Title:	**WP3.11: TSO-DSO Interface Steady-state Model of Aggregated DER as an Activity Entity**
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Table of Contents

Abbreviations and Acronyms

ADMM	Alternating direction method of multiplier
ADN	Active distribution network
AS	Ancillary service
DER	Distributed Energy Resources
DG	Distributed Generator
DS	Distribution System
DSO	Distribution system operator
FL	Flexible load
MILP	Mixed-integer linear programming
MINLP	Mixed-integer nonlinear programming
MIP	Mixed-integer programming
MIQCP	Mixed-integer quadratically constrained program
MPP	Maximum power point
NG ESO	National Grid Electricity System Operator
OLTC	On-Load Tap Changer
RES	Renewable energy source
STATCOM	Static compensator
SVC	Static VAR compensator
TN	Transmission network
TS	Transmission System
TSO	Transmission system operator
UC	Unit commitment
UKPN	UK Power Network

Executive Summary

The integration of Distributed Energy Resources (DERs) is rising in Australia, and according to the Electricity Network Transformation Roadmap, it is estimated that DERs will contribute around 45% of Australis's electricity generation capacity by 2050 [1]. This significant number of DERs can cause several challenges and technical problems, such as network congestion and voltage excursions. To support Renewable Energy Sources (RESs) integration, large investments in new network infrastructure can be avoided by encouraging Distribution System Operators (DSOs) to take a more proactive approach to managing the unpredictable nature of RESs. To achieve this, it is necessary to improve the cooperation between Transmission System Operators (TSOs) and DSOs. In addition, the provision of energy and ancillary services from DERs to the transmission network without compromising the power system integrity needs to be explored. Due to the high complexity and computational burden, an equivalent model for the distribution network needs to be developed for the TSO/DSO interaction and DER services analysis.

Task WP 3.11 aims to build an equivalent steady-state model for the TSO/DSO interface for upstream grid support. To achieve this, the key factors for distribution system equivalent representation need to be determined and the equivalent representations of distribution systems with electrification, deep integration of renewables and storage need to be developed. This report reviews the existing literature on modelling TNs/ADNs coordination approaches, ancillary services provided by the Active Distribution Networks (ADNs) to Transmission Networks (TNs), physical modelling of transmission and active distribution networks, equivalent representative network modelling approaches, control mechanisms, test cases, market analysis, optimisation methods, and the software and tools used for modelling and analysis. The literature review is divided into two main parts – (i) the interaction between TSO and DSO and (ii) energy and ancillary services provided by ADNs to TNs.

1 Background

The energy market has shifted towards sustainable electricity generation in recent years, with a growing emphasis on integrating renewable energy sources (RESs) into the distribution grids [2]. Installation of control modules to regulate the asynchronous power of RESs in the distribution systems is quite costly. As an alternative, planning policies that revolve around the collaboration between transmission networks (TNs) and active distribution networks (ADNs) have emerged for RESs power management [3, 4]. This approach eliminates the need for expensive devices and reduces operational costs for distribution systems [5, 6]. Transmission system operators (TSOs) provide voltage and frequency regulation services along with congestion management for transmission systems. In contrast, distribution system operators (DSOs) focus on managing congestion and voltage within the distribution grid [7]. With proper coordination between TSO & DSO, both entities can accomplish individual goals while maintaining the stability, reliability, and security of the integrated TN/ADN system.

The future distribution networks integrated with numerous active DERs will be able to operate in islanded mode and provide ancillary services for the upstream network in the grid-connected mode, thereby, improving the reliability and resiliency of the whole system in many folds [8]. In recent years, the concept of ADNs providing ancillary support to a higher voltage level has gained momentum, and several proof-of-concept large-scale projects have achieved promising results [9-11]. The UK Power Networks (UKPN) and the National Grid Electricity System Operator (NG ESO) are jointly running the world's first trial to dispatch active and reactive power services to the transmission network utilising different types of DERs, including storage assets. The effective operation requires at least 90% of the response to be provided within 2s [10]. Test cases that developed in the SmartNet (http://smartnet-project.eu/) are being used for the coordination of transmission and distribution system operations [11].

In general, regulatory factors pose significant obstacles to the development and execution of market concepts related to TSOs and DSOs [6]. Several technical challenges have yet to be resolved [12-14]. Various network codes are introduced in the European Union to establish the foundations for creating an effective coordination between TSO and DSO [14]. Further investigation is required to address data sharing, operational protocols, and market design issues. This will allow TSOs and DSOs to support each other in lowering the operation costs while efficiently integrating a large amount of RESs. According to the research in [6], the TSO/DSO hybrid-managed model does have more administrative, computational, and technical complexity, even though it improves overall social welfare. Five strategies for TSO and DSO collaboration for planning are reported in [13]. These include regional ancillary service (AS) markets, local AS markets, shared balancing responsibility models, and AS markets for TNs and ADNs. The authors in [13] reported that the business procedures and communication infrastructure must be updated for the RES integration irrespective of the coordination models. The technical viability and obstacles of these conceptual models have been evaluated in a recent review [12]. The work in [15] has focused on the financial aspects of several conceptual market options. Based on a shared AS market, the TSO/DSO hybrid-managed model produced the best economic results [6].

There is a need for equivalent representative modelling of active distribution system and transmission network that can be used to analyse the TSO-DSO interaction and perform sensitivity analysis regarding the model generalisation capabilities with electrification scenarios. In this report, the key findings from the literature review of academic papers and industrial reports related to the TSO-DSO interactions and energy and ancillary services provided by ADNs to TNs, including the methods for the equivalent representation of an active distribution system, are summarised. The report is divided into two main parts – (i) the interaction between TSO and DSO and (ii) energy and ancillary services provided by ADNs to TNs.

The first part of the report reviews the literature related to the cooperation between TSO and DSO to integrate DERs into the grid to achieve a higher penetration of renewable resources in the whole network. This study is important to identify and address the congestion, voltage control and security issues in the network because of TSO-DSO interaction. The visibility and controllability of the grid can be improved through the information and data exchange in TSO/DSO interaction. By coordinating their planning and operation, TSOs and DSOs can jointly optimise the use of existing network assets, reduce operational costs, and facilitate the participation of DERs in energy markets.

The second part of the report reviews the literature related to the energy and ancillary services (AS) provided by ADNs to TNs to maintain the adequacy and security of the network. DSOs can provide AS to TSOs in several ways depending on the cooperation and interaction between them. These ancillary services include energy arbitrage, congestion management, voltage support, frequency regulation, black-start capability, and other functions. There are some barriers and challenges in providing AS to TNs such as the need for enough regulation, market design, technical and operational issues, and communication and coordination between TSO and DSO. This report reviews the existing literature on modelling TNs/ADNs coordination approaches, ancillary services provided by the ADNs to TNs, control mechanisms, test cases, market analysis, physical models and their detailed/reduced representations, optimisation methods, and the software and tools used for modelling and analysis. The interaction between TSO-DSO is presented in **Section 2**. The energy and ancillary services provided by ADS to TS along with a review of the model reduction techniques for TSO/DSO study are presented in **Section 3**. Finally, the report is concluded by providing final insights and recommendations in **Section 4.** Summaries of the literature review for TSO/DSO interaction studies and the energy and ancillary services provided by ADN for TN are presented in the **Appendix**.

2 Interaction between TSO and DSO

Several frameworks for TSO/DSO coordination are reported in the literature [15-18]. **Table 1** summarises TSO/DSO coordination approaches used in the literature. To meet the requirements of both systems, energy resources, such as generators and storages, are used at both transmission and distribution sides in the centralised method [15]. Market balancing mechanism is used for the balancing of the grid. The balancing market mechanism faces several challenges, such as negative prices or volatility in electricity prices with the increasing penetration of RESs [5]. Moreover, it is difficult to centrally control many small-scale factors such as service restoration, outage management and reactive power control at the distribution grid from the transmission side [15].

The effectiveness of the centralised and decentralised TSO/DSO coordination approaches has been discussed in the recent literature, such as in [16, 19]. The work in [16] considered a centralised approach for their TSO/DSO coordination study in which the TSO has control over the entire system with access to the DSO data. The authors focused on the following objectives: transmission system operating costs, costs of distributed resources, and voltage deviations. A comparison of two decentralised and one centralised approach has been presented in [19]. According to [19], the centralised strategy performed better than the decentralised strategies in terms of resource allocation as the system imbalance increased in the decentralised approaches.

However, decentralised approaches are becoming more prominent in TSO/DSO coordination frameworks that address operational grid issues as outlined in **Table 1**. The ascendancy of decentralised methods is largely attributed to the current intricacy and rapid expansion of power systems, which is incorporating numerous distributed RESs across different voltage levels. The TSO's ability to centrally manage the power system has been challenged by these issues.

Several factors must be considered to apply a hierarchical or distributed method to solve a decentralised TSO/DSO coordination problem. Usually, distributed methods have proven to be more effective in addressing optimisation issues at the nodal level, whereas hierarchical methods are better at tackling optimisation challenges at the area-based level [19]. The hierarchical strategy outperforms the distributed approach in resource allocation and provides more profits for the TSO, as reported in [19].

According to the literature, decentralised strategies are currently the best way to handle the problems that arise with the coordination of large-scale TSOs and DSOs. However, their inherent decentralised nature tends to exacerbate system imbalances [19]. Moreover, several technological and practical challenges continue to prevent their complete implementation.

Hierarchical architectures still require access to sensitive distribution network information, even though decentralised approaches require this information less than centralised methods. Unfortunately, DSOs are not always willing to disclose sensitive information due to data privacy issues. As a result, it may be difficult to apply a decentralised strategy in a real-world distribution setting where parameters are unclear, unknown, or proprietary [19]. However, decentralised approaches— distributed or hierarchical—cannot be effective unless accurate data is seamlessly exchanged between TSOs and DSOs. Delays in communication and data order distortion are listed as the other main drawbacks of the decentralised methods [14].

Table 1. Summary types of TSO/DSO coordination approaches

Coordination Approach	Reference
Decentralised	[3, 7, 15, 18, 20-29]
Centralised	[17, 30-53]

2.1 Optimisation Problem Formulation

Various optimisation problem formulations have been used in TSO/DSO coordination studies. These optimisation models are focused on optimising an objective function within the TSO/DSO coordination framework considering the operational and physical constraints [54, 55]. **Table 2** represents the frequently used optimisation problem formulations from the selected manuscripts. The specific choice of the objective function in TSO/DSO coordination may vary, with some focusing on the operational costs and others focusing on the security/stability aspects of the power system, such as its voltage stability [49]. The Unit Commitment (UC) and OPF are commonly used to address the various aspects of TSO/DSO optimisation, such as in [7, 22, 24, 26, 45, 51, 52].

Table 2. Types of optimisation problem formulations

Optimisation Problem Formulation	Manuscripts
Optimal power flow	[7, 22, 24, 26, 27, 31-35, 37, 39, 40, 43, 44, 47, 51-53]
Unit commitment	[22, 28, 45, 56]
Volt-Var optimisation	[49, 50]
Others	[17, 18, 23, 25, 30, 41, 42, 46, 48]

2.2 Optimisation Problem Solution

To obtain the optimal solution for the TSO/DSO, coordination is a crucial task. This is because the solution quality directly affects the financial and technical aspects, feasibility of the implementation, and the time and resources required. Various techniques are available in the existing literature for addressing these optimisation problems. These methods encompass a spectrum of widely used commercial solvers like CPLEX, Gurobi, KNITRO, and others [33, 57]. **Figure 1** represents the commonly used optimisation problem-solving techniques based on the reviewed literature.

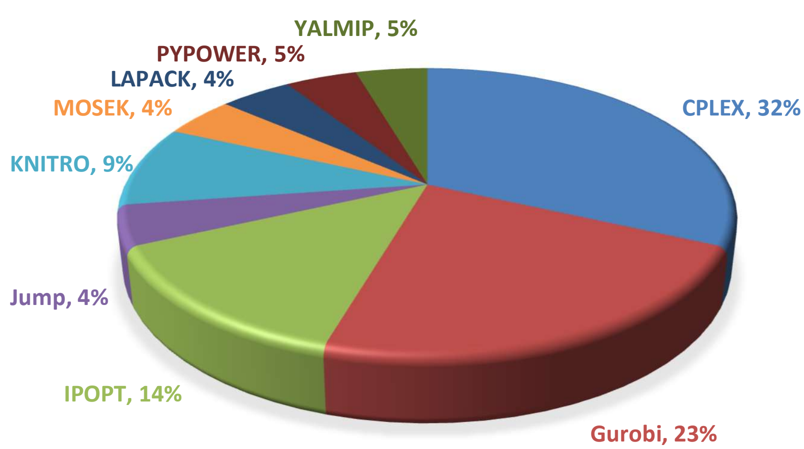

Figure 1. Optimisation problem solvers.

As the bidirectional AC power flow constraint exists in distribution and transmission networks, thus, the power balance equation contains nonlinear elements [16]. It is possible to define and solve the optimisation problem for TSOs and DSOs as a Mixed-Integer Nonlinear Problem (MINLP) [24, 33, 47, 58, 59]. KNITRO, as an advanced nonlinear optimisation solver, can be used to solve the MINLP problem [24]. The method proposed in [59] can effectively coordinate the real-time OPFs by ensuring compliance with voltage and reactive power set points. The work in [58] proposed a novel strategy to manage TSO/DSO reactive power using IPOPT solver. The method proposed in [58] minimises reactive power deviations while ensuring the permissible voltage limits. In [24], an active distribution system management strategy based on a dual-horizon rolling scheduling model is presented. It is formulated as a two-stage planning/operation model considering the scheduled power flows at the connection point with the transmission network.

Non-linearities in distribution and transmission systems can be solved through solving the MINLP problem with tools like KNITRO and BARON. However, this approach is time-consuming and computationally demanding [17, 48, 60]. Thus, several literatures focus on alternative strategies to simplify the optimisation problem. For instance, they accomplish this by representing the power flow equations governing distribution and transmission systems in a linearised form [61]. Typically, these studies advocate the Mixed-Integer Linear Programming (MILP) formulations, as observed in a range of studies [17, 48, 60]. Similarly, the work in [60] outlines a novel TSO/DSO coordination model with a focus on power balancing. This study reported two optimisation problems: the optimal utilisation of flexible units and the distribution of flexibilities using the GUROBI solver. The outcome reported in [60] revealed that the distributed flexibility may not be economically feasible for the re-dispatch support. However, it could contribute to the reduction of TSO's operational costs.

2.3 Physical System Modelling

According to the reviewed literature, it is evident that the majority of the studies focused on static nonlinear AC modelling [7, 17, 18, 24-27, 30-34, 47, 48, 51-53], while the work in [35] used static linearised AC modelling. The static AC model is widely employed due to its lower computational burden and data requirements. On the other hand, the studies in [49, 50] used quasi-dynamic modelling for their studies. In addition, the works in [36, 41, 45] used the dynamic modelling for the TN/ADN interaction study. **Table 3** gives the types of models used in the selected manuscripts. As seen, only a few studies have used quasi-dynamic modelling and dynamic modelling due to the complexity, data requirements, and computational burden. Furthermore, most of the TSO/DSO interaction studies that employed detailed TNs and ADNs models used simple optimisation approaches with a single objective to make their optimisation problems tractable.

Table 3. Study model types

Type of Study Model	Reference
Linearised Static AC modelling	[35]
Nonlinear Static AC modelling	[7, 17, 18, 24-27, 30-34, 47, 48, 51-53]
Quasi-dynamic modelling	[49, 50]
Dynamic Modelling	[36, 41, 45]

2.4 Model Implementation

There are a few real-world studies reported in [61] on TSO/DSO coordination. In this regard, the European SmartNet project is described as a real-world investigation carried out in the articles [61-64]. The authors in [41-46] explored diverse TSO/DSO coordination strategies and assessed the key benefits and the associated challenges. Moreover, they delved into numerous types of RESs and studied their effects on the performance of TN/ADN coordination to gain a deeper understanding of potential advantages and primary operational hurdles.

According to the literature, most of the reviewed manuscripts report the numerical outcomes from various power system simulation tools. For this purpose, MATPOWER and MATLAB are widely used, such as in [27, 50, 56, 58]. Also, the dynamic interaction studies mainly used commercial software, e.g., PowerFactory, Pandapower, and PSS®E. Notably, the SmartNet Simulator has been introduced in [65]. This tool is different from the other simulation tools used in most of the publications. This simulator has been developed specifically for the SmartNet project and is intended to be used for the precise impact estimation of TSO/DSO coordination methods. **Figure 2** lists the simulation tools frequently used in TSO-DSO coordination studies in the selected references.

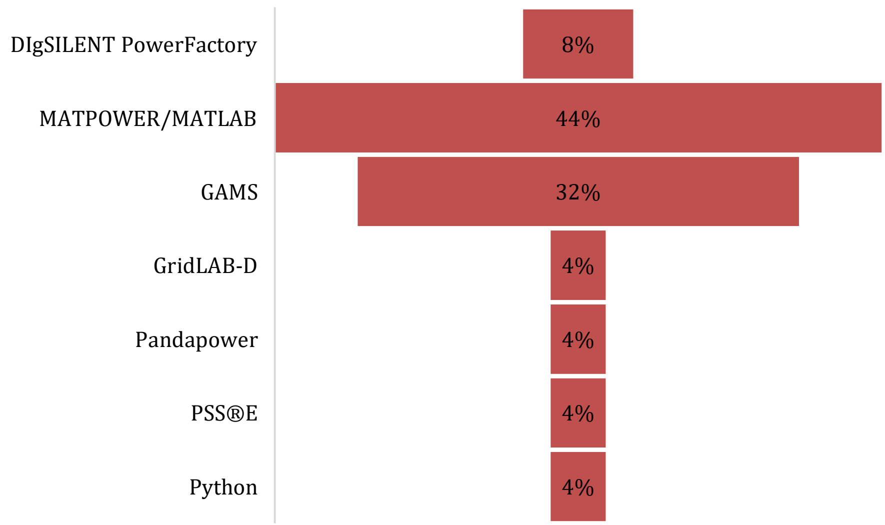

Figure 2. Simulation tools.

2.5 Objectives and Test Cases

Table 4 presents the main TSO/DSO interaction issues considered in various literature. **Figure 3** presents the frequently used test cases in these studies. In **Figure 3**, the size of each block represents the usage frequency of that test system; a bigger block size represents a more frequently used test system and vice versa. **Table 4** makes it clear that most of the methods discussed in the literature focus on different facets of grid operations concerning TSO and DSO coordination. Grid congestion management, operation cost minimisation, operational planning, voltage regulation, and reactive power management are some of the main objectives. However, as noted in [66], it remains a challenge to develop a thorough and efficient TSO/DSO coordination strategy to handle all of the fundamental coordination tasks.

Table 4. Objective of the selected manuscripts

Main objective	Reference
Voltage control	[7, 35, 65, 67, 68]
Support fast frequency response	[18]
Operation cost	[17, 21, 23, 26, 28, 29, 37, 39, 45, 47, 48]
Reactive power management	[34, 36, 67, 69]
Reduce power losses	[43, 46, 57, 70]
Operational planning	[15, 20, 22, 31, 32, 38, 42]
Congestion management	[67]

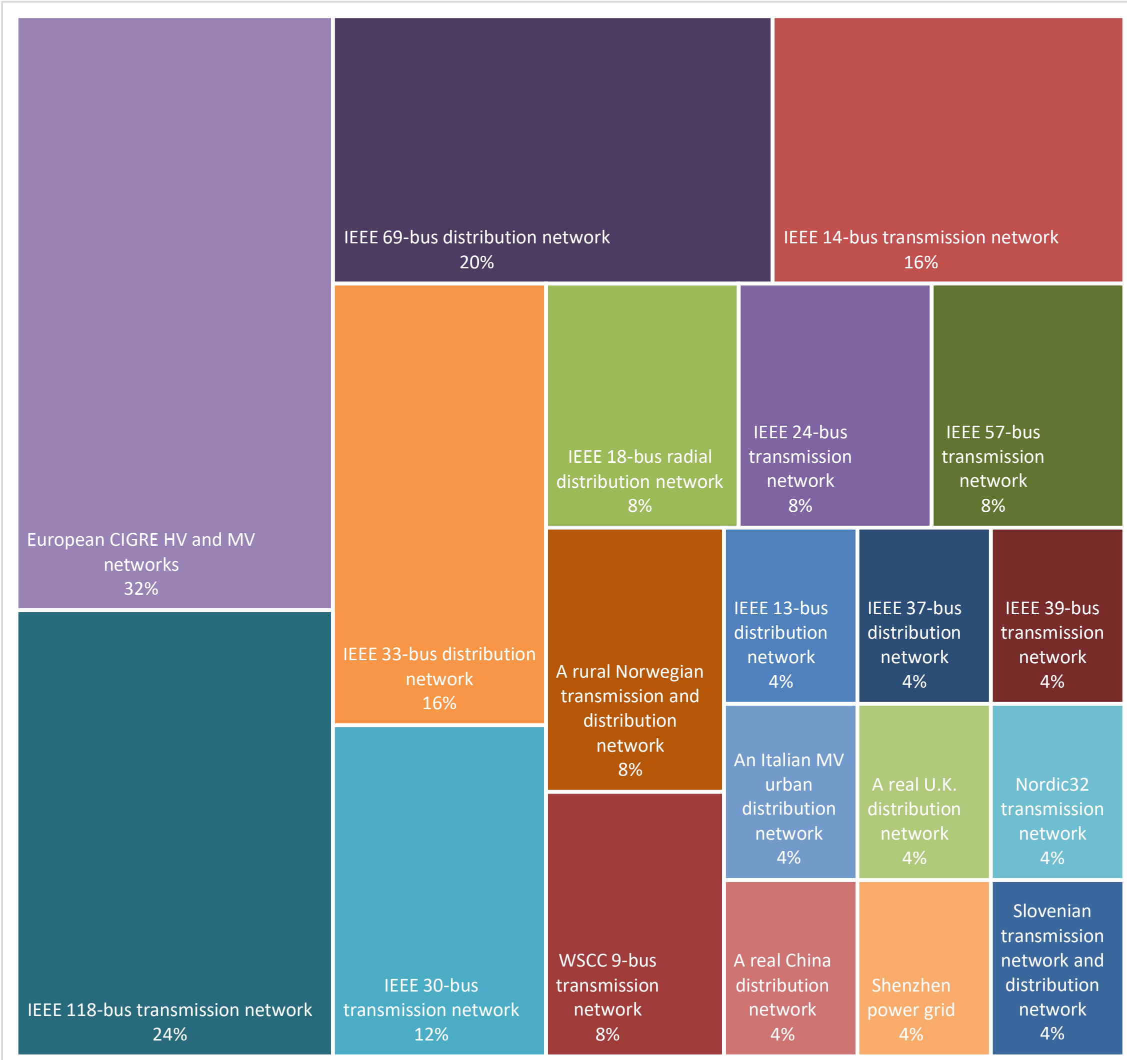

Figure 3. Frequently used test systems for TSO/DSO interaction studies in the literature.

3 Energy and Ancillary Services Provided by ADS to Transmission System

Usually, various ancillary services, including voltage regulation, frequency response, black-start capability, and so on, are deployed by TSOs [71]. In the National Electricity Market (NEM), AEMO is responsible for ensuring the safe, secure, and reliable operation of the power system under the National Electricity Rules. To fulfil this obligation, AEMO controls the key technical characteristics of the network, such as voltage and frequency, through ancillary services [72]. Synchronous generators, capacitors, static VAR compensators (SVCs) and static compensators (STATCOMs) are traditionally being used to provide ancillary services to the network. Although they are effective in maintaining voltage stability, these resources are characterised by significant capital costs [73]. With the massive integration of active DERs, the ADNs will not only solve their operational problems, such as congestion management and power quality problems, but also will be able to provide energy arbitrage and ancillary services to the TNs [74]. Providing energy arbitrage and ancillary services using the DERs of ADNs to TNs can potentially result in significant operational and economic benefits to the whole network. Microgrids' capability to offer ancillary services to the upstream grid is demonstrated in [75] by using an optimal scheduling model. Another optimisation model is developed in [76] targeting to minimise the cost of DER control and network losses. A coordinated process is proposed in [77] that minimises the network loss while also maintaining the technical limits of the TNs.

The network assets in TNs and ADNs need to communicate with each other for better TSO-DSO coordination and maintaining the system security. The coordination can be done in a centralised, decentralised, and distributed manner. In the centralised approach, a single operator is considered responsible for controlling the whole system. A centralised control with existing infrastructure is a valid assumption for a system not covering a large geographical area. The TNs' and ADNs' resources are dispatched in this centralised system, considering the integrated optimisation of the entire system [78]. The centralised system suffers from a single-point failure and highly depends on generation and consumption forecasts to determine operating set points for DGs. The centralised approach relies highly on an expensive communication network and computationally prohibits increasing the network size. Several works in the literature [8, 74, 76, 79-83] have used the centralised method because of its simple structure, depicting the best possible scenario.

In the decentralised approach, DERs perform their control actions using local measurements [78, 84, 85] without relying on a central command. Although the decentralised approach improves security by preventing single-point failure, it can face the challenges of network active/reactive balance and data privacy in ADNs with high DER penetration. In many literatures, distributed approaches are proposed to overcome the shortcomings of centralised and decentralised methods [75, 77, 86-90]. The distributed approach uses local measurements and exchanges limited information to ensure the data privacy of consumers. This approach is computationally light and can be used as a solution to emergencies. Different TSO/DSO coordination approaches found in the selected papers are presented in **Table 5**.

Table 5. Types of TSO/DSO coordination approaches

Coordination/Control Method	Reference
Centralised	[8, 74, 76, 79-83]
Decentralised	[78, 84, 85]
Distributed	[75, 77, 86-90]

3.1 Different Services

Ancillary services are essential services that help the secure and reliable operation of the network. Main ancillary services include frequency support, voltage and reactive power management, congestion management, and system restart. DERs are small-scale generation and storage units that can potentially provide ancillary services to the TNs. Different types of ancillary services are described below.

3.1.1 Energy Arbitrage

Traditionally, the TSO relies on fast hydroelectric generators or thermal units to balance mismatches between supply and demand. Due to the longer time requirement to adjust fuel supply, steam pressure, turbine speed and the cooling system, the baseload generation units, such as thermal and nuclear power plants, cannot provide fast ramping [91]. Demand response has also drawn significant attention in recent years. However, demand response requires investment in various infrastructures like advanced metering units, control devices, intelligent energy management systems, and smart buildings. Finally, it depends on the willingness of the customer. The DERs introduce more uncertainty and variability in the supply-load balance. There are different types of energy storage systems that can provide energy arbitrage services, such as batteries, pumped hydro, flywheels, and compressed air. Batteries are the most widely used and highly capable of providing sharp ramps. A microgrid optimal scheduling model is proposed in [75] that is capable of providing hourly ramping, 10-min based load following and 1-min based frequency regulation. A distributed energy and reserve dispatch is presented in [90], where the flexible resources are coordinated in normal and uncertain cases that provide reliability and economic efficiency. Rapid development of coordinated TS and ADNs has the potential to provide flexibility to the TN. An Alternating Direction Method of Multipliers (ADMM) based method is proposed in [83] that can be used to clear the market in a distributed manner. ADMM has the capability to preserve data security and exchange limited information between transmission & distribution network.

3.1.2 Frequency Regulations

Frequency regulation helps the power system to maintain the demand and supply balance, keeping the system's frequency around the nominal value (50 Hz in Australia). DERs can provide frequency regulation services to the power system by adjusting their power output or consumption according to the system frequency or a control signal. The provision of primary frequency response from the distribution grid to TS is discussed in [84]. The work in [8] investigates the capability of ADNs to provide frequency regulation in grid-connected mode and ensure reliable islanded operation. To participate in primary frequency response, the DERs should operate with a headroom under their maximum power point (MPP) that ensures sufficient available generation margin at any time instance.

3.1.3 Reactive Power Support

Reactive power management is the process of controlling the generation and consumption of reactive power to maintain the voltage within acceptable limits [92]. Due to increasing electricity demand, TNs must operate at higher loads and lower capacity, resulting in reactive power shortages at overloaded nodes [89]. Besides, voltage problems become critical in the boundary nodes of the TN, requiring reactive power ancillary services to address these issues [89]. For enhancing system flexibility and voltage stability, a bulk power system usually has its own reactive power devices, such as static VAR compensators (SVC) and capacitors at specific locations. Since these devices are costly, newer methods are sought to utilise active DERs in the distribution system to provide reactive power support to the TN [88]. It is demonstrated in [93] that existing reactive power from DERs can be used in the TS-DS interconnection to provide voltage support instead of conventional compensation devices.

Effective coordination of thousands of DERs, not centrally monitored, is a challenge for voltage support [87]. For voltage support provision, DERs must be capable of (1) dynamically adapting to changes in the system voltages, (2) responding to TSO instructions within 2s, and (3) providing the first two requirements with maintaining communication efficiency [10]. The present voltage support requirements of Switzerland are identified in [76], and the potentials of ancillary services considering various DER operational modes are investigated. A new coordination scheme is proposed in [85] that sends periodic signals to downstream devices according to the requirements of the TN. During an emergency, DERs and flexible loads (FL) decide how to respond using local measurements. Another technology-neutral strategy is proposed in [3] that only uses suitable command actions involving all existing equipment as per their capability without investing in new devices. The grid codes of European countries have already considered the ADNs' participation in providing voltage support in TNs [87]. A recent project focuses on enabling DERs of the distribution grid to provide services in Great Britain, mainly dynamic voltage control and reactive services, to TN in a coordinated manner [94]. The On-load Tap Changers (OLTC) can also provide additional reactive power flexibility if the voltage at ADN reaches its limit [77].

3.1.4 Congestion Management

Congestion management services are required to avoid the overloading of network elements and ensure optimal power flow in the system. Several models have been proposed in the literature to provide network congestion management services [78, 82, 95]. A joint chance-constrained optimisation framework is presented in [95] to provide upstream voltage and congestion support at MV-LV interconnection. Another investigation has proposed an innovative control strategy that explores the full capacity of TN based on a re-dispatching strategy while keeping the conductors under thermal limits that are prone to weather conditions [82].

3.2 Optimisation Problem Formulation

An optimisation problem can have different types depending on the complexity and nature of the problem formulation. Nonlinear modelling of the problem of ancillary services' procurement by ADNS for a TN, considering its inherent nonlinearities, can provide a more accurate representation of the problem and more accurate results for it. However, the process of linearising this complex problem can simplify its solution and make possible attaining the global optimum of the linearized problem.

In addition to nonlinearities, power generation and forecast uncertainties of this problem are considered in some literatures, which have been modelled using stochastic mixed-integer linear programming (stochastic MILP) approaches [81, 90, 95, 96]. However, most of the available problem formulations for ancillary services' procurement by ADNS for a TN have ignored uncertainties to reduce data requirements and computational complexities in their proposed methods and to enhance their practical implementability. A list of different types of optimisation formulations found in the selected manuscripts for this problem is presented in **Table 6**.

Table 6. Optimisation problem formulations from selected manuscripts

Problem type	Reference
Mixed Integer linear programming (MILP)	[75, 76, 79]
Mixed-integer Nonlinear Programming (MINLP)	[11, 77, 80, 82]
Mixed-integer quadratically constrained program (MIQCP)	[8, 97]
Stochastic MILP	[81, 90, 95, 96]

3.3 Solution of Optimisation Problem

Complex optimisation problems for energy and ancillary services can be solved using several open-source and commercial solvers. Different types of solvers are available on various platforms. GAMS has been used in most studies since specific types of solvers are available for particular types of optimisation problems. Besides GAMS, MATLAB solvers are also used. Julia is an open-source platform where Gurobi can be used as the optimisation problem solvers, and JuMP can be used as the modelling language. A list of solvers along with their platforms, is presented in **Table 7**.

Table 7. Optimisation solver from the selected manuscripts

Platform	Solver	References
MATLAB	CPLEX	[90]
Julia	Gurobi	[97]
MATLAB	Gurobi	[8, 76]
GAMS	CONOPT	[80]
GAMS	IPOPT	[77, 79]
GAMS	CPLEX	[79, 81, 95]
GAMS	BONMIN	[79, 98]
MOSEK	MOSEK	[83, 96]

3.4 Objectives and Test Systems

In many papers, the provision of energy and ancillary services to the TNs from ADNs is presented as an optimisation problem. The objectives used in these optimisation problems are reducing network loss, increasing net profit, voltage regulation, and frequency support. Objectives used in the surveyed literature are given in **Table 8**.

Table 8. Categorised objectives from the selected manuscripts

Main objective	Reference
Reactive power support	[79, 80, 86-88]
Optimal sizing of ESS	[97]
Cost (Procurement/operation)	[8, 29, 74-76, 78, 81, 83, 89]
Network loss	[76, 77, 84, 95]
Social welfare	[96]

Several benchmark IEEE test systems are used in the literature to model TNs/ADNs to study the ancillary services and validate proposed approaches [74, 77, 78, 80, 83, 85, 86, 88-90, 96, 97, 99]. Besides IEEE test systems, the European CIGRE grid and several European networks are frequently used to study ancillary service provisions by ADNs for TNs. A representative chart is given in **Figure 4** to show the frequency of different test systems used in the literature.

In the figure, various models are presented in different colours, and a larger area represents a higher frequency of use of a test system. From **Figure 4**, the most frequently used models in the literature are – IEEE 33-bus system, IEEE 30-bus, IEEE 118-bus, IEEE 123-bus and the European CIGRE MV grid. On the other hand, from **Figure 3**, the most frequently used models in the TSO-DSO interaction study are the European CIGRE HV-MV grid, IEEE 118-bus, and IEEE 69-bus systems.

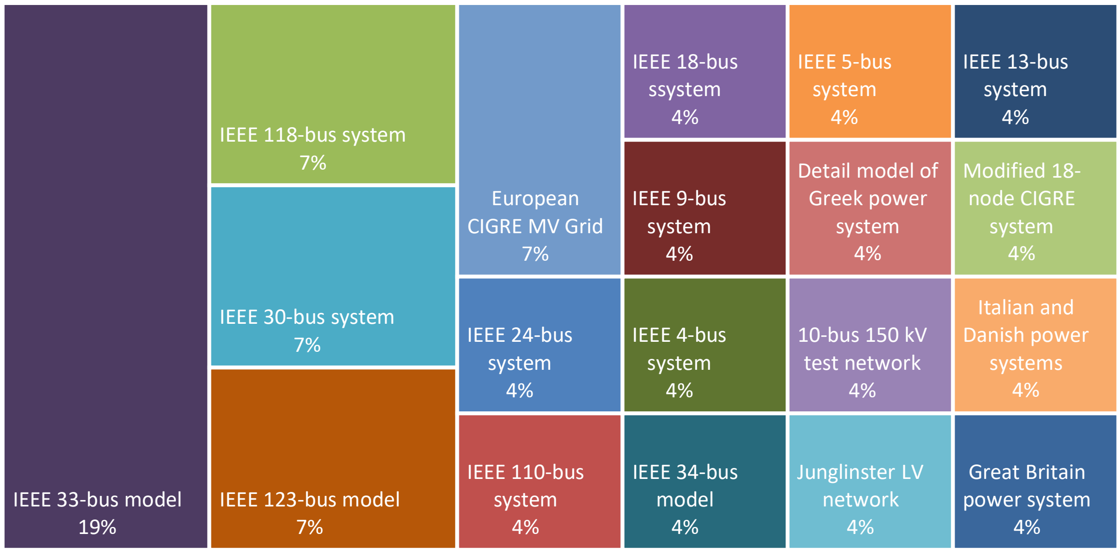

Figure 4. Frequently used test systems for providing ancillary services to TNs from ADNs.

3.5 Simulation Software

Different software is used in the literature to develop and validate physical power system models for ancillary service procurement by active distribution systems for the transmission system. From the literature, it is prominent that MATLAB and various toolboxes associated with MATLAB, such as Matpower [78, 86, 88], YALMIP [8, 76], and CVX [96], have been used in most cases. DIgSILENT PowerFactory is used for phasor-based dynamic stability study [3, 49, 50], and PSCAD/EMTDC is used for electromagnetic transient study of a large-scale TN/ADN network in [3]. In [84], the optimal power flows are solved in Python using the Scipy library. A comparative chart of different software used within the reviewed literature is presented in **Figure 5**.

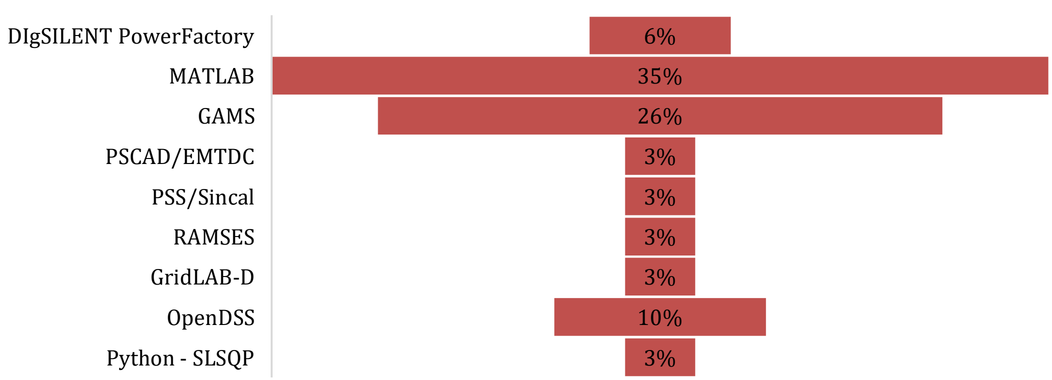

Figure 5. Power system simulation tools.

3.6 Model Reduction Techniques

Many of the reviewed works used the detailed model of small transmission and distribution systems [3, 11, 17, 26, 31, 74, 78, 83, 85, 88-90, 94, 97]. However, using the detailed system modelling for TNs/ADNs interaction and ancillary services studies would be challenging for practical systems due to the huge data requirements and computational burden as well as scalability issues. Therefore, the equivalent distribution or transmission system representation using network reduction approaches may need to be considered for TSO/DSO interaction studies [7]. Thevenin equivalent techniques are used in [7, 38, 76, 87] to represent the transmission network. The external grid or infinite bus is used in [77, 79, 84, 86, 87] to represent the transmission network behaviour. Using lumped models for TSO-DSO interaction and ancillary services studies can reduce the computation burden [24, 48, 51, 75, 82, 87, 96]. In addition, these approaches can study further aspects of the TNs/ADNs interaction. However, the main problem of these lumped models is their accuracy compared to the detailed modelling.

Up to our knowledge and based on what we found in the literature, there is no dynamic equivalency technique used in the area of TSO/DSO interaction study.

4 Summary and Recommendations

Since DERs are increasing in ADNs, the coordination and cooperation between TSO and DSO will enhance the optimal use of DERs, and ADNs will be able to provide energy and ancillary services to TNs to assist the secure and reliable operation of the whole network. A summary of the reviewed works with recommendations is presented in the following subsections of this section.

4.1 Interaction between TSO and DSO

The increasing installation of DERs poses several operational and planning complexities in TS and DS. However, the interaction between TSO-DSO also has the potential to provide flexibility and ancillary services to the network. The development of smart meters, sensors, communication networks and data platforms provide more visibility and control of the grid and resources. The technologies can facilitate the coordination and optimisation of TSO-DSO interaction. However, it also requires new standards, protocols, and regulatory measures. A summary of the core research gaps identified from the literature review of the selected manuscripts is presented in **Figure 6**.

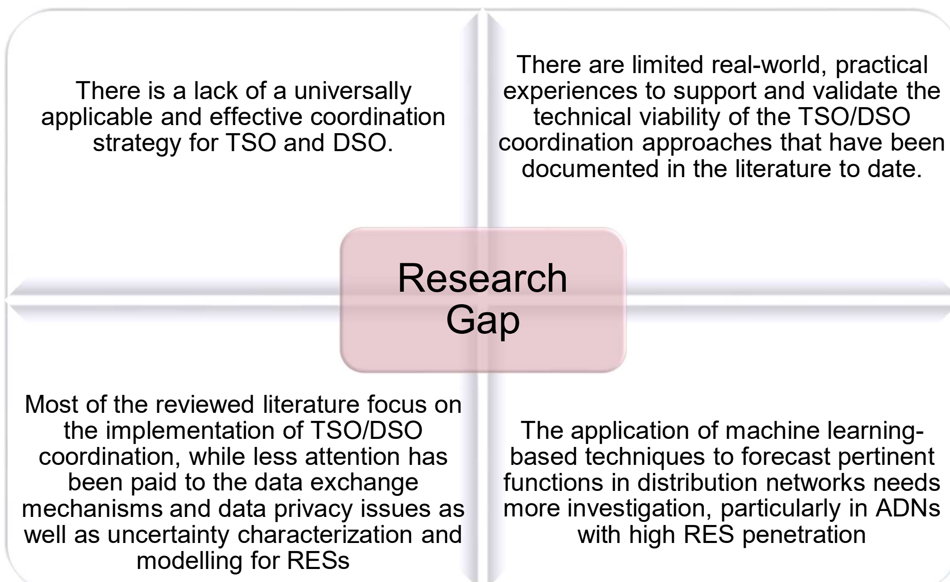

Figure 6. Summary of research gaps (TSO/DSO interaction).

A summary of the literature review for TSO/DSO interaction studies is presented in **Table A1** of the **Appendix**. **Table A1** mainly focuses on the objectives of the studies, TSO/DSO coordination model type, interaction type, physical system modelling, various optimisation problem formulations, study model, different optimisation problem solvers, power system simulation environment and test systems used. All relevant articles are reviewed one by one, and the crucial information is extracted and summarised for further comparison throughout the report.

4.2 Energy and Ancillary Services Provided by ADNs to TNs

TSOs and DSOs are the main actors responsible for the planning, development and stable operation of TS and DS, respectively. Generally, TSOs are responsible for providing flexibility and ancillary services to the TNs. However, active DERs connected to the distribution system can provide energy and ancillary services to the transmission systems. The energy and ancillary service provisions can be formulated as an optimisation problem and solved using available solvers such as GAMS. Stochastic modelling addresses the uncertainties but increases complexity, data requirement, and computational burden. The IEEE and European CIGRE test systems are used most frequently in the literature. A summary of the research gaps in this area, identified from the reviewed literature, is presented in **Figure 7**.

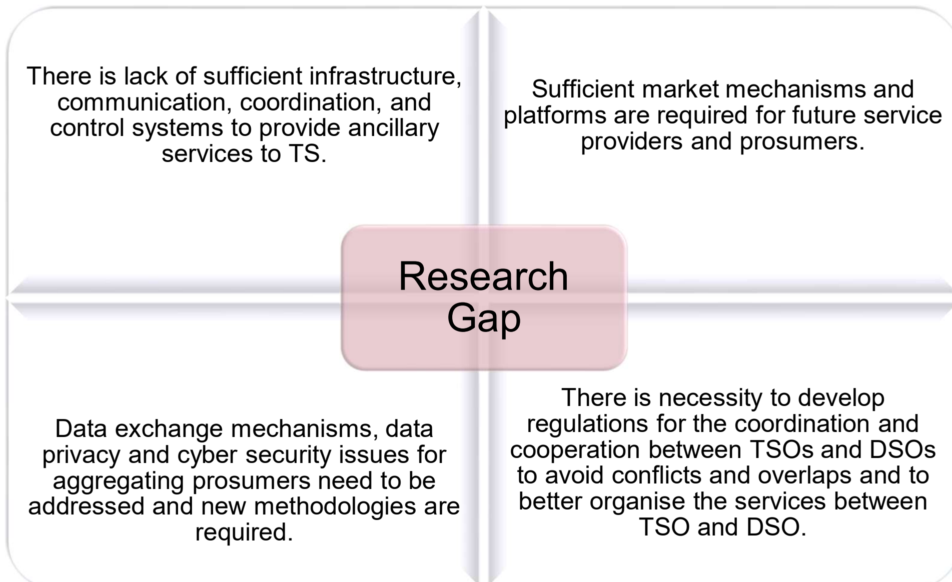

Figure 7. Summary of research gaps (energy and ancillary services provided by ADNs to TNs).

A summary of the literature review for energy and ancillary services provided by ADN for TN is presented in **Table A2** of the **Appendix**. **Table A2** summarises the objective of the study, support/ancillary services provided, control method, power flow modelling, optimisation problem formulation approaches, test systems, optimisation problem solver, power system simulation tools and uncertainties considered in the selected manuscripts at a glance.

4.3 Recommendations

Based on the presented literature review and evaluation of different research works in the TN/ADN coordination area, the following future recommendations can be made:

- The detailed system modelling for TSO/DSO studies would be challenging for practical systems due to the substantial data requirements, computational burden through co-simulation packages, and scalability issues. Therefore, a step-by-step method for an equivalent representation of the distribution system, considering grid feeding and grid forming resources, needs to be developed to study the interactions between the distribution system and the upstream grid.
- A promising research direction in this area is to develop a TSO/DSO coordination strategy that incorporates RESs by employing data mining and machine learning

techniques to forecast their uncertain behaviours based on historical data. This would reduce the need to obtain proprietary and commercially sensitive data, which frequently poses implementation problems in the traditional centralised and decentralised TSO/DSO coordination techniques.

+ Modelling uncertainties pertaining to TNs and ADNs is a key issue for their coordination that needs to be addressed. In parallel, out-of-sample evaluation methods should be developed accordingly.
+ Standardised metering, communication and control solutions are a crucial area for future research because it can bridge the gap between TSOs, DSOs, and relevant stakeholders in achieving more standardised and effective data exchange mechanisms.
+ There is a necessity to develop regulations for the coordination and cooperation between TSOs and DSOs to avoid conflicts and overlaps in using the same resources.
+ For spontaneous participation of prosumers, data exchange mechanisms, data privacy, and cyber security issues for aggregating prosumers need to be addressed.

4.4 Future Insights

Future insights from the literature review task are presented below:

+ DIgSILENT PowerFactory is a powerful software for power system modelling and performing static and dynamic analysis for different scenarios. Therefore, we will use DIgSILENT for physical network modelling and simulation, and GAMS to provide optimisation solvers.
+ Most of the reviewed literature used static nonlinear AC modelling for TSO-DSO interaction study because of the high complexity and computational burden of the quasi-dynamic and dynamic models. In addition, quasi-dynamic and dynamic modelling requires a considerable amount of dynamic data (often not readily available within the DNSPs). Therefore, our study in the next phase will be limited to nonlinear Static AC modelling.
+ Planned interaction between TSO and DSO, such as evaluating the services that DSO can provide to TSO, will be considered in the study. However, the unplanned interactions, such as power quality, short circuit, and fault issues are beyond the scope of the project.

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Appendix

Table A1. A summary of the literature review for TSO/DSO interaction studies

No.	Ref.	Target	TSO/DSO coordination model	Interaction type	Physical System Modelling	Optimisation Problem Formulation	Study model (QS/ AC/ DC)	Optimisation Problem Solver	Power system Simulation Environment	Test System
1	[7]	To minimise TSO and DSO losses in the control strategy.	Decentralised	Reactive power	Distribution network detail modelled & Thévenin equivalent for the upstream grid.	Optimal power flow/ Linear Programming	Static AC	PYPOWER	Pandapower	Transmission network: Modified CIGRE HV network. Distribution network: Modified CIGRE MV network
2	[18]	To minimise the inertia weighed maximum frequency deviation following a disturbance.	Decentralised	Active power	An unbalanced three-phase transmission and distribution network modelled in DIgSILENT PowerFactory	Non- linear programming (NLP)	Static AC	Harmony Search Algorithm {Evolutionary algorithm}	DIgSILENT PowerFactory	Cigre Task Force C6.04.02, including transmission network and distribution network
3	[17]	To minimise the total cost in the planning horizon, which comprises line investment cost, distributed generation cost, load shedding cost, energy storage operation cost and electricity purchase/sell cost	Centralised	Active power	Detailed model of the transmission network and distribution network	Mixed Integer Linear Programming (MILP)	Static AC	YALMIP; Gurobi	MATLAB	IEEE 33-bus distribution grid and IEEE 24-bus transmission grid
4	[30]	This work does not have any optimisation model. It is a simulation work to simulate interconnection power flow (IPF) between TS and DS	Centralised	Active and reactive power	Detailed model for Transmission and MV networks with Lumped model (single load) for LV network	Nonlinear simulation model	Static AC	Simscape Power System library	MATLAB	European configuration of the HV transmission network & MV distribution network
5	[41]	This work has just a nonlinear optimisation to provide initial estimate of the state vector. It is an identification work to identify the state vector with a reduced number of states.	Centralised	Active and reactive power	Detailed model of Distribution network & External grid for transmission network	NLP for the initial estimate and nonlinear identification model for the state vector	Dynamic Modelling	Levenberg-Marquardt algorithm	Simulink Power System blockset environment; MATLAB	Cigre Task Force C6.04.02 MV distribution network; HV network has been presented as an external grid; Two ADN equivalent models are presented.
6	[47]	To minimise the wear and tear operation cost of OLTC transformers	Centralised	Active and reactive power	22 load points are transformed from HV (400 kV) to MV (20 kV) with OLTC transformer. The loads are modelled as constant apparent power. Detailed model is used for transmission network and lumped model (equivalent load) for distribution network	Optimal power flow/ MINLP	Static AC	Simple branch and bound (SBB)	GAMS version 23.9.3	Nordic32 System as transmission system, then MV load are presented by the load behind the HV/MV transformer
7	[48]	Minimising the total cost of power system operations (Both TS and DS sides)	Centralised	Active power	Lumped model for both transmission network and distribution network	MILP	Static AC	YALMIP; GUROBI	MATPOWER; MATLAB	Synthetic distribution and transmission system model has been used. Transmission system got two buses, and each connected to distribution system represented by a single bus.
8	[49]	It is a simulation work to simulate TSO–DSO interactions considering the Volt-Var control at smart-inverters	Centralised	Active and reactive power	Detailed model for transmission network and 3 distribution feeders. The remaining 11 distribution feeders have lumped model	N/A	Quasi-dynamic modelling (quasi dynamic voltage profile)	N/A	DIgSILENT PowerFactory	Transmission network and distribution network regional system of Vestfold and Telemark, Norway

9	[24]	To maximise renewable generation penetration, minimise deviations from time-ahead schedules	Decentralised	Active and reactive power	Detailed model for distribution network & Lumped model (External grid) for transmission network	Optimal power flow/ NLP	Static AC	KNITRO	GAMS	A real U.K. distribution network, Transmission network has been modelled as an external grid with step down transformer (HV/MV)
10	[50]	There is no optimisation function used in this paper. It is a simulation work to simulate TSO–DSO interactions considering the Volt-Var control at smart-inverters.	Centralised	Active and reactive power	Detailed model for transmission network and 3 Distribution feeders. The remaining 11 distribution feeders have lumped model	N/A	Quasi-dynamic modelling	N/A	DIgSILENT PowerFactory	Transmission network and distribution network regional system of Vestfold and Telemark, Norway
11	[51]	Active power loss minimisation and DER cost minimisation	Centralised	Active power	Detailed model for Distribution network & External grid for transmission network	Optimal power flow/ NLP	Static AC	Julia	JuMP	IEEE 5-node, IEEE 13-node, IEEE 37-node, and IEEE 123-node distribution test networks
12	[25]	It is a simulation work to simulate a decentralised TSO-DSO coordination scheme to implement the reactive power set points given by the TSO	Decentralised	Reactive power	Detailed model for the Transmission network at 110 kV, 220 kV and 400 kV nodes/bus bars, detailed MV network, lumped model for LV network as load behind the OLTC.	N/A	Static AC	N/A	PSS®E	Slovenian transmission network and distribution network
13	[26]	To minimise network operation costs for TSO and to minimise network violations, and load and RES curtailment for DSO	Decentralised	Active and reactive power	Detailed model for transmission network and distribution network	Optimal power flow/ NLP	Static AC	Pyomo optimisation modeling language	Python	IEEE 57-bus transmission network, and a set of 14 IEEE 18-bus radial distribution network
14	[52]	To maximise the active power flexibility at the TSO-DSO interface	Centralised	Active and reactive power	Detailed model for Distribution network & External grid for 15transmission network	Optimal power flow/ NLP	Static AC	YALMIP	MATLAB	Modified 18-bus distribution network
15	[53]	To maximise flexibility aggregation	Centralised	Active and reactive power	Detailed model for MV distribution network, lumped model in the form of a single bus for transmission network and lumped model in the form of a single load for the LV distribution network	Optimal power flow/ LP	Static AC	CPLEX solver	MATLAB	European CIGRE MV Grid
16	[31]	To minimising total cost of supply of transmission network and distribution network	Centralised	Active and reactive power	Detailed model for transmission network and distribution network	Optimal power flow/ Sequential Linear Programming	Static AC	LAPACK	MATLAB	CIGRE European HV and MV networks
17	[32]	To minimise the cost due to the use of flexibility resources (load curtailment or storage power re-dispatch), and the cost related to TSO-DSO power exchange mismatch at the point of interconnection.	Centralised	Active power	Detailed model for MV distribution network and lumped for the sub transmission network	Distribution Optimal power flow/ NLP	Static AC	Quasi-Newton method and Barzilai and Borwein methods	N/A	An Italian MV urban distribution network
18	[27]	To minimises the operation point deviation for each flexibility providing grid	Decentralised	Active and reactive power	Detailed model for distribution network & external grid for transmission network	Optimal power flow/ LP	Static AC	MATLAB liner programming tool	MATLAB	A real urban distribution network
19	[33]	To minimise the total generation cost as well as the total cost of power exchange of the TSO and DSOs	Centralised	Active and reactive power	Detailed model for distribution network & external grid for transmission network	Optimal power flow/ MINLP	Static AC	CPLEX	GAMS	118-bus transmission system with up to 32 distribution system 34-bus systems
20	[34]	To minimise the net reactive power demand at the substation	Centralised	Active and reactive power	Detailed model for distribution network & Lumped model (External grid) for transmission network	Optimal power flow/NLP	Static AC	N/A	GridLAB-D	IEEE distribution 37 bus test system; IEEE 123 node test systems

21	[3]	To increase visibility of system conditions upstream in the network and support increased resource provision from distributed assets	Decentralised	Reactive power	Detailed transmission and distribution network	N/A	Static AC	N/A	PowerFactory DIgSILENT	TSO-DSO systems is validated using real-time simulation and hardware-in-the-loop (HIL) testing
22	[35]	To minimise the total downward adjustments for the upper power boundaries and minimise the total upward adjustments for the lower power boundaries	Centralised	Active and reactive power	A detailed three-phase distribution system & external grid for transmission network	Optimal power flow/MILP	Static linearised AC	CPLEX	GAMS	IEEE 123 node test system with EV charging stations obtained from a transportation simulation tool that uses real-world data
23	[36]	To minimise the Mean Squared Error (MSE) of the NN prediction for active and reactive power exchange between TS and DS	Centralised	Active and reactive power	Black box model implemented through two NNs for distribution network and detailed model for TS	NLP	Dynamic Study	Genetic Algorithm	DSA tool	CIGRE benchmark ADN connected to a bus of the 9-bus WSCC benchmark transmission network
24	[15]	To maximise load recovery amount which contains loads in the TS and DS, and minimise the load pickup/operation time T	Decentralised	Active and reactive power	Detailed model for transmission and distribution network	MIQP & MILP	Static AC	Gurobi	N/A	Three test systems: The first one, named as T6D2, include one six-bus TS and two ADSs. The second system is T118D30 which contains the IEEE-118-bus test system and 30 ADSs. The third one is a real-world TS-DS system in Dongying City, Shandong province, China. It has 5 major plants in the TS and 23 DGs in DS, 113 nodes, 52 transmission lines and 77 distribution lines of 220 kV and 110 kV voltage level, respectively
25	[28]	To minimise commitment and dispatch cost of TS and DS	Decentralised	Active power	Detailed model for transmission and distribution network	Unit Commitment/ MILP	Static AC	Gurobi	GAMS	Two test cases: Tran6+Dist7+Dist9 and Tran118+Dist30×5
26	[37]	To minimise the total transmission and distribution operational cost	Centralised	Active and reactive power	Detailed model for transmission and distribution network	Optimal power flow/ NLP	Static AC	IPOPT	MATPOWER within MATLAB	Four test cases: T14D1, T14D4, T57D10 and T57D14
27	[29]	To minimise the overall daily TS and DS operation cost	Decentralised	Active and reactive power	A detailed distribution system & external grid for transmission network	second-order cone programming	Static AC	GAMS	MATLAB	Two test cases: IEEE 14-bus transmission system integrated with three IEEE 69-bus distribution systems and IEEE 118-bus transmission systems integrated with thirty IEEE 69-bus distribution systems
28	[20]	To minimise the annual investment cost plus the annual expected operation cost of TS and DS plus the dispatch cost	Decentralised	Active power	Detailed model for transmission and distribution network	MILP	Static AC	Gurobi	MATLAB	Modified IEEE 24-bus RTS as TN and the five 24-bus active DNs
29	[21]	To minimise the total generation costs	Decentralised	Active power	A detailed distribution system & external grid for transmission network	second-order cone programming	AC and DC	CVX package	MATLAB	Modified IEEE 14-bus system connected to four distribution systems at transmission buses #6, #9, #13, and #14

30	[38]	To maximise the EVs and PVs level that can be connected to the distribution network	Centralised	Active and reactive power	Detailed model for distribution network & Thévenin equivalent for upstream grid	stochastic programming	Static AC	GAMS Optimization package (Optimization solver is not specified)	GAMS	IEEE 69-bus standard MV distribution network
31	[22]	The proposed algorithm reduces computational time and resources for large-scale systems	Decentralised	Active power	A detailed distribution system & external grid for transmission network	Optimal power flow/NLP	Static AC	N/A	MATPOWER; MATLAB	Modified IEEE 118 bus as a transmission system while 9-bus (ADG1) and 7-bus (ADG2) systems are utilised as distribution systems
32	[39]	To minimise the overall distribution system cost and reduce system risk	Centralised	Active and reactive power	Detailed model for transmission and distribution network	Optimal power flow/NLP	AC and DC	N/A	MATPOWER; MATLAB	IEEE 30-bus system as TS while the IEEE 13-bus as DS
33	[40]	Optimizing the contractive noise symbol intervals	Centralised	Active power	A detailed distribution system & external grid for transmission network	Optimal power flow/LP	Static AC	N/A	N/A	IEEE 39-bus TN, the IEEE 33-bus DN, the IEEE 69-bus DN, and the actual Shenzhen power grid
34	[42]	To maximising active power injection, minimise active power injection, maximise reactive power injection, and minimise reactive power injection at the root node	Centralised	Active and reactive power	Detailed model for transmission and distribution network	LP	Static AC	CPLEX	MATLAB	Modified IEEE case69 DN and IEEE case14 TN
35	[43]	To minimise system network losses and maximising economic benefits	Centralised	Reactive power	A detailed distribution system & external grid for transmission network	Optimal power flow/ second-order cone programming	Static AC	N/A	MATPOWER; MATLAB	IEEE-30 node transmission system and IEEE-33 node distribution system
36	[23]	To minimise the total cost, which includes the transmission system and the summation of all distribution systems cost	Decentralised	Active and reactive power	Detailed model for transmission and distribution network	MILP	Static linearized AC	CPLEX	GAMS	Modified IEEE 118-bus transmission system and IEEE 33-node distribution system
37	[44]	A synthesised objective combining objectives of TSO and DSO	Centralised	Active power	Detailed model for transmission and distribution network	optimal power flow	Nonlinear AC	IPOPT	MATLAB	Modified IEEE case69
38	[45]	To minimise the overall system operating cost, thereby maximising social welfare	Centralised	Active and reactive power	Detailed model for transmission and distribution network	Unit Commitment / linear programming with complementarity constraints	Dynamic Study	CPLEX	MATLAB	i) a real-world distribution grid in China and IEEE 30-bus system, ii) a Caracas 141-bus distribution network and IEEE 118-bus transmission grid
39	[46]	To minimise power losses and voltage deviation	Centralised	Active and reactive power	Detailed model for transmission and distribution network	NLP	Static AC	Multi-Objective Particle Swarm Optimisation	MATPOWER; MATLAB	Western System Coordinating Council network (WSCC) as TN and IEEE 16 nodes as DN
40	[100]	No objective – an assessment study	Centralized	Active and reactive power	Detailed model for transmission and distribution network	It is not an optimization study- an assessment study	Static AC	It does not have any optimization solver as it is not an optimization study	MATLAB	A modified IEEE 14-bus transmission system at transmission buses

Table A2. A summary of the literature review for energy and ancillary services provided by ADNs for TNs

No.	Ref.	Target (main objective function)	Support/Ancillary Service Provided	Control Method	Power Flow Model	Optimisation Problem Formulation	Test Systems			Optimisation Problem Solver	Power system Simulation Tools	Uncertainty
							HV Network	MV Network	LV Network			
01	[77]	To minimise the network losses	Reactive power support	Distributed	AC OPF	MINLP	External Grid/Infinite bus	Detail modelling of the IEEE 33-bus network	N/A	IPOPT	GAMS, OpenDSS and MATLAB	Not considered
02	[86]	To minimise the real-time voltage-tracking mismatch while satisfying local physical network constraints	Voltage support	Distributed	AC OPF	Dynamic Online Optimisation Framework - Online Convex Optimization (OCO)	The DN is connected to a TN. The TN can update the voltage set point that DN follows	Detail modelling of the IEEE 33-bus test feeder (12.66 kV) and the IEEE 123-bus test feeder (4.16 kV)	N/A	MATLAB/ Matpower	MATLAB/ Matpower	Not considered
03	[76]	To minimise the cost of DER control and the network losses. It also optimises the costs of providing voltage support to the TN	Voltage support	Centralised	Backward/ Forward Sweep (BFS) PF {BFS-OPF uses a good approximation of the nonlinear AC OPF}	MILP	Thevenin equivalent of the Swiss system	Detail modelling of European MV grid (balanced single-phase)- the Swiss case	Detail modelling of European LV grid (balanced single-phase)- the Swiss case	Gurobi	MATLAB, YALMIP	Not considered
04	[84]	This is not an optimisation problem.	Primary frequency response	Decentralized - P(f) droop control	AC OPF	N/A	External grid	The European MV benchmark grid of CIGRE	N/A	SciPy library	Python - Sequential Least Squares Programming (SLSQP)	Forecast error is considered
05	[79]	To minimise sustainability deterioration, i.e., to maximise the injected active power from renewable PV generation.	Voltage support	Centralised	AC OPF	MINLP model formulation and then linearise to MILP	N/A	Infinite bus	Detail modelling of the modified version of the 18-node CIGRE two-feeder unbalanced LV network;	IPOPT (NLP), CPLEX (MILP), BONMIN (MINLP)	GAMS	Not considered
06	[8]	To minimise the DN operation cost	Frequency regulation	Centralised	Chance-Constrained (CC)-OPF using BFS algorithm	Mixed-integer quadratically constrained program (MIQCP)	External Grid	MV ring model	Detail modelling of CIGRE LV network (balanced single phase)	YALMIP, Gurobi	MATLAB	PV generation and forecast errors
07	[87]	This is not an optimisation problem.	Voltage support	Coordinated control with Decentralised and Distributed levels	AC OPF	N/A (time-series power flow simulations)	1st system: N/A 2nd system: N/A 3rd system: Thevenin equivalent	1st system: External grid (MV substation.) 2nd system: Detailed modelling of DS	1st system: Detailed modelling of a practical LV network 2nd system: Lumped modelling	MATLAB	OpenDSS; MATLAB/Matpower	Not considered

								3rd system: detailed modelling	3rd system: detailed modelling			
08	[80]	To minimise the active power and reactive power drawn/imported from the transmission system, or equivalently to maximise the power injected/exported into the transmission system, while maximise these powers.	Ancillary services	Centralised	AC OPF	MINLP	External grid	Detail modelling of modified 34-bus distribution network	N/A	CONOPT	GAMS	Not considered
09	[75]	To minimise the daily microgrid operation cost	1-minute frequency regulation, 10-minute load following, hourly ramping	distributed	DC OPF	MILP	N/A	A practical microgrid with four dispatchable units, two non-dispatchable units including wind and solar, one energy storage, and five adjustable loads	N/A	CPLEX	GAMS	Not considered
10	[85]	This is not an optimisation problem.	Voltage support	decentralised	AC OPF	N/A	Detail modelling of IEEE 4-bus system; bus-1 is modelled by a Thevenin equivalent	Detail modelling of MV network	Detail modelling of LV network	N/A	RAMSES	Not considered
11	[81]	To maximise the profit from trading in the Day-Ahead Market (DAM) and Ancillary Services Market (ASM) while also minimising the imbalance costs that may be incurred due to mismatches between traded and actual RES production.	Frequency Containment Reserve (FCR), Frequency Restoration Reserve (FRR)	Centralised (RES aggregator)	DC OPF	Stochastic - Mixed Integer Linear Problem (MILP)	N/A	Detailed model of the Greek power system	Aggregated model of distributed resources	CPLEX	GAMS	wind generation, day-ahead and real-time locational marginal prices, and deviation penalty rates
12	[82]	This is not an optimisation problem.	Enhance the Dynamic Thermal Rating of Transmission Lines	Centralised	Weather-based OPF/AC OPF	N/A	External grid	Detail model of the Italian sub-transmission system (10-bus 150 kV test network)	Lumped load	fmincon function	MATLAB	power injection fluctuations, conductor parameter drifting, and weather volatility
13	[3]	This is not an optimisation problem. Dynamic and transient studies are conducted and validated through hardware-in-the-loop testing.	Voltage ancillary Services (Both static and dynamic reactive support)	Centralised	N/A	N/A	Detailed model	Detailed model	N/A	N/A	DIgSILENT PowerFactory, PSCAD/EMTDC	Not considered

14	[95]	To minimise the flexibility request and losses.	to provide voltage and congestion support Ancillary Services (AS)	N/A	N/A	Stochastic - Mixed Integer linear problem (MILP)	N/A	External grid	Detailed modelling of the real residential Junglinster LV network (data provided by CREOS, Luxembourg's TSO/DSO).	CPLEX	GAMS	End user uncertainty
15	[99]	This is not an optimisation problem.	N/A	Coordinated control	AC OPF	N/A	Infinite bus/ External grid	the IEEE 123-bus test feeder (4.16 kV)	N/A	N/A	MATLAB	Uncertainty of transfer capability (Probabilistic model of linear discriminant analysis-LDA)
16	[101]	This is a report from Global PST consortium.	Frequency response, more flexibility for real-time balancing, voltage control, congestion management, power system restoration, resource adequacy	'Traditional' centralised control approaches do not scale well with the increasing complexity of managing exceptionally high numbers of DERs; Implementing decentralised and distributed control is suggested.	N/A	N/A	N/A	N/A	Most DNSPs in Australia do not have validated/ complete electrical LV circuit models.	N/A	N/A	Uncertainties are due to the weather-related variability of renewable generation, the local settings (e.g., frequency response, Volt-Watt functions, etc.) and the future uptake of the technology.
17	[102]	This is a report from Project EDGE.	To provide network support services (such as wholesale market arbitrage, Frequency Control Ancillary Services (FCAS), Reliability and Emergency Reserve Trader (RERT) contracts, Dynamic Network Pricing or local network support services (NSS))	N/A	N/A	N/A	N/A	N/A	3-phase LV network modelling from the "CSIRO LV Network Taxonomy Report" for city and suburban network to determine Dynamic Operating Envelope (DOE)	N/A	OpenDSS used in the "CSIRO LV Network Taxonomy Report". PowerFactory, OpenDSS, PSS/Sincal	Forecast uncertainty. Especially, the power flow of non-participating customers is a large source of forecast uncertainty.
18	[98]	To estimate the hourly flexibility areas at the TSO-DSO interface that maximise the daily flexibility capacity of the distribution grid.	Active and Reactive Power flexibility	N/A	AC OPF	Nonlinear	Infinite Bus	Detailed modelling of the 20kV radial three-phase MV network	N/A	BONMIN	GAMS	Not considered

19	[88]	To minimise the net reactive power demand at the substation for the grid	volt/var ancillary services	Distributed	Distributed OPF (AC OPF)	Linearised	Detailed modelling of IEEE 9-bus transmission system	highly detailed unbalanced 3-phase distribution system of the IEEE 13-bus distribution feeder	N/A	MatPower for transmission solver, GridlabD for distribution solver	MATLAB	Not considered
20	[89]	Multi-objective function is to minimise the operating cost of the transmission network comprising the network loss penalty term, reactive power generation cost, and the reactive power ancillary service (RPAS).	Reactive power ancillary service	Distributed market clearing mechanism	Both AC and DC OPF	linearised using the binary expansion (BE) method.		Detailed modelling of the IEEE 5-bus and the IEEE 30-bus transmission network	Detailed modelling of the modified IEEE 33-bus ADNs.	The general alternating direction method of multipliers (ADMM) consistency optimisation method	N/A	Not considered
21	[78]	To minimise the cost of reserve activation	Services related to energy balancing and congestion management.	Decentralised	DC OPF	Linear	Detailed modelling of IEEE 5-bus transmission system	Detailed modelling of IEEE 18-bus distribution system	N/A	MATPOWER	MATLAB	Not considered
22	[11]	It is not an optimisation problem.	Manual frequency restoration reserve and congestion management services	N/A	TN- DC OPF DN- AC OPF	N/A	The test cases are considered from the European project SmartNet (http://smartnet-project.eu/). Detailed modelling of Italian and Danish power systems	N/A	N/A	JuMP LPs, SOCPs, MILPs, MISOCPs, are solved using Mosek; NLPs are solved using IPOPT.	Julia GAMS	Not considered
23	[94]	It is not an optimisation problem. Simulation study is performed.	The dynamic voltage control and the provision of reactive services	N/A	N/A	N/A	Detailed dynamic modelling of transmission network in Great Britain (Southeast region)	Detailed dynamic modelling of transmission network in Great Britain (Southeast region)	N/A	N/A	N/A	Not considered
24	[90]	To minimise total operation cost, the system power balance cost and the power imbalance cost	Energy and reserve support	Distributed	DC OPF for TS AC OPF for DS	Stochastic-MILP	Detailed modelling of 6-bus and 118-bus transmission networks	Detailed modelling of 2-bus, 10-bus and 30 bus distribution networks	N/A	CPLEX	MATLAB	source-load power uncertainties
25	[74]	• The objective of the TSO is to minimise the net cost, which is defined as the difference between the cost resulting	Reserve service	Centralised and local market	DC OPF for TS Linearised AC OPF for DS	N/A	Detailed modelling of IEEE 30-bus and 343-	Detailed modelling of IEEE 33-bus and	N/A	N/A	MATLAB	Not considered

		from the energy and reserve provided by the resources of the TS and the revenue by selling energy and reserve to the DSO in the day-ahead clearing market. • The objective of the DSO is to minimise the cost defined as the sum of the cost resulting from the energy and reserve provided by the resources of the DS and the cost paid to the TSO for the energy and reserve in the day-ahead clearing market.					bus transmission system	110-bus distribution system				
26	[97]	To optimise ES siting and sizing decisions for the coordinated operation of the transmission and distribution systems	wholesale electricity market managed by the TSO, installed ES units can provide both the transmission and distribution system support.	N/A	DC OPF for TS AC OPF for DS	mixed-integer quadratic programming (MIQP)	Detailed modelling of the IEEE 118-bus transmission system	Detailed modelling of the IEEE 33-bus radial distribution systems	N/A	JuMP Gurobi	Julia	Not considered
27	[83]	To minimise flexibility procurement cost.	Flexibility support (the ramping capacity (power) demanded by the transmission system operator (TSO) for power balancing services in real-time dispatch.)	Centralised solution	DC OPF	N/A	Detailed modelling of the IEEE 30-bus transmission network	Detailed modelling of two IEEE 33 mode ADNs	N/A	MOSEK	CVX toolbox of MATLAB	uncertainty of renewable generation
28	[96]	To maximise the social welfare, i.e., utility of demands minus the production cost of conventional generators, renewable power units, and the load curtailment cost.	Regulation service provision	N/A	AC PF	Mixed integer linear problem	Detailed modelling of the IEEE 24-bus reliability test system	Lumped modelling of radial distribution network	N/A	MOSEK 8.0	MATLAB using CVX	the renewable power generation uncertainty is considered