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Ancillary Services in Active Distribution Networks: A Review of Technological Trends from Operational and Online Analysis Perspective

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Abstract: Originally, ancillary services (ASs) are provided by large-scale power plants to ensure the secure and reliable operation of power systems. However, with the advent of renewable energy sources either in large-scale or as smaller distributed generation units, there is a strong need to revisit the structure and aim of traditional ASs and reconsider them under two main concepts; ASs provided to distribution networks (DNs), aiming to solve local issues at the distribution level, and ASs offered to transmission system (TS), targeting to solve issues having a wider impact on the power system. The former can be considered as DN-oriented ASs, while the latter as TS-oriented ASs. In this changing environment, the increasing installation of measuring infrastructure has created new sources of data, providing the opportunity to improve the performance of several ASs by applying measurement-based analysis. This review paper gives an insight into the most important DN- and TS-oriented ASs foreseen to apply in future power systems. Additionally, state-of-the-art on measurement-based analysis techniques that can be used to facilitate the provision of several ASs by providing in real-time critical information regarding system dynamic performance is presented.

Highlights

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- Detailed review on future ancillary services (ASs) in transmission systems
- Detailed review on future ASs in distribution systems
- Overview of measurement-based techniques to facilitate the provision of ASs
- Discussion on future research areas regarding ASs provision

Keywords: ancillary services; congestion management; distributed generation; equivalent models; inertia estimation; inertia response; measurement-based analysis techniques; mode estimation; power smoothing; primary frequency response; renewable energy resources; voltage regulation; voltage unbalance.

Word count: 9916.

Nomenclature

ADN	Active Distribution Network
APC	Active Power Curtailment
AS	Ancillary Service
COI	Centre of Inertia
DN	Distribution network
DGS-SVM	Double Grid Search Support Vector Machine
DR	Demand Response
DRES	Distributed Renewable Energy Source
DSM	Demand Side Management
DSO	Distribution System Operator
ESS	Energy Storage System
EV	Electric Vehicle
FACTS	Flexible Alternative Current Transmission System
FD	Frequency-Domain
HV	High Voltage
LS	Least squared
LSRES	Large-Scale Renewable Energy Source
LV	Low-Voltage
MPP	Maximum Power Point

MV	Medium-Voltage
OLTC	On-Load Tap Changer
PEV	Plug-in Electric Vehicle
PFR	Primary Frequency Response
PLL	Phase-Locked Loop
PMSG	Permanent Magnet Synchronous Generator
POI	Point of Interconnection
PV	Photovoltaic
RES	Renewable Energy Source
RoCoF	Rate of Change of Frequency
RPC	Reactive Power Control
SG	Synchronous Generator
SoC	State of Charge
TD	Time-Domain
TS	Transmission System
TSO	Transmission System Operator
VISMA	Virtual Synchronous Machine
VPP	Virtual Power Plant

1 Introduction

ASs are traditionally provided by conventional large-scale power plants to ensure the secure and reliable operation of the grid. They can be classified to [1]: a) ASs for congestion management, b) non-frequency ASs, e.g. voltage control, and c) frequency ASs. In recent years, this operational scheme has been influenced by the advent of RESs. RESs in the form of large-scale plants at the transmission or of DRESs at the distribution level lead to the gradual decommissioning of conventional, fossil-fuel-based power plants and thus to reduced capacity regarding the provision of AS. Additionally, several new technical challenges have emerged either at a system-wide or at local grid level [2], [3]. One of the most important issues at the system-wide level is the increased uncertainty regarding the real-time power system operation, caused by the volatile and intermittent operation of RESs that may lead to abnormal frequency deviations and dynamic stability issues [4]. On the other hand, local issues, e.g. voltage control and congestion, usually occur in DNs due to the active power injections of DRESs [5]–[8]. To solve the above-mentioned issues several control strategies have been proposed [9],[10]. However, the participation of LSRES plants and DRESs in frequency control influences both the frequency and small-signal stability of power systems [11], [12], affecting also the related inter-area oscillation characteristics; typically used to fine-tune power system stabilizers [12], [13]. Similarly, the participation of DRESs in voltage control of DNs may influence the voltage stability of the whole power system [14].

Therefore, there is a strong need to revisit the structure and aim of the traditional ASs to address the new challenges posed by the advent of RESs, and especially of DRESs [1], [15]. In this context, two types of ASs are foreseen in the near future: DN- and TS-oriented. In the former, DSOs by their own or via aggregators shall coordinate the operation of DRESs with local ESSs and flexible loads to solve local DN problems, e.g. overvoltages, power quality and thermal limit violations, etc. In the latter, TSOs by their own or via market entities shall coordinate and control the operation of LSRES plants and DRESs to solve issues having a wider impact on the power system, e.g. abnormal frequency deviations and dynamic instability. In addition, to fully exploit the flexibility offered by LSRES plants and DRES, DSOs and TSOs shall establish a stronger coordination among them by exchanging in real-time control signals and information concerning the operational condition of the power system [16].

Towards these objectives, online analysis techniques can be used by both TSOs and DSOs to estimate directly from measured responses the overall system inertia [17] as well as to identify the system modes (eigenvalues) [18]. These estimations can provide vital real-time information regarding the dynamic performance of distribution and transmission systems and further improve the design of corrective control centralized or distributed techniques to prevent system instability [19]. Also, by applying measurement-based techniques reduced order equivalent models of system components (generators, loads, network areas, etc) can be derived online [20]. Significant advantages of such models are the reduced complexity and their inherent ability to directly reflect the system characteristics. In this sense, measurement-based models can be used to enhance the information exchange between TSOs and DSOs and facilitate, in terms of close to real-time decision making, the application of centralized and distributed techniques to optimally coordinate the operation of DRESs [12].

Scope of this paper is to present a review of potential future DN- and TS-oriented ASs that can be provided by exploiting the flexibility of LSRES plants, DRES, and network assets, e.g. ESSs and flexible loads. Voltage control, congestion management and active power smoothing are analysed as the most important DN-oriented AS. On the other hand, reactive power support, inertial and PFR as well as power smoothing for grid stability are reviewed regarding the TS-oriented AS. In addition, online analysis techniques facilitating the real-time provision of ASs are reviewed in terms of inertia time constant estimation, system mode estimation and reduced order modelling. Finally, the conclusions of the paper present future research areas identified by this review.

2 DN-oriented ancillary services

In this section, a review of the ASs that can ensure the secure and reliable operation of DNs is presented. These ancillary services can be classified into the following three main categories, i.e. voltage regulation, congestion management, and power smoothing. Voltage regulation involves the development of methods to tackle potential under- and over- voltages as well as to mitigate voltage asymmetries caused by the unbalanced loading and network asymmetries. Congestion management deals with the development of algorithms to alleviate overloading of the main network elements, i.e., transformers and lines. Finally, power smoothing includes methods related to smoothing the output power of DRESs with variable primary source, e.g. wind turbines, PVs, etc. A review of the most indicative papers on the above-mentioned ASs is presented in the next subsections.

2.1 Voltage regulation

Conventional DNs were designed to operate under an unidirectional power flow, i.e., from the HV/MV transformer towards end-users connected either at the MV or the LV level. However, the advent of DRESs has led to bidirectional power flows, causing overvoltages along the network affecting also conventional voltage regulation methods. Several solutions have been proposed to tackle voltage limit violations in DNs by exploiting network elements; depending on the type of the network element used for voltage regulation, the proposed solutions can be classified in the following main categories: (a) DRES-based control methods, (b) use of ESSs, and (c) DSM techniques [6], [7], [10]. These categories are analytically described below.

2.1.1 DRES-based control methods

There is lot of past and ongoing research in developing new methods that exploit the controllability DRES technologies can offer to effectively address voltage violation issues. One of the most promising solutions is the RPC approach that uses the available reactive power of DRESs to regulate network voltages. A simple RPC method is introduced in [21] where DRESs absorb reactive power to fully compensate the voltage rise caused by active power injections. The use of $Q(P)$ droop curve is proposed in [22]; the reactive power of each DRES is calculated with respect to the active power output. The settings of the droop curve applied to each DRES are calculated by employing sensitivity theory. A similar approach is proposed in [23], where a $Q(V)$ droop curve is used instead of $Q(P)$, i.e., the reactive power output of each DRES is calculated based on the voltage at POI with the grid. Furthermore, the $Q(V)$ settings are individually calculated for each DRES using the sensitivity theory and solving a multi-objective optimization problem. In [24], a two-level RPC control strategy is proposed. In the first level, fast disturbances of voltage are locally mitigated, while in the second level, a centralized solution is adopted to allocate the reactive power among DRESs. A nearly decentralized RPC method is introduced in [25]. The proposed strategy targets to the minimization of network losses, while it can be combined with the operation of OLTC transformers to further reduce the network losses. The authors in [26] propose a distributed RPC by combining the available reactive power of DRESs and shunt reactors. Although RPC methods are designed for both LV and MV DNs, the effectiveness of reactive power in voltage regulation is less significant in LV networks due to the relatively high R/X ratio of the lines [27].

Several voltage regulation methods have been proposed combining the available reactive power of DRESs with the OLTC of the transformers. Note that HV/MV transformers are equipped with OLTC, while LV networks are connected to the MV grid through transformers with off-load tap changer [1]. Therefore, most of the existing methods refer to MV grids. In particular, the authors in [28] propose the coordinated operation of OLTC of the HV/MV transformer and DRESs to regulate the network voltages, while also minimizing the number of the regulating actions. Furthermore, the combined operation of the OLTC with the available reactive power of turbines is investigated in [29]. A coordinated strategy of OLTC and reactive power control of distributed PV inverters is proposed in [30], suitable to handle different voltage conditions in multi-feeder networks. Moreover, in [31], optimal voltage regulation is achieved by coordinating the RPC of DRESs combined with OLTC operations. Specifically, a methodology is proposed to solve the bi-objective optimization problem of two conflicting objectives, i.e., minimization of power losses and tap actions. Furthermore, in [32] a scheme for voltage control in DNs is proposed, through coordinated control schemes that prioritize the use of OLTC, the reactive, and finally the active power of DRESs. In [33], a consensus-based distributed voltage regulation strategy is introduced aiming to utilize effectively the active and reactive power of DRESs and the OLTC.

Although RPC methods are an effective solution for voltage regulation of MV grids, in LV grids, large amounts of reactive power are needed to tackle voltage violations due to the relatively high R/X of the lines. Thus, network losses are inevitably increased due to the increased currents [34]. Additionally, to achieve large amounts of available reactive power at DRESs, either the active power output of each DRES should be reduced or the DRES has to be oversized [35]. Thus, APC methods have been also introduced for voltage regulation of DNs. An active power capping method is developed in [36] to prevent voltage violations caused by increased PV penetration, using local voltage and power measurements. In [34] a local voltage regulation strategy through a droop-based APC for distributed PV inverters is proposed. A similar APC droop-control is introduced in [37]. Both methods exploit the sensitivity theory to uniformly allocate the curtailed power among the PV owners. In [38], two coordinated PV control strategies are proposed aiming to enhance the fairness of APC schemes in terms of uniform allocation of curtailed power among PVs.

APC methods have been combined with RPC strategies to enhance the voltage regulation of DNs. An optimal control of active and reactive power of PV inverters is presented in [39] for voltage regulation of LV DNs. In [40], a distributed control scheme for voltage regulation of LV feeders is introduced that prioritizes the use of reactive power prior to APC; communication requirements among PV inverters is low. A local voltage regulation method is developed in [41] through APC and RPC of PV inverters, based on short-term PV power forecasts. Authors in [42] developed a local voltage regulation methodology for distributed PV microinverters. The proposed method is based on the correction of voltage measurements at the ac-side of microinverters to ensure unnecessary curtailment of active power and avoid the use of reactive power.

2.1.2 Use of ESSs

The RPC and APC techniques lead to increased network losses and green energy curtailment, respectively. A promising alternative for voltage regulation is the use of ESSs, constituting the most reliable and efficient solution for voltage regulation against APC and RPC techniques [1], [35]. Several ESS-based methods have been proposed that can be classified in two main categories based on the voltage level of the DNs, i.e., MV- and LV-oriented control methods. Note that ESSs can be operated either by their owners (prosumers), an aggregator, or the DSO.

Considering MV grids, the use of central (community level) ESS is a promising solution which is investigated in various research works. Specifically, an optimal scheduling and sizing method is proposed in [43] for community-based, DSO-operated battery ESS, providing among others voltage regulation services at the DNs. Authors in [44] propose a coordinated control for PV inverters and battery ESSs for voltage regulation, ensuring that deep discharge of battery is prevented. Additionally, distributed ESS units may be connected in various points of a DN to efficiently regulate grid voltages. Voltage regulation is achieved by utilizing reactive power of distributed ESSs in [45], through a localized and a consensus-based control. Network loading management is also achieved by a distributed control of the active power of the ESSs. In [46] a coordinated control for voltage regulation is proposed, based on three fuzzy controllers managing the OLTC of the transformer as well as the reactive and active power of DRESs and/or ESSs. Moreover, in [47], a coordinated control of distributed battery ESSs for voltage regulation and mitigation of frequency deviations is introduced. The proposed approach groups neighbouring ESSs and prioritizes the use of the largest. In [48], a distributed control of heterogeneous ESS is designed to provide voltage/frequency support, while synchronizing the active/reactive power sharing and energy levels of the participating ESSs.

The concept of the central (community level) ESS has been also adopted for LV networks. Specifically, a methodology for siting and sizing central battery ESS is developed in [49]; the active and reactive power contribution of the central ESS is utilized to maintain the voltage into permissible limits, increasing the hosting capacity of the grid. In [50], the optimal sizing and placement of a central battery is defined based on multiple objectives, e.g., voltage regulation of the LV network. The use of distributed-located ESSs for the voltage control of LV grids has been investigated in numerous studies. The developed strategies of ESSs can be classified into centralized, distributed, and localized control schemes, and are analytically described below.

Considering centralized strategies, the authors in [51] propose the combined operation of ESSs and available reactive power of DRESs to tackle voltage violation events. The centralized coordination controller of [52] decides the charging/discharging profiles of distributed ESSs and the tap changes of active distribution transformers for overvoltage mitigation. The main target is to relieve the tap changer stress, by limiting the required voltage control actions. Authors in [53] developed a centralized control for the co-operation of both utility- and prosumer-owned batteries, that exploit the real and reactive power of the ESSs to improve the voltage profile. The combined operation of droop-based controlled ESSs and PVs is proposed in [54] and [55]. These works assess the impact of the R/X ratio on the performance of the proposed control and the required size of distributed ESSs. Moreover, in [56], a coordinated control scheme for distributed utility-scale ESS is proposed. The control utilizes both reactive and active power capabilities of ESS inverters, and efficiently selects the most appropriate ESSs to regulate voltage, taking into consideration battery life span extension.

Although centralized controls are capable to maintain the voltage into the permissible limits, they are based on the uninterruptable communication of the central and ESS controllers. In case that the communication with the central controller is lost, the objective of the centralized strategy cannot be guaranteed. To overcome this issue, distributed control schemes have been proposed. These solutions need only a communication link between neighbouring installations, while control decisions do not require global grid information [57]. Authors in [58] propose a distributed control for battery ESSs based on the consensus algorithm to regulate the voltage of LV feeders. A localized control is also utilized to maintain the battery SoC within the operational limits. Authors in [59] use two consensus-based controls for voltage regulation utilizing distributed battery ESSs with PVs. These controls ensure that batteries contribute fairly to voltage regulation taking into consideration the capacity and the ESS SoC. A similar control approach for voltage regulation is also proposed utilizing PEVs for voltage regulation in [60]. Since the connected PEVs are not capable to mitigate overvoltages, APC of PV generation is applied.

Both centralized and distributed methods for voltage regulation rely on the reliable and uninterruptible communication between storage controllers. Therefore, they may not ensure successful voltage regulation under communication errors. To avoid the dependence on communication systems, several localized controls have been developed. The most common ESS local control strategy, integrated in prosumer-owned storage systems, charges the battery since PV surplus is realized, while discharges when PV power in not sufficient to supply the consumption [61]. Under the previous strategy, battery capacity is fully charged prior to peak PV generation. Hence, increased PV injections during noon are not avoided, resulting into overvoltage incidents. To tackle this issue, a peak shaving control strategy is introduced in [62]. The same work incorporates several local controls of ESS combining also the capabilities of PV inverter for voltage regulation. Similarly, in [63] a battery management strategy that activates the charging process, after PV production exceeds a predefined power threshold is proposed, aiming to alleviate overvoltages. This threshold-based charging process is combined with a discharging strategy [64], to mitigate also undervoltages occurring during peak load periods. Voltage limit violations are alleviated by efficiently controlling the ESS power and SoC level in the localized control strategy of [65]. Furthermore, an adaptive battery charging and discharging scheduling strategy is developed in [66] to alleviate voltage and thermal issues of DNs by efficiently utilizing the capacity of the ESSs.

2.1.3 Use of DSM techniques

The participation of loads in the voltage regulation process via DSM techniques is a well-established research topic. The authors in [67] propose a scheduling algorithm for deferable residential loads, aiming to alleviate voltage rise issues and mitigate peak load demand based on DSO signals. A hierarchical DR scheme is proposed in [68]. The proposed method uses controllable loads, DRESs, and capacitor banks to regulate the voltages at DNs, while fulfilling the transmission system DR requests. In [69], a real-time voltage control approach for emergency conditions is developed, using a DR scheme that focuses on load curtailment. A multi-agent system architecture has been developed in [70] for voltage control and congestion management of MV feeders, exploiting the DR capabilities of LV residential loads. Moreover, a strategy that combines DR with reactive power control for voltage support is studied in [71]. Compared with a standalone DR control, the integrated strategy improves the voltage profile and requires lower load curtailment. The authors in [72] propose a combined voltage regulation strategy using DR and OLTC management for LV DNs. The integrated control scheme manages residential appliances and transformer taps to mitigate voltage violations. A DR mechanism is introduced in [73] focusing on the operation control of heat pumps and EV to mitigate undervoltages occurring during peak demand period. In [74], a load-shifting DR model is integrated with a conservation voltage reduction control to support the voltage of DNs. Finally, a two-stage hierarchical DR scheme for voltage regulation and overload prevention is introduced in [75] exploiting residential appliances. A special reward mechanism based on the customer willingness to participate is developed to support the DR strategy. Finally, in [76] a scheduling method of residential appliances is proposed to minimize both voltage violations and the customer's electricity bill. The method is based on a community energy management system that optimizes the load performance based on electricity market and DSO signals.

2.1.4 Voltage unbalance mitigation

To alleviate voltage unbalance issues at LV DNs, several methods have been proposed. In [77], a two-stage methodology is introduced to regulate voltage in unbalanced radial DNs, by optimally coordinating OLTC and static VAr compensators. Furthermore, several research works exploit the capability of three-phase, converter-interfaced DRESs to modify the power flow among the three-phases to mitigate voltage asymmetries. Specifically, authors in [78] propose a scheme for voltage unbalance mitigation through a sophisticated control of converter injected currents. The scheme is based on a damping control strategy that efficiently mitigates voltage unbalances by injecting higher currents in the lower voltage phase and lower current in the higher voltage phase. This is achieved by varying the damping conductance (G) of the inverter. A similar approach is used in [79] and is tested both in single- and three-phase inverters. The approach of variable G can be also combined with voltage regulation methods. A two-layer control method is developed in [80] to mitigate overvoltages and voltage unbalance in LV feeders. A local $G(V)$ droop curve is utilized to mitigate voltage unbalance, while a centralized control coordinates the OLTC and DRES actions for voltage magnitude regulation. The damping control strategy is combined with a voltage-based droop in [81] to simultaneously mitigate overvoltage and voltage unbalance incidents.

Additionally, ESSs may be utilized to improve voltage profile with respect to voltage unbalance in LV DNs. A control of ESSs is proposed in [82] to reduce voltage unbalance of LV feeders. The strategy aims to balance the net power of a PV prosumer exchanged with the grid using the minimum power of ESSs. The use of distributed single-phase batteries connected at the three phases of a network is optimized in [53] to improve the voltage profile in terms of voltage magnitude and voltage unbalance. The authors in [83] designed three voltage unbalance mitigation techniques for the cooperation of distributed single-phase ESSs coupled with PVs, aiming to reduce voltage unbalance in LV grids. Moreover, static transfer switches (STSs) can be utilized to mitigate the power unbalance of a feeder, by rearranging consumers between the phases [84]. A centralized control scheme for STSs is developed in [85] to alleviate voltage unbalance in DNs with PV prosumers by managing the prosumers' load between the three phases.

2.2 Congestion management

Overloading of network equipment, e.g., lines and transformers, is one of the most important technical problems DSOs have recently started to face due to the advent of DRESs. Thermal limit violations can damage the network equipment and limit the DRES penetration level in a DN. To overcome this issue, several congestion management solutions have been proposed that can be classified into the following categories:

- DRES generation curtailment
- use of ESSs
- DSM
- combined solutions.

described in detail in the next paragraphs.

Considering DRES generation curtailment, [86] investigates the performance of two curtailment algorithms, namely the hard and soft. In the former, all DRESs are disconnected from the grid in case an overload incident occurs, while in the latter, the generated power of the DRESs is reduced to eliminate the overload. A similar approach to soft curtailment is adopted in [87], aiming to tackle both voltage and thermal violations by modifying the active and reactive power output of DRESs.

An efficient solution to network equipment overloading is to increase grid flexibility by using ESSs. An optimal planning and scheduling algorithm for ESSs is presented in [88] focusing on the minimization of the total power flow, thus relieving the congestion. A similar approach is adopted in [89] where distributed battery ESSs are employed for voltage control and line congestion management. The authors in [90] propose the use of a community battery ESS to mitigate potential thermal violations. Finally, a congestion management scheme is presented in [91]; EV are used in a coordinated way to ensure that the power flowing through the network lines is within the permissible thermal limits.

The third category contains all methodologies related to the use of DSM as the primary means for tackling thermal violations. In [92], a DR-based congestion management strategy for smart DNs is developed using a bi-level optimization framework. A gossip algorithm-based architecture for controlling the power flowing in radial DNs is proposed in [93]. Its distinct feature is the introduction of a decentralized DSM scheme. An enhanced version of the above-mentioned DSM techniques is proposed in [94]. The developed algorithm combines direct and indirect methods for controlling loads. In the former, DSO directly controls the loads to alleviate network equipment overloading, while in the latter, end-users are indirectly motivated to shift their power consumption through price changes.

Several congestion management techniques adopt combined solutions. In [95] ESSs are combined with DSM techniques to alleviate current congestion in DNs. A swap method is proposed in [96] for real-time congestion management. The proposed method uses EV in conjunction with heat pumps to maintain the power balance of the grid and avoid the imbalance cost of activating flexibility services. A centralized algorithm is developed in [97], coordinating the ESS and load operation to avoid any congestion incident with the minimum cost. The combined operation of DRESs and ESSs is presented in [98] using a grid congestion management controller. Furthermore, a hierarchical congestion management scheme for DNs with high DRES penetration levels is presented in [99]. This solution exploits the controllability offered by DRESs and loads to alleviate thermal violations. Finally, a similar approach is presented in [100], where the information gap decision theory is used to tackle the variability and uncertainty of DRESs when optimally controlling DRESs and loads.

In terms of implementation, congestion management methods can be classified into two categories, namely direct and indirect, market-based methods [94]. In the former, DSO directly controls loads, ESSs, and DRESs to alleviate the overloading of network equipment [101], [102]. In the latter, the operation of each network element is indirectly controlled by providing economic incentives [103].

Market-based methods have recently drawn the attention of the research community, thus a detailed analysis is conducted. In [104] a day-ahead market framework for congestion management in DNs is developed. The proposed framework includes a platform for collaboration between market operator and DSO to mitigate congestion problems and a mechanism for exploiting the flexibility offered by EV in an aggregated way. Furthermore, a day-ahead market-clearing model for DNs is proposed in [105], where all network elements that can provide flexibility to the grid, i.e., DRESs, ESSs, and loads, are used. The research activity in [106] goes a step beyond the previous works by considering the “rebound effect” that may occur when DSM techniques are used for congestion management. Moreover, in [107], the conventional distribution locational marginal price method is improved by including the reserve provision from buildings in DNs. In [108], an uncertainty management scheme is proposed to quantify and mitigate the risk of congestion since a significant difference between the day-ahead forecast that determines the dynamic tariffs of the next day and the actual behavior of the grid is identified. A comprehensive scheme for day-ahead congestion management of DNs is presented in [109], combining three well-established methods, i.e. network reconfiguration, dynamic tariffs, and re-profiling products. An alternative solution is proposed in [110], where the concept of dynamic power tariff is introduced. Furthermore, a new dynamic subsidy method is proposed in [111] including the market mechanism and a two-level optimization technique. Finally, a dynamic tariff-subsidy method is presented in [112], as an extension of the method presented in [111]. Following this approach, the regulation prices can be positive (tariff) or negative (subsidy), resulting in an effective solution for congestion management.

2.3 Power smoothing

The vast majority of DRESs consists of PVs and wind turbines. Their common characteristic is the highly variable output power depending mainly on the availability of the primary energy source, i.e., solar irradiance and wind potential. As a result, this variability may affect the reliable operation of DNs, since voltage fluctuations may occur (flickering effect) affecting the performance of voltage-sensitive devices. Generally, power smoothing capability can be provided by adopting at least one of the following solutions [113]:

- control of DRESs to operate below the MPP,
- active participation of loads to mitigate the variable output power of DRESs,
- utilization of ESSs, e.g., ultracapacitors, batteries, flywheels, etc.

In this context, smoothing techniques can be classified into the following main categories [114]:

- filtering-based algorithms, where the output power is filtered to reduce the frequency spectrum of the injected power [115]. The moving average algorithm is one of the most well-established solutions in this category [116];

- ramp rate control schemes, where the output power saturates when the calculated ramp rate reaches a specific limit [116].

These approaches are discussed below.

Considering filtering-based algorithms, the authors in [117] use a supercapacitor to absorb high frequency components of DRES output power. This is attained by applying a high-pass filter on the actual power provided by the DRES; a sizing method for the supercapacitor is also introduced. A similar approach is proposed in [118], using a flywheel instead of a supercapacitor to absorb/provide any mismatch between the actual and the reference/smooth power that should be provided by the DRESs. An improved version of these solutions is proposed in [119]. More specifically, an adaptive design of the high-pass filter cutoff frequency is proposed, to achieve a smooth power variation and SoC sharing among multiple ESSs within a DN. A battery ESS is used in [120] to compensate the difference between the smoothing reference and the wind farm output. The developed method exploits short-term forecast to avoid any violation of SoC limits and ensure the continuous operation of the battery ESS in terms of performing power smoothing. Finally, in [121] a moving average method is applied to smooth the PV output power fluctuations. An electric double layer capacitor is employed to absorb/provide any mismatch between the smoothed and the actual PV power.

A common drawback of the filtering-based algorithms is related to the inability of directly controlling the ramp rate of the DRES output. To overcome this limitation, several solutions have been proposed aiming to control the DRES active power ramp rate. In [122] a new control strategy is proposed; the output power of the ESS is controlled following an inverse relationship with the DRES output ramp rate to improve the fluctuation mitigation performance. In [123], ESS is employed to control the ramp rate of the output power of a system consisting of PV and wind power generation. Its distinct feature is the use of an algorithm that actively controls the ESS SoC within a certain range to prevent the forced down of the ESS and ensure the continuous provision of power smoothing. An alternative solution is proposed in [113], where a ramp rate control is applied to ESS constituting a modified, self-adapted exponential power smoothing method. The proposed methodology addresses effectively the memory effect occurring in filtering-based algorithms, e.g., moving average. An improved version of the ramp rate control is presented in [124]. Scope of the therein developed algorithm is to smooth the DRES voltage at POI with the DN. This is attained by combining two control schemes: (a) ramp rate limitation of the DRES output active power and (b) use of a volt-var $Q(V)$ curve.

A solution combining ramp rate control and filtering-based algorithms has been recently proposed in [125]. The proposed methodology performs two separate control actions, i.e. power smoothing at the POI with the DN targeting to mitigate fast power fluctuations and ramp rate control and shifting over short-term and long-term periods.

New sophisticated techniques have been recently proposed to smooth the output power of DRESs. In [126], a model predictive control is used to determine the output power of the ESS, taking also into account the technical characteristics related to the health and stability of the ESS. Furthermore, fuzzy-based discrete Kalman filter is proposed in [127] for smoothing output power fluctuations of wind and PV generation systems applying a battery ESS. This approach incorporates the state of health of the battery as a feedback, not only to obtain smooth output power but also to improve the health of the ESS. Finally, a battery-less short-term smoothing algorithm for PVs is presented in [128]; the authors propose the use of a sky camera to perform a short-term forecast of the irradiation. Based on forecast analysis, the output power of the PV is modified, operating below the MPP to compensate the effect of highly variable irradiation on the MPP.

3 TS-oriented ancillary services

In this section, the research activity regarding ASs provided by DSOs to TSOs is reported. The main reactive power support methods to the transmission system are discussed, followed by an extensive review on inertia response techniques. Afterwards, power smoothing techniques to tackle DRES power fluctuations that influence the dynamic performance of the transmission system are described. Finally, a relatively new research topic related to the provision of coordinated PFR from DSOs to TSOs is discussed.

3.1 Reactive power support

Traditionally, the provision of reactive power to the transmission system was mainly undertaken by large-scale conventional power plants and FACTS devices, e.g., static synchronous compensators [129]. Nevertheless, the gradual decommissions of large-scale power plants caused by the advent of DRESs has reduced the available reactive power sources. Therefore, issues related to voltage regulation and voltage stability at the transmission system may occur [130]. A promising solution is the active participation of DNs by providing reactive power support functionalities [131]. This research topic has recently started to gain the attention of the research community. More specifically, in [132] a centralized approach is proposed for the real-time operation of DNs; the available reactive power of DRESs is used in a coordinated way to actively control the voltage at POI with the transmission system. A similar solution is presented in

[133], where instead of reactive power setpoints, controllable $Q(V)$ droop curves are applied to DRESs. Finally, a unified approach is proposed in [134]; the voltage control problem is solved by employing optimization-techniques including both the distribution and transmission networks.

3.2 Inertial response

The reduction of the system inertia is one the most important issues caused by the gradual replacement of SGs by DRESs, connected to the grid via inertia-less, grid-interfaced converters [135]. A promising solution is to modify the control and operation of the grid-interfaced converters to imitate the dynamic behaviour of SGs. In this context, in [136] and [137] the VISMA concept is introduced, by employing the traditional synchronous machine model to control the output current of the grid-interfaced converter, thus each converter-interfaced DRES can virtually provide inertia to the grid. It can be shown that, under certain conditions, the dynamic performance of the VISMA model resembles the use of frequency droop curves of converter-based microgrids [138]. A similar approach has been recently presented in [139], where an algorithm to determine *RoCoF* at POI with the grid based on the data received from a PLL is proposed. The variation of the output power (ΔP) in p.u. with respect to the *RoCoF* (in p.u.) is calculated by using the well-established swing equation of synchronous machines ($\Delta P = 2HRoCoF$, where H is the inertia constant in s). Finally, ΔP is forwarded to a current control loop to build the desired output currents. A common drawback of the above-mentioned methods lies on the use of the current control loop, making DRESs to behave as variable current sources, from a power systems perspective. Consequently, contrary to SGs that operate in grid-forming mode, the DRES grid-interfaced converters operate in grid-following mode.

A similar concept to VISMA is proposed in [140], [141], and [142], introducing the synchronverter. On this basis, the detailed mathematical model of SGs is incorporated into DRES grid-interfaced converters. More specifically, the converter operates as an ideal controllable voltage source in series with an impedance. The angle and the magnitude of the voltage source are determined by the following factors: (a) the voltage at POI with the grid, (b) the active power of the primary source connected at the dc-link of the grid-interfaced converter, (c) the output reactive power of the DRES, and (d) the dynamic behavior of the synchronverter as mathematically expressed by the detailed model of SGs. Contrary to VISMA, the synchronverter offers a grid-forming capability, since it operates as a controllable voltage source. Improved versions of the synchronverter model are proposed in [143] and [144]. In particular, a new synchronization process of the synchronverter with the grid is presented in [143]. Its distinct feature is the lack of dedicated synchronization units. Moreover, the dynamic performance of the synchronverter towards voltage and frequency deviations at the POI with the grid is improved in [144] and [145] by introducing virtual inductors/capacitors and developing a bounded dynamic controller. Nevertheless, in these implementations, the synchronverter cannot actively control the output currents, since it operates as controllable voltage source. Thus, in case of a fault close to the POI with the grid, the output currents of the synchronverter will be uncontrollably increased, exceeding nominal values. Contrary to SGs, converters present a limited overloading capability; thus, uncontrollable currents can damage the converter.

To overcome this problem, a restraining method of fast transient inrush fault currents is presented in [146]. The main idea behind this method is that when a fault occurs, the converter controller activates an emergency condition. During this condition, the control of the grid-interfaced converter switches from a voltage control loop (used in synchronverters) concept, to a current control loop using a hysteresis algorithm. Nevertheless, according to control theory [144], the switching between different control schemes should be generally avoided to prevent oscillations and repeated activation-deactivation cycles.

An alternative implementation to provide virtual inertia is presented in [147] - [150]. This method builds on the existing control algorithms used for commercial PV plants. In particular, the converter of a PV plant usually operates as a current source with unit power factor, thus a change at the magnitude of the output current will affect the injected power to the grid. The magnitude of the output current is determined by a controller aiming to keep the voltage at the dc-link close to a reference value. A constant voltage at the dc-link indicates that no energy is stored at the capacitor of the dc-link, i.e., the power generated by the primary source is also provided to the grid. The authors in [147] and [148] propose a modified version of this scheme by dynamically changing the voltage reference at the dc-link with respect to frequency variations. In this way, a mismatch between the generated power of the primary source and the power provided to the grid is introduced, forcing the capacitor at the dc-link to store or provide excess energy to the grid, as conventional SGs. A similar approach is presented in [149] and [150]; the active power output is correlated to the square of the voltage at the dc-link, since it is more consistent with the power balance equations. However, in all the above solutions, the capacitor used for commercial applications is very small, leading to limited inertia response. In [151], an enhanced virtual inertia control is presented, where the primary source contributes to the inertial response. This is attained by forcing the primary source to operate below MPP, thus being capable to provide a enough power during underfrequency events. Nevertheless, this solution reduces the green energy provided to the grid.

All the above-mentioned drawbacks have been addressed in [152] by employing a sophisticated control scheme. The proposed control scheme consists of two cascaded control loops: current and voltage control loop. The former is the inner control loop and is employed to actively control the DRES output currents. Thus, in case of large disturbances, e.g. faults, the output currents are actively controlled, avoiding the converter overloading. The latter is the outer control loop, used to actively control the voltage of the DRES. Therefore, the DRES is considered as a controllable voltage source providing grid-forming capabilities. In [153], a new algorithm is proposed to provide virtual inertia under unbalanced operational conditions. Finally, an improved damping strategy for virtual synchronous machines is proposed in [154], operating as an enhanced power system stabilizer in SGs.

Based on the above, it can be deduced that ESSs are needed to properly provide inertial response. In this sense, optimal sizing of such ESSs is important, though not well investigated [155]. Currently, all proposed solutions are based on deterministic and analytical approaches. A simple approach for ESS sizing in presented in [156]. The ESS size is calculated with respect to the worst-case scenario, i.e., power mismatch ~ 4% to 10%. Similarly, in [157] an exhaustive search is proposed on the basis of worst-case scenarios; the main advantage of this approach is the inclusion of nonlinear frequency dynamics to the optimization problem. In [158], an analysis is performed to estimate the inertia deficiency of a low-inertia microgrid. This inertia deficiency directly determines the ESS sizing, since there is a strong coupling between inertia constant and ESS size. Although this method focuses on low-inertia microgrids, it can be also applied to large power systems [159]. In [160], an analytical methodology based on the frequency characteristics of the power system is proposed for sizing ESS. A simplified model of the power system is initially derived to represent rotor and speed-governor dynamics. Afterwards, a parametric analysis is performed by modifying the ESS size and control parameters to evaluate their impact on the network dynamic performance. Based on the results of this analysis, the most suitable ESS size is selected. A frequency-based sizing methodology is also developed in [161] to optimize a hybrid system consisting of fast and slow response ESS. By employing Fourier analysis to the power imbalance response between generation and demand, the low and high frequency power fluctuations are supplied to slow and fast ESSs, respectively. A similar approach is presented in [162], introducing a methodology based on the equivalent inertia calculations for sizing a hybrid ESS to provide both inertia and PFR. Finally, an optimization process is proposed in [163] to determine the optimal ESS sizing for inertial response. Initially, a simplified dynamic model of the system is derived taking as important parameters the damping and the inertia constant. Next, an optimization problem is solved to minimize the overall installed capacity of the ESSs, by satisfying technical constraints, e.g., permissible limits of network frequency. A similar approach is proposed in [164]; the ESS sizing problem is formulated as a standard, cost-based optimization problem and solved using metaheuristic optimization algorithms.

It can be concluded that significant research effort has been devoted to incorporate the inertial response functionality into converter-interfaced DRESs. The participation of loads in the inertial response has also recently gain the research interest. In [165] the effect of replacing conventional loads with new ones equipped with inertial response capability on the dynamic behavior of the power system is evaluated. In [166], a new controller is proposed, incorporating virtual inertia functionality to thermostatically controlled loads, e.g., air conditioners. The aim of this controller is to provide inertial response to the grid, maintaining also customers' comfort levels. Finally, a modified version of the well-established electric spring concept to provide virtual inertia is proposed in [167]. However, all these implementations use PLLs to measure *RoCoF*, resulting into questionable accuracy and time delay regarding virtual inertia calculations.

3.3 Power smoothing for grid stability

Apart from local problems in DNs, e.g. power fluctuations, power smoothing techniques have been also proposed to improve power systems frequency stability. A comparative assessment of various storage-free control strategies related to positive ramp limitations of large-scale wind farms in Spain is conducted in [168]; positive ramp refers to the increase of injected power to grid with respect to time. In [116] an enhanced version of the conventional ramp rate control is proposed for large-scale PV plants combining two solutions, i.e. PV output power curtailment and use of ESSs. The proposed control strategy results in reduced ESS size by using conventional methods. In [169], a power smoothing control strategy for variable-speed wind turbine generators has been developed, employing an additional control loop based on the system frequency deviation operating in conjunction with the MPP tracking control loop. The exponential moving average is used in [170] to smooth the injected power of converter-interfaced, PMSG-based wind power plants. A coordinated approach is proposed exploiting specific characteristics of the wind power plant, i.e. the energy stored in the dc-link of the converter, the variable rotor speed, and the variable pitch angle.

A receding horizon control framework for wind farms is proposed in [114], consisting of an optimization module to generate the optimal control reference by considering wind-fluctuation-induced frequency stabilization cost, and a real-time control module to timely track the smoothing reference. In [171] a new smoothing algorithm for large-scale PV power plants with ESSs is presented. The proposed algorithm combines DGS-SVM power prediction and first-in-first-out robust smoothing. In [172], a hybrid ESS consisting of an ultracapacitor and lithium-ion battery bank is used to compensate short- and long-term power fluctuations of a wind farm, respectively. This is attained by using a two-stage online-wavelet based coordination scheme. Furthermore, an additional control loop is employed to maintain the SoC of the battery bank within a specified range.

The contribution of loads in power smoothing is a relatively new research topic. In [173] a methodology for controlling energy-intensive loads for long-term power smoothing in wind power plants is proposed. Furthermore, thermostatically controlled loads are employed in [174] in a coordinated way to examine the smoothing capability on the output power of wind power plants.

3.4 Frequency response

The incorporation of the PFR functionality to DRESs constitutes another emerging research topic. Currently, the main research effort has been devoted to develop methods for coordinating the PFR among multiple DRESs, and especially wind turbines. In [175], a centralized, optimization-based control algorithm is proposed to maintain a certain reserve of power to be utilized for PFR. The algorithm is designed to minimize wind farm power losses by optimizing the share of each wind turbine. An improved solution to the optimization procedure of [175] is presented in [176]. Wind turbines are initially grouped by means of cluster analysis according to their wind profiles. In this way, the same control commands apply to each wind generator belonging to the same group. Each group can be modelled with an equivalent wind turbine model, reducing the number of control variables and the computational complexity of the optimization problem. In [177], an optimization method is applied to wind farms to support three operation strategies: (a) maximization of the wind farm power while maintaining a constant rotational kinetic energy, (b) maximization of the wind farm kinetic energy while maintaining a constant output power, and (c) a de-loading strategy where the wind farm rotational kinetic energy is maximized for a fixed de-loading margin. All strategies are formulated as nonlinear optimization problems solved separately by the central controller of the wind farm.

Contrary to centralized methods, a distributed approach is adopted in [178]. A distributed Newton method is developed to optimally share the power among the wind turbines of a wind farm. Although limited exchange information is required among neighbour wind turbines over a sparse communication network, the proposed method presents super-linear convergence rate.

In [179] and [180] the concept of the VPP is adopted to provide PFR service. The VPP plant acts as an aggregator of DR resources and wind farms; their optimal control is achieved by employing an intraday and a close to real-time scheduling algorithm.

In [181], a two-stage method is proposed to coordinate the droop controls between wind turbines and the associated ESSs for supporting PFR. In the first stage, the available power reserve from the de-loaded wind turbines is estimated. In the second stage, the coordinated droop control between the wind turbines and ESS is redesigned based on the available power reserve of wind generation.

The provision of PFR from distributed battery ESSs is proposed in [182]. ESSs are optimally coordinated to maximize their profit by adopting a two-stage approach. The first stage is related to frequency regulation; the regulation failure penalty is minimized by optimally coordinating the operation of multiple ESSs in case of frequency events. In the second stage, the SoC of the participating ESSs is recovered to a proper range to avoid regulation failure in the next frequency event.

Finally, in [183] a framework for DRESs located at DNs is proposed to provide PFR. A methodology is presented to determine the parameters of the DRESs power/frequency droop curves to ensure specific frequency regulation characteristics at the POI of the DNs with the transmission system.

4 Online techniques for operational analysis

In this section online analysis techniques and tools that can be used to facilitate the development of ASs are described. In Section 4.1 online inertia estimation methods are discussed. These methods can be used to assess in real-time the system total inertia, providing this way feedback to system operator to modify virtual inertia parameters of DRESs in order to restrict system *RoCoF* within permissible limits. In Section 4.2 online measurement-based identification techniques for mode estimation are presented, while in Section 4.3 different types of equivalent models are reviewed. The former can be used to assess in real-time stability margins of power systems, thus allowing the real-time fine-tuning of DRESs control parameters, enhancing in this way grid stability and reliability. The latter can be used to represent extended parts of the power system, facilitating this way the information exchange between system operators as well as the application of centralized and distributed techniques aiming to optimally coordinate the operation of several DRESs.

4.1 Real-time estimation of inertia time constants

Several approaches have been proposed for the estimation of inertia constants. A comprehensive description is provided below.

In [184], a fifth order polynomial is applied to measured frequency transient responses by means of the LS method. LS fitting is used to restrain the influence of oscillatory components superimposed on frequency signals due to intra- and inter-area oscillations. The method is tested only on field measurements; thus, its performance and accuracy assessment are limited. A similar approach is also presented in [185]. In this case, a linear model is used to fit frequency signals and determine the corresponding *RoCoF*. The method is further tested in [186] to estimate the overall system inertia of the Great Britain power system. However, to perform satisfactorily, the method requires the monitoring of the most critical power system nodes as well as the use of probing signals.

In [187], the inertia constant of SG is estimated using the swing equation and the sliding window technique, used to determine the frequency and real power changes due to disturbances. The overall system inertia is computed based on the inertia estimates of each generator individually. However, the method requires the accurate identification of the time of disturbance, i.e. the exact time that the disturbance occurs. Towards this objective, the method in further extended in [188] to automatically identify the time of disturbance using sequential data windows. Validation results reveal that the performance of the method is considerably affected by the definition of the sequential windows as well as by the type of the PMUs used to acquire the required measurements [189].

In [190] a method based on historical data to correlate generator capacity with *RoCoF* values and inertia constants is proposed. With this knowledge, the typical *RoCoF* of a power system is roughly estimated. However, systematic evaluation and testing of the method performance is missing. A Gaussian Markov Model is proposed in [191] to correlate frequency responses with inertia constants. However, the model requires the fine-tuning of several parameters to provide satisfactory results.

In [192] the relationship between power system eigenvalues and inertia constants of SGs is derived. Additionally, a methodology based on the eigenvalue sensitivity matrix is proposed to estimate in real-time the inertia constant of SG using wide area measurements. In [193] and [194], the use of inter-area oscillations for the estimation of inertia time constants is investigated. These methods require the identification of pilot buses, i.e. buses that represent the COI. Therefore, in [195] a method to determine COI and to estimate the overall power system inertial response is introduced. The method initially identifies clusters of generators that form aggregate sources of inertial response. The overall dynamics of each cluster are synthesized using PMUs placed at selected buses that represent the COI.

Finally, several methods have been proposed to estimate the inertia constant as perceived by particular buses [196] – [200]. These approaches are very useful to quantify the virtual inertia of DRESs at the PCC with the transmission grid [197]. Estimation techniques of these works include ARMAX models [196] - [198], dynamic regressors [199] and the micropetrubation method [200]. The performance of all above methods has not been tested in detail, i.e. in terms of both ringdown and ambient data, while only in [198] field measurement have been used.

4.2 Identification techniques for modal analysis of power systems

Vital information regarding grid oscillations and consequently stability margins of the power system can be provided by mode estimation [201] - [203]. For this purpose, nowadays, online identification techniques are continuously used due to the increasing deployment of synchronized measurement technology at power systems, enabling the close to real-time estimation of oscillatory modes [204]. Online measurement-based methods can be performed by using [202], [205]:

- Ambient data: obtained when the system is operating under an equilibrium condition; responses are excited due to small load variations.
- Ringdown data: obtained during or after major disturbance events (short circuits, line tripping, large load step-up, etc.).

Several mode identification techniques have been proposed to perform modal analysis of power systems. Considering the form of the data they use, they can be classified into TD, i.e. by processing directly the measured response and FD, i.e. applied to the spectrum of the measured signals [205].

Originally, mode identification entails the analysis of system responses as single entities (single-signal approach). To obtain representative mode estimates of the overall system rather of specific parts, multi-signal techniques have been also introduced to process a set of measured signals [206].

A summary of the most important methods is presented in Table I.

TABLE I: Summary of mode identification techniques

Method	Form of Data	Type of Response	Single-signal	Multi-signal
Prony based	TD	Ringdown	[201], [207] - [214]	[204], [215] - [221]
Eigenvalue Realization Algorithm based	TD	Ringdown/Ambient	[222], [223]	[204]
Matrix Pencil	TD	Ringdown	[224]	[204]
Subspace Identification	TD	Ringdown/Ambient	[225] - [228]	[204]
Prediction Error Method	TD	Ringdown	[229]	[204]
Minimal Realization Approach	TD	Ringdown	[230]	-

Fast Fourier Transform based	FD	Ringdown/Ambient	[231] - [234]	[204], [235] - [240]
Hybrid FD/TD	FD/TD	Ringdown	[241]	[204]
Kalman Filter based	TD	Ringdown	[242], [243]	[240], [244]
Mode Decomposition	TD	Ringdown	[245]	[245]
Vector Fitting	FD or TD*	Ringdown	[246], [247]	[204], [248], [249]*
Autoregressive / Autoregressive Moving Average based	TD	Ringdown/Ambient	[250] - [254]	[255]
Wavelet Transformations	TD	Ringdown/Ambient	-	[256], [257]
Other Single Value Decomposition based methods	TD/FD	Ringdown/Ambient	[258]	[259]

4.3 Equivalent models for ADN analysis

Traditionally, in power flow simulations and dynamic analysis, DNs are modelled as aggregated loads, containing different types of individual components, i.e. motors, lighting and electronic devices [260] - [262]. Nevertheless, the increased penetration of DRESs eventually alter the performance of these systems, [263] - [266]. Therefore, during the last years, serious efforts have been initiated to improve modelling practices and develop advanced aggregate equivalent models to simulate more accurately the complex behaviour of ADNs, [263] - [265], [267].

In this sense, the component- and the measurement-based modelling approaches have been proposed [268]. The component-based approach requires reliable data concerning the load class mix, the load components, and *a priori* knowledge of typical characteristics of individual devices. Therefore, the application of this method requires accurate data, which usually are difficult to be determined in DNs due to their extended size, confidentiality issues [269] and need of operational conditions forecasting. On the other hand, in the measurement-based approach, the model parameters are estimated from in-situ measurements, by applying system identification techniques [269], [270]. This approach can be especially favoured in smart grid environments, since the available measuring infrastructure can provide almost continuously the required information to derive in close to real-time equivalent models [270], [271].

Measurement-based models can be generally classified into two main categories, i.e. static and dynamic. Static models express the real and reactive power at any time instant as algebraic functions of the bus voltage and frequency at that instant [260], [261]. Static equivalent models can be used for power flow analysis [261], [266] and grid optimization [272]; however, they are not suitable for voltage and angular stability studies [260], [261]. For this purpose, dynamic equivalent models are used. Dynamic equivalents express the real and reactive power as a function of voltage and frequency by including also time dependence [260], [261].

The main challenge concerning the development of static and dynamic equivalent models is to determine the aggregated representation of different types of loads and DRESs that are connected to the same DNs [273]. Generally, the equivalencing procedure consists of two main stages [268], i.e. specification of the model structure and model parameters derivation [268]. Depending on the available information and insight of the true system, three modelling approaches can be used, namely white-, black-, and grey-box.

In the white-box approach [268], the topology of the DN, the type and the control of the DRESs as well as the exact load composition are assumed *a priori* known. The aim of white-box modelling is to derive an exact mathematical model of the true system [268]. In many cases, the development of white-box models is very complex and hard-to-achieve, since several data are required [274]. In these cases, black- and grey-box equivalents are used.

In the black-box approach [266], [274], the topology of the DN, the location and control of DRESs as well as the load composition are not known. Only the input – output data of the true system are available [274]. The aim of black-box modelling is to map the input data set to the output data set by adjusting free model parameters to force the output of the equivalent model to become as similar as possible to the output of the true system [266].

In the grey-box approach [274], [275] basic information concerning grid topology, control systems of DRESs and the composition of the load are known. However, the exact components and their rates are not available. Therefore, grey-box models are developed using the known structure of the system considering unknown parameters [274]. The model parameters are identified similarly to black-box modelling [274], [275].

In Table II a taxonomy of the most-known equivalent models is presented.

TABLE II: Taxonomy of the reviewed equivalent models

Type	**Modelling approach**	**References**
Static	White-box	[276] - [279]
	Grey-Box	[261], [266], [280], [284], [285]
	Black-box	[281] - [283]
Dynamic	White-box	[204], [286], [287]
	Grey-Box	[274], [275], [301] - [305]
	Black-box	[288] - [300]

5 Conclusions and Future Research

In this paper, state-of-the-art of DN-oriented and TS-oriented ASs is reviewed. Regarding DN-oriented ASs, voltage regulation, congestion management, and active power smoothing are reported. The TS-oriented ASs include reactive power support for voltage stability improvement, virtual inertia, PFR, and power smoothing for frequency support. Nevertheless, the application of TS-oriented ASs requires critical information regarding the system stability and inertia constant that can be provided by online identification techniques. In this context, the state-of-the-art regarding online identification techniques is also reviewed. Based on the conducted review, new areas for future research are identified and summarized below:

- *Active participation of DNs to transmission system congestion management:* DRESs, ESSs, and flexible loads add an increased flexibility to the DNs. Thus, new control schemes can be developed exploiting this flexibility in an aggregated way to mitigate potential congestion issues in the transmission system. This is a new research topic which was recently introduced in [306].
- *Coordinated provision of inertial response:* The vast majority of the research activity on this topic focuses on the development of new control schemes for the efficient integration of inertial response to the converter-interfaced DRESs. Nevertheless, the uncoordinated provision of inertial response by DRESs may lead to operational limits violation at the DNs, e.g., overvoltages, congestion issues, etc. The same issue applies for the transmission system in case the inertia response is provided by several DNs. Consequently, new methods shall be developed to coordinate the inertia response of DRESs within DNs, as well as among them.
- *Integrate online identification techniques to TS-oriented AS:* To enhance the robustness of power system to frequency problems, the developed solutions should be adapted to the varying operating conditions of the power system. Thus, new control methods should be developed integrating the online identifications techniques to TS-oriented AS.
- *Exploit network equivalent models to facilitate the development of new AS:* Equivalent models can be used to represent specific parts of the transmission and/or the distribution system. In this way a better understanding of system properties is achieved, and a better visibility of the grid is ensured, thus allowing the design of more sophisticated AS.

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