 223, 224, 226, 231, 233, 234 and 236 are load buses. Table IV presents the summary results of violated bus group at 18:00.

TABLE IV
SUMMARY RESULTS OF VIOLATED BUS GROUP

Scenario	Violated bus group		
	The maximum (p.u.)	The minimum (p.u.)	Average (p.u.)
A	0.9496	0.9380	0.9411
B	0.9480	0.9401	0.9426

Once the periods with violations have been identified, the DSO requests non-frequency AS pre-acquisition in the market. The aggregator is responsible for carrying out the offer selection process. This subsection presents the results for offer selection considering the different strategies to create the offers. Table V presents the comparison results of pre-acquisition offers at 18:00.

TABLE V
COMPARISON RESULTS OF PRE-SELECTION OFFERS AT 18:00

Scenario	Strategy	Total offers	Total offer amount (kWh)	Accepted offers	Selected amount (kWh)	Clearing price (€/kWh)	Offer cost (€)
A	1	98	55.75	69	39.14	0.013	0.513
	2	98	55.75	75	39.10	0.015	0.579
	3	98	55.75	68	32.65	0.014	0.471
B	1	98	54.25	67	36.80	0.012	0.459
	2	98	54.25	56	26.27	0.013	0.332
	3	98	54.25	56	25.21	0.013	0.322

Table V shows the results for scenario A and scenario B, considering all acting strategies. In both scenarios, all strategies present 98 offers. The total offer amount in scenario A is 55.75 kWh, and that in scenario B is 54.25 kWh. The difference in the values between the two scenarios is related to the total load consumed in each scenario. In both scenarios, the offer bid amount is equal in terms of percentage. Moreover, the offer amount in kWh is different because in scenario B with inclusion, the higher value of DG, the load of some consumers decreases.

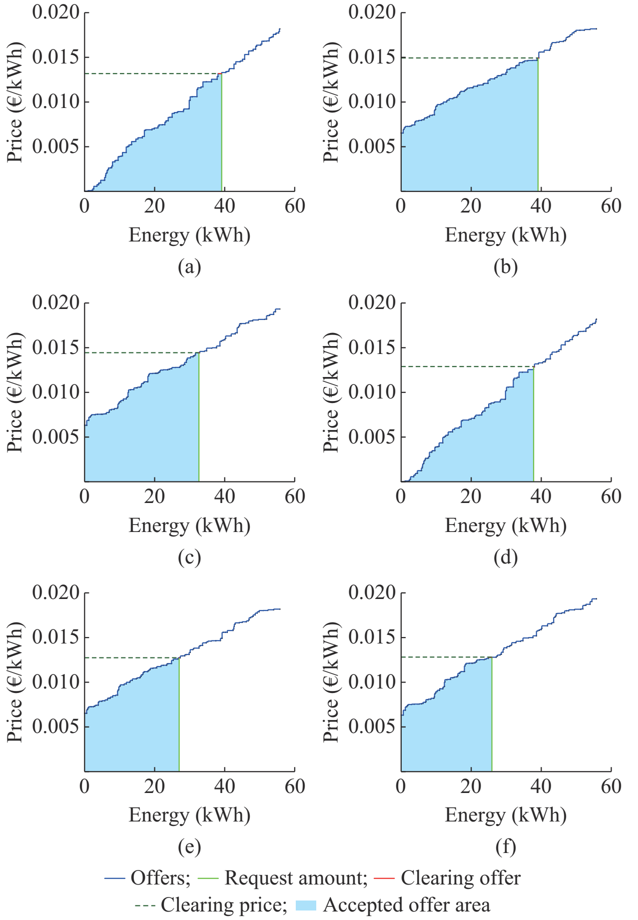
The offers consist of a reduction amount and a price, as shown in the Fig. 4. Depending on the pricing strategies, the amount is always the same, and the price varies depending on the strategy used. Considering scenario A, the number of accepted offers is different for the different strategies adopted. Strategy 2 presents the higher value of offers accepted, but it presents the smallest selected amount with 39.10 kWh, while presenting the higher clearing price and the higher costs. In this case, strategy 2 presents the bids with comfort effect when the higher value of offer amounts presents higher values of offer prices. The higher offer prices cause an increment in the clearing price. Comparing the strategy 3 with strategy 2, a small number of accepted offers and selected amount are verified. As it is explained, in strategy 3, the offer prices suffer a change, when in this case, the buses with violations adopt a benevolent behavior. With the benevolent behavior, the prices of these buses decrease, and they are accepted making lower clearing price and selected amount. In this scenario, the use of strategy 3 brings benefits for the DSO, reducing the offer costs used for the non-frequency AS acquisition.

In scenario B, the differences between strategy 2 and strategy 3 are reduced. In this scenario, the tendency between strategies does not repeat. Strategy 1 presents higher values in all sub-categories. Comparing the strategy 2 and strategy 3 presents the same number of accepted offers, although accepted offers are different sets. It is found that the sets are different because the offer amount accepted is different, and if the sets are the same, they would require having the same accepted amount. In the accepted offer, strategy 3 presents a value slightly lower than that of strategy 2. The clearing price (strategy 2 and strategy 3) in Table V is equal, but the values have a small difference (1.34×10^{-4}). Considering the offer costs, strategy 3 also presents the smallest value, as shown in scenario A.

In Fig. 4, the graphical results from the asymmetric pool market are presented. Figure 4(a) and (d) represents the strategies where the offer prices are randomly created, bringing the prices close to zero.

B. Real-time Non-frequency AS Activation Results

This subsection presents the non-frequency AS activation results in real time.



(a) (b) (c) (d) (e) (f)

Fig. 4. Graphical results from asymmetric pool market. (a) Scenario A, strategy 1. (b) Scenario A, strategy 2. (c) Scenario A, strategy 3. (d) Scenario B, strategy 1. (e) Scenario B, strategy 2. (f) Scenario B, strategy 3.

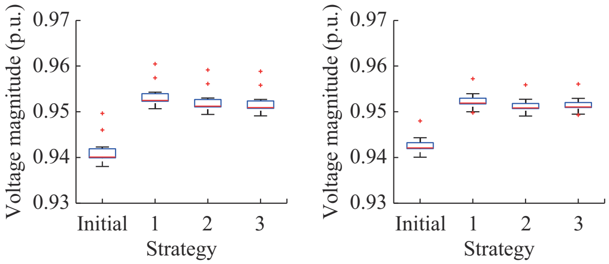
The results presented are obtained for each hour and shown for all periods together. As it is stated in *Step 1* of Algorithm 2, the forecast is updated at each hour and DSO re-executes the power flow analysis to test the control variables. After the 24-period simulation, it was verified an average error of 0.350 kWh of the hourly total consumption regarding the forecasted value. For the total generation in scenario A, an average error of 0.038 kWh is verified, and in scenario B, the average error is 0.008 kWh. Considering the resulting power flow analysis, the DSO activates the selected AS. Table VI presents different components of operation cost.

TABLE VI
DIFFERENT COMPONENTS OF OPERATION COST

Scenario	Strategy	Loss cost (€)	Flexibility cost (€)	Aggregator cost (€)	Bonus cost (€)	Operation cost (€)	Difference (€)	Time (s)
A	Initial	2.29	0	0	0	2.29		
	1	2.18	0.51	0.02	0.0025	2.72	0.44	11.20
	2	2.19	0.57	0.02	0.0011	2.80	0.51	11.89
	3	2.20	0.47	0.02	0.0026	2.70	0.41	11.11
B	Initial	2.13	0	0	0	2.14		
	1	2.04	0.45	0.02	0.0032	2.53	0.36	11.03
	2	2.06	0.33	0.01	0.0121	2.43	0.29	8.76
	3	2.07	0.32	0.01	0.0124	2.42	0.28	8.65

The column with initial in Table VI presents the initial operation costs with violations at 18:00, as shown in Section V-A. Notice that the operation costs presented by the different strategies are both larger than those initially presented. However, this increase in cost is justified since the solution now presents no violations. The initial loss costs are also higher than those presented by the different strategies in both scenarios, but this only reflects a different transit of power in the network. Considering the results of flexibility acquisition is already commented in Section V-A. The aggregator costs have a direct relationship with the amount of selected energy, so if more energy is selected a greater fee, he will receive. The bonus should be distributed to the consumers with accepted offers. Strategy 3 gets a greater value of the bonus. This strategy is characterized by the adjustment of the offer prices, considering the behavior adopted by the consumer. When the consumers located in buses with violations adopt the benevolent strategy, their offers have higher acceptance possibility. The system resolves the problems with less costs and the consumers receive a great value of the bonus. Strategies in both scenarios can solve the problem, as can be observed by Table VI. Strategy 3 presents the smallest operation costs and the smallest differences with the operation costs of initial analysis with violations, which achieves an average time of 10.44 s to run the scenarios. Regarding this time, consider all processes from initial analysis, selected offers, and final analysis with offer activations. In order to compare the value, we reduce the number of buses and lines to 1/3 and 2/3 of the actuals, and the resolution time are 2.17 s and 3.21 s, respectively. The time values achieved are less than half, but in the run scenarios, the process of selection bids is not executed because there are no problems with grid operation.

Figure 5 presents the boxplot analysis for magnitude voltage comparison for the buses with violations at 18: 00 as identified in Section V-A.



(a) (b)

Fig. 5. Magnitude voltage comparison for buses with violations. (a) Scenario A. (b) Scenario B.

The figure presents the distribution of magnitude voltage values considering minimum, first quartile, median, third quartile and maximum. Boxplot with label "initial" represents the distribution of magnitude voltage considering the network's initial state in both scenarios. As shown in Fig. 5, all values are below the minimum limit of magnitude voltage (0.95 p.u.). Figure 5 shows that with the use of the different strategies in both scenarios, the violations can be avoided, and all the minimum limits are above the 0.95 p.u.. Considering strategy 1, where the greater offer amount is selected, the improvements in the voltage magnitudes are more visible, yet need more costs for the AS acquisition.

C. Discussion

Considering different offer strategies used to simulate consumer behavior, for strategy 1, although the network violations are avoided, the results are the worst. Strategy 2 creates the offer prices considering a linear expression. The use of linear expression tries to simulate the comfort influence felt by the consumer. In this strategy, the consumers with small offer amounts also have small offer prices. Strategy 3 tries to simulate the intelligent behavior of the consumers. Thus, when the consumers are located on buses with problems, they reduce their offer prices with the intention that these will be accepted before the others. The created case study envisages the participation of consumers, reducing their load consumption when the aggregator requests flexibility. Two different scenarios have been explored to study the influence of DG production. As the results show, the number of accepted offers decreases with this strategy, incrementing the bonus. The final results show that violations can be avoided by using the non-frequency AS provided by consumers. Comparing the results at 18: 00 (the period where the non-frequency AS was activated), the initial costs are lower than the costs when violations are avoided. The merit of using the three different strategies is the ability of the aggregator to catch the different negotiation profiles from end-users to maximize the profit of the implemented market by adjusting the operation to the different negotiation contexts.

VI. CONCLUSION

The non-frequency AS acquisition at low-voltage level has been explored as a solution to solving the issues that may arise in distribution networks. This paper presents a methodology for non-frequency AS acquisition in low-voltage distribution networks, and three different strategies for the creation of offer prices are implemented and compared. The simulation is performed using real attributes of a distribution network located in Portugal. The use of non-frequency AS by DSO brings advantages to the quality of operation and payments for consumers due to the non-frequency AS provision. Considering the DSO role for operating the distribution networks with control variables between limits, the simulation demonstrates that marker-based non-frequency AS at the local level is a good option for enabling the active participation of consumers and guaranteeing a smooth grid operation. This work opens different research lines that are worth following as future work. For instance, it is interesting to study different market structures that allow the participation of final consumers to discover suitable market structures for the benefit of all participants. Another relevant line of research is related to the optimal location of DG to minimize the voltage and line violations. The consideration of different assets in the power grid and distributed resources (e. g., electrical vehicles and store systems) and their impact on operation costs under the proposed framework is another line of research. Finally, the possibility of extending this approach to networks with different voltage levels is also an idea for future work. In this case, a possible approach would be to divide the network into different clusters, each with a different market operated by a different aggregator.

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