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RESEARCH ARTICLE

Dynamic Virtual Power Plant: A New Concept for Grid Integration of Renewable Energy Sources

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ABSTRACT The concept of Virtual Power Plant (VPP) has arisen over a decade ago from the relatively low competitiveness of the back then emerging non-dispatchable RES. A set of smaller generators imitates the behavior of large synchronous generators. So far, static aspects such as generation or slow dynamics have been of interest, as it is the case for the zonal secondary frequency control scheme in Spain, which can be viewed as a VPP. However, considering *dynamic aspects* is of high importance, especially to further increase the current penetration level of Renewable Energy Sources (RES). Indeed, one should deal with the *full* participation of RES in grid ancillary services. This means not only to get some positive impact on grid voltage and frequency dynamics but to bring concepts which allow integrating RES to existing secondary regulation schemes on the same level as classic synchronous generators. For that, we propose here a new concept called Dynamic VPP (DVPP) which fully integrates the dynamic aspects at all levels: locally (for each RES generator), globally (for grid ancillary services and interaction with other close-by elements of the grid) and economically (for internal optimal dispatch and participation in electricity markets). A DVPP is a set of dispatchable and non-dispatchable RES along with a set of common control and operation procedures. The latter procedures include the choice of dispatchable and non-dispatchable RES constituting the DVPP, the control of DVPP generators for local objectives and participation of the DVPP as a single unit in ancillary services (especially in case of loss of natural resources - e.g., wind, sun - on a part of the DVPP), the limitation of the risk of adversely interaction with close-by elements and the feasibility in both current power systems scenarios and future ones with large share of RES. This new DVPP framework and approaches developed for its implementation allows ensuring optimal operation of a mixed portfolio of dispatchable and non-dispatchable RES generators for planning, participation to the markets and real-time control. For the control, all time-scale dynamics are considered to improve RES management (internal re-dispatch inside the DVPP to take advantage of dispatchable/non-dispatchable nature of each RES and to optimally manage the lack of natural resources in some regions of the DVPP) and their participation to grid ancillary services. Concrete structures of DVPP as well as ways to address the other control and economical aspects will be shown. This new DVPP concept is now under development in the H2020 POSYTYF project (https://posytyf-h2020.eu/).

INDEX TERMS Grid ancillary services, grid integration, renewables, virtual power plant.

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I. INTRODUCTION

Renewable Energy Sources (RES) are key for the global energy transformation. The volume of RES has been increasing during the last decades in all power systems. Fig. 1 shows that, in Europe, the RES share nearly doubled from 2005 to 2015. By using more RES to meet its energy needs, the European Union (EU) lowers its dependence on imported fossil fuels and makes its energy production more sustainable, in line with the energy union strategy.

The EU is on track to meet its target of a share of at least 32% of renewable energy in 2030 and 66% in 2050 according to the new revised Renewables energy directive (2018/2001) and the EU SET Plan [1]. Although an impressive progress has been achieved as a result of the ambition and vision to meet climate targets, more effort will be needed to meet long-term decarbonisation objectives. By 2050, renewable energy could be the largest source of energy supply, representing two-thirds of the energy mix. This requires an increase in the share of RES of about 1.2% per year, a sevenfold acceleration compared to recent years. To achieve these objectives, one must lead the development of the next generation of RES technologies, but also integrate the energy produced from RES into the energy system in an efficient and cost-effective manner.

However, a high share of variable renewable generation will pose new challenges for the operation of power systems. A key question is whether there will be sufficient power system flexibility to deal with the increased variability in generation effectively. Flexibility denotes here the ability to constantly keep generation and load in balance and to respond to (quick and large) generation-load unbalances. Flexibility can be provided by generators (both, conventional and dispatchable RES), consumers, energy storage systems, and delivered through networks or appropriate system operation rules.

A power system is composed of transmission and distribution grids. Transmission grid operates at Very High Voltage (VHV) levels to transmit energy over long distances, with minimal losses. Distribution grids operate a lower voltage levels and distribute the energy among the connected customers (some industrial customers may be connected to the transmission level directly). Importantly, they are operated by distinct actors: transmissions grids are run by Transmission System Operators (TSO), whereas distribution grids are operated by Distribution System Operators (DSO). RES can be connected to both grids: large RES plants (and systematically all offshore wind parks) are directly connected to transmission grids, whereas smaller RES generators are connected to and spread among the distribution grid.

Stability of power systems is a quality of their control by which they progressively return from moderately disturbed condition to a state of equilibrium. Power system control (servo-control process acting on a dynamic system) aims at keeping the frequency and voltage magnitudes close to their set points. Stability is a major concern of power system operation: the system has to reach a stable operation point after any disturbance (short-circuit, line or generator trip, etc). This constraint impacts:

- The device – generator level: it is required that the physical variables of the generator (voltage and currents) remain within security limits so that the material is not damaged in case of disturbance and the generator can continue operating.
- The system – grid level: it is required that the overall generation-load balance is respected for the whole interconnected system. This means that physical variables of the system (voltages, currents and frequency) remain within security limits, which is guaranteed by setting up and activating so-called system or ancillary services. Therefore a global – system – view of the whole interconnected power system is required (not only on one or some generators).

Variable RES such as solar PV and wind generation are i) intermittent and causing fluctuations on all time scales, which need to be balanced by dispatchable generation, ii) spatio-temporally correlated, iii) geographically dispersed (on both transmission and distribution parts), and iv) connected to the grid through power electronics and thereby lacking the physical robustness (inertia) of rotating machines. To accommodate the increasing amount of variable RES generation, a sufficiently strong transmission grid is needed. The grid's capacity should be high enough to transmit this generation under dynamic stability constraints (dynamic limit of power lines). This limit is systematically lower than the thermal limit of the transmission lines and it is difficult to assess and ensure by regulation. Storage is an alternative to the direct evacuation and transmission of RES generation, but it implies high costs. In addition, the large-scale use of electrochemical batteries may have a significant environmental impact. Altogether, the stability issues related to RES limit their use. Indeed, in many power systems around the globe (such as Ireland, Australia, or small island systems) ensuring system stability is the main bottleneck to further integrate sustainable RES. A possible solution consists in increasing the share of so-called *dispatchable* RES, i.e., the ones which have a natural energy storage capacity (solar thermal or hydropower plants, for example). In this context, the concept of smart grid offers important opportunities to manage large scale renewable power plants appropriately. [2], [3]

System integration of RES faces major limitations when high penetration is expected (more than 50%). They are mainly related to several aspects of stability assessment and secure operation:

- A dynamic stability margin (secure power transmission) should be ensured in case of meteorological hazards. One should thus prevent any risk of generalized blackout.
- RES should systematically participate in ancillary services: this is not the case today since RES generation is not the predominant generation at the overall scale of interconnected systems. In case of an increase in the share of RES this situation should change. RES connection at distribution level is further challenging since

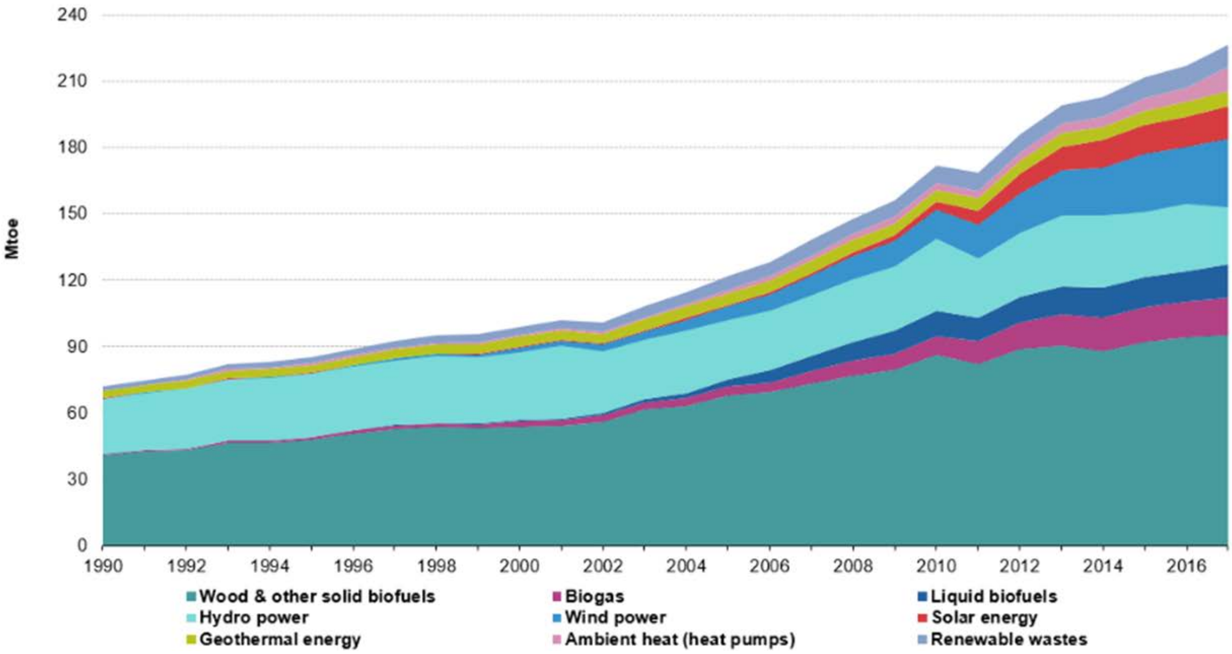

FIGURE 1. RES production in Europe (source: Statistical Office of the European Union).

ancillary services are provided by generation connected at the transmission level.

- Frequency stability - in terms of electric synchrony, i.e., keeping the electric frequency in a tight band around a target (50Hz in Europe) as a necessary and sufficient condition of stability - raises a question since RES are systematically connected to the grid via power electronics and have naturally low or zero inertia. Massive integration of RES poses not only a question of stability but also the question of revisiting from a theoretical point of view such notion and conditions of stability.

We present here a new concept called Dynamic Virtual Power Plant (DVPP) to tackle the aforementioned challenges to large-scale implementation of RES. A DVPP consists of a set of different, dispatchable and non-dispatchable RES, as generally shown in Fig. 2. These RES are well chosen in order to ensure safe and optimal grid insertion and operation by offering their combined flexibility (ramping up and down for frequency control: from fast frequency response to secondary control), internally balancing their fluctuations, and selling their aggregate generation output in the wholesale energy and ancillary service markets.

To further elaborate upon these points consider the task that a set of distributed renewable energy resources (DERs) should collectively provide a post-fault response similar to that of a traditional thermal generator. However, no single individual DER can typically provide such a response. For example, some sources are limited in energy (e.g., supercapacitors), others in reactive power capacity (e.g., a wind turbine), others in bandwidth (e.g., a hydro governor), others in peak power (e.g., PV), and so on. Hence, the desired response has to be disaggregated to the DERs taking their individual constraints into account, and the individual responses have to be realized by decentralized control so that the aggregate DVPP behavior matches that of a synchronous machine. Further problems arise from the DERs being typically spatially distributed, the disaggregation having to be adaptive (accounting for intermittency of renewables), and so on. In summary, in future power systems, ancillary services have to be increasingly shouldered by DERs and the DVPP framework conceptualizes this problem and formalizes an approach based on disaggregation of the desired behavior and coordinating heterogeneous DERs.

The concept of Virtual Power Plant (VPP) has already been used in literature but mostly for *static* aspects. Indeed, the existing work on VPP deals with a set of RES generators but limited to economic dispatch (e.g., [4]), static ancillary services such as baseline injections, tracking of power and voltage set-points, or RES integration in electricity markets [2], [5], [6], [7]. The fastest dynamics studied in a VPP concern the secondary frequency-power control [8], [9]. Reference [10] considers also a bi-level optimization model to manage the distribution network losses and voltage deviation in conjunction with the VPP participation into the energy and reserve markets. In [11] setting and sizing of VPPs in distribution networks is analyzed. In comparison, a DVPP is concerned with *dynamic* ancillary services, such as fast frequency and voltage control. For such services the spatial aspect (i.e., DERs dispersed over the grid) is important as well as and dynamic constraints of the DERs, such as the bandwidth of the individual sources. To the best of our knowledge, conventional VPPs are not concerned with fast ancillary services, spatial aspects, or dynamic constraints. Further, heterogeneity of the DERs is a minor aspect in

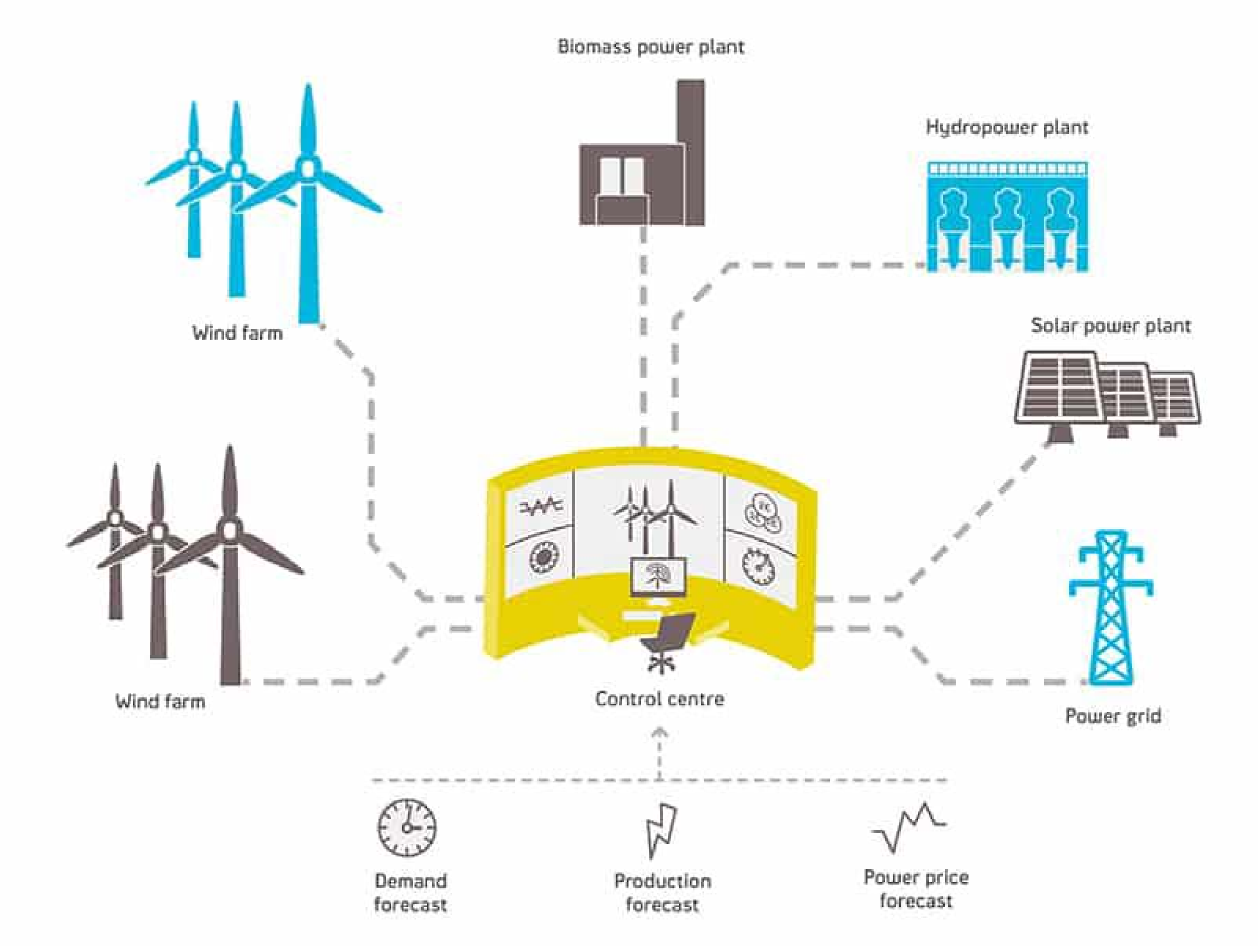

FIGURE 2. **DVPP Concept a). Source: Renewablepedia.**

conventional VPPs, whereas it is a key enabling concept for DVPPs: in a DVPP DERs can collectively provide an aggregate response which no device can achieve alone. This entirely novel problem setting as well as the various disaggregation and control challenges alluded to before led us to coin the term DVPP.

The power electronics used to connect RES generators to the grid brings fast dynamics, which need to be taken into account. Within the proposed concept of DVPP, *all dynamics* of the DVPP and neighbor AC grid are taken into account. This is mandatory for a full integration of the DVPP to existing control (primary and secondary) schemes in order to allow full participation of the DVPP to grid ancillary services. Our DVPP concept integrates all aspects: static (load-flow), optimal (perimeter definition for short/medium and long-term run) and dynamic (control for local - machine - and global - grid - objectives). It allows thus reaching optimality at all levels of operation: planning (long term), participation in secondary control (medium term operation) and fast control (for internal re-dispatch (among RES generators inside the DVPP) and fast ancillary services (voltage and frequency)).

The paper is structured as follows: in Section II the specifications and objectives of the DVPP are explained. In Section III the components of the DVPP are given. Section IV deals with the static aspects of the DVPP and Section V with the dynamic ones. In Section VI are discussed the approaches used to reach the DVPP objectives while Section VII is devoted to conclusions.

II. SPECIFICATIONS AND OBJECTIVES

The main objective of the DVPP is to integrate a portfolio of dispatchable and non-dispatchable RES, which allows participating in ancillary services and providing flexibility.

Starting from limiting facts of today's situation, specific scientific and technical objectives are deduced.

Fact 1: the increase of the share of dispatchable RES allows for the integration of a higher share of non-dispatchable RES and thus for a significant increase of the overall installed RES.

The implementation of the general DVPP idea above requires first a coordination between the two kinds of RES and along with conventional generation. Thus, the aggregated DVPP may present itself to the grid as a single dispatchable and fully controllable source. Resources of the DVPP may thus be optimized. They may participate also in ancillary services.

Fact 2: to achieve a high penetration level of RES, such sources should participate in ancillary services.

To that end, the controls implemented for such services should be revised. The prevalent multi-layer structure should evolve to become compliant with the DVPP notion above. Also, the time scales of the controls should be revisited to deal with the fast dynamics of most of the RES (interfaced with power electronics) (e.g., [12]).

Objective 1: define the structure and controls of the DVPP to enable the full participation in ancillary services.

Stability definitions (as well as assessment) in actual power systems rely on the notion of synchrony. Deviations from synchronous operation are limited by large synchronous generators which provide the global inertia of the system. In case of high penetration of RES, a stable grid frequency should be ensured also by other means [13]. Power electronics could be operated in grid forming mode, i.e., like a voltage source. Stability analysis and control under current saturations (''hard'' limitations) is a difficult task to be addressed. The DVPP would have a main role in settling such a new synchrony. This is a matter of control. The analysis of such new notion of stability needs also to be done in a new manner (to be defined) [14]. Indeed, fast dynamics due to high penetration of RES and power electronics no longer allow for usual hypothesis in stability studies like the ones which led to classic classification of angle, frequency, voltage and small-signal and large-disturbance stability.

Fact 3: RES grid integration cannot rely on synchrony and ''grid frequency'' as inputs/hypothesis.

Objective 2: new means (methodologies) for analysis and assessment of stability should be introduced for the control of the DVPP.

RES are geographically distributed. The individual injections are small in comparison to those of conventional generators, but the sum of all these injections is important at the scale of the overall system. To include them in a DVPP concept, *methodologies to aggregate specifications of control* are needed.

On the one hand, the control actions should extend also to voltage and transient dynamics. In presence of massive power electronics penetration, this leads to multi-scale (fast/slow) problems. Classic assumptions of decoupling and non-interaction no longer apply. Indeed, fast operation of converters (due to operation switching or other external commutations due to, e.g., rapid setpoint changes communicated from a higher system operation layer such as pricing signals) may lead to currently rarely encountered and possibly even unforeseen types of interactions. One such class consists on coupling modes studied in [15], [16], and [17]. These are electric interactions between geographic distant devices which are different from the classic inter-area modes put into evidence between large inertia thermal synchronous generators. Thus, such interactions should be taken into account not only among RES of the DVPP but also with other external elements like, e.g., converters of HVDC links in the neighborhood of the DVPP. On the other hand and with the amount of RES connected at distribution level becoming important, the DVPP concept should include those generators as well. This means that the aggregation logic should cover both distribution and transmission levels of the grid. Such an aggregation is addressed in [18]. It should be extended here to include the analysis and control points raised above. Moreover, to physically apply the controls to the RES generators, a disaggregation methodology of the DVPP controls should be proposed. Notice that there is no general methodology available for *disaggregation of dynamic control* and this should be developed. Also, *resilience* is an important item to be integrated: if a lot of local controllers are designed so that the global DVPP response is as desired, the closed-loop response should still be satisfactory if any single one of them fails.

Fact 4: RES connected to distribution grids should participate in new ancillary services and be part of the DVPP.

Objective 3: define a way of aggregating DVPP objectives and actions compliant with the split of the grid into transmission and distribution levels.

To capture the time-scales and phenomena mentioned above, new models are needed. Indeed, hypothesis of separation between voltage and frequency phenomena is no longer valid in the new context. Models should be revisited both at simulation and control levels/purposes [14].

Fact 5: the hypothesis of separation between voltage and frequency phenomena should be revisited.

Objective 4: propose models adequate to the multi-scale and coupling dynamics of the new grids.

Objective 5: define the perimeter of DVPP (to ensure economic efficiency).

This should be done both for long-term and real-time. The DVPP's resource portfolio should be optimized in function of availability of DVPP sources (related to meteorological conditions and to maintenance/failure constraints), grid conditions and market prices. This leads to a real-time redispatch tool which must assess both economic and security (N-1 stability) issues.

Long-term optimality of the solutions should be analyzed, especially against solutions using electrochemical storage.

Objective 6: Prove that the proposed solution is competitive compared with solutions combining variable RES with electrochemical storage.

The DVPP is a new concept which brings together generation and grid aspects. Moreover, as RES can be connected both to transmission and distribution grids, the DVPP perimeter may contain both types of grids. This raises thus also regulatory questions. Proposals should be made at this level to facilitate DVPP integration.

Objective 7: Provide business cases and regulatory solutions to allow DVPP development.

The DVPP concept should be flexible enough to allow implementation in several stages which could progressively be followed by the TSOs, DSOs and generators:

- Applicable today in the actual regulatory framework and structure
- Near future scenario in which RES penetration will overpass the threshold to invalidate the classic hypotheses

of dynamic behaviour of interconnected power systems: higher frequency variation, separation between voltage and frequency dynamics (Fact 5) and classification of stability in angle, frequency and voltage stability. Objectives 4 and 5 should be treated in this new context in a different way.

Objective 8: Implementation in two stages for TSOs, DSOs and generators.

A generic example of a DVPP developed to meet all above objectives is given in Fig. 3. Indeed, it contains several kinds of RES (different technologies for different natural resources, of dispatchable and non-dispatchable type), geographically spread on both transmission and distribution levels. Several points of grid connection may exist. DVPP generators are thus not necessarily close one to each other. Conversely, some RES generators can be close to other dynamic elements of the grid (other generators, FACTS, HVDC, ...) that do not belong to the DVPP.

III. COMPONENTS

The proposed DVPP concept is based on the following types of units:

- PV: solar photovoltaic power plants (large scale)
- ST: solar thermal power plants, including thermal energy storage in molten salts.
- W: offshore or onshore wind power plants
- HYD: hydropower power plants
- PS-HPP: pumped-storage hydropower with bidirectional operation
- BIO: biomass power plants
- GEO: geothermal power plants
- Conventional thermal units already existing in the system can also be considered, and they can be integrated in the DVPP and coordinated with the renewable units: CF-TPS coal-fired thermal power station, CC-TPS combined-cycle thermal power station and N-TPS nuclear thermal power station
- Additional units like batteries, hydrogen electrolyze, flexible loads, etc., can be potentially added to the concept

The previous units can be classified in terms of dispatchability as follows:

- The primary energy availability permanently constraints the power output capability. PV
- The primary energy availability constraints the power output capability, but the power can exceed the threshold temporarily (short time-seconds). W
- The primary energy availability influences the power output capability. However, the power output can be increased by means of a secondary (inherent storage) energy source. ST
- The primary energy availability is sufficient to not constrain the output power. However, in some cases the time response will be slow (see Table 1). BIO HYD CF-TPS CC-TPS N-TPS
- The primary energy availability does not constraint the power output capability and it is possible to reverse the power plant to produce primary energy from the surplus of electricity in the network (bidirectional capability). PS-HPP

Table 1 shows the response time, the inherent storage time and the generation technology employed by the different components discussed. Response time is understood as the time elapsed between the acknowledgement of a new power reference and its successful tracking. Inherent storage time is the total amount of time in which an electricity generation technology can provide electricity at full capacity by means of its inherent energy storage. The underlying generation technologies are PE: power electronics, SG: synchronous generator and IG: induction generator. These aspects determine the role that each technology may have within the electric power system. PV and wind present fast response times (from milliseconds to a few seconds), whereas the other technologies are much slower as they are solely based on synchronous generators. However, the inherent storage time of PV and wind is zero, whereas the other technologies offer this characteristic, from hours to months (conventional plants).

IV. STATIC ASPECTS

A. TOPOLOGIES AND SCENARIOS

The DVPP concept introduced here is flexible in the sense that covers several power systems situations:

- *continental and island power systems*: it can insert a set of RES in an interconnected power system or in an isolated island. In the first case, it will participate to existing control schemes for the large thermal plants. In the second case, it will directly ensure voltage and frequency services.
- *transmission and distribution grids*: RES can be connected on both transmission and distribution sides as shown in Fig. 3. The new DVPP concept should allow for participation of RES generators from both sides. This implies coordination of the control actions through the border between the two grids [19]. This coordination is intended at both administrative (share of the data/measures and control actions) and technical (different voltage levels and different structure (radial for distribution versus meshed for the transmission) of the grids) levels. Data availability is important, especially for second level controls (to ensure ancillary services) and for coordination of control actions in general (as DVPP actuators are geographically distant). It is supposed that voltage and frequency measures from both transmission and distribution sides will be available at a common control point called *DVPP dispatching* in the sequel. Controls will be computed in the DVPP dispatching and sent back to the DVPP actuators. The above mentioned measures can be classic or PMU.
- *several grid connection points:* insertion of the DVPP in the rest of the system may be via several connections

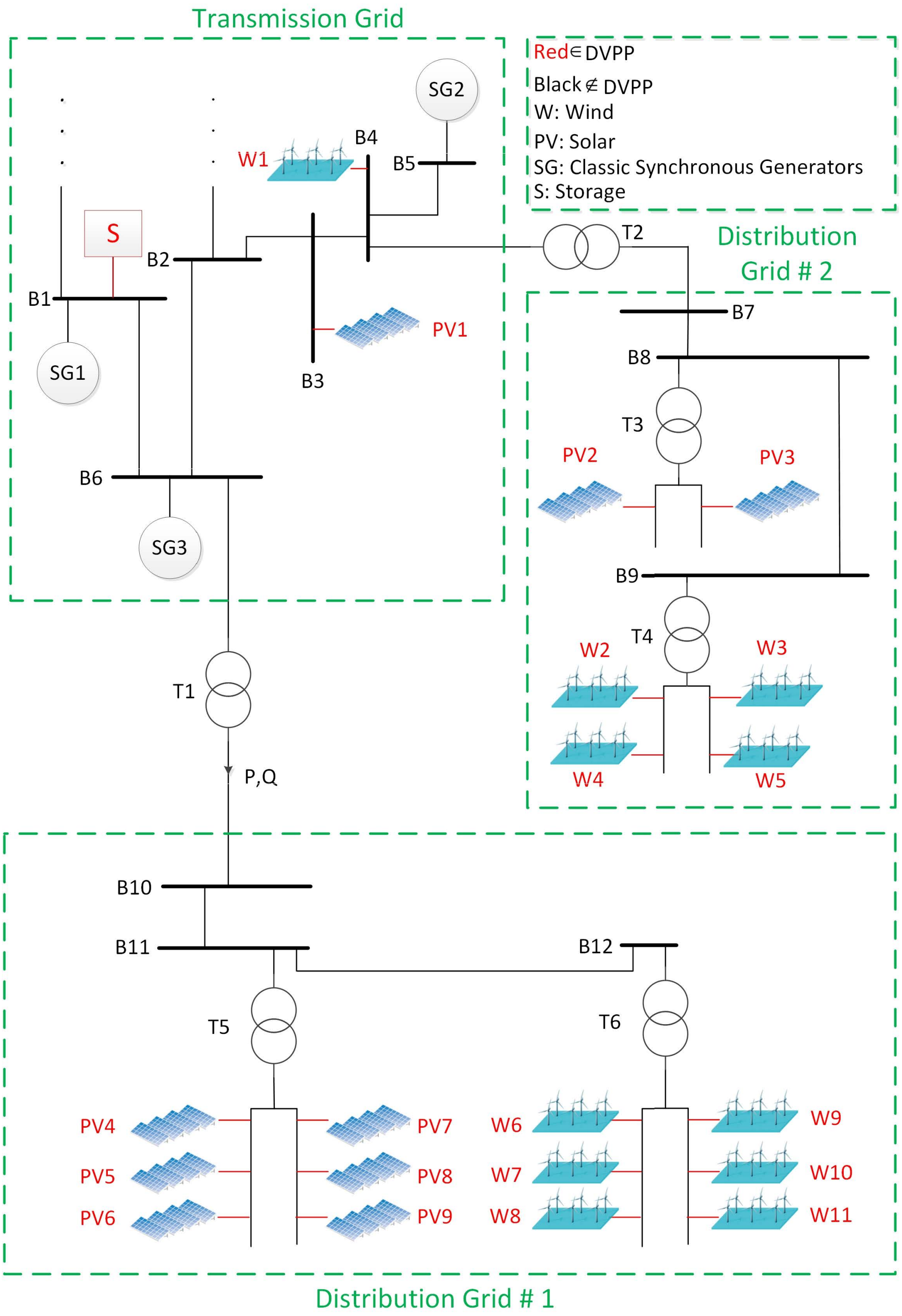

FIGURE 3. DVPP concept b).

points as in Fig. 3. Moreover, the DVPP may have RES generators in several distribution grids.

- *imbricated structure*: RES generators participating in the DVPP are not chosen from geographical or topological considerations. As a consequence, components of a DVPP are not necessarily close. Moreover, some close-by generators may not participate in the DVPP (devices in black in Fig. 3). They should be considered as disturbances/dynamic interactions in synthesis of the DVPP controls.

The following scenarios have been defined:

- Type I: islanded scenarios are in general smaller and simpler as compared to continental scenarios. Therefore, a smaller number of buses (in this case, 7) and a single voltage level is considered for this case (Figure 4).

TABLE 1. Response and storage times for different technologies.

	Response time	Inherent storage time	Generation technology
PV	100 ms - 5 s	0	PE
ST	15 min – 4 h	0 - 24 hours	SG
W	0.5 ms - 1 s	0	SG/IG+PE
HYD	2 - 5 min	4h - 16h	SG
BIO	10 min – 6 h	weeks	SG
CF-TPS	80 min - 8 h	months	SG
CC-TPS	5 min – 3 h	months	SG
N-TPS	≈ 24 h	months	SG
PS-HPP	2 - 5 min	4h - 16h	SG
GEO	30 s – 2 min	∞	SG

- Type II: the vast majority of scenarios are AC interconnected systems, and they are typically bigger and more meshed. Therefore, a higher number of buses (in this case, 13) and different voltage levels (i.e., transmission and distribution) are considered. Moreover, two different versions of this type of scenario are considered. One corresponds to a typical scenario with good solar resource (for example southern Europe) (Figure 5), whereas the other corresponds to a typical scenario with good onshore and offshore wind resource (Figure 6), including HVDC interconnected offshore wind (for example northern Europe).
- Type III: regarding HVDC interconnected scenarios without AC interconnections, they typically correspond to bigger islands. For that reason, the grid layout considered is slightly more complex, with a higher number of buses as compared to Type I (in this case, 11). Also, different voltage levels are also considered in this case (Figure 7).

B. OPTIMIZATION

The original concept of VPP germinated from the need of tackling the relatively low competitiveness of the back then emerging non-dispatchable RESs such as wind and solar generation when compared with large, dispatchable conventional generation such as hydro and thermal power plants. Most power system regulators require a minimum bid size to be submitted to electricity market auctions, leaving most stochastic, non-dispatchable RESs out of market, being remunerated by ex-post settlements with generally lower profitability than that of market participants. Increasing this competitiveness is essential to pave the way to an eventual mass integration of such renewable sources. In this vein, aggregation of non-dispatchable RESs in the form of a VPP as a single offering unit in electricity markets with a total size larger than the minimum bid size becomes apparent.

An alternative to the VPP concept that is rapidly gaining interest is the installation of electrochemical (battery) energy storage systems (BESS) due to their capability to provide both active and reactive power regulation with very short time responses (down to several tens of milliseconds). Moreover, the advances in the BESS technology and their modularity imply a remarkable flexibility that allows the installation of BESSs of up to 100 MW and over 100 MWh such as the lithium-ion BESS installed in Hornsdale, Australia, in 2017. The potential of BESSs to provide a large number of ancillary services and to mitigate the impact of the stochastic nature of non-dispatchable RESs, together with the gradual decrease in the price per MW and MWh, justify their current popularity as a solution to increase the competitiveness of non-dispatchable RESs.

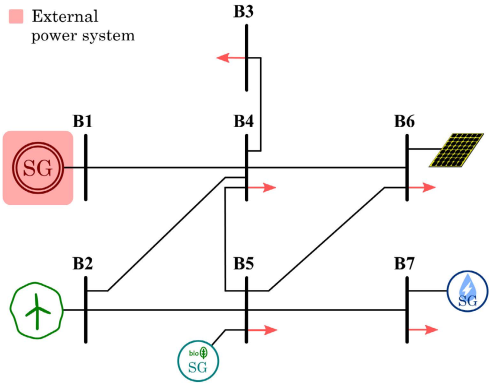

FIGURE 4. Scenario type I.

However, the main limitations of BESSs, that prevent their massive integration in the power grids, are their still high installation (capital) costs, their relatively short life span (up to 7 years, or a few thousands of cycles), their intrinsic self-discharge (up to two perceptual digits per day of their state of charge), the limited availability of the materials required in their construction, and their negative environmental impact at the time of their disposal.

The RES-based DVPP proposed in this work thus appears as a promising approach to overcome the limitations of BESSs listed above, and as a competitive solution to increase the viability of non-dispatchable RESs. The DVPP is composed of already installed RESs (both dispatchable and non-dispatchable) and demands that can provide some level of flexibility, thus reducing the installation costs to only the deployment of the communication infrastructure required to coordinate all assets. Moreover, by optimally operating all assets, the increase of non-dispatchable RES competitiveness may even surpass the benefits achieved with BESS solutions.

Electricity generation companies rely mostly on power and energy markets for obtaining revenues from electric energy trading. This is so since the late 1990s, where a transition from optimal control strategies took place worldwide at a remarkable pace [20].

Long-term electricity trading is mostly based on bilateral contracts, whereas short-term trading is generally based on competitive auctions or pools. The latter represents over 75% of the total energy traded [21]. Short-term markets thus appear as the most relevant for the studies considered in this work given their competitive nature. Short-term electricity trading usually spans a time window of 24 hours, and different pools take place prior to the power delivery. Two main groups of participants are present in such pools, namely generation (electricity producers) and demand (retailers and large

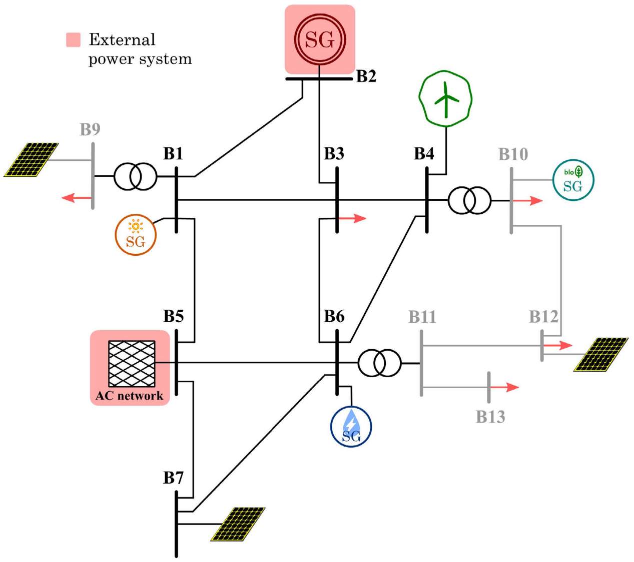

FIGURE 5. Scenarios type II - South Europe.

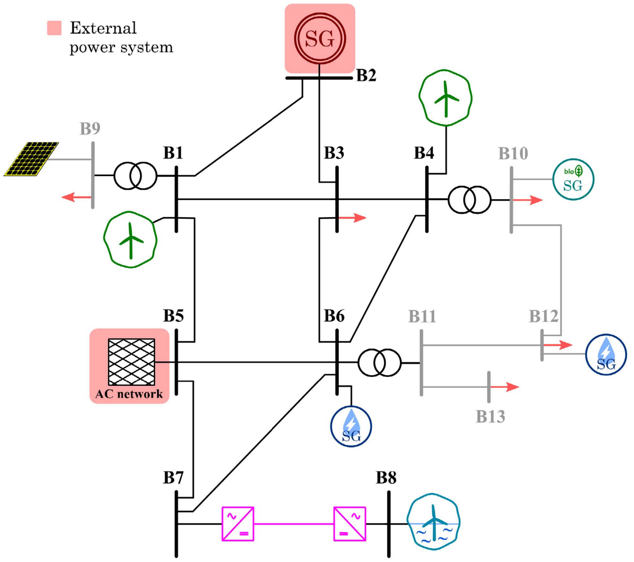

FIGURE 6. Scenarios type II - North Europe.

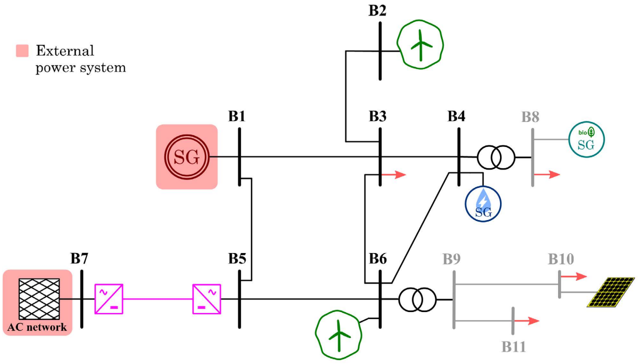

FIGURE 7. Scenarios type III.

consumers). According to the quantity traded, short-term electricity markets can be also categorized into energy markets, in which the market operator gives/receives payments according to the amount of energy supplied to/consumed from the network. Other markets are based on the trading of power for ancillary service provision (mostly active, although reactive power-based markets are starting to become relevant).

The optimal participation of the proposed RES-based DVPP in the aforementioned energy and power markets (operation) will thus be a key point in development of the DVPP concept. The impact of uncertainties that characterize both the stochastic RESs of the DVPP and market prices will also be duly analyzed. To this aim, robust optimization [22], [23] will be implemented, where uncertainties of stochastic generation and market prices are modeled as confidence bounds and intervals.

Another important aspect is the *market power* of the DVPP. Generally, market offering units based on RESs other than hydroelectric power plants are relatively small. This implies that their auction participation does not change the resulting clearing price of electricity, i.e., they are *price takers*. However, if enough RESs are aggregated in the form of a DVPP, the volume of energy auctioned could be high enough to alter such a price, making the DVPP a *price maker*. In this situation, the DVPP is aware of its own market power, and will naturally tend to alter the price in such a way that its benefits will be maximized. However, the regulatory agent will attempt to minimize the influence of all price makers in the system when clearing the market. This converts the single-stage optimization problem solved for a price taker DVPP into an iterative, multi-level problem when the DVPP is a price maker, with a significant increment in complexity.

For the aspects mentioned before, it has been assumed that the DVPP configuration was *given*, in the sense that the DVPP is composed of a known set of already installed RESs and flexible demands. However, the determination of which configuration of DVPP (total size, share of the different RES technologies and demands, geographical location of the assets, etc.) would maximize the overall profit of the DVPP in electricity markets while minimizing associated risks is the result of an optimization problem that needs to take into account, apart from the concepts outlined above, e.g., the costs associated to the installation and exploitation of the assets. The optimal configuration of the DVPP for the variety of scenarios listed in Section IV-A is also an important output of the DVPP concept.

V. DYNAMIC ASPECTS

A. GENERATOR CONTROL

Dynamics of each RES generator should be managed in order to ensure safe operation (from the material point of view, i.e., keeping currents, voltages and mechanical loads (in case the mechanical structures of wind generators) within technological limits of operation) and contractual obligations. The latter are mainly on the active power production. To ensure that, controls should be implemented to track set points for active power, voltage and mechanical speed. As RES are usually connected to the grid by power electronics, supplementary controls for the used power converters and the DC part are needed.

In order to be able to operate a RES-based grid control without BESS (see Section IV-B), it is necessary that the non-dispatchable power plants (PV, W) also provide a required gradient of active power. The achievable power gradient is thereby strongly dependent on the used control method. For example, the usual control strategy of wind power plants aims at a maximization of the power output (maximum power output tracking - MPPT) in partial-load region and a limitation of power above rated wind speed [24]. In contrast, compared to the usual strategy, demanded power point tracking (DPPT) leads to an increased operating range, which must be managed by the controller in terms of load reduction with fast response times to be optimized [25]. The operating trajectory that results in a desired power output, however, is not unique and therefore depends on the choice of the operational scheme encoded in the control concept. This can be illustrated by considering the generator power given as

$$p(v) = \omega_g(v)\, T_g(v)\,, \tag{1}$$

where ω_g and T_g are the rotational speed and generator torque, respectively, and v represents the current effective wind speed. From (1), it is apparent that a variation of power output to the demand can be achieved by an adjustment of either the rotational speed, the generator torque or both. Consequently, there is a need to study the implications of different operating strategies for power tracking about the structural loading and possible response dynamics in DVPP operation. To illustrate this, the power demand transmission behavior of a wind turbine generator for two different operating strategies (OS) proposed in [26] will now be briefly presented. In the first concept, termed OS1, the demanded power is achieved by a variation of the generator torque only while keeping the rotational speed at its nominal value at the current wind speed. Contrarily, in OS2 the controller enforces a variation of both, the generator torque and rotational speed to meet the power demand. For comparison of the dynamics, the results are shown in Figure 8 as normalized step responses of ΔP_{ref} by ΔP, where ΔP_{ref} denotes the demanded and ΔP the power generated by the wind turbine generator. To assess the dynamics involved, the turbine is faced with instantaneous demand changes while operating in different constant wind conditions at a constant power output of 70 percent of nominal power. The step wise changes in the power demand P_{ref} are bidirectional, i.e., increase and reduction of the power output demand at steps of $\Delta P_{ref} = \{-0.3,\ -0.2,\ -0.1,\ 0.1,\ 0.2,\ 0.3\}$ is conducted. The simulation is repeated for wind speeds of $v = \{8,\ 12,\ 16\}$ m/s to roughly cover a range of common operating wind speeds, and in conjunction with the bidirectional steps possibly reveal nonlinear effects. In analogy to the wind turbine control, the PV system should be operated with a DPPT instead of a MPPT.

Thus, based on the results obtained so far validated on a realistic high order wind turbine model, it is possible to use non-dispatchable RESs as power generators in the DVPP concept. Further investigations are being performed specifically for PV power plants, solar thermal and hydro power plants with equally realistic scenarios as for the wind turbine generators.

B. GRID CONTROL

Ancillary services are important to maintain operation in case of system incident or variation of operating conditions. Till today, few requirements at this level are made for RES generators. RES generators of the DVPP should *fully* participate to grid services. This means not only to provide some support for voltage and frequency control, but for the entire DVPP to be able to participate to actual implemented control schemes in same conditions as the large thermal plants. For this, it is not sufficient to add a supplementary control layer. The control at the generator level should be revised. For example, as mentioned in Section V-A, RES generators cannot be run with MPPT [27], [28] and a reserve should be managed for grid frequency services via *deloading control* (see, e.g., [29]). Also, DPPT control [27], [28] can be used with a reserve for grid frequency services. Moreover, multiplication of the controls needs and actions led us to a *dynamic system view* for the DVPP for modeling, specifications and control levels as shown in the next section. This means a new approach for the control, with a global view of the system and specifications and a maximum coordination in the control actions.

C. INTERNAL REDISPATCH

Local and grid objectives should be ensured not only for nominal operation but also in case of failure or variation of availability of resources (sun or wind, for example). The latter variations have an important impact on non-dispatchable RES of the DVPP. To ensure a continuous run of the DVPP (especially for the ancillary services), enough fast *internal redispatch* of the RES resources is needed. This is done via a tool for the *real-time portfolio optimization* of the DVPP. It mainly consists into a security-constraint optimization problem for which both generators and grid constraints (and even overall system constraints) must be taken into account. The time constant of such redispatch loop can be chosen around one minute in order to integrate it in the overall control dynamics given in Fig. 9 with no parasitic interactions.

D. INTERACTION WITH NEIGHBOUR DYNAMIC ELEMENTS OF THE GRID

As mentioned before, the DVPP is not necessarily a geographically exclusive grouping. Indeed, between the devices selected to be included in a DVPP, other static and dynamic devices of the grid exist and may have a coupled behaviour with the ones of the DVPP. Also, the same holds for devices in the neighborhood of the geographic perimeter of the DVPP.

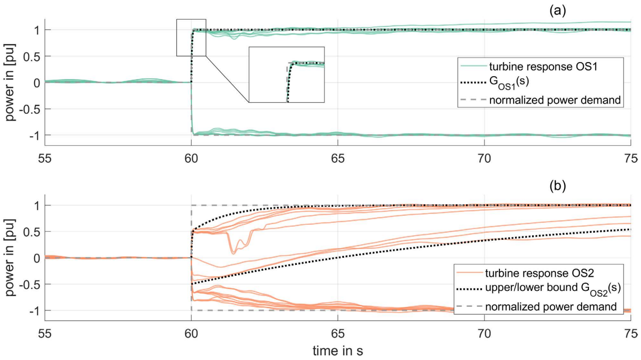

FIGURE 8. **Normalized step response for demand steps of ΔP_{ref} at constant wind speeds of $v = \{8, 12, 16\}$ m/s, Source [26].**

Such interactions can be globally taken into account in the aggregated control models mentioned in Section VI. However, certain devices require some particular caution. First, the power electronic based ones may have higher interactions with the converters of the DVPP, especially in case of rapid control of the latter ones (see, e.g., [13], [30]). Second, coordinated control with HVDCs and FACTS like SVCs and TCSCs may have a beneficial impact on overall grid performances and avoid oscillations between converters [31].

E. DYNAMICS OF SYSTEMS DOMINATED BY POWER ELECTRONICS

Modern power systems are increasingly dominated by power electronics, including FACTS devices, HVDC converters, renewable energy interfaces and loads driven by power electronics. The special nature of power electronics compared to synchronous generators have motivated significant research in the last decade. However, the issues related to system dynamics and stability have still to be investigated. The DVPP concept should integrate this in order to be applied to future power systems.

Novel methodologies will have to be developed both for analysing, simulating and understanding the system under study as well as for the control.

The development of models of different degrees of complexity and granularity (including non-linear detailed models of power electronics as well as linearized simple models) together with employing co-simulation techniques will allow developing sound analysis and identifying the possibilities and limitations of the considered systems [32], [33].

As mentioned before, the conventional power system stability definitions, their assessment, and the control thereof through ancillary services rely on the notion of synchrony. The latter is ensured in a conventional grid through large rotational generation and tight control of frequency and voltage predominantly by actuating synchronous machines. The replacement of synchronous machines by power electronics-interfaced generation not only changes the qualitative power system dynamics towards more brittle dynamics (with shorter time scales), but the system is also subject to increasingly many fluctuations (due to variable renewable generation) and with interfaced with ever-more fragile devices (e.g., converter-interfaced generation) that cannot tolerate large fault currents. Finally, also the conventional classification and separation into voltage, angle, and frequency stability does not hold anymore in future power systems that operate possibly far from a nominal equilibrium and are driven by disturbances on all time scales [13].

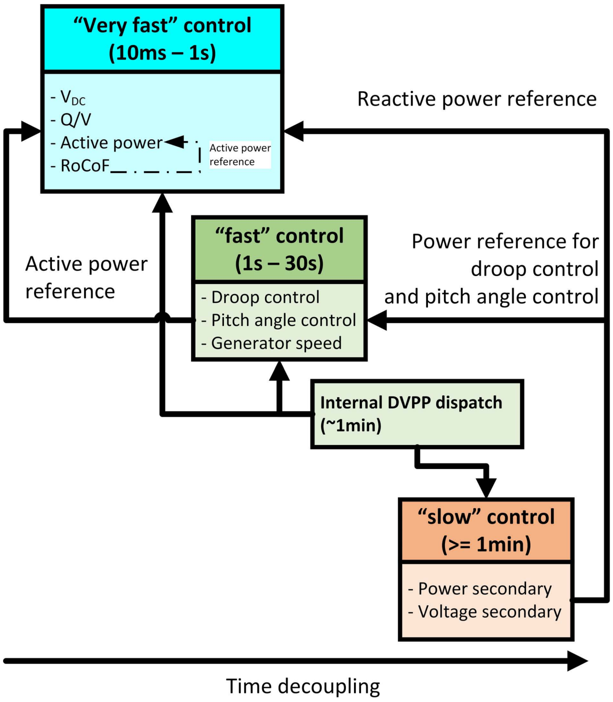

FIGURE 9. **Time decoupling.**

Novel stability definitions and analysis concepts are required that not only take into account the volatile physics of future power systems but also hard operational limits, accounting e.g. for converter over-currents. Hence, rather than looking for the conventional "stability of a stationary equilibrium point", one should investigate how disturbances amplify fluctuations in a neighborhood of the nominal synchronous operation.

Control, including ancillary services, should also be designed in accordance to this new context, as discussed in the next section.

VI. DISCUSSION OF APPROACHES

This section discusses the main approaches to implement the DVPP concept.

A. MODELS

To achieve the system-level view mentioned above, we believe that models should be constructed in a new way. They should be global (include both device and system-level dynamics) but also sufficiently simplified and tractable to cover the DVPP perimeter and to be used for control design. Modern power systems contain hybrid, i.e., both slow and fast dynamics. Fast dynamics come from power electronics which are systematically used to connect RES to grid and to reinforce transmission grids (with direct-current – HVDC - lines). Modeling should be innovative both for simulation as well as for control purposes. Indeed, to prevent from unnecessary and unmanageable high-dimension of the resulting models, specific approaches to capture dynamics of interest should be used. For simulation, the so-called *co-simulation* method can be used. It mainly consists in simulating a large zone of the power system with different degrees of details for well-chosen sub-zones. For the synthesis of the control models, identification of the models in specific bands of frequency closely linked to the phenomena to be preserved would allow low-order yet highly expressive mathematical models.

The assumptions underpinning these models are also different from the ones used till now in power systems. First, the DVPP perimeter is not compliant with classic assumption of split of the grid into very-high and low and medium voltage levels. Indeed, this voltage separation is strong as followed by administrative and control/operation separation since the grids are run by different entities: the high-voltage ones by TSOs and the others by DSOs. Strong hypothesis of non-interaction of controls and separation of data and information are at the basis of this structure. As RES are connected at both voltage levels, to ensure optimality in DVPP definition and operation, one should thus envisage DVPP perimeter which include both sides of the grid. Hypothesis mentioned above should be revisited to construct models adequate for this kind of DVPP perimeter.

Next, in perspective to participation to ancillary grid services, a larger view is needed: include future grid dynamics, include not only one DVPP but several to deal with coordination (in secondary controls for voltage and power) and competition in operation, include other dynamic power-electronic based devices like, e.g., HVDC, to deal with interactions and to damp some oscillations which might exist between these devices and the RES generators of DVPP.

Finally, all aspects should be considered in the DVPP design and control: voltage, frequency, internal robustness/resilience/re-dispatch (N-1 grid stability). Because of the fast/slow time-scales mentioned above, it is no longer possible (as in classic today approaches) to treat these phenomena separately and the new models should integrate all of them.

B. OPTIMAL OPERATION AND CONFIGURATION OF DVPP

The operation of DVPPs is separated into an internal and external operation architectures. DVPPs are currently grouped into technical (TDVPP) and commercial (CDVPP) ones, interacting mutually by allocating power commitment (CDVPP) and rescheduling due to technical reasons (TDVPP).

Although separation between TDVPP and CDVPP has been made, the nowadays massively available amount of information and data has not been systematically considered yet. Further, most of the models used to formulate the internal set-points (i.e., references for the dynamic control loops such as active or reactive power set-points) for the economic operation are non-linear models, leading to mixed integer non-linear optimization problems. These problems can, for the case of power systems, be however transformed into mixed integer linear problems for which efficient and scalable (possibly suboptimal) approaches exist by now [34], [35], [36], [37].

Large-scale deployment of DVPPs further complicates computation of centralized set-points. Aggregation and disaggregation strategies will become of high importance to improve applicability. Combination of centralized and distributed internal set-points might be an interesting alternative. Large-scale deployment also heavily increases burdens due to additional system and grid constraints. Particularly, dynamic constraints have not been addressed widely. Finally, large-scale deployment turns DVPPs from price taker to price maker, requiring not only models of the DVPP but also of the complete power system. Large-scale deployment of DVPPs with dispatchable and non-dispatchable RES requires new modeling and solution approaches. The mutual impact of DVPPs and the power system will be addressed in an iterative manner. A simplified power system model will be used, where generation is grouped according to its generation technology and by making use of standardized techno-economic parameters for each group. The concept of clustered unit commitment can be used [38].

Uncertainties of stochastic renewable sources and of electricity market prices need to be duly taken into account in the optimization problem in order to obtain accurate information of expected revenues and costs for a given DVPP operation. Uncertainties will be taken into account through the so-called *robust optimization* [22], [23], where the objective of the optimization problem is the maximization of the revenue (minimization of the costs) for the worst-case realization of the uncertain profiles.

Modeling will include a linear representation of the network by using a DC power flow model for active power [39]. Dynamic constraints will be included as well. Models will be linearized through equivalent, linear expressions. Internal and external management algorithms (i.e., internal dispatch and external market participation) will be addressed by proposing appropriate aggregation and disaggregation strategies, and by combining centralized and distributed controls. Finally, reactive power constraints will also be considered by modeling the network with a linearized AC optimal power flow model.

Finally, the appearance of new ancillary service markets will affect planning and operation of DVPP. New services include ramping, inertial response services, fast-frequency response (FFR) service, etc. [40], [41], [42]. In addition, rules of existing markets may be needed to be updated. For instance, the implementation of the Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO) will profoundly modify the market rules of the secondary reserve market in Spain. New ancillary service markets will come along with new requirements for market agents. Indeed, for fast frequency response or secondary reserve markets, compliance with dynamic response criteria (although of different scale) must be guaranteed apart from having sufficient power and energy margin to deliver the response or typical requirements on minimum bid size. Conventional units might not be able to cope with new dynamic response criteria for having slow activation responses, whereas single non-synchronous RES plant are sufficiently fast but without the needed firmness. The DVPP can provide fast responses while guaranteeing the necessary power and energy margins due to its inherent portfolio effect and the algorithms for planning, operation and control. The DVPP will be technically able to participate in most of the emerging ancillary service market. Changes in market design and rules that modify the type of the bids or the frequency of market celebrations will modify the planning and operation of DVPPs. Indeed, PICASSO transforms power bids to energy bids, but the bids are only cleared when a need for secondary reserve provision arises, changing the operation planning for this market. The trend towards more frequency market celebrations benefits DVPPs dominated by non-dispatchable, non-synchronous RES.

C. ADVANCED MODEL-BASED DVPP CONTROL

The traditional approach to automatic control is based on a first-principle model of the physical system to be controlled. These models come in different parameterizations, e.g., frequency-domain transfer functions, state-space models, or higher-order differential equations. Uncertainties are inevitable in the modeling process, and are handled in model-based design through either robust or adaptive control techniques [43], [44], [45]. Both the literature on power systems modeling as well as model-based control are mature and highly developed.

However, sometimes first-principle physical models are too complex to be useful for control design (e.g., the wake interactions inside a wind farm), too high-dimensional and large-scale for the considered control objective (e.g., to damp inter-area oscillations it is not required to know the detailed continental power grid model), or simply too cumbersome to calibrate (e.g., precisely fitting the values of all passives inside a converter). In such cases one would opt for reduced-order models (e.g., an area equivalent), identify non-physical (e.g., an ARMA model for load behaviour) models from time series data, or directly go for a data-driven control design leveraging recent advances and methodologies from the machine learning community. Another way to construct a *control-model* for the DVPP is to extract dynamics of interest of the overall system into an as simple as possible (from the state dimensional point of view) mathematical object [46].

From the control point of view, there are two ways to tackle the DVPP control problem. First, a *centralized control* can be used, which takes a maximum benefit from the unified *system-view* of the DVPP and the surrounding power system. A control model which takes into account all dynamics and interactions is used along with classic robust control methods and, as a consequence, one can expect maximum coordination, performances and robustness. The price to pay is the use of several measurements (and some of them could be from distant generators) and a lack of resilience in case of failure of one actuator (RES generator). Next, as opposite philosophy of control, *decentralized approaches* can be used. They use only local measurements to design control loops around each device. Among these extreme cases that will be presented below, intermediate control solutions can be envisaged like, for example, centralized synthesis of controllers with decentralized implementation.

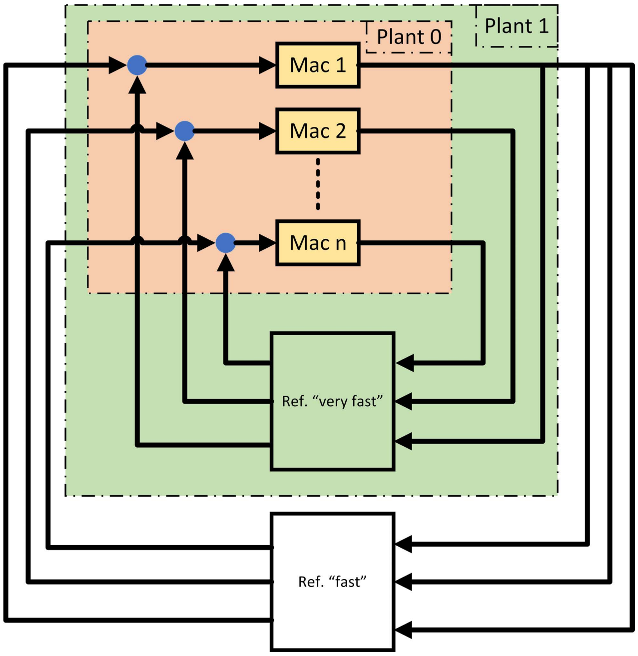

FIGURE 10. Centralized control.

1) CENTRALIZED AND COORDINATED CONTROL

The control schematized in Fig. 10 is a centralized approach to handle several RES generators according to the time-decoupling of the dynamics of the phenomena shown in Fig. 9. Compared with the classic vector control, the control is not structured around each actuator, but according to the time response (frequency band) of the actuators and open-loop plant dynamics [46].

Several stages of control are proposed according to the time scales. The closed-loop obtained at one stage is the plant for the next stage. In this way a hierarchical and sequential synthesis is possible, with, at each level, account for the faster controls of lower levels and with minimal risk of parasitic dynamic interactions. Notice also that this strategy is compliant with actual organization of controls in power systems (structured in primary/secondary layers) and opens the way to direct integration of RES into existing power systems controls and market mechanisms.

2) DECENTRALIZED CONTROL

In parallel to the centralized control approach, we also pursue a fully decentralized approach, where the device-level controllers employ only local measurements as well as a

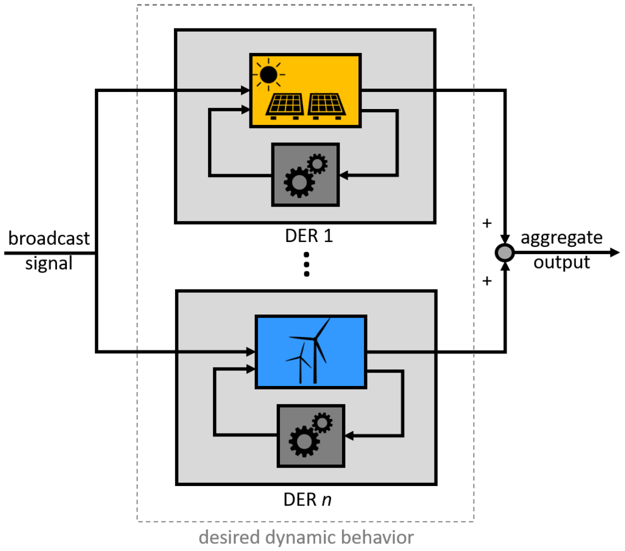

FIGURE 11. **Decentralized control.**

few selected global broadcast signals. As a prototypical example, consider a fast-frequency response provided by a DVPP in grid-following mode; see Fig. 11 for an illustration. In this scenario, a selected global frequency measurement signal is broadcast to the local controllers of the devices comprising the DVPP. The local controllers are designed so that the aggregate response of the DVPP – from the frequency measurement to the aggregate power output – meets the aggregate dynamic specification, in this case a desired droop and virtual inertial response. Aside from the aggregate design specification, the local controllers also have to take the local device-level limitations into account, such as bandwidth limitations, energy and power constraints, overcurrent limitations, and so on. In summary, the DVPP control design is posed as a *decentralized matching problem*: local controllers should meet the aggregate specification subject to device-level constraints.

We pursue two distinct approaches to this problem. Our first approach is based on a divide-and-conquer strategy: the aggregate specification is disaggregated to purely local specifications by means of dynamic participation factors (a dynamic extension of the well-known static participation factors). Next local matching controllers are tasked to meet the disaggregated specification; see [47] for a preliminary exploration of this approach and a case study coordinating hydro and wind power for fast frequency response. Our second approach falls square in between the centralized and decentralized control paradigms: optimal and structured controllers are designed in a centralized fashion but so that they allow for a decentralized implementation. For both approaches we envision also grid-forming as well as adaptive strategies that adapt online to changing conditions inside the DVPP, e.g., fluctuations of wind and solar production.

VII. CONCLUSION

The DVPP concept presented in this paper will pave the way to top-down solutions to increase the penetration of dispatchable and non-dispatchable RES in actual and future power systems.

It allows treating all the aspects - static, dynamic, optimality/efficiency - at once and in a coordinated way in order to provide TSOs, DSOs and generators with knowledge, models and tools.

It enables local decentralized small power plant operators that join together in a DVPP to offer suitable grid services for the transmission grid level. Stabilization of the grid and further ancillary service will no longer depend on large power plants; instead, a massive number of distributed generators will contribute to ensuring that the grid can be operated reliably. This will open up new business models for both the generator and the operator side.

The DVPP concept provides the scientific basis for the controller design since the requirements to support the grid are formulated at an aggregated upper level and then disaggregated to the local level for controller design. The local power plants can be specified and upgraded with these dynamic requirements. Previously (for today's existing VPP), it has not been possible to do this because only static power requirements have been specified.

Controls for both local (production) and grid (ancillary services) objectives specifications will be provided for the actual power systems in full compliance with the existing regulations schemes, as well as for future power systems with massive RES penetration and low inertia systems.

More specifically, the outputs will be:

- optimality criteria to define the perimeter/portfolio of DVPP both for long term and real-time application: this allows improving in a compliant/coordinated way both optimal (from the economical point of view) configuration of the DVPP and its participation to electricity markets and ancillary services (from the dynamic point of view)
- new controllers to allow RES to fully contribute to ancillary services ultimately enabling system stability
- new business cases for the optimal operation and configuration of DVPP
- regulatory recommendations to enable DVPP development and operation in conjunction with the generators' operation in a classic way. Current rules should be revised in order to allow economic and social welfare improvement as well as security (stability in general and blackout prevention in particular) assessment
- the assessment of the economic competitiveness of the DVPP compared with solutions combining variable RES with electrochemical storage
- new stability definitions and methodologies for stability analysis and assessment. The classic framework and hypothesis will be revisited to obtain approach for DVPP in the context of power electronics dominance. The latter

both inside the DVPP (because of the RES systematically connected to the grid by power converters) but also outside the DVPP which may be in future a power grid with high power electronics penetration

Part of the approaches mentioned in Section VI are innovatory and at a basic research stage now. They will be fully reported in forthcoming publications. Other are based on classic methods which are used in a new manner in the specific DVPP context. Part of our ongoing POSYTYF project is to also consider economic aspects. Within the near future joint technical and economical proof-of-concept demonstrations and commercial avenues will be reported.

REFERENCES

[1] *Energy Roadmap 2050*, European Commission, Bruxelles, Belgium, 2012.
[2] T. Zhang, Y. Li, R. Yan, A. Abu-Siada, Y. Guo, J. Liu, and R. Huo, "A master-slave game optimization model for electric power companies considering virtual power plant," *IEEE Access*, vol. 10, pp. 21812–21820, 2022.
[3] A. Fakhar, A. M. A. Haidar, M. O. Abdullah, and N. Das, "Smart grid mechanism for green energy management: A comprehensive review," *Int. J. Green Energy*, pp. 1–25, Feb. 2022.
[4] C. Huang, D. Yue, J. Xie, Y. Li, and K. Wang, "Economic dispatch of power systems with virtual power plant based interval optimization method," *CSEE J. Power Energy Syst.*, vol. 2, no. 1, pp. 74–80, Mar. 2016.
[5] D. Koraki and K. Strunz, "Wind and solar power integration in electricity markets and distribution networks through service-centric virtual power plants," *IEEE Trans. Power Syst.*, vol. 33, no. 1, pp. 473–485, Jan. 2018.
[6] N. Pourghaderi, M. Fotuhi-Firuzabad, M. Moeini-Aghtaie, and M. Kabirifar, "Commercial demand response programs in bidding of a technical virtual power plant," *IEEE Trans. Ind. Informat*, vol. 14, no. 11, pp. 5100–5111, Nov. 2018.
[7] S. Camal, A. Michiorri, and G. Kariniotakis, "Optimal offer of automatic frequency restoration reserve from a combined PV/Wind virtual power plant," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6155–6170, Nov. 2018.
[8] E. L. Miguélez, Ignacio E. Cortés, and G. L. Camino, "An overview of ancillary services in Spain," *Electr. Power Syst. Res.*, vol. 78, no. 3, pp. 515–523, 2008.
[9] I. Egido, F. Fernandez-Bernal, and L. Rouco, "The Spanish AGC system: Description and analysis," *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 271–278, Feb. 2009.
[10] S. A. F. Asl, L. Bagherzadeh, S. P. M. Norouzi, and M. Lehtonen, "A new two-layer model for energy management in the smart distribution network containing flexi-renewable virtual power plant," *Electr. Power Syst. Res.*, vol. 194, May 2021, Art. no. 107085.
[11] A. Z. G. Seyyedi, S. A. Nejati, R. Parsibenehkohal, and M. Hayerikhiyavi, "Bi-level sitting and sizing of flexi-renewable virtual power plants in the active distribution networks," *Int. J. Elect. Power Energy Syst.*, vol. 137, May 2022, Art. no. 107800.
[12] E.-E. T. G. on High Penetration of Power Electronic Interfaced Power Sources. (2020). *High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters*. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/Publications/SOC/High_Penetration_of_Power_Electronic_Interfaced_Power_Sources_and_the_Potential_Contribution_of_Grid_Forming_Converters.pdf
[13] F. Milano, F. Dorfler, G. Hug, D. J. Hill, and G. Verbic, "Foundations and challenges of low-inertia systems (Invited Paper)," in *Proc. Power Syst. Comput. Conf. (PSCC)*, Jun. 2018, pp. 1–25.
[14] M. H. Project. (2019). *Deliverable 3.6: Requirement Guidelines for Operating a Grid With 100% Power Electronic Devices*. [Online]. Available: https://www.h2020-migrate.eu/downloads.html
[15] M. Kouki, B. Marinescu, and F. Xavier, "Eigencalculation of coupling modes in large-scale interconnected power systems with high power electronics penetration," in *Proc. Power Syst. Comput. Conf. (PSCC)*, Jun. 2018, pp. 1–7.
[16] L. Arioua and B. Marinescu, "Robust grid-oriented control of high voltage DC links embedded in an AC transmission system," *Int. J. Robust Nonlinear Control*, vol. 26, no. 9, pp. 1944–1961, Jun. 2016.
[17] I. Munteanu, B. Marinescu, and F. Xavier, "Analysis of the interactions between close HVDC links inserted in an AC grid," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2017, pp. 1–5.
[18] M. Belhocine, B. Marinescu, and F. Xavier, "A generic model for power park modules for both transient and small-signal stability analysis," in *Proc. Power Syst. Comput. Conf. (PSCC)*, Jun. 2018, pp. 1–7.
[19] ENTSO-E. (2017). *Distributed Flexibility and the Value of TSO-DSO Coordination*. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/Publications/Positionpapersandreports/entsoe_pp_DF_1712_web.pdf
[20] A. J. Conejo and L. Baringo, *Power System Operations*. Cham, Switzerland: Springer, 2018.
[21] A. Dagoumas, "Impact of bilateral contracts on wholesale electricity markets: In a case where a market participant has dominant position," *Appl. Sci.*, vol. 9, no. 3, p. 382, Jan. 2019.
[22] D. Bertsimas and M. Sim, "The price of robustness," *Oper. Res.*, vol. 52, no. 1, pp. 35–53, Jan. 2004.
[23] M. Rahimiyan and L. Baringo, "Strategic bidding for a virtual power plant in the day-ahead and real-time markets: A price-taker robust optimization approach," *IEEE Trans. Power Syst.*, vol. 31, no. 4, pp. 2676–2687, Jul. 2016.
[24] E. A. Bossanyi, "Wind turbine control for load reduction," *Wind Energy*, vol. 6, no. 3, pp. 229–244, 2003.
[25] F. Pöschke, E. Gauterin, M. Kühn, J. Fortmann, and H. Schulte, "Load mitigation and power tracking capability for wind turbines using linear matrix inequality-based control design," *Wind Energy*, vol. 23, no. 9, pp. 1792–1809, 2020.
[26] F. Pöschke and H. Schulte, "Evaluation of different APC operating strategies considering turbine loading and power dynamics for grid support," *Wind Energy Sci. Discuss.*, vol. 2021, pp. 1–14, Mar. 2021. [Online]. Available: https://wes.copernicus.org/preprints/wes-2021-80/
[27] A. Fernández-Guillamón, E. Gómez-Lázaro, E. Muljadi, and Á. Molina-García, "Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time," *Renew. Sustain. Energy Rev.*, vol. 115, Nov. 2019, Art. no. 109369.
[28] D. P. Hohm and M. E. Ropp, "Comparative study of maximum power point tracking algorithms using an experimental, programmable, maximum power point tracking test bed," in *Proc. Conf. Rec. 28th IEEE Photovoltaic Spec. Conf.*, Sep. 2000, pp. 1699–1702.
[29] M. Dreidy, H. Mokhlis, and S. Mekhilef, "Inertia response and frequency control techniques for renewable energy sources: A review," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 144–155, Mar. 2017.
[30] K. Schönleber, E. Prieto-Araujo, S. Ratés-Palau, and O. Gomis-Bellmunt, "Extended current limitation for unbalanced faults in MMC-HVDC-connected wind power plants," *IEEE Trans. Power Del.*, vol. 33, no. 4, pp. 1875–1884, Aug. 2018.
[31] I. Munteanu, B. Marinescu, and F. Xavier, "Analysis of the interactions between close HVDC links inserted in an AC grid," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2017, pp. 1–5.
[32] E. Prieto-Araujo, A. Junyent-Ferré, C. Collados-Rodríguez, G. Clariana-Colet, and O. Gomis-Bellmunt, "Control design of modular multilevel converters in normal and AC fault conditions for HVDC grids," *Electr. Power Syst. Res.*, vol. 152, pp. 424–437, Nov. 2017.
[33] E. Prieto-Araujo, A. Egea-Alvarez, S. Fekriasl, and O. Gomis-Bellmunt, "Dc voltage droop control design for multiterminal HVDC systems considering AC and DC grid dynamics," *IEEE Trans. Power Del.*, vol. 31, no. 2, pp. 575–585, Apr. 2016.
[34] G. Morales-Espana, A. Ramos, and J. Garcia-Gonzalez, "An MIP formulation for joint market-clearing of energy and reserves based on ramp scheduling," *IEEE Trans. Power Syst.*, vol. 29, no. 1, pp. 476–488, Jan. 2013.
[35] G. Morales-Espana, J. M. Latorre, and A. Ramos, "Tight and compact MILP formulation for the thermal unit commitment problem," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4897–4908, Nov. 2013.
[36] D. A. Tejada-Arango, P. Sánchez-Martín, and A. Ramos, "Security constrained unit commitment using line outage distribution factors," *IEEE Trans. Power Syst.*, vol. 33, no. 1, pp. 329–337, Jan. 2018.
[37] S. Cerisola, Á. Baíllo, J. M. Fernández-López, A. Ramos, and R. Gollmer, "Stochastic power generation unit commitment in electricity markets: A novel formulation and a comparison of solution methods," *Operations Res.*, vol. 57, no. 1, pp. 32–46, Feb. 2009.
[38] G. Morales-Espana and D. A. Tejada-Arango, "Modeling the hidden flexibility of clustered unit commitment," *IEEE Trans. Power Syst.*, vol. 34, no. 4, pp. 3294–3296, Jul. 2019.

[39] F. M. Echavarren, E. Lobato, and L. Rouco, "Full active-reactive DC power flow model with loss compensation," IIT, Madrid, Spain, Tech. Rep. IIT-16-119A, 2016.

[40] IRENA. (2019). *Innovative Ancillary Services—Innovation Landscape Brief*. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovative_ancillary_services_2019.pdf?la=en&hash=F3D83E86922DEED7AA3DE3091F3E49460C9EC1A0

[41] INTERRFACE. (2019). *D3.1 Definition of New/Changing Requirements for Services*. [Online]. Available: http://www.interrface.eu/sites/default/files/publications/INTERRFACE_D3.1_V1.0.pdf

[42] F. A. Wolak, "Market design in an intermittent renewable future: Cost recovery with zero-marginal-cost resources," *IEEE Power Energy Mag.*, vol. 19, no. 1, pp. 29–40, Jan. 2021.

[43] K. Zhou, J. Doyle, and K. Glover, *Robust and Optimal Control*. Upper Saddle River, NJ, USA: Prentice-Hall, 1996.

[44] A. Bemporad and M. Morari, "Robust model predictive control: A survey," in *Robustness in Identification and Control*. Cham, Switzerland: Springer, 1999, pp. 207–226.

[45] X. Wu, F. Dörfler, and M. R. Jovanović, "Input-output analysis and decentralized optimal control of inter-area oscillations in power systems," *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 2434–2444, May 2016.

[46] B. Marinescu, E. Kamal, and H.-T. Ngo, "A system model-based approach for the control of power park modules for grid voltage and frequency services," 2021, *arXiv:2107.02000*.

[47] J. Björk, K. H. Johansson, and F. Dörfler, "Dynamic virtual power plant design for fast frequency reserves: Coordinating hydro and wind," *IEEE Trans. Control Netw. Syst.*, early access, Jun. 10, 2022, doi: 10.1109/TCNS.2022.3181553.

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