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Coordination of Smart Home Energy Management Systems in Neighborhood Areas: A Systematic Review

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ABSTRACT High penetration of selfish Home Energy Management Systems (HEMSs) causes adverse effects such as rebound peaks, instabilities, and contingencies in different regions of distribution grid. To avoid these effects and relieve power grid stress, the concept of HEMSs coordination has been suggested. Particularly, this concept can be employed to fulfill important grid objectives in neighborhood areas such as flattening aggregated load profile, decreasing electricity bills, facilitating energy trading, diminishing reverse power flow, managing distributed energy resources, and modifying consumers' consumption/generation patterns. This paper reviews the latest investigations into coordinated HEMSs. The required steps to implement these systems, accounting for coordination topologies and techniques, are thoroughly explored. This exploration is mainly reported through classifying coordination approaches according to their utilization of decomposition algorithms. Furthermore, major features, advantages, and disadvantages of the methods are examined. Specifically, coordination process characteristics, its mathematical issues and essential prerequisites, as well as players concerns are analyzed. Subsequently, specific applications of coordination designs are discussed and categorized. Through a comprehensive investigation, this work elaborates significant remarks on critical gaps in existing studies toward a useful coordination structure for practical HEMSs implementations. Unlike other reviews, the present survey focuses on effective frameworks to determine future opportunities that make the concept of coordinated HEMSs feasible. Indeed, providing effective studies on HEMSs coordination concept is beneficial to both consumers and service providers since as reported, these systems can lead to 5% to 30% reduction in electricity bills.

INDEX TERMS Coordination, decomposition, home energy management, neighborhood coordination, smart grids, demand response.

I. INTRODUCTION

A. MOTIVATION

Electric power systems play a significant role in generating CO2 emissions [1]. This has caused an increased interest in utilizing renewable energy resources along with energy storage systems [2]–[4]. Consequently, developing innovative energy management methods in neighborhood areas of distribution grid is critical to enable Home Energy Management Systems (HEMSs) with ability to integrate distributed generations (DGs), and ESSs in neighborhood areas. In this regard, coordination between smart HEMSs can be defined as an appropriate solution for designing novel EMSs for neighborhoods, comprising DGs, EVs, and ESSs. Coordination is the unification, integration, and synchronization of group members' efforts to yield unity of actions to pursue common goals [5]. In the smart grid, coordination is the process of organizing entities to properly work together to

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achieve joint purposes. These entities can be smart homes (SHs), coordinators, aggregators, producers, and utilities in terms of rational and autonomous players [6], [7]. Recently, the coordination concept has been applied for improving demand side management (DSM) [8], demand response (DR) [9], EV scheduling [10], renewable energy management [11], storage systems exploitation [12], and optimal power flow (OPF) exercises [13]. [14]–[16] have coordinated entities at the neighborhood level and reported consumers' electricity bill reductions by 26.63%, 18%, and 9.4%, respectively. From a feasible standpoint, technologies and platforms such as pando by lo3energy [17], Brooklyn Microgrid [18], Hilo by Hydro-Québec [19], virtual power plants [20], OpenADR [21], and VOLTTRON [22] have been developed to facilitate the implementation of coordinated EMS. These frameworks utilizes information and communication technologies, cloud computing, and Internet of things for data sharing and communication [23]. On the other hand, selfish HEMSs account for SHs that only exchange data with utility, avoid participating in coordination with their neighbors, and make decisions independently without considering the others. The penetration of such systems can bring different challenges to neighborhood areas such as rebound peaks, instabilities, and contingencies [6]. Besides, they can challenge aggregated load profile flattening and consumers' electricity cost savings. Coordinated HEMSs has several advantages over the selfish ones. In coordinated HEMSs, SHs share data and collaborate with each other to satisfy consumers' preferences, individual objectives, and neighborhood goals. SHs coordination concurrently leads to optimize energy efficiency, utilize flexibility potentials, and reduce electricity bills. The coordination by exploiting consumers' flexibility can be intended to design innovative solutions to mitigate power system stress and address neighborhood challenges without considerable investments and infrastructure development [24]. HEMSs coordination can provide facilities that not only encourages SHs participation, but also serves distribution networks by solving neighborhood challenges, flattening load profile, promoting energy trading, managing distributed energy resources, modifying consumers' consumption/generation patterns, and diminishing reverse power flow. Furthermore, it can indirectly assist with other benefits such as increasing load factor, decreasing network losses, improving service reliability, deferring network development, and reducing environmental pollutants. Coordinated HEMSs that regularly use a distributed decision-making framework can decrease computations, increase processing speed, deal with data exchanges and interactions between consumers, and stimulating coordination against competition or selfishness. However, conventional DSM approaches cannot offer the benefits provided by coordinated HEMSs [6]. As a result, HEMSs coordination has become a research hot-spot.

B. SUMMARY OF RELATED SURVEYS

Several studies have reviewed the recent research on coordination mechanisms for power system applications with different focuses. Table 1 summarizes the existing related review papers in the literature and compares our review paper's main contributions with other surveys. [25]–[28] discussed existing EMSs without considering the interaction between entities. [29] compared three different approaches to coordinating a heterogeneous group of utilities in order to speed up the related OPF in a huge inter-connected power grid. Molzahn *et al.* [30] reviewed distributed optimization and control algorithms to coordinate agents for exercising offline and online OPF in power systems. [31] surveyed coordination algorithms for power system operation applications such as OPF, unit commitment, economic dispatch, and other distributed practices. Kargarian *et al.* [13] summarized coordination mechanisms to coordinate OPF of multiple control entities in different physical regions. Al-Sumaiti *et al.* [32] studied existing DSM approaches and their research gaps. Furthermore, they presented an approach to facilitating electricity access in developing countries considering the impact of weather conditions. However, the authors have not considered distributed EMSs, the interactions between consumers, and coordination mechanisms for leading consumers to satisfy neighborhood objectives. [33] reviewed EMS based on a limited number of algorithms consisting of game theory, multi-agents, and optimization. Nevertheless, it did not sufficiently discuss decentralized algorithms and their use of decomposition methods. In fact, in [33], the authors focused on existing EMS and control methods for harnessing flexibility. However, interactions between multiple entities were not considered. Hu *et al.* [34] classified various types of negotiation behaviors in MGs. They used the same categories as [33], and did not discuss challenges, research gaps, and players' concerns. Mbungu *et al.* [35] studied technological aspects of MGs coordination such as communications, smart metering, and data management. Guerrero *et al.* [36] studied virtual power plants, OPF, and energy trading from the perspective of transactive energy systems on DGs integration. [37] reviewed and compared HEMSs in the literature by focusing on their models. Particularly, DR model of devices, consumer comfort, multi-objectivity, uncertainties, and required communications were analyzed in [37]. Although some reviews have been conducted on coordination for power system applications, a multifaceted literature is required to investigate other essential matters that have been lacked especially in HEMSs coordination application. Indeed, the analysis of the lacking subjects can assist with defining research gaps and subsequently, providing useful solutions. These elements that have been deduced from previous surveys, discussed above, are pointed out as follows.

- There is a lack of comprehensive literature review on the concept of HEMSs coordination.
- Some surveys have analyzed coordination mechanisms for power system applications but not for HEMSs.
- A few works have analyzed the coordination concept in neighborhood network areas, but they have not fairly studied coordination techniques and topologies as well as their related challenges.

TABLE 1. Comparison between the presented review paper and other existing related surveys.

Review papers	Study field	Requisite steps	State of the art	Research gaps and future opportunities	Coordination topologies	Coordination techniques	Decomposition based techniques	Advantages and disadvantages of techniques	Solutions for practical issues
[25]–[28]	Selfish DSM	✗	✓	✗	✗	✗	✗	✓	✗
[29]	Coordinated OPF	✗	✗	✗	✗	✓	Three approaches	✓	✗
[30]	Coordinated OPF	✗	✓	✗	✗	✓	Seven approaches	✓	✗
[31]	Distributed optimization	✗	✓	✓	✗	✓	Six approaches	✗	✗
[13]	Coordinated OPF	✗	✓	✗	✗	✓	Six approaches	✓	✗
[32]	DSM & load models	✗	✓	✓	✗	✗	✗	✗	✗
[33]	HEMSs coordination	✗	✓	✗	Four topologies	✓	✗	✗	✗
[34]	MG negotiations	✗	✓	✗	Four topologies	✓	✗	✗	✗
[35]	MG technology & communication	✗	✓	✗	✗	✗	✗	✗	✗
[36]	Transactive energy	✗	✓	✗	✗	✓	✗	✓	✗
[37]	HEMSs models	✗	✓	✗	✗	✗	✗	✓	✗
The presented review paper	HEMSs coordination	✓	✓	✓	Seven topologies	✓	Thirteen approaches	✓	✓

- The previous works have not introduced innovative ideas to address neighborhood challenges in order to ease its practical implementation.
- Generally, future opportunities, research gaps, players' concerns, coordination prerequisites, mathematical issues, and implementation concerns have not been thoroughly analyzed in the literature.
- Moreover, the best compatible coordination techniques and topologies for existing neighborhood structures have not been introduced.

C. CONTRIBUTIONS

This comprehensive review is aimed at addressing the aforementioned limitations and filling the gaps in previous studies. It should be noted that due to the broad subject of coordination, this study focuses on coordinated HEMSs, which have undeniable applications for power grid services. This survey intends to analyze,

- The need for considering coordination between SHs in the future smart neighborhoods.
- The requisite steps for performing coordinated HEMSs, including coordination topologies and coordination mechanisms.
- The state of the art studies about coordinated and selfish (the opposite concept) HEMSs.

These analyses assist with a better understanding of opportunities and challenges of coordinated HEMS and lead to the following contributions.

- Identifying research gaps and future opportunities from the perspectives of HEMSs coordination process, players concerns, implementation prerequisites, and mathematical challenges.
- Providing innovative ideas to tackle issues that challenge actual implementation of SHs coordination systems.
- Defining the most suitable HEMS coordination topology for implementing in existing neighborhoods based on sensible classifications.
- Presenting most compatible coordination techniques for HEMSs implementation in existing neighborhood areas through mainly analyzing decomposition methods consisting of Dual Decomposition, Alternating Direction Method of Multipliers (six ADMM-based techniques), Augmented Lagrangian Alternating Direction Inexact Newton (ALADIN), Analytical Target Cascading (ATC), Optimality Condition Decomposition (OCD), Auxiliary Problem Principle (APP), Consensus + Innovations (C+I), and Proximal Message Passing (PMP).

Table 1 compares the subjects that have been concerned in this survey with that of other related reviews.

D. ORGANIZATION OF PAPER

The rest of this paper is organized as follows: Section II presents the concept of HEMSs coordination. Section III discusses the coordination steps. Coordination topologies are classified and explained in section IV. Section V explains coordination techniques. Research gaps and future opportunities for coordinated HEMSs are described in Section VI, which is followed by the conclusion in Section VII.

II. HEMSs COORDINATION

Different methods and topologies have been employed to implement coordination. Figure 1 exemplifies a neighborhood area network with coordinated HEMSs. Each HEMS can control different elements such as residential loads, local resources, and ESSs. Each aggregator supplies several neighborhoods at the secondary level of the distribution transformer. Aggregators are responsible for exchanging data with the utility and neighborhoods. According to the type of coordination topology, each neighborhood can be connected to

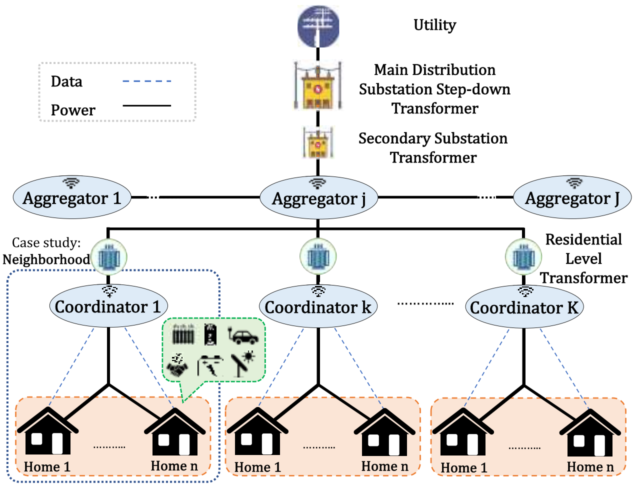

FIGURE 1. An example of coordinated residential building architecture.

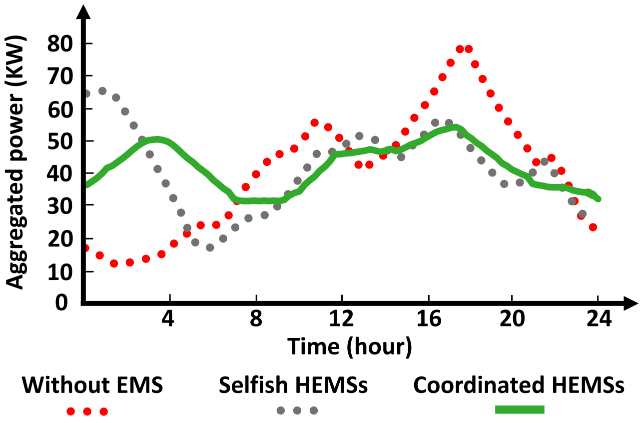

FIGURE 2. Neighborhood load profiles associated with all cases: Without EMS, Selfish HEMSs, and Coordinated HEMSs" [6]".

a coordinator as an independent entity. The coordinator is responsible for coordinating SHs by exchanging their data with the aggregator. It communicates with SHs to lead their actions and guarantee neighborhood objectives. Depending on the coordination topology and mechanism, the decision-maker can be either HEMSs, the coordinator, the aggregator, or the utility. The neighborhood consists of homes with different levels of flexibility, distinct preferences, various types of loads, DGs, and ESSs. The main idea is to address local grid challenges by using coordination in the targeted neighborhood. The coordination algorithm should be simply applicable to not only existing distribution systems but also consumers who desire to participate with no difficulty. Besides, the coordination strategy should be pertinent to owners of regular dwellings who decide to upgrade their homes to smart ones. HEMSs should collaborate like members of a team to achieve both individual and team objectives. To clarify the coordinated HEMSs idea, two examples are provided. In [38], a coordination process has been presented in which HEMSs receive the electricity price from the aggregator, optimize their assets schedules, and send the results back to the aggregator. Consequently, the aggregator calculates the aggregated load profile and sends it back to consumers with other required information. Afterward, consumers optimize their profile again to flatten the total load demand and save their previous cost results. In this example, an external coordinator has not been considered and thus; the aggregator directly coordinates SHs. Besides, by coordination between homes, it is possible to decrease peaks and avoid rebound effects. These effects can be created where HEMSs work selfishly to shift their controllable loads to periods with the lowest prices. This fact has been demonstrated in [6] where a decentralized optimal residential load management has been suggested that compares a neighborhood aggregated load profile under conditions i) without any DSM, ii) with a selfish DSM, and iii) with a coordinated DSM. Figure 2 compares the coordinated HEMSs with the selfish HEMSs in this neighborhood area. Based on the comparison, depicted by Fig. 2, the peak has occurred around 18h without any DSM while the rebound peak has taken place around 2h in the selfish DSM. It can be observed that coordinated DSM has resulted in a flatter load profile.

The implementation and applications of HEMSs coordination mechanisms are different among countries due to their regulations, pricing policies, weather conditions, availability of renewable energies, consumption patterns, and power system structures [46], [47]. HEMSs coordination applications are various. The coordination concept can help to mitigate adverse effects such as rebound peaks, instabilities, and contingencies without significant investments or developments. It leads to fulfill the neighborhood's objectives and solve local challenges. The coordination concept can be used to flatten neighborhood aggregated load profile, decrease consumers' electricity bills, facilitate energy trading among SHs, diminish reverse power flow, manage distributed energy resources, and modify consumers' consumption/generation patterns. Indeed, these benefits have been the intention of numerous research studies, conducted on selfish and coordinated EMS in the smart grid. Table 2 presents an overview of these studies. Additionally, numerous works on HEMSs have reflected important matters related to different energy sources, diverse uncertainty parameters, various scheduling methods, consumer comfort, load models, and multi-objectivity. Figure 3 has provided an overview of existing HEMS models by exemplifying them according to six major classes. It should be noted that due to the broad subject of coordination, the main focus of this literature is coordinated HEMS, which can bring valuable benefits to neighborhood area networks. Notwithstanding, existing selfish HEMSs, as the opposite concept, has been reviewed to further clarify the opportunities and challenges of coordinated ones. Coordination mechanisms have been elaborately discussed in section V.

III. COORDINATION STEPS

The required steps for coordination between SHs are summarized in Fig. 4. Coordination topology defines how agents communicate with each other, how they share data in

TABLE 2. Overview of researches on coordinated and selfish EMSs.

Research papers	Study field	Coordinated	Selfish	Decentralized	Centralized	HEMSs applications	Other applications	Decomposition based techniques
[6]	HEMSs coordination	✓	✓	✓	✓	✓	✗	✗
[38]	HEMSs coordination	✓	✓	✓	✗	✓	✗	✗
[14]	HEMSs coordination	✓	✓	✓	✓	✓	✗	✗
[20]	Energy hub scheduling	✗	✓	✗	✓	✗	Energy hubs	✗
[16]	HEMSs coordination	✓	✗	✓	✗	✓	✗	✗
[39], [40]	Combined power and natural gas systems	✓	✗	✗	✓	✓	P2G	✗
[41]	HEMSs coordination	✓	✗	✗	✓	✓	✗	✗
[42]	Multi-network constrained unit commitment	✓	✗	✗	✓	✓	P2G	✗
[43], [44]	Coordinated OPF	✓	✗	✓	✗	✗	OPF	✓
[7]	Energy hub scheduling	✓	✓	✓	✓	✓	Energy hubs	✓
[45]	HEMSs coordination	✓	✓	✓	✓	✓	✗	✓

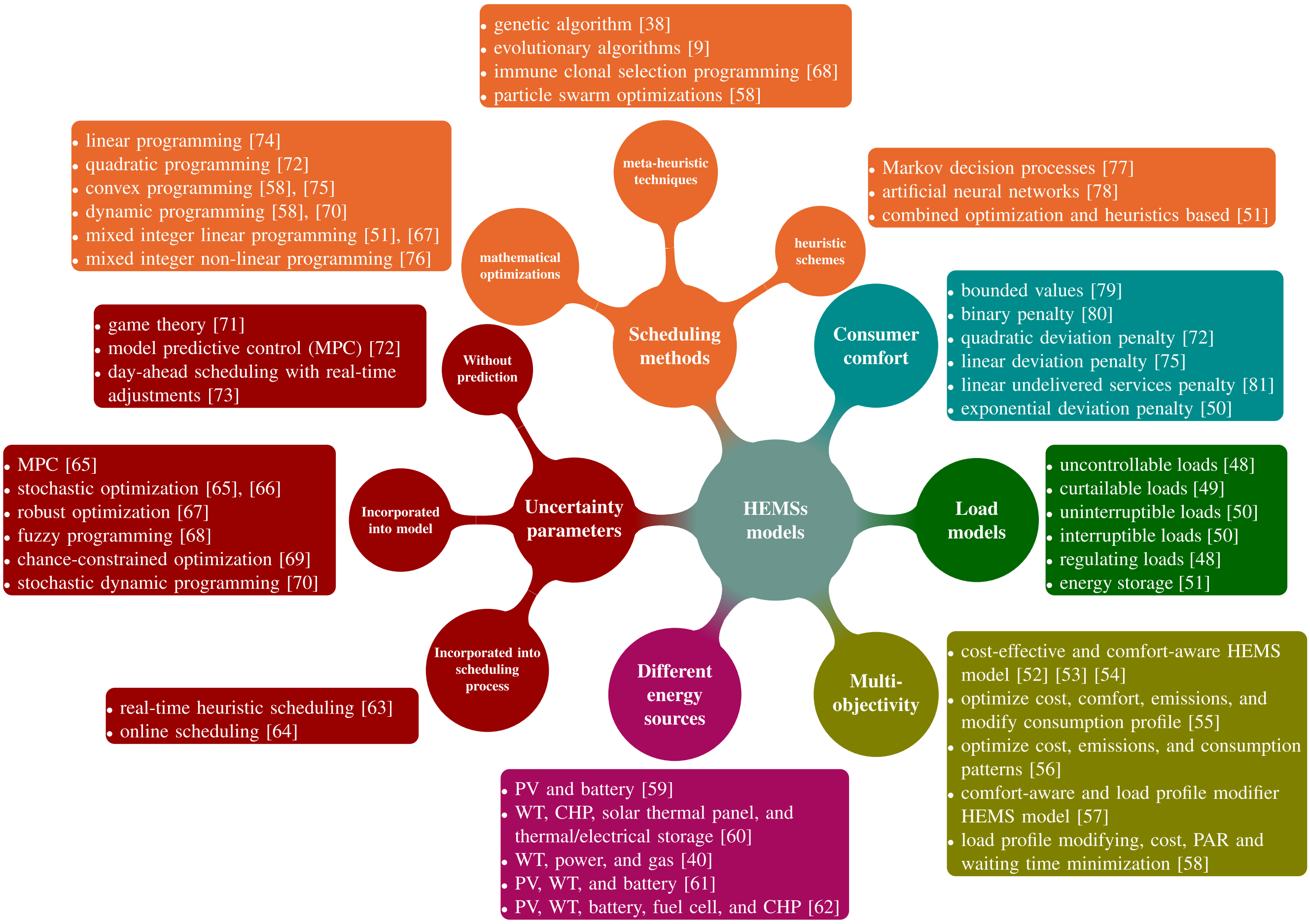

FIGURE 3. Overview of existing residential EMS models considering different energy sources, diverse uncertainty parameter models, various scheduling methods, consumer comfort models, different loads models, and multi-objectivity feature.

a community, and who is responsible for making decisions. The coordination technique explains how agents are coordinated and achieve both team and individual goals at the same time. The optimization phase searches for an optimal way to coordinate SHs. DSM targets techniques for energy efficiency improvement in SHs. DR aims to change the load profile from the viewpoint of the aggregator in order to balance demand and supply [25]–[28], [82].

IV. COORDINATION TOPOLOGIES

In order to coordinate SHs, the primary step is to choose a coordination topology. The coordination topology clarifies

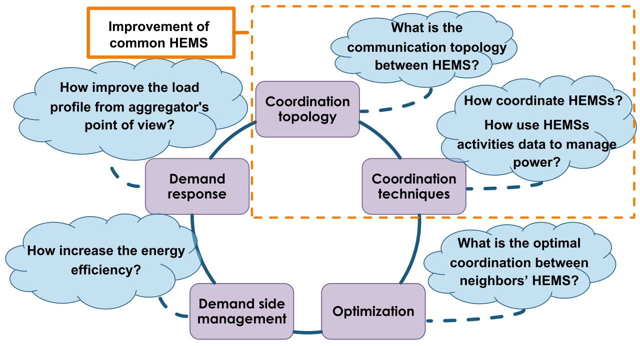

FIGURE 4. **Required steps to coordinate SHs in neighborhoods. Coordination techniques and topologies can be used to improve common HEMSs to coordinated ones.**

the communication between players (HEMSs, coordinator, aggregator, and utility) in a neighborhood area. Furthermore, it determines a centralized or decentralized control system in terms of the decision-maker. A coordination topology should be compatible with utility regulations and neighborhood architecture. Coordination topologies can be classified into seven classes, accounting for:

- Centralized
- Distributed or Star-Connection (with coordinator)
- Decentralized or Fully-Distributed (w/o coordinator)
- Partially-Distributed (with coordinator)
- Ring-connection
- Random-connection
- Desired-connection

Figure 5 illustrates the architecture of these topologies and their both connections and decision-makers. It should be noted that the choice of topology can affect the utilized coordination technique, for example, its convergence rate [31], [83]. Generally, the topologies are divided into centralized and decentralized. Figure 6 explains common coordination topologies that are detailed in what follows.

A. CENTRALIZED

The centralized topology has been shown in Fig. 5 (a). In this topology, a central entity is the decision-maker that can be the utility, the aggregator, or the coordinator [14], [59], [84]–[92]. All consumers send their information about energy consumption profile, generation, and preferences to the central entity. SHs cannot directly communicate with each other. After data collection, the central entity solves the coordination problem in order to coordinate SHs and schedule controllable loads. Besides, it suggests the best trade possible between prosumers and consumers. Actually, this trade explains energy exchange between prosumers who have surplus power from their RESs and consumers who need to buy more power in a neighborhood. In [14], coordination between several SHs has been studied. The authors have considered day-ahead scheduling of controllable appliances and electricity trade between homes. They have compared the aggregated load profile under four different conditions based on baseline algorithm (without using any EMS), selfish EMS, distributed coordinated EMS, and centralized coordinated EMS. [59] has used a centralized topology to coordinate HEMSs and minimize the aggregated power consumption regarding the transformer constraints. The neighborhood has consisted of EVs, RESs, ESSs, and controllable loads. Moreover, SHs have been managed to trade electricity either between themselves or with utility. Solanki *et al.* [84] have proposed a centralized coordinated DR by using the model predictive control method for an isolated MG with RESs, ESSs, and controllable loads. Consequently, the MG central operator has transmitted the scheduling plans to all agents. In [85], 56642 controllable assets have been optimally scheduled in 5555 SHs through a centralized topology. A central entity has collected all information and sent the scheduling decisions to SHs. Ouammi [86] has proposed a centralized HEMSs coordination in a neighborhood to schedule controllable assets and control power exchanges between SHs. A centralized coordinated DR for a neighborhood has been suggested by [87]. The proposed DR program has improved network voltage and consumer satisfaction. Moreover, it has reduced aggregated power consumption during peak period. [88] has proposed a centralized coordinated DSM in an electricity network. The results have shown that the proposed approach has reduced peak demand and losses. In [89], a centralized topology has been used to manage energy usage in a smart MG by coordinated scheduling of EVs and controllable appliances with presence of RESs. [90] has suggested a control center for scheduling controllable appliances on a coordinated day-ahead basis. The effect of load scheduling on cost efficiency, considering three consumption patterns has been studied. In [92], a central entity has optimized and coordinated power generation and electricity consumption in an off-grid hybrid MG, supplied by RESs. According to the results, the total electricity cost has been decreased by 27.0%.

B. DISTRIBUTED (STAR-CONNECTION) TOPOLOGY WITH COORDINATOR

This topology has been illustrated in Fig. 5 (b). The star-connection topology uses a coordinator rather than a central entity for decision making. The coordinator can be either the aggregator, an independent agent, or one of the SHs in the neighborhood. The coordinator collects all consumers' data. In this topology, HEMSs cannot directly communicate with each other. Each HEMS handles its own local problem in order to schedule its controllable loads and find the best trade possible with other HEMSs from the same neighborhood. Afterward, each HEMS sends the results to the coordinator. Subsequently, the coordinator returns data to agents and leads them to achieve coordination. This type of topology presents the most compatible coordination of neighborhood in power distribution system since the neighborhood layout is similar to a star-connection. In this topology, an agent at the transformer level can be considered as the coordinator. Moreover, the distributed topology is robust because its coordination system can operate at an optimal point after losing several homes (agents). Consensus ADMM and ALADIN based

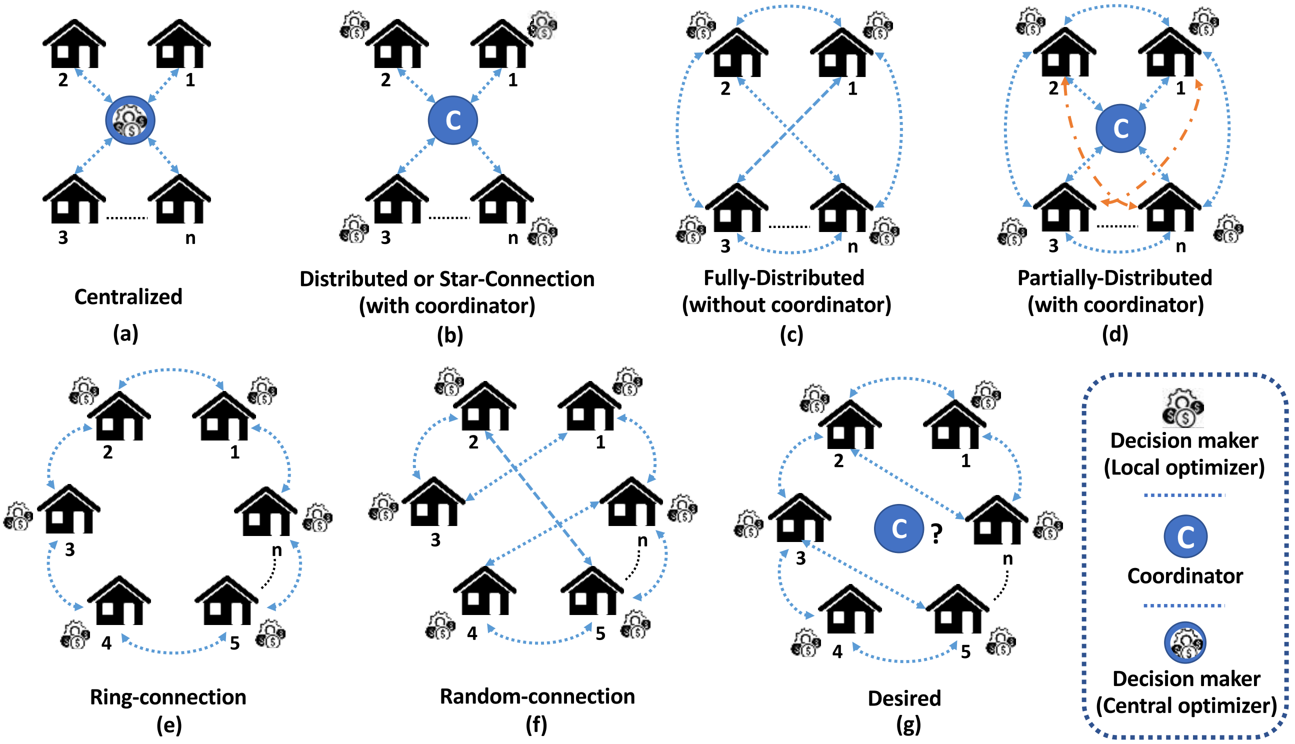

FIGURE 5. The architecture of different coordination topologies that illustrates connections between agents and determines the decision-makers.

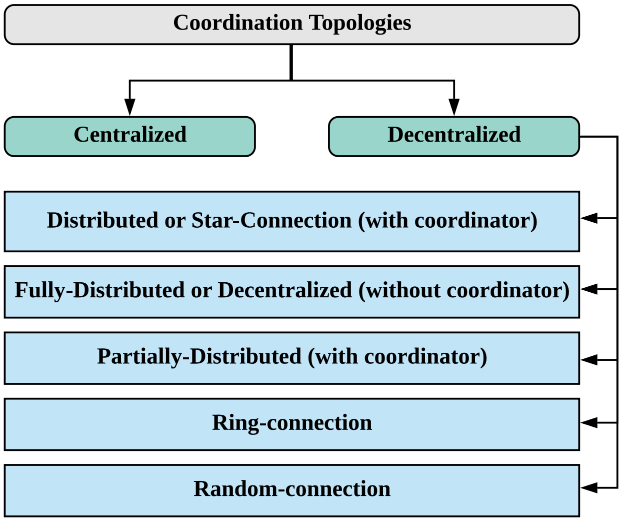

FIGURE 6. The most common coordination topologies: Centralized and Decentralized.

techniques are the best options for handling a coordination problem in the distributed topology, which are described in Section V. Applications of the distributed topology have been studied in different researches. Celik *et al.* [38] have used the distributed topology to coordinate HEMSs in a neighborhood. A day-ahead DSM has been investigated through decentralized coordination between SHs with electricity trade, RESs, and ESSs. A multi-agent system (MAS) has been employed to model SHs, the aggregator (coordinator), and the utility as agents. Results have shown the cost reduction by 3.35%. In [45], a star-connection has been employed to model a smart grid with SHs, ESSs, RESs, and EVs. An ADMM-based algorithm has been applied to coordinate SHs in order to flatten the aggregated load profile. All SHs have sent their data only to the coordinator due to privacy concerns. Afterward, the coordinator has shared new global variables with all SHs. Nguyen *et al.* [93] have exploited the distributed topology and the ADMM method to coordinate local generators in MGs and minimize the electricity generation cost. In [94], the distributed topology and the fast ADMM decomposition approach have been considered to provide a coordinated day-ahead scheduling for an integrated electricity and natural gas system.

C. DECENTRALIZED (FULLY-DISTRIBUTED) TOPOLOGY WITHOUT COORDINATOR

This topology has been depicted in Fig. 5 (c). The fully-distributed topology employs neither a central entity nor a coordinator. Therefore, all SHs directly communicate with each other and share their information with other neighbors. In addition, each SH locally manages schedulable loads and trades energy. This topology can be inappropriate for some neighborhoods in power distribution systems because of privacy regulations and direct connections between homes. The fully-distributed topology is robust as it can maintain an optimal operation in the case of losing several homes. Furthermore, this topology does not employ any coordinator that increases the robustness. For implementing the HEMSs coordination through the fully-distributed topology, APP, PMP, C+I, and OCD based algorithms are recommended. These algorithms are explained in Section V. In [74], risk aversion EMS for a distribution system with several MGs has been proposed. The MGs can exchange data and energy with each other. The fully-distributed topology without any coordinator has been chosen for the HEMSs coordination. The authors have used the APP method to handle the coordination problem. In the proposed approach, MGs have exchanged a limited amount of data to coordinate with each other. Customers' privacy, RESs, load consumption uncertainties, and computer hardware limitations have also been considered. The effectiveness of the suggested coordinated EMS approach for both islanded and grid-connected modes has been tested based on the IEEE 33-bus distribution system. In [95], the transition from conventional top-down hierarchical topology to a new peer-to-peer market has been analyzed. The proposed topology has been useful for the utilization of distributed RESs at the distribution level. The peer-to-peer market has been based on a multi-bilateral economic dispatch and allowed prosumers and regular customers to trade electricity regarding their preferences. For solving the related coordination problem, a relaxed consensus plus innovation method has been utilized. The solution has been converged by sharing a limited amount of information between prosumers and regular customers. [96] has proposed transient stability-constrained optimal power flow (TSCOPF). The proposed approach is a tool to connect steady-state OPF with transient and dynamic processes under a set of simulated contingencies. The exact optimality condition (OC) approach has been used to implement the coordinated TSCOPF. Due to complexity issues, the proposed method has decomposed the main problem into several sub-problems. The method has been evaluated by applying NE 39-Bus, IEEE 300-Bus, 703-Bus, and 1047-Bus systems. The proposed method can handle problems that simple or sequential OPF methods cannot deal with. The convergence rate of TSCOPF is higher than the sequential OPF. In [97], a completely decentralized coordination approach for OPF in a power network has been suggested. The proposed method is robust and feasible for real-time operation of the network. The suggested OPF has coordinated agents in the network through the fully-distributed topology. PMP has been used to handle the coordination problem. The agents in the network have exchanged a limited amount of data. For evaluating the proposed method, a smart grid with 8000 elements has been employed that exchanges power at 3000 nodes. The developed framework has resulted in a huge coordination problem with more than one million variables. But, the error and the convergence rate are quite acceptable.

D. PARTIALLY-DISTRIBUTED TOPOLOGY WITH COORDINATOR

Figure 5 (d) illustrates a partially-distributed coordination topology. This topology does not utilize any central entity to make decisions. However, it can take advantage of a coordinator. An external entity or one of the agents can be used as the coordinator. This type of topology is a combination of the fully-distributed and the star-connection layouts. Peer-to-peer communication between SHs is used in this layout. Besides, all SHs directly communicate with the coordinator. The EMS of each SH (scheduling and trading) is executed locally. In this topology, the coordination problem can be implemented by using coordination methods based on as ADMM, ALADIN, APP, PMP, C+I, and OCD. HEMSs transmit their decisions to other neighbors and the coordinator. This topology can be inappropriate for some neighborhoods in the power distribution system because of privacy regulations and direct connection between homes. However, the partially-distributed topology is robust since it can retain an optimal operation after losing several homes (agents). [98] has studied a coordinated residential energy consumption scheduling by using the partially-distributed coordination topology. The proposed approach has used dual decomposition to decompose the problem, find the Nash equilibrium for each subproblem, and coordinate agents. In the suggested method, one of the users acts as the coordinator and exchanges neighborhood data with the utility. In [99], a coordinated HEMS has been used to avoid rebound peaks that can occur in selfish EMS structures. A novel model of schedulable loads like plug-in hybrid EVs has been recommended. A decentralized approach has been utilized that allows HEMSs to locally optimize their solutions to their assets scheduling. Each HEMS shares data and exchanges messages with other neighbors through the partially-distributed coordination topology. The simulation results have demonstrated that the suggested coordination approach can effectively improve real-time power balancing.

E. RING-CONNECTION TOPOLOGY

Figure 5 (e) shows the ring-connection topology. This topology does not use an external coordinator and instead, two adjacent neighbors exchange information with each other. The local optimization problems are solved in each HEMS by using the information, provided by the communication line. One SH failure in communication leads to a non-optimal operation condition. [31], [83].

F. RANDOM-CONNECTION TOPOLOGY

This topology has been depicted in Fig. 5 (f). In the random topology, the connection/communication between agents varies by the time [31], [83]. This topology can be used for applications that require a time-varying communication line.

G. DESIRED-CONNECTION TOPOLOGY

Figure 5 (g) illustrates the desired-connection topology. In this layout, the connection and the decision-maker are designed based on the neighborhood requirements and architecture. According to the above discussion, a centralized topology is not appropriate for the coordination of HEMSs in the future smart neighborhoods. The distributed HEMSs coordination have several advantages over the centralized ones. In the distributed topology, agents share a limited amount of data with others and entities (such as either the coordinator or the aggregator). This, in turn, reduces

TABLE 3. The pros and cons of the coordination topologies.

Categories	PROS	CONS
Centralized	i) decision maker is utility or aggregator ii) direct communication between consumers and utility iii) no need for a iterative process	i) large amount of computations in one processor ii) share a big amount of data with high communication burden iii) scalability is limited iv) vulnerable against individuals failures v) considerable period of processing time vi) vulnerable against cyber-attacks vii) sharing personal data with utility
Distributed	i) small amount of computations in several processors ii) share a small amount of data iii) compatible with existing neighborhoods structure iv) robust against individuals failures v) proper processing time vi) decision maker is each home vii) satisfy data privacy and cyber-security standards viii) scalable with low communication burden	i) direct communication between small group of SHs and coordinator ii) need a coordinator for sharing data among SHs iii) iterative process between SHs and coordinator iv) sharing personal data with coordinator
Fully Distributed	i) small amount of computations in several processors ii) share a small amount of data iii) robust against individuals failures iv) proper processing time v) decision maker is each home vi) satisfy data privacy and cyber-security standards vii) low communication burden viii) no need for a coordinator for sharing data	i) direct communication between a small group of SHs ii) iterative process between SHs iii) sharing personal data with a small group of SHs
Partially Distributed	i) small amount of computations in several processors ii) share a small amount of data iii) robust against individuals failures iv) decision maker is each home	i) communication between SHs together and/or coordinator ii) need an iterative process iii) sharing personal data with coordinator and other SHs iv) need a coordinator for sharing part of data
Ring Connection	i) share a small amount of data with adjacent neighbors ii) no need for a coordinator iii) decision maker is each home	i) direct communication between adjacent neighbors ii) turn-based and slow process between SHs iii) vulnerable against individuals failures
Random Connection	i) useful for time varying communications	i) complex and expensive implementation
Desired Connection	i) proper for specific applications	i) may not follow the common standards

the expenses of the required communication infrastructures. Besides, it simplifies computations and increases the processing speed. Consequently, it can result in addressing a larger problem. A distributed topology can lead to a robust coordination between HEMSs since individual agents' failure can be recovered by remaining ones to guarantee a correct and optimal operation. Indeed, in the centralized case, if the central entity fails, the neighborhood optimal operation can be jeopardized. The distributed coordinated HEMSs satisfy data privacy requirements and cyber-security standards [30]. Achieving the aforementioned distributed topology features is feasible since several processors can be used in parallel to handle the coordination problem. The pros and cons of the coordination topologies are summarized in Table 3.

V. COORDINATION TECHNIQUES

This section reviews the coordination between SHs based on the approaches that have been proposed in the literature. These methods can be separated according to their utilization of decomposition techniques. The classification of the coordination manners has been shown in Fig. 7.

A. COORDINATION METHODS BASED ON DECOMPOSITION

HEMSs coordination methods can employ the decomposition concept and thus, decompose their big and complex problem into several sub-problems. Each sub-problem can be locally solved by an agent. In fact, these methods realize the coordination between agents by calculating coupling and global variables. The former variable is used for the decomposition while the latter one is utilized for the coordination. The required data can be shared by either the coordinator, a direct peer-to-peer communication, or a proper communication topology between agents. This survey presents an extensive overview of decomposition-based coordination methods, which can be used to coordinate SHs.

1) DUAL DECOMPOSITION

A large HEMSs coordination problem can be decomposed into several sub-problems by Dual Decomposition. This can be achieved by regionalization of the main system and minimization of the interaction between regions. Consequently, more independent zones can be obtained that increase the algorithm convergence rate. For decomposition, two factors are necessary. The decomposition process should concurrently decrease variables in the overlap region between SHs and increase their coupling relaxation [100]. For HEMSs coordination problem with separable cost functions, it is possible to calculate the Lagrangian function by using dual decomposition [101]. Consider the convex coordination problem with separable objective functions f and the equality

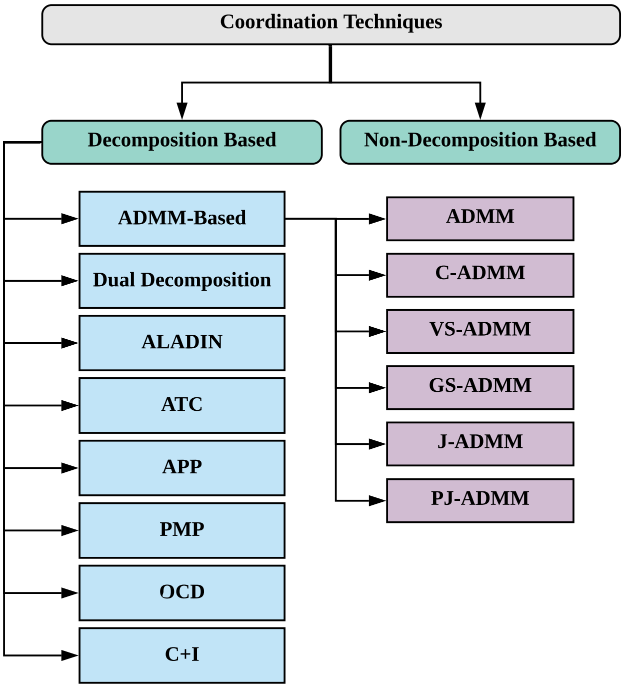

FIGURE 7. Coordination techniques classification: Decomposition Based and Non-Decomposition Based.

constraint in (1a) [101].

$$\min_{x} \sum_{i=1}^{N} f_i(x_i), \quad s.t.: \sum_{i=1}^{N} A_i x_i = b \tag{1a}$$

The Lagrangian function is calculated by,

$$\sum_{i=1}^{N} L_i(x_i, y) := \sum_{i=1}^{N} \left(f_i(x_i) + y^T A_i x_i - (1/N) y^T b \right) \tag{1b}$$

that f presents the objective function of an agent (HEMS), $L(x, y)$ is separable in x, and the x minimization can split to several separate sub-problems, which can be solved in a parallel manner. (1c) and (1d) functions update the decision (x_i) and dual variables (Lagrange multiplier) of each agent, respectively.

$$x_i^{k+1} := \underset{x_i}{\operatorname{argmin}} L_i\left(x_i, y^k\right) \tag{1c}$$

$$y^{k+1} := y^k + \alpha^k \left(\sum_{i=1}^{N} \left(A_i x_i^{k+1} \right) - b \right) \tag{1d}$$

where k defines the number of iterations, N presents the number of agents, $x_i \in R^N$ are decision variables, $y \in R^M$ stands for the dual variable, $A \in R^{M \times N}$ and b represent local and global parameters, respectively, α is the convergence rate, and $A_i x_i^{k+1} - b$ expresses the dual residual. (1c) shows that agents can handle the related local problem in parallel regarding a distributed coordination implementation. The (1b)-(1d) processes are iterative. Each iteration employs two main steps of data broadcasting and data gathering. In the dual variable update step, i.e. (1d), the term $A_i x_i^{k+1}$ calculates the dual residual. Subsequently, the dual variable is broadcasting to each agent via (1c). The main advantage of coordination approaches based on dual decomposition is the decomposability feature. However, they are slow and have poor convergence properties [102]. The convergence of dual decomposition is not guaranteed since it depends on the convergence rate and the problem specifications. Defining a coordinator is essential for the implementation of dual decomposition in coordinated HEMSs. [103] has proposed a decentralized scheduling scheme to coordinate the charging of heterogeneous plug-in EVs. The dual decomposition method has been used to design a charging algorithm that is iterative, incentive-based, and decentralized. The proposed coordination approach is efficient because an uncoordinated charging can cause the aggregated power to exceed the capacity of the distribution substation transformer.

2) ADMM

The ADMM algorithm, executed in [45], [101], [104]–[110], takes advantage of both the decomposability of dual-ascent method [111] and the convergence characteristics of the multipliers technique [112]. Similar to the dual decomposition, the ADMM algorithm includes decision variables minimization and dual variables update. However, ADMM exploits an additional term known as augmented Lagrangian function. The ADMM algorithm can be used to solve a convex HEMSs coordination problem in the form of (2a) [101].

$$\min_{x,z} f(x) + g(z), \quad s.t.: \; Ax + Bz = c \tag{2a}$$

that $f(x)$ and $g(z)$ are convex objective functions. z and x present decision variables. Considering some assumptions, ADMM-based coordination converges even under general circumstances for example where f and g are not strictly convex and differentiable. The assumptions imply that f and g in (2a) are closed, proper, and convex [101]. The augmented Lagrangian function can be calculated by (2b).

$$L_\rho(x, y, z) := f(x) + g(z) + y^T(Ax + Bz - c) \tag{2b}$$
$$+ (\frac{\rho}{2})||Ax + Bz - c||_2^2 \tag{2c}$$

where the augmented term is the squared-norm of the Primal-residual. ADMM-based HEMSs coordination algorithms include three iterative steps of x-minimization (2d), z-minimization (2e), and dual variable update (2f).

$$x^{k+1} := \underset{x}{\operatorname{argmin}} L_\rho\left(x, z^k, y^k\right) \tag{2d}$$

$$z^{k+1} := \underset{z}{\operatorname{argmin}} L_\rho\left(x^{k+1}, z, y^k\right) \tag{2e}$$

$$y^{k+1} := y^k + \rho\left(Ax^{k+1} + Bz^{k+1} - c\right) \tag{2f}$$

that k is the number of iterations. $x \in R^N$ and $z \in R^M$ are decision variables. y presents the dual variable or Lagrange multiplier. $A \in R^{P \times N}$ and $B \in R^{P \times M}$ present local parameters. $C \in R^P$ stands for global parameters. ρ is the convergence rate or the penalty parameter with a positive value. The choice of ρ can greatly influence the convergence of the

ADMM-based HEMSs coordination. Larger (smaller) values of ρ lead to a faster (slower) convergence with lower (higher) accuracy. In (2d) and (2e), the price y is fixed and does not change. First, the primary agent fixes z and minimizes objectives over x in (2d). Afterward, the other agent fixes x and minimizes objectives over z in (2e). In the basic version of ADMM, we need x^{k+1} to calculate z^{k+1}. Therefore, the process is sequential. Nevertheless, it is possible to practice a parallel operation based on the C-ADMM approach, explained below. In ADMM, z and x are updated in a sequential manner. When f and g are separable, the problem division over x and z yields to decomposition. To minimize over z, the first agent only needs B (it does not need to know f). Likewise, to minimize over x, the other agent only needs A (it does not need to know g). Therefore, two separate processors can be considered to optimize f and g. Subsequently, the coordinator can exchange their global values to coordinate them. The local processors as agents carry out the algorithm until either the dual residual becomes zero or the maximum predefined iteration number is reached. The main advantages of ADMM are decomposability and powerful convergence properties. However, the drawback of ADMM can be its sequential process. The classic form of ADMM considers only two agents however, it can be developed for coordination between more agents. [45] has presented a coordinated DR for SHs with EVs and RESs. A dynamic electricity price has been proposed to decrease the peak. Consumers can sell their surplus energy to utility or other neighbors. The coordinated DR has been implemented by using ADMM. The proposed method has satisfied privacy requirements because each consumer sends data of their power consumption only to the utility company. The results have shown that the suggested ADMM-based coordination is able to flatten the aggregated load profile despite its uncertainties. [104] has studied a ADMM-based coordination of distributed power generators for secure and economical operation. The method performance has been tested by using a modified IEEE 33-bus power system. [105] has examined ADMM-based distributed OPF, and [106] has studied ADMM-based distributed economic dispatch in islanded MGs. [107] has intended online EMS based on the online ADMM approach for MG networks by using the past power generation data. [108] has presented a coordinated EMS model for prosumer communities by considering uncontrolled/controlled consumption and generation. [109] investigated a distributed, asynchronous, and incremental implementation of ADMM to solve a nonsmooth nonconvex optimization problem. [110] has explored an offline ADMM-based coordination in order to schedule residential electro-thermal heating units through a day-ahead scheduling to fulfill space heating demand and power balance.

3) C-ADMM

C-ADMM is a version of ADMM, in which all local agents have a consensus. It forms a convex coordination problem in terms of (3a) [101].

$$\min \sum_{i=1}^{N} f_i\left(x_i\right), \quad s.t.:\ x_i - z = 0 \tag{3a}$$

HEMSs objective functions f_i and decisions x_i are convex. The C-ADMM based HEMSs coordination can be executed by (3b)-(3d).

$$x_i^{k+1} := \underset{x_i}{\operatorname{argmin}}(f_i(x_i) + y_i^{kT}(x_i - z^k) + (\frac{\rho}{2})||x_i - z^k||_2^2) \tag{3b}$$

$$z^{k+1} := (1/N)\sum_{i=1}^{N}\left(x_i^{k+1} + (1/\rho)\, y_i^k\right) \tag{3c}$$

$$y_i^{k+1} := y_i^k + \rho\left(x_i^{k+1} - z^{k+1}\right) \tag{3d}$$

where k is the number of iterations, x presents agents (HEMSs) decision variables, N defines the number of agents, y stands for the dual variables, ρ is the convergence rate (penalty) with a positive value, and Z represents global variables. The first step of the coordination algorithm, expressed by (3b), is carried out independently and in a parallel manner by each agent (HEMS) to minimize its objectives. Likewise, the last step of the algorithm, explained by (3d), is processed to update the dual variables. The global variables, z^{k+1}, are computed by the coordinator and consequently shared with all HEMSs to make a consensus. Therefore, each HEMS handles the related local problem in coordination with other agents. The computation process stops where the value of dual residual becomes zero or the maximum predefined iteration number is met. Each HEMS handles its own local objectives, constraints, and quadratic terms. The linear part of the quadratic term is updated in every iteration in order to force local variables to converge to a common value as the optimal solution of the whole system. The C-ADMM algorithm can be simplified. The reduced C-ADMM is an unscaled form of GS-ADMM, in which agents update the local and dual variables in a parallel manner [113]. The objective and dual variable convergence is guaranteed when $\rho > 0$. C-ADMM is a proper choice to implement coordinated HEMSs because it matches the neighborhood structure and facilitates locating the coordinator at the residential transformer level. C-ADMM has powerful convergence properties. Furthermore, it is fast and enables a parallel coordination between agents. [114] has compared three different C-ADMM based algorithms for coordinated dynamic DC-OPF in the context of a DR program. Each agent has executed the local DC-OPF individually in parallel with other agents. The studied coordination algorithms have been C-ADMM with a coordinator, fully distributed C-ADMM without a coordinator, and finally accelerated C-ADMM. The calculation of required coupling and global variables respectively for decomposition and coordination processes has been provided as well. [115] has proposed an inexact C-ADMM based coordination algorithm, in which agents perform one proximal gradient update at each iteration. The proximal gradients are usually easy to calculate.

Convergence conditions for the inexact C-ADMM algorithm have been analyzed as well. Numerical results have illustrated that the inexact C-ADMM algorithm reduces computational complexity; however, it converges slower than the original C-ADMM algorithm.

4) VS-ADMM

VS-ADMM based HEMSs coordination algorithms substantially increase the number of variables and constraints in the neighborhood coordination problem, especially when the number of SHs is large [116], [117]. The VS-ADMM based coordination can be executed by (4a)-(4d) [116].

$$\min_{\{x_i\},\{z_i\}} \sum_{i=1}^{N} f_i(x_i),\ s.t.: A_i x_i - z_i = \frac{c}{N} \,\&\, \sum_{i=1}^{N} z_i = 0 \tag{4a}$$

$$z_i^{k+1} := (A_i x_i^k - \frac{c}{N} - \frac{\lambda_i^k}{\rho}) - \frac{1}{N}\sum_{j=1}^{N}(A_j x_j^k - \frac{c}{N} - \frac{\lambda_j^k}{\rho}) \tag{4b}$$

$$x_i^{k+1} := \underset{x_i}{\operatorname{argmin}}(f_i(x_i) + (\frac{\rho}{2})||A_i x_i - z_i^{k+1} - \frac{c}{N} - \frac{\lambda_i^k}{\rho}||_2^2) \tag{4c}$$

$$\lambda_i^{k+1} := \lambda_i^k - \rho\left(A_i x_i^{k+1} - z_i^{k+1} - \frac{c}{N}\right), \quad \rho > 0 \tag{4d}$$

where x presents x-subproblem, Z states Z-subproblem, λ stands for dual variables, f defines agent objectives, ρ expresses the convergence rate, k is the number of iterations, and N defines the number of agents. [117] has compared two coordinated DR programs based on VS-ADMM and PJ-ADMM. The authors have considered distribution system uncertainties and constraints. The VS-ADMM based HEMSs algorithm that has a low speed is not suitable for big coordination problems.

5) GS-ADMM

Gauss-Seidel ADMM is an extension of the general form of ADMM [101], [113]. GS-ADMM can increase the number of blocks (agents) in the ADMM algorithm without significant changes. The GS-ADMM based HEMSs coordination techniques can be designed by the basic form of GS-ADMM presented in [113] through (5a)-(5b).

$$\begin{aligned} x_i^{k+1} := &\underset{x_i}{\operatorname{argmin}}(f_i(x_i) \\ &+ (\frac{\rho}{2})||\sum_{j<i}^{N} A_j x_j^{k+1} + A_j x_j \sum_{j>i}^{N} A_j x_j^k - c - \frac{\lambda^k}{\rho}||_2^2) \end{aligned} \tag{5a}$$

$$\lambda^{k+1} := \lambda^k - \rho\left(\sum_{i=1}^{N} A_i x_i^{k+1} - c\right), \quad \rho > 0 \tag{5b}$$

that x defines agents (HEMSs) decision variables, λ stands for dual variables, f expresses agent objectives, ρ is the convergence rate, k represents the number of iterations, and N is the number of agents. The HEMSs coordination approaches based on GS-ADMM suffer from poor convergence properties. Besides, the coordination process is sequential. [113] has shown the efficiency of GS-ADMM based approaches to coordinate agents in the electrical network. However, these methods are not the best choice for coordination applications. The GS-ADMM algorithm has two main disadvantages [116]. The first is that if the number of agents is more than three, the convergence cannot be guaranteed. The second is that the blocks are updated in a sequential way rather than in a parallel manner. Consequently, this method is not proper for parallel operations in HEMSs coordination practices.

6) J-ADMM

Jacobian ADMM (J-ADMM) based HEMSs coordination can be formulated by developing the ADMM algorithm [113], [116]. Unlike the GS-ADMM sequential operation, J-ADMM can permit the parallel update of the blocks. However, this method is more subject to divergence than GS-ADMM technique considering the same convergence rate (ρ). The J-ADMM algorithm formulation has been presented by (6a)-(6b) [116].

$$\begin{aligned} x_i^{k+1} &:= \underset{x_i}{\operatorname{argmin}}\ L_\rho(x_i^k, \lambda^k) \\ &= \underset{x_i}{\operatorname{argmin}}(f_i(x_i) + (\frac{\rho}{2})||A_i x_i + \sum_{j\neq i} A_j x_j^k - c - \frac{\lambda^k}{\rho}||_2^2) \end{aligned} \tag{6a}$$

$$\lambda^{k+1} := \lambda^k - \rho\left(\sum_{i=1}^{N} A_i x_i^{k+1} - c\right) \tag{6b}$$

where x expresses agents (HEMSs) decision variables, f defines agent objectives, λ stands for dual variables, ρ is the convergence rate, k represents the number of iterations, and N states the number of agents. In fact, J-ADMM can face convergence issues even for coordination problems with two blocks. In order to guarantee J-ADMM convergence, additional modifications and assumptions should be added to the algorithm [116]. A J-ADMM based coordinated OPF has been proposed by [113] that can be used to coordinate SHs.

7) PJ-ADMM

PJ-ADMM based HEMSs coordination can be implemented by adding a proximal term ($\frac{1}{2}||x_i - x_i^k||_{P_i}^2$) and a damping parameter (γ) to the J-ADMM algorithm [116]–[119]. The PJ-ADMM algorithm can be formulated as,

$$\begin{aligned} x_i^{k+1} := &\underset{x_i}{\operatorname{argmin}}(f_i(x_i) + (\frac{\rho}{2})||A_i x_i \\ &+ \sum_{j\neq i} A_j x_j^k - b - \frac{\lambda^k}{\rho}||_2^2 + \frac{1}{2}||x_i - x_i^k||_{P_i}^2) \end{aligned} \tag{7a}$$

$$\lambda^{k+1} := \lambda^k - \rho\gamma\left(\sum_{i=1}^{N} A_i x_i^{k+1} - b\right), \quad \gamma > 0 \tag{7b}$$

where x states agents decision variables, f defines agent objectives, λ stands for dual variables, ρ is the convergence rate, k represents the number of iterations, and N states the number of agents. $P_i \geq 0$ expresses a symmetric matrix that is positive semi-definite. The damping parameter is always positive during the dual variables updating process. The proximal term can be calculated regarding $||x_i||^2_{P_i} := x_i^T P_i x_i$. PJ-ADMM based coordination techniques have several advantages. The added proximal term can act as a convex relaxation for sub-problems, which are not strictly convex. Moreover, good choices of P_i and γ can ease the algorithm convergence. [113] has described how to coordinate agents by PJ-ADMM based algorithms for power system applications such as AC or DC OPF. Triplex-area DC-OPF and duplex-area AC-OPF have been studied in [113] based on 2-blocks ADMM, N-block ADMM, C-ADMM, and PJ-ADMM. Two scenarios of distributed with a coordinator and fully decentralized without a coordinator have been used for data exchange in the implementation of PJ-ADMM and C-ADMM algorithms. The proposed approach can be applied to the coordinated HEMSs problem. [117] has compared VS-ADMM and PJ-ADMM based DR programs. [118] has intended a decentralized PJ-ADMM based renewable production management and DR in power systems. [119] has proposed a distributed PJ-ADMM technique to solve a linearly constrained optimization problem for a network of agents.

8) ALADIN

The ALADIN algorithm is a developed version of ADMM that can convert non-convex coordination problems to convex ones and thus, guarantee convergence [44], [120], [121]. Furthermore, this algorithm can simultaneously decrease the number of iterations for a faster coordination and maintain higher accuracy [44]. ALADIN based coordination can be used to coordinate a large number of HEMSs. The coordination problem can be modeled as,

$$\begin{aligned}\min_x \sum_{i\in N} f_i\left(x_i\right), \quad s.t.: \sum_{i\in N} A_i x_i = 0|\lambda \ \ h_i(x_i) \\ = 0|\ \zeta_i \ \ \& \ \ \underline{x_i} \leq x_i \leq \overline{x_i}|\ \xi_i \qquad (8a)\end{aligned}$$

where λ, ζ, and ξ stand for dual variables of related constraints. f_i represents i^{th} objective function. x_i expresses i^{th} agent decision. h_i states additional local equality constraints, and N indicates the number of agents. A coordination problem in the form of (8a) can be reformulated to the general form of the ALADIN algorithm as,

$$\underset{x_i\in[\underline{x_i},\overline{x_i}]}{\operatorname{argmin}} \ f_i(x_i) + \lambda^{kT} A_i x_i + \frac{\rho^k}{2}||x_i - z_i^k||^2_{\sum_i} \qquad (8b)$$

that $\sum_{i\in N} A_i(x_i) = 0|\lambda$ and $h_i(x_i) = 0|\zeta_i^k$ are constraints. ρ stands for penalty parameter. f_i and h_i are assumed to be twice continuously differentiable but not necessarily convex. $\sum_i \geq 0$ and $\rho \geq 0$ are other required assumptions [120]. The coordination technique consists of five main steps. In the first step, the decomposed non-linear coordination problem is solved in a parallel manner through (8b). This process can be implemented either exactly or approximately. In the former case, global and fast local convergence are guaranteed. However, in the latter case, only the second condition (fast local convergence) is assured. Consequently, in the second step, the termination criterion is defined by $|| \sum_{i\in N}^{N} A_i x_i^k || \leq \epsilon$ and $||x^k - z^k|| \leq \epsilon$. Afterward, a local solution for the coordination is realized. If the termination criterion is not satisfying, gradient g_i^k, Hessian approximation B_i^k, and constraint Jacobian C_i^k are computed by means of $g_i^k = \nabla f_i(x_i^k)$, $C_i^k = \nabla h_i(x_i^k)$, and $B_i^k \approx \nabla^2(f_i(x_i^k) + \zeta_i^T h_i(x_i^k))$ in the third phase. Subsequently, the Quadratic Programming consensus (coordination) problem is carried out by (8c) subject to $\sum_{i\in N} A_i(x_i^k + \Delta x_i) = \Psi|\lambda^{QP}$, $C_i^k \Delta x_i = 0$, and $(\Delta x_i)_j = 0 \ (j \in A_i^k \ \& \ \forall i \in N)$. Since the quadratic problem does not employ any inequality constraint, it is equivalent to solve a linear system of equations. Finally, the λ^k and z^k variables, as well as ρ^k and μ^k parameters are updated by using (8d)-(8f) [44], [120].

$$\min_{\Delta x,\Psi} \sum_{i\in N} \left(\frac{1}{2}\Delta x_i^T B_i^k \Delta x_i + g_i^{k^T} \Delta x_i\right) + \lambda^{k^T}\Psi + \frac{\mu^k}{2}||\Psi||_2^2 \qquad (8c)$$

$$z^{k+1} \leftarrow z^k + \omega_1^k \left(x^k - z^k\right) + \omega_2^k \Delta x^k \qquad (8d)$$

$$\lambda^{k+1} \leftarrow \lambda^k + \omega_3^k \left(\lambda^{QP} - \lambda^k\right) \qquad (8e)$$

$$\rho^{k+1}\left(\mu^{k+1}\right) = \left\{\begin{matrix} r_\rho \rho^k \ (r_\mu \mu^k) \ if \ \ \rho^k < \overline{\rho} \ (\mu^k < \overline{\mu}) \\ \rho^k \ (\mu^k) \qquad otherwise \end{matrix}\right\} \qquad (8f)$$

where ω_1^k,ω_2^k, and ω_3^k are predefined parameters. Coordinated HEMSs can be implemented by the ALADIN algorithm. This method has powerful convergence properties and proper accuracy. Additionally, it is faster than classical forms of ADMM. [44] has used the ALADIN algorithm to coordinate agents in a non-convex non-linear AC-OPF. Unlike the general form of ADMM, ALADIN has been able to locally maintain the quadratic convergence of the AC-OPF problem. The simulation results have shown that the number of iterations in the ALADIN algorithm is less than ADMM. This advantage is usually gained by increasing communication and computation efforts at each iteration. However, [44] has introduced a variant of the ALADIN approach that employs the inexact Hessian method to decrease the required communications. Moreover, ALADIN-based algorithms have been compared with ADMM techniques from different viewpoints. This comparison has been provided by using IEEE 5-bus, 30-bus, 57-bus, 118-bus, and 300-bus case studies. The suggested algorithm is useful for SHs coordination. [121] has proposed a coordinated AC-DC OPF in a hybrid AC-DC grid through ADMM and ALADIN approaches. The coordinated OPF techniques have been applied to IEEE 5-bus and 66-bus systems. The simulation results have demonstrated that for both approaches, the optimality gaps are less than 0.01%. Nevertheless, the ALADIN algorithm has converged faster than the ADMM method. Moreover, two different decomposition strategies for the hybrid AC-DC grid, consisting of shared-DC decomposition approach (where subsystems are hybrid AC-DC regions) and joint-DC decomposition method (where subsystems are AC or DC regions) have been suggested.

9) ATC

ATC can be used to coordinate agents (HEMSs) in a hierarchical iterative process [122]–[128]. ATC transfers a problem into sub-problems through a hierarchical structure. Sub-problems should be convex to ensure convergence. The ATC needs a coordinator to correlate the agents' decisions. In a multi-level ATC structure, upper-levels are parents and lower-levels are children. Parents and children share data by using coupling variables. The coupling variables, created by penalty functions, are updated in every iteration [122]. In the ATC, parents determine targets for children. Consequently, children try to satisfy tasks, assigned by parents, based on local constraints. Parents can coordinate children either explicitly with shared values or implicitly with the integration of the analysis into the parent level. The penalty of each agent, the ATC-based coordination process, and the formulation have been described in [122]. For the implementation of ATC-based HEMSs coordination, a coordinator is required. In the coordination, all problems are solved independently. In fact, during the problem execution, all inputs are considered fixed. One interesting way of treating such a problem is to utilize the two-level approach. In this approach, the top-level problem is solved first. Subsequently, all lower-level problems are processed and updated to be exploited in the top level. This procedure is repeated until the top-level penalty term is fixed. ATC can be used to design coordinated HEMSs. [123] has suggested an ATC-based coordinated day-ahead load scheduling in a distribution system. The authors have considered controllable loads, DGs, RESs, as well as ESSs. [124] has coordinated long-term operations of regions in an interconnected multi-regional power network by using ATC. A parallel process has been suggested that utilizes neither a coordinator nor a hierarchical structure for the ATC-based coordination. The suggestion has improved the robustness and speed of the operation as well as the data integrity. Furthermore, it has created an opportunity to implement ATC-based HEMSs coordination either with or without a coordinator. [125] has presented a coordinated decentralized OPF approach in a distribution system. The proposed ATC-based coordination algorithm has transferred the primary problem into a multi-level hierarchical one. The transmission system operator has calculated the OPF for the upper level of the hierarchy while the distribution system operator has computed that for the lower level. The local problems have been solved in parallel without any coordinator. Besides, the ATC algorithm has been compared with the APP and ADMM methods. The recommended approach can be used for the coordination of SHs. [126] has analyzed a decentralized method to implement coordinated network-constrained unit commitment in a multi-regional power system. Furthermore, it has developed ATC by eliminating the central coordinator to solve the problem in parallel. The upper-level has handled the problem of the control entity while the lower-level one has coordinated this entity with neighbors. The proposed method has increased the reliability of the coordination problem by eliminating the coordinator. [127] has practiced the same problem as [126] with almost the same method. However, the solution to the problem in [127] has necessitated the utilization of a central coordinator. In [128], all required steps for the implementation of ATC-based coordination have been explored.

10) APP

APP-based coordination approaches can be used to coordinate HEMSs [29], [43], [74], [100], [129]. Each agent handles the related local problem and shares information with other agents [129]. The APP uses the augmented Lagrangian method to guarantee convergence and consistency among agents (HEMSs). The HEMSs coordination can be modeled through a decomposed convex problem as (9a) [29].

$$\underset{\substack{(x,y_a)\in A\\(y_b,z)\in B}}{argmin}\ f_a(x)\ +f_b(z)+\frac{\gamma}{2}||y_a-y_b||^2,\ s.t.:y_a-y_b=0 \tag{9a}$$

where x and z denote decisions of agents a and b. y presents common variables between the agents. γ is a predefined parameter. f_a and f_b are agents' convex objective functions. The main disadvantage of the augment Lagrangian [101] is eliminating the separability between x and z in the augmented term. In the augmented term, x and z are inseparable because of term $\frac{\gamma}{2}||\mathrm{Ax}-\mathrm{Z}||^2$. APP solves this problem considering both vectors of agents decisions (x and z) and one vector of common variables (y). The augmented term does not contain any inseparable term between x and z. Moreover, equality and inequality constraints involve one of the combinations of y and x or y and z. Thus, the augmented term does not include any term with a combination of x and z or x, z, and y. In APP, the augmented term ($||y_a-y_b||^2$) does not have any effect on the solution because the constraint $y_a-y_b=0$ forces the augmented term to be zero in any solution. However, during the coordination, it guarantees the convergence. The algorithm can be executed by,

$$(x^{k+1},y_a^{k+1}) := \underset{(x,y_a)\in A}{argmin}\ \{f_a(x)\ +\frac{\beta}{2}||y_a-y_a^k||^2 + \gamma y_a^T\cdot(y_a^k-y_b^k)+(\lambda^k)^T(y_a)\} \tag{9b}$$

$$(z^{k+1},y_b^{k+1}) := \underset{(y_b,z)\in B}{argmin}\ \{f_b(z)\ +\frac{\beta}{2}||y_b-y_b^k||^2 - \gamma y_b^T\cdot(y_a^k-y_b^k)-(\lambda^k)^T(y_b)\} \tag{9c}$$

$$\lambda^{k+1} := \lambda^k+\omega\left(y_a^{k+1}-y_b^{k+1}\right),\ \omega>0,\beta>0 \tag{9d}$$

where $\left(\lambda^k\right)^T$ is the Lagrange multipliers transposition. β and ω are predefined parameters. The convergence is always guaranteed if sub-problems are convex. The APP-based HEMSs coordination techniques do not need a coordinator. Moreover, the two-norm in the augmented Lagrangian has been linearized. However, in ATC and ADMM-based algorithms, this term has been directly modeled. In APP, the auxiliary problem principle is utilized to linearize the two-norm. This method decomposes the overall coordination problem into a set of local sub-problems without any coordinator [100]. Therefore, APP is useful for implementing HEMSs coordination through a decentralized topology. [74] has suggested the EMS of interconnected MGs and distribution networks considering the uncertainty of their sources. MGs trading has been suggested to improve the coordination performance. The stochastic linear programming has been used to carry out the EMS scheme. The APP method has been exploited for the coordinated EMS in a decentralized structure. The performance of the proposed scheme has been verified based on IEEE 33-bus system. [29] has presented a method for coordination of agents in an OPF problem. The approach has been proposed to coordinate a heterogeneous collection of utilities by means of APP and ADMM. [43] has proposed a distributed coordination scheme for an economic dispatch by using APP. A lengthy time interval has been divided into several coupled ones to solve each one separately. The performance of the proposed method has been tested on IEEE 118-bus system through a week-ahead economic dispatch problem. [129] has suggested a decentralized generating unit scheduling in a multi-layer power system with uncertainties related to wind sources. The proposed design has been dealt with by APP without any central entity for decision-making.

11) PMP

The PMP approach is a modification of the ADMM algorithm to a simpler version [97], [130], [131]. PMP-based HEMSs coordination allow to decompose a coordination problem in a network with several agents into one with several nets (N) and their associated agents (A). In the decomposed structure, the same terminal is considered for each net and its related agents. The algorithm is iterative. Each agent handles its local problem at each step regarding messages, received from its neighbors. The messages are modeled as an augmented term in the objective function of each agent. The algorithm converges to an optimal solution if objectives and constraints of agents are convex. The PMP-based coordination techniques are entirely decentralized with no external coordinator. However, agents should be synchronized at each iteration and solve their local problems in parallel. The PMP-based coordination can be formulated as [130],

$$\min \sum_{a\in A} f_a\left(x_a\right) + \sum_{n\in N} g_n\left(z_n\right), \quad s.t.: x = z \tag{10a}$$

where for N nets and A agents, $g_n\left(z_n\right)$ represents n^{th} net indicator function. $f_a\left(x_a\right)$ and x_a stand for a^{th} agent objective function and decision variable, respectively. $u = \frac{y}{\rho}$ explains the scaled dual variable and ρ presents the convergence rate. The term $||x - z + u||_2^2$ can be formulated across agents or nets in terms of $||x - z + u||_2^2 = \sum_{a\in A} ||x_a - z_a + u_a||_2^2 = \sum_{n\in N} ||x_n - z_n + u_n||_2^2$. The resulting algorithm can be written as, (10b)-(10d).

$$x_a^{k+1} := \underset{x_a}{argmin}\, (f_a(x_a) + (\frac{\rho}{2})||x_a - z_a^k + u_a^k||_2^2),\, a\ \in A \tag{10b}$$

$$z_n^{k+1} := \underset{z_n}{argmin}\, (g_n(z_n) + (\frac{\rho}{2})(||z_n - u_n^k - x_n^{k+1}||_2^2),\, n \in N \tag{10c}$$

$$u_n^{k+1} := u_n^k + (x_n^{k+1} - z_n^{k+1})\ , n \in N \tag{10d}$$

that (10b) is calculated by all agents in parallel. The equations (10c) and (10d) are computed by all nets in parallel. The equation (10d) can be rewritten as $z_n^{k+1} := u_n^k + x_n^{k+1} - \overline{u}_n^k - \overline{x}_n^{k+1}$. The resulting algorithm can be simplified through (10e).

$$Prox.\, updates: (x_a^{k+1}) := \underset{f_a,\rho}{prox}\, (x_a^k - \overline{x}_a^k - u_a^k),\ a \in A \tag{10e}$$

$$Definition: \underset{g,\rho}{prox}(X) \ = \ \underset{Y}{argmin}\, (g(Y) + (\frac{\rho}{2})||\text{X-Y}||_2^2) \tag{10f}$$

Accordingly, the scaled price updates are expressed by $u_n^{k+1} := \overline{u}_n^k + \overline{x}_n^{k+1},\ n \in N$. The name of the PMP algorithm has been taken from the proximal function and the message passing process. At each iteration, every agent computes the proximal function in order to estimate the objective function whose argument depends on messages, received by its neighbors nets. Subsequently, each agent transfers its new decision x_a^{k+1} to the associated net terminal. Each net computes its proximal function, calculates the new average ($\overline{x}_n^{k+1}$), updates its dual variables (u_n^{k+1}), and broadcasts the updated values across its terminal. PMP convergence characteristics are the same as ADMM. ρ is the convergence rate in PMP and ADMM. Contrarily to other forms of ADMM, ρ in PMP can be updated online without entailing further computation. The main disadvantages of PMP are a large amount of message passing between agents and its low speed. Besides, it needs a decentralized communication between agents and a direct communication between SHs. [130] has developed a coordinated EMS method based on PMP for a network with fixed and schedulable loads, generators, as well as ESSs. In the proposed method, each agent has exchanged a simple message with neighbors and handled its local problem considering its received messages. The local optimization problem has comprised two terms. The first has been the main objective and the second has been determined by exchanged messages. The results have shown that the centralized form of the problem has 30 million variables and takes 5 minutes to converge. However, the proposed distributed method has converged in less than one second. Accordingly, the suggested approach can ease online coordinated EMS implementations. [131] has proposed a coordination algorithm based on PMP to solve a security-constrained OPF problem in a power network. The PMP algorithm has been employed to handle reliability constraints and expedite the problem-solving process. The proposed approach is scalable considering the network size.

In HEMSs applications, this feature helps to coordinate SHs in different levels of a distribution system.

12) OCD

In HEMSs coordination based on the OCD approach, specific primal and dual variables are allocated to each agent [45], [96], [123], [132], [133]. In other words, each agent optimizes its assigned variables based on a local problem, in which other agents' variables are considered fixed [30], [132]. A linear penalty is added to the cost function in order to explain variables coupling, assigned to other agents. Lagrangian multipliers, obtained from other agents, are used to model the coefficients of the linear penalty. Each agent iteratively solves the local problem and shares the results (dual and primal variables) with other agents. Agents execute one step of the Newton-Raphson technique considering Karush-Kuhn-Tucker (KKT) conditions [134]. The general form of OCD can be expressed by (11a)-(11b) [135].

$$\begin{aligned}&\mathit{minimize}\ \psi_k(\bar{x}_1, .., x_k, ..\bar{x}_N)\\ &s.t.:\ H^c_{k,j}(\bar{x}_1, .., x_k, ..\bar{x}_N) = 0\\ &\qquad M^c_{k,j}(\bar{x}_1, .., x_k, ..\bar{x}_N) \le 0\\ &\qquad H^l_k(x_k) = 0,\ \ \&\ M^l_k(x_k) \le 0 \end{aligned} \tag{11a}$$

$$\begin{aligned}&\psi_k(\bar{x}_1, ., x_k, .\bar{x}_N) = f_k(x_k)\\ &+ \sum_{j=1, j\neq k}^{N} \bar{\eta}_j^T H^c_{j,k}(\bar{x}_1, ., x_k, .\bar{x}_N)\\ &+ \sum_{j=1, j\neq k}^{N} \bar{\gamma}_j^T M^c_{j,k}(\bar{x}_1, ., x_k, .\bar{x}_N)\end{aligned} \tag{11b}$$

where x_k indicates optimization variables of each subproblem. The variables with bar ($\bar{x}_i$) states that the corresponding value is preset by the subproblem other than subproblem k. The complicating equality and inequality constraints between two sub-problems (k and j) are $H^c_{j,k}$ and $M^c_{j,k}$, respectively. H^l_k and M^l_k express local equality and inequality constraints of each subproblem, respectively. Vectors $\bar{\eta}_j^T$ and $\bar{\gamma}_j^T$ are defined by subproblem j and express the Lagrange multipliers of constraints $M^c_{j,k}$ and $H^c_{j,k}$. In the OCD-based HEMSs coordination techniques, it is necessary the objective as well as inequality and equality constraints to be differentiable so as to satisfy the KKT conditions. The complicated verification process of these conditions and the difficulty of convergence proof are the main drawbacks of OCD. The main advantage of the OCD method is no need for a coordinator. Indeed, in this case, agents communicate with each other in a decentralized manner. [45] has presented a coordinated DSM system for SHs with EVs and RESs. The suggested coordinated EMS algorithm has been implemented by using the ADMM and OCD techniques. The results have demonstrated that the algorithm converges faster by means of ADMM in comparison with OCD. [133] has employed the approximate Newton directions to coordinate agents with different assets such as ESSs and RESs. The coordination of ESSs in the power network has led to an efficient EMS. The coordination has been performed by exchanging data between agents and using both OCD and MPC methods. [96] has proposed a transient stability constrained OPF scheme based on OCD.

13) CONSENSUS + INNOVATIONS

In the C+I algorithm, each agent has access to local information and communicates with other agents to optimize the global decision-making task [83], [95], [136]. This technique is known as C+I since the update process includes consensus and innovation steps. In the consensus step, each agent updates its state by weight averaging its data and its neighbors' states. In the innovation step, each agent processes its current local observations. In C+I, for a system with J agents, a restricted agreement exists. This agreement is a consensus on common value z between J agents that are subject to equality and inequality constraints. The C+I algorithm can be written as [136],

$$g(z) = \sum_{j=1}^{J} h_j(z) = \sum_{j=1}^{J}\sum_{n\in\Omega_j} d_n(z) = 0 \tag{12a}$$

$$\underline{d}_n \le d_n(z) \le \bar{d}_n,\ n \in \Omega_j,\ j = 1, 2, .., J \tag{12b}$$

$$\begin{aligned} z_j^{(i+1)} &:= z_j^{(i)} - \beta_i \sum_{l\in\omega_j}\left(z_j^{(i)} - z_l^{(i)}\right) - \alpha_i \sum_{n\in\Omega_j} \hat{d}_j^{(i)}\\ \hat{d}_n^{(i)} &= F_n\left[d_n\left(z_j^{(i)}\right)\right],\ n \in \Omega_j \end{aligned}$$

$$\hat{d}_n(\lambda) = F_n(\lambda) = F_n\left[\frac{\lambda - b_n}{a_n}\right] \tag{12c}$$

$$\lambda_j^{(i+1)} := \lambda_j^{(i)} - \beta_i \sum_{l\in\omega_j}\left(\lambda_j^{(i)} - \lambda_l^{(i)}\right) - \alpha_i \sum_{n\in\Omega_j} F_n^{(i)} \tag{12d}$$

$$\begin{aligned} F_n^{(i+1)} &= F_n[\frac{\lambda^{(i+1)} - b_n}{a_n}]\\ &\doteq \underset{F_n^{\min}\le F_n\le F_n^{\max}}{argmin} \|F_n - \frac{\lambda^{(i+1)} - b_n}{a_n}\|^2 \end{aligned} \tag{12e}$$

where $g(z)$ and d_n are equality and inequality constraints, respectively. Indeed, the main goal of agents is to agree on the average value, $(\frac{1}{J})\sum_{j=0}^{J} x_j$, in which x_j stands for each agent decision and j represents the number of agents. In C+I, each agent keeps a local copy, $z_j^{(i)}$ of the common variable z, which is updated in each iteration. i states the number of iterations, Ω_j stands for the components of the related system, and ω_j defines the communication topology between agents. α_i and β_i are weight parameters. In C+I algorithm, agents successively update the copy of z and $\hat{d}_n^{(i+1)}$. Finally, agents exchange the local value of $z_j^{(i+1)}$ with other neighbors (agents) in ω_j. The algorithm converges when $z_j^{(i)}$ is very close to the value of z [136]. The main difference between C+I and other primal-dual approaches is direct tracking of the consensus. In fact, other methods need additional indirect sets of Lagrangian-multipliers to achieve the consensus. Local innovation terms (12d) are commonly used for C+I and other primal-dual techniques. The C+I method is robust in the presence of different perturbations. The common value (z) depends on the marginal cost, λ within a specific time-step that the constraints, $g(z)$, are fulfilled. The local component, $\hat{d}_n(\lambda)$ is a function of λ that is updated by agents through (12c). [136] has presented an intelligent coordinated EMS to balance supply and demand. The C+I algorithm has been utilized to coordinate agents for managing DGs, schedulable loads, and ESSs. Each agent has determined the demand and the cost functions of generators and consumers. Additionally, agents have been managed to communicate with each other. The communication system has been aimed at creating a consensus on the incremental price of power supply in order to balance generation and consumption. The proposed C+I based coordination algorithm has provided robust and fully-distributed coordination of MGs agents. Furthermore, the authors have combined the C+I approach with model predictive control that can be useful for online applications and system information update. Table 4 summarizes the main characteristics of HEMSs coordination approaches based on decomposition algorithms.

B. NON-DECOMPOSITION BASED COORDINATION METHODS

This section focuses on the coordination of agents without utilizing the decomposition concept for improving either individual or social benefits in a neighborhood. In the literature, some papers have proposed non-decomposition based coordination approaches that can be used in HEMSs coordination. For example, Fan *et al.* [7] have presented coordinated economic scheduling for a community with multiple energy hubs that possess RESs, ESSs, and loads. The coordinated EMS has been modeled in terms of a coordinated bargaining game. Each energy hub has bargained with other energy hubs about the exchanging energy and the related price. A Pareto optimal balance has been used to achieve a fair negotiation between all energy hubs. Fairness is one of the major advantages of the suggested method. The total cost has been declined by 5.5%. [137] has presented a game theory-based EMS for future residential distribution systems with high penetration of DGs. In the proposed system, consumers have formed coalitions to increase individual payoffs and overall profit. However, teams compete with each other and thus, fairness is not guaranteed. [138] has presented a transactive EMS for demand coordination in a rural community-based energy system. The coordination approach has considered the neighborhood and consumers' energy budget constraints. [38] has proposed a day-ahead multi-agent coordinated HEMSs for a neighborhood. The design of a dynamic price that has resulted in HEMSs coordination can be considered as the advantage of the proposed approach. However, the convergence ability of the algorithm has not been proved. The proposed technique has reduced the cost and peak by 3.35% and 12.41%, respectively. [14] has studied a coordinated HEMSs to exploit local sources potentials, offered by consumers' flexibility, PVs, and batteries. An incentive-based mechanism has been employed to trade energy between neighbors according to exchanging information about aggregated load profile. Additionally, centralized, decentralized, baseline, and selfish control methods have been compared. The results have shown that the coordination between SHs can provide benefits for consumers and the community. The suggested technique has reduced neighborhood consumption by 26.63%. [139] has studied a coordinated EMS algorithm by using both TOU pricing and feed-in-tariff with a constant incentive policy to increase self-consumption in a neighborhood. [58] has proposed single/multi objective-based models for coordinated/uncoordinated day-ahead and real-time appliances scheduling. The scheduling mechanism has intended to reduce consumer electricity bill, decrease the interruption time, and minimize the peak-to-average rate (PAR). The results have shown cost and PAR reduction by up to 77% and 27%, respectively. [140] has studied both decentralized and centralized coordination between SHs in a community to manage loads and reduce power losses. The results have demonstrated a reduction of 4.2% in overall losses. [16] has suggested a two-level hierarchical HEMS in a neighborhood area. The upper-level has created coordination between SHs, and the lower-level has guaranteed the load supplying and minimizing the consumers' energy costs. The coordinated EMS has managed energy consumption, energy trading between SHs, energy storing, and energy generation. The coordination approach has decreased the total energy costs by 9.4% and has increased the SHs' total profit by 4.55%. [141] has intended a load profile flattening through a coordinated EMS in a neighborhood. Each agent has decided about scheduling loads, buying, selling, or storing the electricity. The suggested trading process between SHs is the most notable benefit of the utilized technique. Wang *et al.* [142] have presented a coordination method to coordinate battery storage units in a MG. The coordination remarkably decreases the size of required energy storage for large-scale integration of renewable energy resources. The proposed technique has increased the storage units' average utility by 130.2%. [6] has analyzed a decentralized coordinated residential EMS to avoid rebound peak. The aggregated load profile has been compared through three cases, accounting for baseline (without EMS), selfish DSM (without coordination), and coordinated DSM (with coordination). The results have illustrated load factor increment by 21% in coordinated DSM compare to the selfish one. [39] has assessed the environmental and economic consequences of power to gas (P2G) technology and DR program in the coordination between power and gas systems. The results have shown that the P2G technology and DR program have reduced the total cost by 2.42% and 1.78 %, respectively. [81] has explored coordinated scheduling of residential distributed energy resources in order to compromise between SHs and net benefits. Sixteen scenarios have been studied to validate the proposed approach which have shown a maximum cost reduction by 49.7%. A bi-level multi-house EMS framework has been proposed in [9] to coordinate HEMSs in a group

TABLE 4. The summary of the main features of decomposition-based HEMSs coordination approaches.

HEMSs coordination technique based on	Neighborhood topology	External coordinator	HEMSs computation in each step	Exchanging data	Speed	Number of agents	Additional details
Dual Decomposition [101]	distributed	yes	medium	low	slow	2>	i) decomposability, ii) poor convergence properties, iii) low speed
ADMM [101]	distributed	yes	high	low	medium	2	i) decomposability, ii) powerful convergence, iii) sensitive to tuning parameters, iv) convex objectives
C-ADMM [113], [114]	distributed	yes	low	low	fast	2>	i) consensus between HEMSs, ii) powerful convergence properties
J-ADMM [113], [116]	distributed	yes	medium	low	medium	2>	i) weak convergence properties ii) HEMSs working in parallel manner
PJ-ADMM [116], [117], [119]	distributed	yes	medium	low	fast	2>	i) non-strictly convex objectives, ii) improving algorithm convergence
GS-ADMM [113]	distributed	yes	high	low	medium	2>	i) weak convergence for N>3, ii) HEMSs working sequentially
VS-ADMM [116], [117]	distributed	yes	very high	medium	slow	2>	i) increasing the number of variables and constraints, ii) low speed
ALADIN [44], [120], [121]	distributed	yes	low	low	fast	2>	i) proper for non-convex HEMSs coordination problems, ii) decreasing number of iterations, iii) leading to higher accuracy
ATC [125], [126]	distributed	yes	high	low	medium	2>	i) high level of flexibility, ii) hierarchical structure
OCD [96], [133], [135]	decentralized	no	high	medium	medium	2>	i) non-convex cost function, ii) differentiable cost functions, iii) complicated convergence conditions
APP [43], [74], [129]	decentralized	no	high	low	medium	2	i) guarantee algorithm convergence and consistency between HEMSs, ii) sensitive to tuning parameters
C+I [136]	decentralized	no	medium	high	medium	2>	i) direct tracking of HEMSs consensus, ii) robust against perturbations, iii) large amount of exchanged data between neighbors, iv) low speed
PMP [97], [130]	decentralized	no	medium	high	medium	2>	i) modeling coordination problem as nets contain associated agents, ii) online convergence rate updating, iii) large amount of exchanged data, iv) low speed, v) scalable

of heterogeneous SHs. [143] has discussed an EMS for two cooperative MGs with RESs and ESS. Furthermore, the proposed method has been extended for the coordination of several MGs. The results have explained that the coordination can reduce the required capacity of ESSs. It should be noted that the proposed approach in [143] can be also implemented for the coordination of HEMSs. A dynamic charging coordination mechanism has been introduced by [10] for large plug-in electric vehicles (PEVs) populations in the neighborhood areas. The proposed approach takes advantage of a two-level hierarchical optimization framework to collect the individual PEVs charging flexibility to decrease the optimization's computational complexity. [15] has utilized a decentralized energy trading framework to coordinate entities and optimize both the cost of aggregators and the profit of generators. In order to analyze the uncertainty of RESs, risk measurement has been employed. The results have demonstrated that aggregators can increase their benefit by 17.1% and reduce consumers' electricity bills by 18%. [144] has presented a multi-objective optimization to schedule EVs charging and discharging. The introduced technique has decreased the consumers' energy cost, grid utilization, CO2 emissions, and battery degradation by 88.2%, 90%, 34%, and 67%. [145] has developed a coordinated EMS to minimize electricity bills of multiple houses. The case study has encompassed RESs, ESSs, and different types of loads. Uncertainties have been considered to model generations and demands. [146] has studied a transactive energy coordination approach in multi-dwelling residential apartments. The suggested coordination mechanism coordinates the energy sharing among apartments and manages the trading of excess energy between apartments. [147] has proposed a hierarchical coordinated day-ahead DSM for a neighborhood with RESs. The case study has considered the utility in the upper level, the DR aggregator in the middle level, and customers in the lower level. The utility has minimized the operation cost and given the relevant revenue to the DR aggregator as a reward. Subsequently, the DR aggregator has shared the reward between customers who has changed their profile to decrease utility cost and peaks. The DR aggregator and customers have maximized total benefit and social welfare, respectively. Pareto optimality has been utilized to ensure fairness between costumers. Considering fairness in reward sharing is one of the benefits of the recommended manner. [148] has designed a coordinated EMS by using dynamic pricing that has led to individual (SH) and social optimality, simultaneously. [60] has illustrated that selfish HEMSs may cause ineffectiveness in multiple home MGs system.

The authors have proposed coordination between home MGs by coordinating energy consumptions and generations. The suggested coordination approach has quantified each player's importance in the coordination, which is one of the advantages of the proposed coordination approach. [149] has presented a coordinated HEMSs that coordinates the ESS of all SHs in a neighborhood. The HEMSs coordination has minimized the total cost for the neighborhood.

VI. HEMSs COORDINATION: RESEARCH GAPS AND FUTURE OPPORTUNITIES

In the previous sections, this survey has detailed the current knowledge on coordinated HEMSs. It has provided a thorough investigation into the coordination concept in neighborhood area networks based on various categorizations. Such an extensive analysis has led to uncover multiple challenges and provide suggestions that are discussed in the following.

A. CONCERNS OVER HEMSs COORDINATION PROCESS

1) COORDINATION TOPOLOGY AND TECHNIQUE

Our review demonstrates that coordination techniques based on star-connection (distributed) topology are the best fit for the current architecture of neighborhood areas regarding actual implementations of HEMS coordination. These coordination techniques are suitable choices, particularly in the lowest level of distribution systems where a group of residences is connected to one residential transformer. Indeed, in coordination techniques based on distributed topology, the coordinator can be located in the residential transformer level. From our standpoint, algorithms such as C-ADMM and ALADIN are competent to design a coordinated HEMS with star-connection topology. Implementation of HEMSs coordination based on these algorithms can be considered as future works for researchers. The C-ADMM algorithm can share team objectives between HEMSs in the neighborhood. Team objectives can be defined to handle neighborhood challenges such as flattening the aggregated load profile. This algorithm not only is fast but also has powerful convergence properties. Moreover, HEMSs coordination through distributed topology has several advantages over centralized ones. A distributed coordinated HEMSs has the potential for reducing required communication infrastructure expenses, facilitating parallel computations, increasing computation speed and maximum problem scale, improving robustness, and satisfying cyber-security standards. Additionally, it can satisfy end-users' privacy concerns. The proposed HEMSs coordination structure has been shown in Fig. 8.

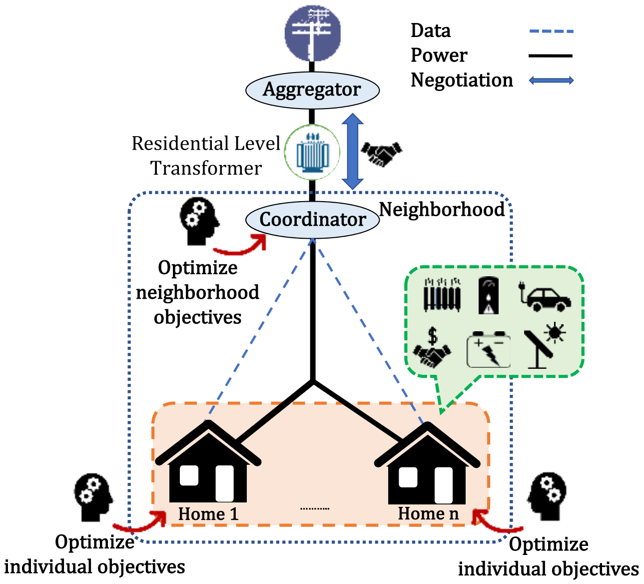

FIGURE 8. HEMSs coordination based on the distributed topology in a neighborhood.

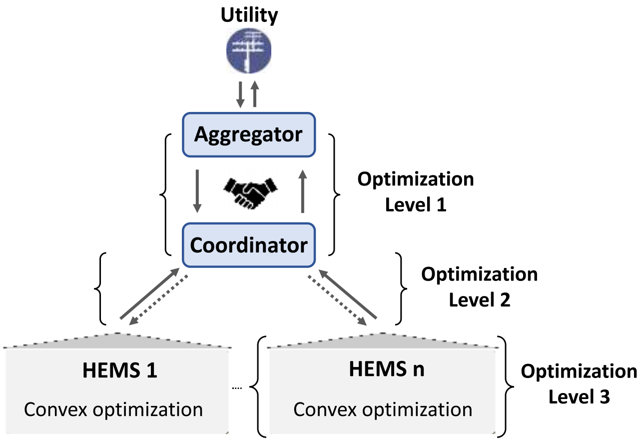

FIGURE 9. Optimization levels in coordinated HEMSs.

2) OPTIMIZATION LEVELS IN COORDINATED NEIGHBORHOOD AREAS

In coordinated HEMSs via star-connection topology, the optimization problems are formed either between aggregator and coordinator, between coordinator and HEMSs, or inside each HEMS. Accordingly, three different levels of optimization can be realized that have been depicted in Fig. 9. In the first level, the coordinator and the aggregator negotiate penalty and reward prices. This negotiation should be fair on both sides like a win-win game or Pareto optimality. The second level coordinates HEMSs in order to reach team goals and share benefits in a fair manner between agents. This can be implemented by coordination techniques based on C-ADMM. Finally, the last level provides the optimization inside each HEMS, which has already been studied in the literature. However, the optimizations between either aggregator and coordinator, or coordinator and HEMSs need more investigation.

3) COOPERATIVE LEARNING

HEMSs coordination is a research hot-spot in the smart grid. SHs can communicate with each other in future smart neighborhoods. Accordingly, their actions can affect each other. In such a framework, the coordinator should concentrate on neighborhood challenges rather than individual SHs' benefits. Furthermore, it should take into account the control objective of each SH with respect to other SHs. Therefore, it is necessary to consider advanced cooperative learning in coordinated HEMSs. Cooperative learning can be used for modeling neighborhood areas, designing price policies, and handling neighborhood challenges. However, few researches have studied cooperative learning for HEMSs coordination.

4) ROBUST COORDINATION

Coordination algorithms based on fully-distributed topology are recommended for maximizing the operation robustness in neighborhood areas. Fully-distributed topology uses neither a central entity nor a coordinator, which increases robustness, especially in cases with HEMSs or communications failures. Decomposition techniques based on APP, PMP, C+I, and OCD are suitable for creating a coordinated HEMS with fully-distributed topology. The effect of these techniques on the robustness of coordinated HEMSs can be investigated in future researches.

5) FEDERATED REINFORCEMENT LEARNING

HEMSs coordination can be developed by using machine learning approaches such as reinforcement learning (RL) to manipulate time-varying operation conditions in the neighborhood region [150]. However, this development requires a large amount of data to train SHs energy consumption models and increase HEMSs computation capabilities. From our perspective, a distributed machine learning structure based on federated reinforcement learning (FRL) [151], [152] approach can deal with such a situation. In FRL-based HEMS coordination techniques, a global server creates a global model based on SHs local models. Each SH creates its model and sends it to the global server. Afterward, the global server collects the local models, updates the global model, and broadcasts it across SHs. In this iterative process, SHs use the new global model to recreate their local models until they obtain the desired model. In this approach, the global server does not need local data sharing, which ensures consumers data privacy. Fig. 10 illustrates the suggested FRL-based HEMS coordination structure. The FRL-based HEMS coordination may constitute the object of future studies.

6) NEW ASSETS IN NEIGHBORHOOD AREAS

Analyzing the coordination problem in neighborhood areas with integrated RESs, EVs, and ESSs is another lack of the relevant studies. These systems can provide agents with services that result in another type of coordination. To be exact, they enable agents to trade energy according to their services schedules. Without these facilities, HEMSs can be coordinated only based on the information of their loads. Two types of coordination processes should be considered for HEMSs. The first one handles SHs load scheduling coordination, and the second one takes care of energy trading coordination between SHs. Further studies should investigate these two coordination classes.

7) NEIGHBORHOOD UNCERTAINTIES

Dealing with uncertainties is another difficulty with the coordination of SHs. Uncertainties can be caused by consumers' actions, loads, distributed RESs, and weather forecasting. This difficulty stimulates the utilization of stochastic and probabilistic approaches to develop coordinated HEMSs. The uncertainties can be modeled by probabilistic estimation of neighborhood load demand. Moreover, an uncertainty set can be used to model RESs uncertainties. Neighborhood uncertainty is an issue for future research to explore.

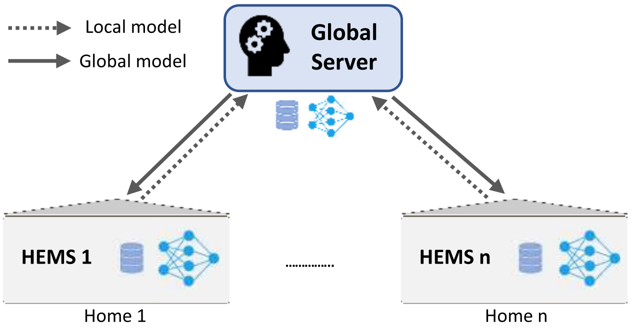

FIGURE 10. Federated reinforcement learning in coordinated HEMSs.

8) ENVIRONMENTAL ISSUES

Several papers have discussed environmental issues without considering any related terms in their cost functions that can represent the relationship between environmental indexes and coordination. For example, it is possible to model the environmental index related to CO2 emissions as a tax and add it to electricity prices or cost function. Environmental issues should be considered in cost functions designing. In the literature, few studies have dealt with environmental indexes in HEMSs coordination problem.

9) BLOCKCHAIN TECHNOLOGY

A blockchain is an updated list of blocks that are connected by cryptography in a decentralized network [153]–[155]. Each block saves data about transactions, participants, and hash code (to be distinguished from other blocks). The blockchain technology can be used to secure SHs data transmission/storage in HEMSs coordination. A blockchain stores data in a decentralized computer network instead of a central database. This, in turn, leads to secure, private, anonymous, and efficient transactions. A blockchain structure of coordinated HEMSs has been illustrated in Fig. 11. In HEMSs coordination through a distributed structure, two types of blockchains are required to ensure data safety and protect consumers' information. First, the coordinator private blockchains save information of each SHs such as consumption profile and consumer behavior. Second, the aggregator consortium blockchains save searchable indexes. Private and public information of each neighborhood are recorded by the server. The public data creates a public index, and private data is encrypted and generates a secure index. The information is transmitted to the corresponding coordinator private blockchains. The searchable indexes are transmitted to the aggregator consortium blockchains. It should be noted that SHs can use public information as a database. This provides a good starting point for discussions and further researches on using blockchain technology in coordinated HEMSs.

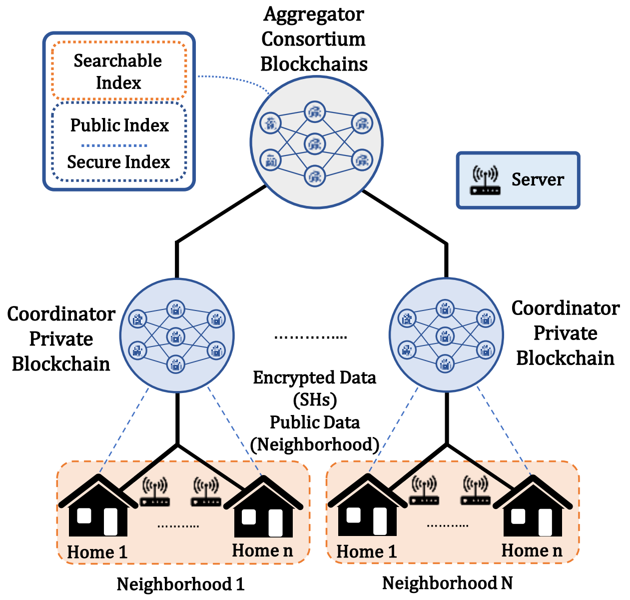

FIGURE 11. Blockchain technology in coordinated HEMSs.

B. PLAYERS CONCERNS

1) PARTICIPANTS' PRIVACY

Sharing data between coordinated HEMSs causes privacy to become an essential challenge of coordination in neighborhood areas. Actually, coordination mechanisms for improving utilities and end-users' benefits while maintaining privacy standards have not been fairly taken into consideration. Innovative coordination approaches can compromise between privacy concerns and coordinated HEMSs operations. From our perspective, coordination techniques based on distributed topologies with partial data sharing can be utilized as a possible solution to guarantee consumers' privacy. Another creative solution for this concern is to use a federated reinforcement learning (FRL) method by developing distributed deep reinforcement learning models [151]. In this approach, the coordinator server and SHs exchange global (neighborhood) and local models. The HEMSs coordination based on FRL ensures consumers' data privacy and decreases the amount of exchanged data. Moreover, the blockchain technology can be adopted for data transmission to ensure neighborhood data integrity and security [152], [153], [155]. Further works are certainly required to investigate the suggested solutions to guarantee consumers' privacy.

2) FAIRNESS IN COORDINATION

Fairness is another issue of coordinated HEMSs that needs more attention. Homes receive rewards or penalties from coordinator, aggregator, or utility for their teamwork under a coordination scheme. Therefore, it is necessary to fairly share these rewards or penalties between agents. The fairness can be achieved through a mechanism that is capable of measuring the effort of each home for coordination regarding the others. However, designing a fair structure is challenging because of complications related to quantifying the efforts and defining a common goal, and it needs further investigation.

3) INDIVIDUAL AND SOCIAL GOALS

Realizing a compromise between individual and social goals for every home cost function is a crucial research gap in coordinated HEMSs. Generally, users utilize individual and coordination indexes to prioritize personal and social terms. Accordingly, a HEMS must decide on the term that should have priority according to user participation level in coordination. An adaptive decision-making process can be utilized that is updated based on approaches like multi-level optimization, in which the upper-level revises information and goals. Indeed, defining applicable individual and coordination indexes for each cost function of coordinated HEMSs needs more analysis.

4) HOMOGENEOUS AND HETEROGENEOUS SHs

The coordination problem can be exercised in homogeneous and heterogeneous neighborhood areas. However, coordination between heterogeneous consumers is more complicated than homogeneous ones. For example, agents with different sizes (big and small) or diverse dynamics (slow and fast) are difficult to coordinate. These differences can influence fairness between agents. Although small consumers demand a lower amount of energy, their efforts at coordination can be higher than big users. Thus, achieving a fair mechanism for heterogeneous HEMSs is complex and needs more exploration.

5) IMPLICIT AND EXPLICIT COORDINATION

Implicit and explicit coordination refers to the level of information that is broadcast by agents. In fact, agents can either hide data or share it completely or partially. These categories of coordination should be studied in future works as they have not been investigated in the related surveys including this one. To be precise, no study has examined the impact of implicit and explicit coordination on costumers' decisions, electricity bills, and aggregated demand profile flatness.

6) UNTRUTHFUL STATEMENTS BY SHs

Untruthful statements in shared information between agents is another concern about coordinated HEMSs that require more research. Indeed, agents possess private information and thus, they can intend either untruthful statements (explicit deception) or information revealing actions (implicit deception) [156]. Consequently, analyzing possible solutions to deception is an important matter for coordinated HEMSs.

C. IMPLEMENTATION PREREQUISITES

1) FEEDBACK MECHANISM

A feedback mechanism is necessary to ensure that HEMSs follow the coordination plan. This mechanism examines the degree of each home to pursue planned actions. However, a system that can examine the inverse procedure, which is the effect of not following planned actions on coordination and decision of other agents, has not been studied. Moreover, it is challenging to find a clear relationship between agents' decisions or social goals. Consequently, designing a feedback mechanism can help to avoid this issue. In addition, it might prove an important area for future research.

TABLE 5. The summary of research gaps and future opportunities for HEMSs coordination in four categories: Concerns in coordination process, Players concerns, Prerequisites, and Mathematical issues.

Categories	Challenges / Potentials	Recommendations / Knowledge gaps / Benefits
Concerns in coordination process	Coordination topology and technique regarding existing neighborhood structure	i) Using distributed topology and coordination techniques based on C-ADMM and ALADIN, ii) Implementation of HEMSs coordination based on these algorithms need more investigations
	Optimization levels in coordinated HEMSs through distributed topology	i) Between aggregator and coordinator (negotiation), ii) Between coordinator and HEMSs (coordination), iii) Optimization inside each HEMS, iv) Further works are required to study negotiation and coordination
	HEMSs cooperative learning	i) Concentrating on neighborhood challenges not individual ones, ii) Considering objective of each SH with respect to others, iii) Useful for modeling neighborhood consumption, designing price policies, and handling neighborhood challenges, iv) Few researches studied cooperative learning for HEMSs coordination
	Robust HEMSs coordination	i) Fully-distributed topology, ii) Using neither a central entity nor a coordinator, iii) Fully-distributed HEMSs coordination based on APP, PMP, C+I, and OCD
	Federated reinforcement learning	i) Taking account of time-varying operation conditions in neighborhood by RL, ii) Creating the global model based on the SHs local models by global server , iii) Ensuring consumers data privacy, iv) FRL-based HEMS coordination may constitute the object of future studies
	Blockchain technology	i) Storing data in a decentralized network, ii) Leading to secure, private, anonymously, and efficient transactions, iii) Sharing public information with SHs as a database (data such as neighborhood power consumption), iv) Provides a starting point for further researches on using blockchain technology in coordinated HEMSs
	Neighborhood uncertainty	i) Utilization of stochastic and probabilistic approaches, ii) Modeling neighborhood demand by probabilistic load estimation, iii) Modeling the RESs uncertainties by uncertainty sets
	New assets in neighborhood	i) Considering future neighborhood assets such as RESs, EVs, and ESSs in coordinated HEMSs, ii) SHs coordination by load scheduling, iii) SHs coordination by energy trading
	Considering environmental issues	i) Modeling environmental index like a tax in electricity prices or cost function, ii) Few studies have dealt with environmental indexes in coordinated HEMS
Players concerns	Privacy of participants	i) Using coordination techniques based on distributed topologies with partial data sharing, ii) Employing FRL-based HEMS coordination for ensuring consumers data privacy and reducing exchanged data, iii) Satisfying neighborhood data integrity and security by applying Blockchain technology iv) Further works are required to guarantee consumers' privacy.
	Fairness in coordination	i) Sharing rewards or penalties fairly between SHs, ii) In future researches, designing a mechanism is necessary to measure the effort of each SH in coordination regarding other neighbors
	Defining individual and social goals	i) Utilization of individual and coordination indexes in cost functions to prioritize personal and social goals, ii) Adaptive decision-making by using machine learning or a multi-level optimization
	Heterogeneous SHs	i) Realizing a fair mechanism for heterogeneous HEMSs is complex and need more exploration
	Implicit and explicit coordination	i) Performing more investigation into the impact of hiding data or sharing it completely or partially on costumers' decisions
	Untruthful statement by SHs (explicit or implicit deception)	i) Designing a mechanism for avoiding deception ii) Conducting more exploration
Prerequisites	Test-benches and database	i) Creating databases leads to valuable research on HEMSs coordination, ii) Easing the usage of powerful tools like machine learning in HEMSs coordination
	Feedback mechanism	i) Ensuring that HEMSs follow the mapped coordination plan
	Other prerequisites	i) Prices, legislation, trading rules, and standardization of technologies
Mathematical issues	Guarantee of coordination convergence	i) Choosing proper convergence rate ii) Ensuring the convergence by using quadratic and convex terms
	Convex cost functions	i) Ensuring algorithm convergence, ii) Modeling objectives by convex functions

2) TEST-BENCHES AND DATABASES IN COORDINATED HEMSs

The shortage of data and test-benches for coordinated HEMSs studies can be attributed to the lack of proper databases. The rules regarding privacy rights and confidentiality agreements aggravate the situation and make it more challenging to use consumers' data for creating a database. A suitable process for constructing proficient databases is an essential prerequisite for conducting valuable research on neighborhood areas coordination. An efficient database provides the opportunity to use powerful tools such as machine learning for HEMSs coordination analyses. The benefits of proficient databases warrant further works for making one.

3) OTHER

It should be noted that prices, legislation, policies, especially on privacy and trading rules between prosumers and consumers as well as standardization of technologies are other major concerns about coordinated HEMSs implementation.

D. MATHEMATICAL CONCERNS

1) COORDINATION CONVERGENCE

The convergence rate of coordination algorithms is another challenge that should be considered in future studies. One of the critical issues related to an algorithm convergence is the required number of iterations, particularly for on-line applications with limited processing time. Normally, quadratic terms are employed to enhance the convergence rate since they are powerful to convexify a coordination problem.

2) CONVEX COST FUNCTIONS

It is necessary to formulate the coordination problem by convex objective functions to ensure the convergence of a solution. Convex optimization in coordinated HEMSs needs more investigation [157]. The cost function should have an innovative design to represent coordination goals and satisfy convexity.

Table 5 summarizes the above discussion and provides an overview of research gaps and future opportunities for HEMSs coordination.

VII. CONCLUSION

The growing presence of selfish HEMSs in neighborhood areas causes undesirable effects such as rebound peaks, instabilities, and contingencies. The concept of coordinated HEMSs is recommended for avoiding these effects and fulfilling local objectives such as flattening neighborhood aggregated load profiles and decreasing consumers electricity bills. Other applications of HEMSs coordination are facilitating energy trading, diminishing reverse power flow, managing distributed energy resources, and modifying consumers' consumption/generation patterns. This concept has recently become a research hot-spot in the smart grid due to its potential for mitigating grid stress without significant investments. This paper has surveyed the latest researches on HEMSs coordination. It has classified the various coordination topologies, techniques, and their applications. This work has classified and analyzed coordination techniques according to their utilization of decomposition concepts. The main features, advantages, and disadvantages of the methods have been highlighted. Research gaps and future opportunities have been clarified over the coordination process, players' concern, implementation prerequisites, and mathematical issues. From our standpoint, coordination techniques based on distributed topology are the best fit for neighborhood areas' architecture. Furthermore, coordination algorithms based on C-ADMM and ALADIN are competent to design a coordinated HEMSs with distributed topology. The distributed HEMSs coordination simplifies the computations, increases the processing speed, satisfies data privacy requirements, guarantees cyber-security standards, and increases the neighborhood robustness. Results have proven that the consumer and the service provider are benefited through HEMSs coordination. The reported results show electricity bill reductions between 5% and 30%. This systematic review can assist researchers with conducting practical analyses on HEMSs coordination.

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