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Ancillary Services 4.0: A Top-to-Bottom Control-Based Approach for Solving Ancillary Services Problems in Smart Grids

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ABSTRACT Power systems are experiencing a large amount of renewable generation with highly stochastic and partly unpredictable characteristics. This change in energy production implies significant consequences related to the provision of ancillary services (AS). Current markets dedicated to the provision of AS are not able to benefit from the flexible energy resources. They also cannot cope with the new level of stochasticity, non-linearity, and dynamics of generation and flexibility. To overcome such issues and exploit the potential of flexibility resources, a new strategy is required. In this paper, by capitalizing on flexibility resources' potential, AS 4.0 approach is proposed, which offers a comprehensive solution for the AS provision in the smart grid era.

INDEX TERMS Ancillary services 4.0, flexible retail electricity price, smart grid, power system operation, peer-to-peer, control-based approach.

I. INTRODUCTION

Power systems are experiencing high penetrations of renewable generation, with stochastic and mainly unpredictable characteristics. According to the Global Wind Energy Council, the global wind energy capacity reached 486.5 GW in 2016, meanwhile this is expected to double by 2021 [1]. Larger share of renewable energy sources (RES) in the generation mix introduces an unprecedented level of complex dynamics and non-linearity because of its dependency on meteorological variations [2]. To guarantee the service continuity, the complexity must be properly handled by the system operators (SOs) in real-time. Unfortunately, this is not always possible for the SOs, as their current practices have not being designed to handle high penetrations of RES. For this reason, an increase in complexity will dramatically affect the service, with consequences to the power system operation (e.g., increasing number of outages [3]) and to the ancillary services (AS) provision (e.g., inflating AS prices [4]).

AS consist of a variety of operations, beyond the generation and transmission, that guarantee service continuity and security from the distribution (e.g., voltage regulation) to the transmission level (e.g., frequency regulation and congestion management). The AS required capacity is procured through conventional market mechanism, i.e., bidding and clearing procedure. This mechanism has been originally implemented to deal with real-time operational issues in conventional power systems. In such a framework, time-varying bids are received every couple of minutes, and the market is cleared accordingly to obtain price and quantity values. The changing market prices reflect the true condition of the grid over time. This approach, which is implemented exclusively at the transmission level, works satisfactorily in case of conventional power systems with low RES penetration (below 30%) [5]. However, when the stochasticity and the dynamics of the generation resources become prominent, the existing AS mechanism becomes less effective, as it does not deal with the new complexity. Higher penetration of renewable energy causes an overall increase of under- and over-frequency events, which requires a higher amount of AS [6]. To avoid costly and environmentally unfriendly capacity reserves for AS provision [7], flexible resources (FRs) found to be a promising solution, by modifying their usual behaviour according to

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the need of the grid. While different studies have already shown the great potential of FRs [8], their application has been undermined because of the existing AS mechanisms, which do not allow a wider utilisation of FRs. Structurally, existing AS mechanisms prohibit FRs at the distribution level from participating in the market, as this is designed only for the resources at the transmission level. Moreover, expanding the existing AS platforms to millions of flexibility entities located at the distribution level would require extraordinary control and computational power. Such a condition is neither practical nor desirable.

Furthermore, an effective solution for the future AS provision should be able to accommodate energy system integration (ESI) concept [9]–[11], as yet another possibility to achieve higher levels of flexibility. ESI takes advantage of the synergies between different energy carriers, e.g., electricity, gas, and heat, to ensure safety and continuity of the service [12]. It provides flexibility and potentially increases the efficiency of the energy system as a whole. In this framework, different assets from various energy carriers are required to combine their strengths to optimally work together [13]. Unfortunately, the existing operational strategies in power system operation do not offer capabilities to integrate multi-energy carriers in a single framework.

To guarantee service continuity and security in spite of the increasing penetration of the intermittent resources, it will be necessary in the future to include every FR into the AS provision [14]. In order to exploit the flexibility potential to the maximum extent, and for the benefit of power system operation, new AS provision mechanisms should be developed. These solutions are a trade-off between computational complexity and simplification without compromising the efficacy. In this paper, we propose a new framework for the AS provision in the future smart grid. The proposed approach holistically changes current practices in the AS market. The structure is based on a hierarchy of nested control problems. It allows participation of every flexibility at various levels of the grid by developing time-varying electricity prices. To the best of our knowledge, no previous study has approached AS provision through the adoption of control problems.

The paper is organised as follows: Section II introduces AS and their role in electricity supply service. Section III focuses on the existing alternatives to the AS market. Section IV introduces the proposed approach of Ancillary Services 4.0 and the necessary tools and methods to implement the new mechanism. Ultimately, the paper is summarised in Section V, where we outline the main findings and suggest future focuses and practical applications.

II. ANCILLARY SERVICES (AS)

In presence of equipment outages and generation/consumption variations, it is fundamental for the power system operation to maintain the balance between generation and demand momentarily. This condition guarantees secure and efficient operation of the power system by adequately responding to the frequency and voltage deviations. At the distribution level, local varying generation and consumption units inject/absorb active and reactive power into/from the system, provoking deviations in the voltage level. At the transmission level, frequency is affected by any mismatch between generation and demand accounting for transmission losses. As a result, frequency and voltage vary with the amount of generation and demand in real-time. For inadmissible values, operation continuity and system stability are compromised. Also, frequency and voltage deviations threaten synchronous operations of the generator machines, which can cause widespread blackouts in the grid. In fact, the number of power interruptions as well as the duration of such events have increased at a rate of two percent in the USA over a period of ten years [15], [16].

In order to ensure the balance between consumption and generation, power system operator should manage the variability of production and demand in real-time. This condition cannot be handled by the energy markets, since they run every 5 minutes or so. Therefore, power mismatch within an interval must be compensated with other means. For the purpose, dedicated AS markets have been designed as parallel services to ensure generation and demand balance in real-time. In reality, AS markets need to procure capacity ramp-up and down in real-time operation, and balance electricity generation, demand and losses. Although literature suggests little harmonisation on the definition of AS [17], they consist of all the services required by the transmission system operator (TSO) and the distribution system operator (DSO), enabling them to maintain integrity and stability of the transmission and distribution systems operation as well as power quality [18]. These services may include spinning and non-spinning reserves and remote automatic generation control for frequency regulation, voltage control, black-start capability, grid loss compensation, and emergency control actions [18]–[20]. Nowadays, AS are provided through classical market operation, where market participants interact with AS market operator through a two-way communication. In this setting, market participants submit their bids, i.e., prices and quantity values [21] and the AS provision takes place in a single session every 5 minutes before the delivery [22]. Various types of commodities are traded in the AS market, depending on the characteristics of the power system disturbances [23]. The AS market design varies from one system operator to another. As an example, we explain here the AS market operation for the case of Denmark. The Danish grid is divided into two main control areas: DK1 and DK2 [24]. In DK1, frequency management is handled through primary (FCR), secondary (aFRR) and manual (mFRR) reserves. For frequency regulation, three levels of operation are defined as follows:

- **Primary reserve**: Named frequency-controlled reserve (FCR), it is the automatic response to frequency deviations. FCR is released increasingly with time over a period of seconds to restore balance between production and consumption. It stabilises the frequency at close to, but deviating from 50 Hz [24]. Characterised by instant response [25] and a full activation time of up to

30 seconds, FCR must be maintained by the production and consumption units for up to 15 minutes, before it is released. It can be activated automatically and locally.

- **Secondary reserve**: Known as automatic frequency restoration reserve (aFRR), it is applied to indirectly restore the frequency balance to 50 Hz following the stabilisation of the frequency. Its purpose is to release FCR and restore imbalances on the interconnections. Instead of FCR, aFRR is activated centrally, delivering energy within 15 minutes [25].
- **Manual reserve**: Named manual frequency restoration reserve (mFRR), it serves in the event of outrages, power restrictions affecting international connections and unexpected sustained activation of aFRR. Activated manually, mFRR has an activation time from 15 minutes to hours.

Additionally, voltage regulation in Denmark is automatically handled by the grid through passive reactive components. Reactive power is injected and absorbed through synchronous sources and static compensators. However, when automatic restoration of the voltage is not possible, suppliers capable of fast regulation are ordered to modify the reactive production/consumption until acceptable levels are achieved [24]. These entities may include spinning generators, synchronous compensators, reactors and capacitors. The request operates similar to the frequency management, normally providing service within thirty seconds [25].

Although this AS mechanism has successfully served power systems in the past, it lacks of certain features and requirements to cope with the emerging requirements. For example, the current AS market structures oversimplify assets' operation to linear price-quantity blocks of bids. The inherent dynamics and uncertainty of underlying systems and equipment are simply ignored. Moreover, the AS market procedures are understandably slow, due to the large-scale optimisation problems they solve. In fact, such problems include thousands of variables and constraints along with power flow equations and require a couple of minutes to provide the solution. The existing AS markets are designed to procure services exclusively from conventional power plants, neglecting any contribution of the end-users' FRs. This flexibility cannot be included in the current mechanism, as it would imply managing bids and activation of millions of FRs, which is not practical. Also, being the current market designed only for electricity resources, it is technically impossible to directly incorporate flexibility of other energy carriers in an ESI framework. Finally, the existing AS market structures are relatively expensive, as they require large power plants to operate below their full capacity to provide the needed flexibility.

III. EXISTING ALTERNATIVE SOLUTIONS

To address the issues related to the existing AS markets, several solutions have been proposed in literature in the recent years. In particular, three major alternatives are transactive energy (TE), peer-to-peer (P2P), and control-based approach (CBA). While not all of these mechanisms are designed for AS provision, they offer features and capabilities, which can partially address the issues of the existing AS markets. In the rest of this section, we explain these solutions in detail and provide a list of their strengths and weaknesses.

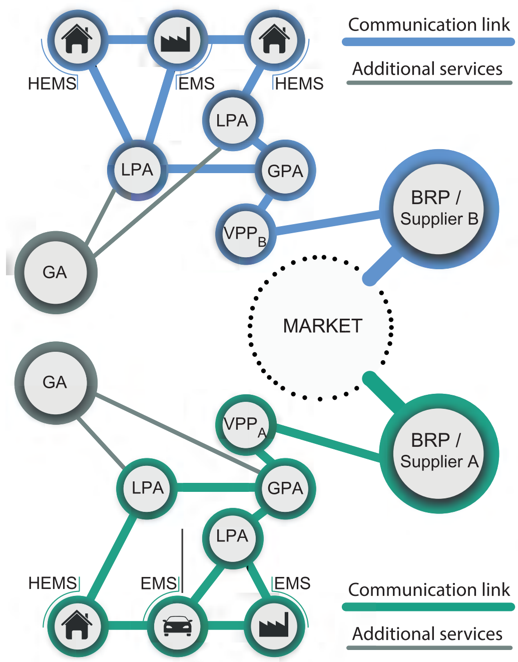

FIGURE 1. Conceptual block-diagram of the TE approach.

A. TRANSACTIVE ENERGY (TE)

TE proposes a market-based solution for energy management of small DERs, storage devices, and other FRs at the distribution level [26]. It adopts classical market principles to trade energy and AS among local players as well as the upper grid, either individually or through aggregators [27]. In this framework, prosumers generate price-quantity pairs through economic optimisation problems that minimise their operation costs [28]. These are submitted from the prosumers to the local operator. Similar to the electricity market at the transmission level, local market operators run day-ahead/real-time energy and AS markets. The ultimate goal of the local markets is to maintain balance between local generation and demand, and to provide services to the upper grid through aggregators.

The core of TE is the definition of a feedback between prosumers and aggregator. The feedback refers to a certain price reaction of the consumers. The market structure uses this information to determine the price and reach the balance between supply and demand at the local level [29]. The feedback is allowed from a proper IT infrastructure to minimise the uncertainty of the customers' behaviour and formulate an electricity price accordingly.

In Fig. 1, a conceptual scheme of the TE framework is provided. In the figure, market, energy suppliers and balance responsible parties (BRPs) mimic the existing mechanisms while preserving the structure of the electricity market schemes at the TSO level. In such a framework, BRPs consist of independent entities that guarantee the constant balance between generation and consumption in the grid. In case of deviation from their own schedule, BRPs can interact with the entities located at the lower levels of the grid to purchase adequate amount of flexibility. For this reason, BRPs are supposed to communicate with the TSO electricity market as well as downstream virtual power plants (VPPs). Every VPP represents a pool of FRs, which virtually behave as an effective power plant. These include any combination of traditional generating units, renewable generators, and pools of flexible prosumers.

To explain the TE operation, we assume a scenario where BRPs detect the deviations from their market schedule. In order to solve such issues, each BRP submits an up- or down-capacity request to the VPPs. At this level, VPPs formulate potential price signals and submit them to the corresponding pool of global prosumer agents (GPAs). GPAs handle a pool of aggregators of smaller prosumer agents, called local prosumer agents (LPAs). LPAs represent specific types of prosumers, which are located at the lowest level of the grid. Once an LPA receives the price signal from the associated GPA, it has to adjust the price signal according to the respective type of load, as each LPA responds to the price in a peculiar way.

In this framework, grid agents (GAs) are asked to provide additional information about the grid condition to the LPAs, so that they can make an informed decision accordingly. In the figure, GAs provide additional services for the greater benefit of the power grid operation. Once the prices are set, each LPA submits them to the pool of residential prosumers, equipped with home energy management systems (HEMS). For commercial and industrial businesses, prices are submitted to energy management systems (EMS). These devices allow prosumers to receive varying electricity prices and run individual optimisation problems to estimate their optimal response. Afterwards, their reaction is communicated back to the PAs through HEMSs/EMSs, as their willingness to alter their operation and provide flexibility. This potential response to price signals is interpreted as the feedback signal, which refers to the quantity of energy that the LPA is potentially willing to purchase/generate at that specific price.

Afterwards, the potential aggregated flexibility is communicated back to the VPPs. At this stage, VPPs can aggregate the price-quantity bids and formulate the ultimate electricity price signal that addresses a certain service at the BRP' s level.

Several benefits can be identified in the TE approach, as highlighted below:

- **Reducing uncertainty in prosumers' response**: Since TE acts upon receiving the reaction of the prosumers to a certain price in almost real-time, the negative impact of stochastic behaviour of the prosumers is minimised. Moreover, the definition of real-time feedback from the prosumers allows LPAs to receive required information about their participation directly. Thus, abstract modelling of prosumers' response to different prices is not needed in this approach.
- **Privacy**: As it was explained earlier, prosumers communicate their preferences in response to certain prices in price-quantity blocks of bids. Therefore, there is no direct access to the prosumers' appliances, generation, and/or storage resources. Exchanged information among agents consists of only price and quantity values, which does not compromise the privacy of the prosumers.
- **Scalability**: TE approach adopts simple bidding mechanism and distributes market operation among various LPAs. For this reason, it allows the inclusion of numerous prosumers into the system, while bid aggregation and price determination can be extended effectively to thousands of prosumers through multiple LPAs. However, scaling-up the approach requires the involvement of many operators.

While the TE approach offers a solution to exploit the FRs potential at the distribution level, it also introduces challenges and limitations, which are highlighted below:

- **Over-simplification**: Similar to the existing market structure at the TSO level, the TE method tends to over-simplify power system operational problems to simple linear bidding mechanism. In this approach, non-linear, dynamic and stochastic characteristics of the FRs are completely ignored.
- **Complexity**: The TE framework requires various entities (e.g., VPPs, GPAs, LPAs, GAs) for the operation. Their coordination is very complex in practice. Moreover, some entities might compete for the required services from the same group of FRs.
- **Optimal solution**: The TE operation involves potential price calculation, bidding aggregation and clearing price mechanism, which are computationally expensive. The computational burden can be lowered by increasing the number of LPAs. However, the involvement of numerous local operations leads to a solution that is not necessarily the global optimal one. This is due to the fact that operators do not interact with each other.
- **Computational time**: Although TE can accommodate thousands of prosumers and devices in a distributed manner, the aggregation and dis-aggregation process can become very slow. For this reason, market schedules are not updated fast enough to cope with the new level of uncertainty.
- **Security**: Because the TE approach demands an intensive exchange of information, it exposes critical operations of power systems to cyber-security threats.
- **No solution for ESI**: While the necessity of the ESI becomes more apparent among all stakeholders, the TE framework does not offer solutions to accommodate multi-energy carriers operation in the framework.
- **Cost**: Although FRs at the prosumers' level might be cheap, the TE method requires minimum latency in

two-way communication channels, which further necessitates adequate IT infrastructure. Moreover, it needs the intervention of different agents (i.e., GA, GPA, LPA). This condition implies high costs for the overall TE operation, which increase when scaling up the approach.

Recently, several TE-based projects have been implemented. These include: Olympic Peninsula Demonstration in USA (2006), represents one of the first efforts to provide automatic load response to price signals every 5 minutes, and the first demo to include the costs of transmission and distribution within that price [30]; Pacific Northwest Smart Grid Demonstration (2010), as a large-scale project involving 60 000 metered customers in the USA [31]; AEP Ohio gridSMART Real-Time Pricing Demonstration (2010), adopting a two-way consumer communication and information sharing approach to integrate RES, energy storage systems and metering infrastructure in power system operation [32]; Couperus Smart Grid (2011) in The Netherlands [33], which manages a pool of heat pumps for 300 residential houses.

B. PEER-TO-PEER (P2P)

Peer-to-peer (P2P) is an emerging electricity trading model, inspired by the sharing economy concept that relies on numerous agents [34]. It consists of a coordinated multi-lateral trading framework [35], whose ultimate goal is to maximise social welfare for all agents [36]. The P2P approach avoids any interference of the market operator [37], as agents interact and trade directly among each other through the use of an online platform that can be based on the blockchain technology. Blockchain is becoming popular in power system as it is claimed to be an ''incorruptible digital ledger of economic transactions, programmed to record virtually everything of value'' (Dan Tapscott, co-founder and executive director at Blockchain Research Institute [38]). It consists of an open and transparent infrastructure that allows agents trading without any middle-man. In such a structure, a digital ledger of transactions is created and shared between distributed computers on a network [39]. The ledger is accessible to every agent and not owned by any authority.

In Fig. 2, we present a general structure of P2P approach. In this setting, the current market structure is omitted. Instead, a community of agents is created to facilitate local energy trading. These agents can include independent prosumers (agents A and C), generators (agent D) and flexible consumers (agent B). Each agent is equipped with HEMS/EMS to collect information about its own consumption and generation in real-time.

Entities communicate with each other through HEMSs/EMSs in an online platform [40], where the price of trading energy are set by each agent. Typically, different surge-pricing algorithms are used for pricing and the generated price varies as supply and demand conditions change [41]. The definition of each price can take into account the preferences of the agents participating in the trade (either buying or selling) by submitting information to the platform. This way, agents' willingness for trading can depend on demand/price condition, on the specific trading agent (i.e., a more favourable price might be evaluated when dealing with relatives), the distance (i.e., preferring short-distance trades to minimise the losses) or on the type of energy resource. Once each agent provides information to the peers, these can run an internal optimisation problem in HEMS/EMS to define their optimal trade. When an agent intends to add a transaction to the digital ledger in the online platform, the transaction information is encrypted and verified by the others HEMSs/EMSs in the network through cryptographic algorithms [39]. The transaction needs to receive the approval from the majority of the HEMSs/EMSs. Afterwards, it is added as a new block of price/quantity data and shared. At this stage, the transaction is paid in crypto-currency.

Besides the agents, P2P operation requires additional two regulating entities: the online-platform coordinator (OPC) (e.g., the utility [42]), which is responsible for the platform maintenance; the regularising grid entity (e.g., the DSO), which ensures the legitimate use of the distribution grid (e.g., limiting the trades below the grid capacity).

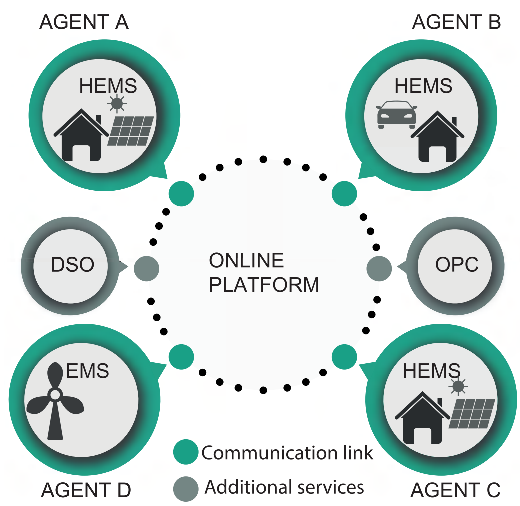

FIGURE 2. Conceptual block-diagram of the P2P approach.

To understand the P2P operation, we assume a scenario where agents C and D in Fig. 2 are encountering overproduction (according to their HEMSs/EMSs). Therefore, they need to sell their excess energy to other agents. At the same time, agents A and B experience an over-consumption situation so that they need to buy electricity from other agents. If the only preference among agents is physical distance, it is more likely that agent A will trade with D, and that agent B will trade with C. The most notable strengths of the P2P method can be identified as follows:

- **Scalability**: Depending on the definition of the community (e.g., neighbourhood, cities), P2P can be scaled-up to different groups of agents. Therefore, there is no limit to the scale of the platform and number of agents to trade energy in theory.
- **Privacy**: Since only price and quantity information is shared over through the platform, the privacy of the

prosumers is preserved, similar to the TE approach. In other words, there is no direct access to the agents devices to compromise privacy of the prosumers.
- **Cost**: Since intermediary entities are ignored in this framework, agents purchase energy and other services directly from providers at the local level. As a result, intermediary costs are avoided. Moreover, trading energy resources within the community minimises the transmission/distribution costs and the system-wide losses.
- **FR exploitation**: Since energy trading takes place in real-time, dynamics of the community generation and demand are reflected in the real-time prices computed by the P2P platform. As a result, it is possible to exploit the full potential of FRs at the distribution level by time-varying prices if the negotiation updates very fast. Moreover, by setting the preferences for trading green electricity, P2P facilitates trading in real-time, where stochasticity, dynamics and non-flexibility of the assets is accounted for to some extent.
- **Computational complexity**: As agents match their generation and demand through a set of interdependent bilateral negotiations, they are able to reach joint optimisation with reasonable computing power [36]. However, computational complexity can become higher for complicated pricing mechanisms.
- **Security**: The information shared in the P2P framework is based on the blockchain concept. This solution prevents information leakage, reduces transaction time, and risk of cyber-attacks. It further allows to observe the transaction in real-time and removes transaction intermediaries [39]. However, it might become more challenging in the future when the solution is extended to large-scale applications.

In spite of the innovative structure and the new opportunities offered by the P2P approach, several weaknesses and challenges can be realised in real-world applications, as highlighted below:
- **Multi-energy systems**: The P2P approach does not offer unified mechanism to integrate other energy carriers, which limits its application in the future. Also, some energy carriers, e.g., gas, are generated centrally and distributed to consumers. Therefore, their operation cannot be easily accommodated in the P2P framework anyway.
- **Electricity availability shortage**: When the trading process among agents does not satisfy the total energy demand of the community, intervention of the existing electricity market is inevitable. This condition leads to purchasing energy from the upper grid. As a result, a new stream of uncertainty is reflected in the TE operation of the upper level of the grid.
- **Computational time**: In real-time, a series of negotiations has to take place among various agents, before settling the price and system operation. This process can be time-consuming, while power system by nature changes rapidly. Additionally, communication delay is always a concern in the P2P approach.

Several P2P energy trading models have already been implemented as pilot studies in different countries. In the Netherlands (2014), Vandebron developed an online P2P energy marketplace [43] for consumers to buy electricity directly from independent producers. In Germany (2015), Sonnen developed a software, SonnenCommunity [44], to support energy sharing generated from RES within a community of prosumers. In Spain (2015) and Finland (2015), EM-Power project and P2P-SmarTest investigated formulation of local electricity markets to promote the role of the prosumer and micro-generation [**?**], [46]. In the UK (2015), Open Utility launched an online P2P marketplace for RES, which is called Piclo [42]. In Australia, Power Ledger implemented P2P by adopting blockchain technology to undertake energy transactions [47].

C. CONTROL-BASED APPROACH (CBA)

CBA refers to the adoption of control theories for energy management in the distribution system [48]–[50]. It introduces an alternative approach to the market operation, offered by the TE and P2P frameworks. In Fig. 3, we present the method and the main entities involved.

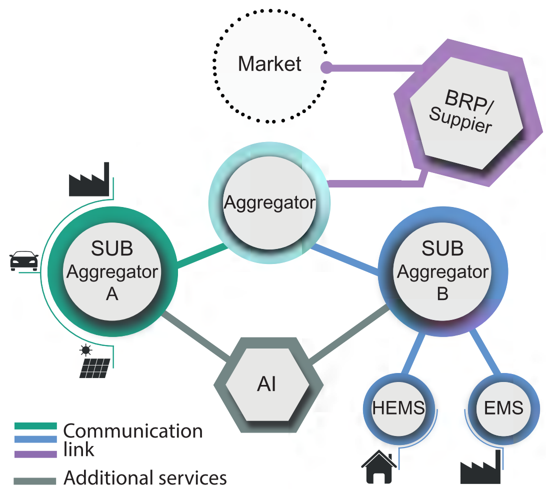

FIGURE 3. Conceptual block-diagram of the CBA.

In the CBA setup, electricity market structure at the transmission level is preserved. It means that wholesale electricity market, energy suppliers and BRPs entities remain intact. At the lower level of the structure, BRP communicates with a new entity, named aggregator. This is an independent entity that operates as coordinator between FRs and the wholesale electricity market. When BRP encounters imbalance in generation or demand from its own schedule, it sends a request to the aggregator. Upon receiving the query, aggregators interact with different sub-aggregators, scattered all over the grid. Each sub-aggregator represents a pool of prosumers and act on behalf of them. They are expected to communicate with the pool of prosumers and collect offline data from prosumers' reaction to different prices. This way, sub-aggregators are able to estimate an aggregated model of the pool, which is used to formulate price-quantity bids for different price signals. In order to achieve a better accuracy of prosumers' behaviour modelling, specialised sub-aggregators can be sought to manage a specific type of FRs. Moreover, sub-aggregators can optionally receive additional information, e.g., weather parameters, in order to improve the accuracy of predicting consumers' behaviour. Such additional services therefore provide additional information (AI).

As shown in Fig. 3, the interaction between sub-aggregators and prosumers can take place in two different manners: through direct (sub-aggregator A) or indirect control (sub-aggregator B) [51]. Direct control (DC) is based on a two-way communication between prosumers and sub-aggregator. Although it requires an adequate IT infrastructure, it enjoys the benefit of directly controlling the loads, minimising the uncertainty of the consumers' response. On the other hand, indirect control (IC) includes the utilisation of HEMSs/EMSs and one-way communication. It implies a simpler communication infrastructure, which significantly reduces the complexity and vulnerability of the system [52]. While DC enables the operator to directly alter prosumers' power consumption and local generation, IC only provides flexibility by using a price signal. However, the optimal utilisation of these solutions relies on the available information and infrastructure [51].

In this paper, we focus on the IC approach, which requires simpler infrastructure. This is formulated in two main steps: 1) a control problem at the sub-aggregator level to determine the price signal, 2) a model-predictive control (MPC) at the prosumers' level, embedded in HEMSs/EMSs to act upon receiving the price signal. Different optimisation problems can be formulated through control concepts at various levels to fulfil the requirements of different stakeholders.

The benefits of the CBA approach through IC method can be summarised as follows:

- **Scalability**: The structure guarantees a scalable solution for the future power system operation at the distribution level because the control problems can be extended to millions of devices without significant computational power requirements.
- **Dealing with mathematical complexity**: It is based on formulating and solving control problems at the sub-aggregator and prosumers' level. Therefore, it deals with non-linearity, real-world dynamics and stochasticity of the power systems with rather simple, fast and cheap communication infrastructure by adopting one-way communication. This is valid only for the distribution system, since the existing wholesale market structure is maintained at the transmission level.
- **Cheap**: The simple architecture in the CBA-IC approach guarantees low-cost implementation and maintenance costs. Moreover, the CBA-IC avoids the cost for distribution-side measurement equipment, as it requires a few measurements at the higher level of the grid for consumers' modelling. This condition facilitates troubleshooting of operational issues in real-time.
- **Privacy**: CBA-IC does not imply privacy issues, as only price signals are broadcasted from the aggregator to the end-users.
- **Security**: The lack of real-time feedback from consumers to the sub-aggregators diminishes risk of communication malfunctions and cyber-attacks.
- **Integrated Energy Systems**: Regarding the possibility of integrating the entire energy system, CBA offers a valid solution via adoption of specialised sub-aggregators for FRs of other energy carriers. These entities can develop a flexibility price-reaction model suitable for their own load, offer a unique price signal, and act in the market afterwards through main aggregator, in the same way as other sub-aggregators.

Despite all the benefits, CBA has its limitations, as highlighted below:

- **Dependency on the market**: Although it can partially exploit existing FRs at the distribution level, it operates as a part of the AS market at the transmission level. Consequently, CBA inherits slowness, linearity assumption, and deterministic approach from the existing wholesale AS market which does not fulfil many of the future power system needs.
- **Uncertainty**: Since prosumers' price-responsiveness is an uncertain phenomenon, the operation of CBA will inevitably have uncertainty with respect to the prosumers' reaction to the price signal [29]. It becomes a significant issue when the model over-estimates consumers' reaction to a set of price signal. This situation might in fact jeopardise the power system stability and safe operation.
- **Market Inefficiencies**: By avoiding any market process, CBA is potentially subject to market inefficiencies, where prices might deviate from the true discounted value of their future cash flows [29].

Several CBA projects have been implemented in the past. These include: FlexPower [53], [54] in Denmark (2010), which is the first project using price-based CBA to control individual power flow of intelligent controllable power units; price-based control of electrical power systems (E-Price) in The Netherlands (2010) [55], focusing on price-based control strategy to facilitate increasing amounts of RES; CITIES [56] in Denmark (2013), which employs the aggregated response of FRs in a control framework design; ECOGRID Eu project in Denmark (2013) [57], where residential consumers participate with flexible demand responses to real-time price signals; SmartNet [58] in Italy, Denmark and Spain (2015), applying economic-model predictive control (E-MPC) technology to swimming-pools.

IV. ANCILLARY SERVICES 4.0 (AS4.0)

From the analysis of the alternative solutions to the existing AS market, it emerges that these lack of certain features to

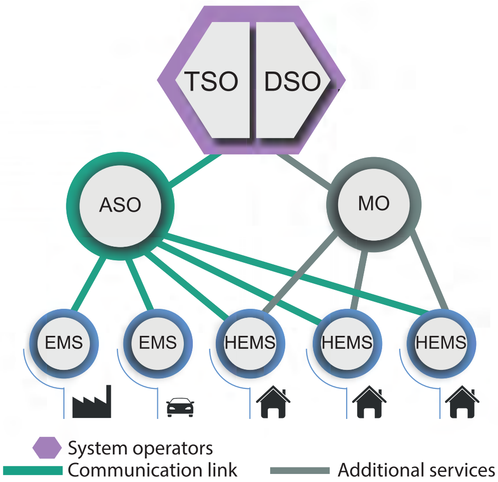

FIGURE 4. Conceptual block-diagram of the AS4.0 approach.

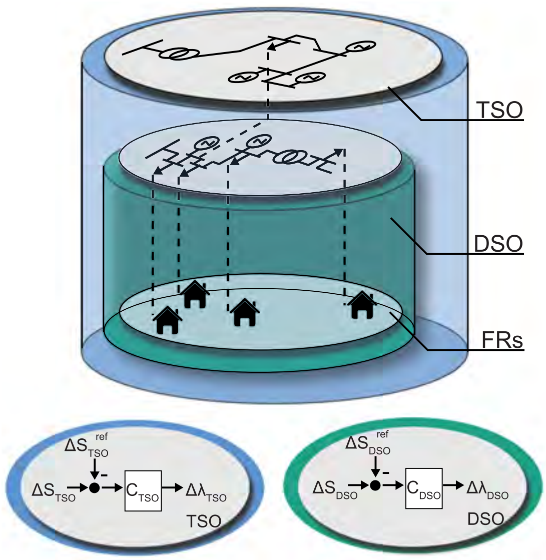

FIGURE 5. The interaction between two operators located at different levels of the grid in the AS4.0 approach.

comprehensively address the requirements of the future smart grid. In this section, we propose a comprehensive solution for AS provision, named AS4.0. In Fig. 4, a schematic diagram of the proposed framework is shown. It refers to a control-based operation to procure required AS, extended to the entire grid management. We build AS4.0 on two main assumptions: firstly, every prosumer device is operated and controlled by an HEMS/EMS. Therefore, we deal with rational prosumers through automated systems (as implicitly assumed in the previous approaches) [49]. Secondly, power system operation problems at different spatial and temporal scales can be split into multiple independent problems in space and time. This assumption roots in the fact that major operation entities, e.g., TSO and DSOs, handle problems at different geographical scales and time-frames, as shown in Fig. 5. It is worth mentioning that the system operator (SO), in the proposed framework, refers to any entity that regulates power system operation at different level. The major SOs consist of TSO and DSO entities. For instance, frequency regulation is the responsibility of TSO, which expands to the whole control area. Meanwhile, voltage management at the DSO level is limited to a certain area of a DSO' s territory. The proposed mechanism employs delta prices to move FRs in the right direction for the benefit of power system operation in real-time. Every SO formulates an independent control problem, based on the required resolution of space and time to generate adequate delta price signals. Afterwards, these delta prices are constantly summed up to the base-line costs (e.g., taxes, profit margin of SOs, O&M costs) and submitted to the rational prosumers, as flexible retail electricity prices. Such new prices intend to exploit the rational behaviour of the prosumers, promoting a certain behaviour from the pool to handle various AS requirements. Time-varying utility pricing is the core concept of the proposed method to effectively exploit FRs potential. Several studies have already been done to evaluate the effectiveness and required mechanisms for real time-time pricing [59], [60], [60]–[62], and associated benefits and impacts on the energy flexibility [48].

At the highest level of the structure, SOs constantly measure the parameters of their interest (e.g., frequency for TSO) in the grid. Due to the varying generation and consumption, these parameters might show deviation from their schedule. When this happens, SOs run independent control problems that evaluate the required FRs from the lower level of the grid to compensate the deviation according to their respective standards. In the definition of the control problems, SOs need to estimate the reaction of their pool of rational prosumers to a certain price. For this reason, each pool requires an accurate price-response model of the associated FRs. Proper models are formulated from the offline information, that is collected from real-time measurements. This is provided by the model operators (MOs), which are specialised entities in modelling price-response behaviour of the prosumers in different time and space resolution. They can sell their services (i.e., models) to SOs according to their needs. Once delta prices are formulated with geotag, they are submitted to the ancillary services operator (ASO), which is responsible to sum-up different delta prices and broadcast the final price to the prosumers located in the right area. ASO guarantees and secures an easier communication with prosumers through their HEMSs/EMSs. We can consider the case of a DSO that operates a low-voltage network of thousands of buses. When a couple of buses has voltage issues, the DSO needs to fix it by generating proper delta prices to submit to the prosumers located in those buses and in the surrounding areas. For this reason, not all the prosumers will receive the same delta prices. When these prices are submitted to the HEMS/EMS, they will change the consumption/generation accordingly.

Studies have shown that FRs can make a significant contribution to the frequency regulation [63], [64]. In the future, severe shortages of flexibility will be avoidable [65] and AS will not need services from conventional generators. A wider application of HEMS/EMS, as predicted for the next few years, will provide a higher amount of FRs at different levels of the grid. This way, the AS4.0 intends to provide all the AS requirements through FRs instead of conventional generators with reserve capacity.

A. GENERATING DELTA PRICES AT THE DSO AND TSO LEVEL

At the distribution level, numerous DSOs own and operate medium- and low-voltage delivery network. Each SO attempts to satisfy its objective by generating appropriate delta prices based on the system condition. In Fig. 5, we show a hypothetical power system, with a TSO at the highest level, and a DSO at the lower level. These are generally referred to as S_i, where $i = TSO, DSO$. Every SO might need different services S_i^j, where $j = 1...n$ and n is the number of services of SO_i. For example, the TSO might request services for frequency regulations or congestion management. Each service is defined independently with specific time and space tags.

The SO constantly formulates delta prices $\Delta\lambda_i$ that can alter the generation/consumption of prosumers. Such prices consist of the required efforts for the SO to fulfil services. As shown in Fig. 5, delta prices are generated through a control model, C_i. It takes into account the price-response characteristics of FRs and it is formulated independently at every SO level. C_i needs to be continuously updated, ideally every few seconds, to follow the true conditions of the system. Existing standards (e.g., frequency regulations) can be accommodated in the control problem of C_i and updated by the associated SO, when needed.

B. MODELLING PROSUMERS' BEHAVIOUR

Prosumers' price-response model is used to formulate appropriate delta prices. Therefore, each SO needs to have access to the aggregated information of the prosumers' behaviour at their respective scale for an accurate modelling. The aggregated data at the distribution substation is measured and collected so that proper models can be created offline. Therefore, no real-time or extra communication channels are needed in AS4.0 framework from HEMS/EMS to the SOs for prosumers' modelling. In fact, aggregated prosumers' models are different at each SO level because of the different amount and composition of FRs. In AS4.0 framework, models' accuracy can be improved by MOs, which develop aggregated models of the prosumers in different time and space scale. In fact, these have directly access to the prosumers' HEMS/EMS with their permission under bilateral contracts. They can also be specialised in a specific type of prosumers' load/generation (e.g., summer pools or roof-top PV) so that the model can estimate prosumers' behaviour more accurately. The models can be updated frequently to increase the accuracy. This process can be done through historical data time series modelling/analysis [48], [66] and machine learning approaches (e.g., neural network [67]). Moreover, prosumers could be represented by different models that are specialised based on several factors, e.g., season and day. This way, accuracy of the models will be improved, and the uncertainty of the consumers' response to a set of prices will diminish substantially.

C. FORMULATION OF FLEXIBLE AS-RETAIL-PRICE

Once delta prices are formulated by the SOs, these are submitted, together with geographical tags, to the ASO. The tags determine the area requesting the service. Afterwards, the ASO sums-up the delta price components, $\Delta\lambda_i$, with a baseline price, λ. The latter price is defined by the DSO to cover taxes and fixed costs. This can be assumed as flat, as it is today in many utility companies and retailers. Alternately, it can be based on the day-ahead market prices, to ensure legitimacy from the bidding and clearing process. The aggregated price, named flexible retail electricity price, is broadcasted to the HEMS/EMS at the prosumers' premises. In this setting, there will be different prices based on the geographical tags of the delta prices. It implies that different end-users might receive different prices according to the condition of the power system in their respective areas. Naturally, such a mechanism can provoke an unfair penalisation of the end-users which are located in specific areas that receive higher prices. In order to deal with this issue, the sum of the daily delta prices to every prosumer should always be zero. In other words, the sum of the negative prices should be equal to the accumulated positive prices within every day. This solution prevents discrimination against prosumers that are located in different areas. In fact, consumers will be encouraged to modify their consumption throughout a day in order to minimise their operational cost without reducing their overall daily consumption. A similar concept has already been adopted by PJM for frequency regulation [68], forcing the load deviation within one hour to be zero.

D. HIERARCHICAL OPERATION MODEL

SOs operate with different granularity in time and space. For this reason, it is unlikely that they compete over the flexibility provided by a particular group of end-users in a way that compromises the system operation. When such a conflict of interest occurs, it might promote chattering and oscillations in the prosumers' response, by cancelling the delta prices of the counterparts. In order to handle this situation, a hierarchical structure can be developed with pre-specified priority list for different conditions. Hierarchical operation is delegated to an independent entity (e.g., the federal energy regulatory commission for the case of USA [69] or ASO), which meddles in for the greater benefit of the power system security. This way, different SOs can fulfil their needs without interfering or competing with other SOs. The priority is given to the SO, which requires the most critical services for the benefit of power system operation as a whole. In a scenario where TSO asks for frequency regulation-up service (by generating a negative delta price to encourage more consumption), and a DSO encounters low voltage issues in a specific area, priority is given to the frequency regulation requested by the TSO, as it maintains the integrity of the power system operation.

E. AS4.0 INFRASTRUCTURE AND REGULATORY REQUIREMENTS

In this subsection, we investigate the required infrastructure and regulations for successful implementation of AS4.0. At the prosumers' level, HEMSs/EMSs run optimisation problems to take advantage of the time-varying prices by minimising operational cost. Although a limited number of HEMSs/EMSs are installed at the prosumers' level, these already established a multi-billion dollar business with increasing market value to US$4 billion in 2017 [14], [70]. By many brands (e.g., Apple, Google and GE) being involved and invested tremendous amount of money in this business, it is expected to have many enclosed areas equipped with HEMSs/EMSs in the near future. Therefore, AS4.0 will be able to benefit from the existing potential of HEMSs/EMSs and their capabilities at that time to achieve their goals. Specifically, in AS4.0, HEMSs/EMSs are supposed to receive price signals from a communication channel. This channel might consist of encrypted exclusive radio signal or a regular encrypted internet packet of signal. Moreover, since an ASO is responsible for maintaining communication channels and broadcasting the signal to the prosumers, it needs an adequate IT security infrastructure. This can include several firewalls, where the access to the information is always restricted and limited to the entities in charge. In AS4.0, SOs formulate their own control problems, accounting for the technical constraints of the system. To achieve this and determine the delta price $\Delta\lambda_i$ in almost real-time operation, appropriate computational power is required. Also, SOs have to measure and store prosumers' response to different prices in order to update the aggregated prosumers' model. For this reason, big data warehouses are needed to store and maintain large amount of information.

Besides physical infrastructures, AS4.0 requires a set of new regulations at different levels of the electricity system to transform existing market-based AS into a control-based structure. Real-time utility pricing, anti-discriminatory pricing in different areas, subsidising HEMS/EMS business to develop faster, and changing existing business models of AS at the transmission level are among the most important regulatory revolutions, which have to be initiated by the policymakers.

F. AS4.0 FOR THE AS PROVISION: SUMMARY

The advantages of AS4.0 over the existing alternative approaches for AS provision can be identified as follows:

- **Stochasticity, dynamics and non-linearity**: The AS4.0 framework manages stochasticity, non-linearity and dynamics of the prosumers by defining a suitable control problem. In fact, a SO price-response controller could be non-linear while accounting for the inherent stochasticity of the power system operation. Different tools at the higher (optimisation control problems, e.g., price-based control) and lower level of the grid (HEMS/EMS, e.g., E-MPC) can be employed to achieve this goal.
- **Simplicity**: It simplifies real-time energy management for AS provision for the entire grid within a set of control-based problems, where the electricity price is the only driver.
- **ESI**: The proposed methodology facilitates ESI because different energy carriers can be represented to the prosumers by a price signal. In this framework, each HEMS/EMS can select its preferred source of energy at any moment based on economic preferences.
- **Scalability**: Finally, this method can be extended to distribution and transmission systems, enhancing the provision of the AS to every flexibility [51]. In fact, there is no operational nor computational limit in the number of FRs and SOs involved in the AS4.0. approach.

In spite of its promising features for the future smart energy-system management, some challenges have to be properly addressed:

- **Lack of agreement on price**: In classic market structure, buyers and sellers submit their bids to determine a commodity price. This procedure implies an indirect agreement among the entities. In AS4.0, however, prices are obtained based on the expectations of the SO from the prosumers and their own needs. Therefore, additional mechanisms should take place (e.g., upper limit on the delta prices and daily price neutrality) to avoid price discrimination and pressure on the prosumers with unreasonable delta prices.
- **Models uncertainty**: SOs model the prosumers' behaviour considering available historical data. Nevertheless, the aggregated price response must be analysed considering a certain level of uncertainty. This is a challenge for the SO, and the MOs tries to minimise it by specialising in prosumers' behaviour modelling.
- **Conflict of interest**: When SOs look after fulfilling contradictory objectives, there is conflict of interests. Such a situation can be handled by hierarchical operational algorithms and prioritisation mechanisms.

V. CONCLUSIONS

In this paper, we present AS4.0 as a comprehensive and novel solution for AS procurement in the future energy system. It is developed as an alternative to the current market-operation structure for the AS provision. Nowadays, the AS market is deterministic, linear, static and does not include any mechanism to utilise FRs located at the distribution level. By offering price-based control mechanism to exploit the entire fleet of FRs, AS4.0 is able to manage AS provision for the entire grid while handling stochasticity, non-linearity and dynamics in a fast and simple way. This paper firstly explains the role of AS in presence of smart grid functionality and investigates existing alternatives to the market-based AS in literature. Analysing the alternative approaches (in terms of the core challenges regarding the AS procurement in the future) shows that none of them can provide a comprehensive solution accounting for spatial and temporal variability and potential of FRs.

In order to fill the gap, the concept of AS4.0 is here proposed. In the new framework, SOs can exploit the price-responsiveness of the prosumers according to their need by time-varying electricity prices. These are formulated through independent control problems for every SO. Time-varying prices are lately summed-up together with fixed price components (e.g., taxes) to generate flexible retail electricity prices. These are received from the prosumers through HEMS/EMS which can rationally react to minimise their own cost. The entire process is automatic and requires no manual interaction from the consumers.

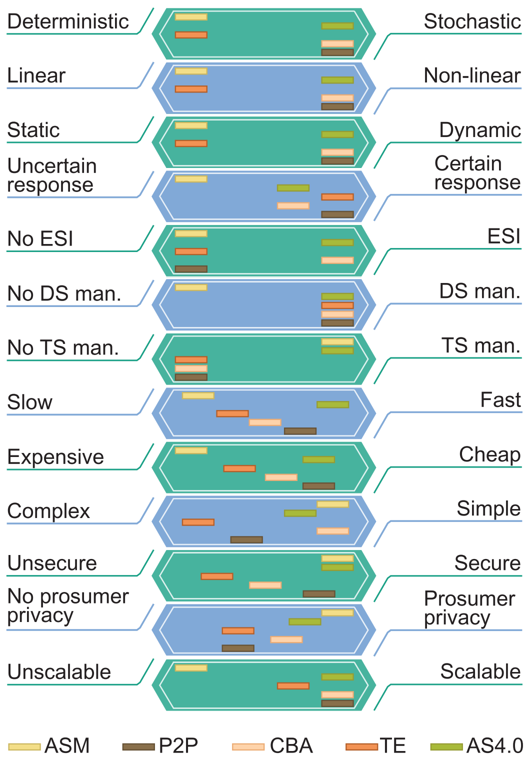

FIGURE 6. Comparing the current AS market with the main features of TE, P2P, CBA, and AS4.0 frameworks, required by the future AS provision.

To summarise the advantages of the proposed framework, different alternative approaches are compared in Fig. 6, in terms of core features required by the future power system and AS procurement. In this benchmark, AS4.0 looks very promising as it deals with all the requirements of the smart AS provision. In the future work, the AS4.0 mechanism will be implemented in several simulation studies to quantify the associated benefits and challenges.

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