Comprehensive Overview of Multi-agent Systems for Controlling Smart Grids

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***Abstract*—Agents are intelligent entities that act flexibly and autonomously and make wise decisions based on their intelligence and experience. A multi-agent system (MAS) contains multiple, intelligent, and interconnected collaborating agents for solving a problem beyond the ability of a single agent. A smart grid (SG) combines advanced intelligent systems, control techniques, and sensing methods with an existing utility power network. For controlling smart grids, various control systems with different architectures have already been developed. MAS-based control of power system operations has been shown to overcome the limitations of time required for analysis, relaying, and protection; transmission switching; communication protocols; and management of plant control. These systems provide an alternative for fast and accurate power network control. This paper provides a comprehensive overview of MASs used for the control of smart grids. The paper provides a wide-spectrum view of the status of smart grids, MAS-based control techniques and their implementation for the control of smart grids. Use of MASs in the control of various aspects of smart grids—including the management of energy, marketing energy, pricing, scheduling energy, reliability, network security, fault handling capability, communication between agents, SG-electrical vehicles, SG-building energy systems, and soft grids—have been critically reviewed. More than a hundred publications on the topic of MAS-based control of smart grids have been critically examined, classified, and arranged for fast reference.**

***Index Terms*—Coordinated control, multi-agent systems, renewable energy sources, smart energy infrastructure, smart grid.**

I. INTRODUCTION

DEVELOPMENTS in the field of grid-connected renewable energies from solar and wind power sources, as well as recently introduced loads such as electric vehicles and heat pumps, are assumed to pose great trials for global electricity power networks [1].

The essential solution is to upgrade the existing power system infrastructure into an intelligent electricity grid known as a Smart Grid (SG). It is regarded as a novel form of power grid that incorporates smart metering infrastructure and has the capability of sensing and measuring the consumption of power using a combination of pioneering information and communication technologies, and encompass energy production and delivery [2], [3]. There are many novel features in smart grids and they cover wide fields such as demand response (DR), renewable energy sources (RES), vehicle to grid capability, microgrid, advanced metering, two-way communications, and so on [4]. The smart grid is also a new area for the implementation of new functions of analysis, control, instrumentation, and protection. Its main objective is to increase the power grid efficiency to reduce carbon emissions, to limit the development of the power network to improve the security and reliability, and to explore markets [5], [6]. Many smart grid techniques and algorithms have been described in literature. Real *et al.* [7] presented an extended distributed model predictive control (DMPC) structure and its applications in a smart grid with the help of a case study, to solve a combined environmental and economic dispatch problem. A smart home test bed to perform the journey from a conventional power system to modern day smart grid has been reported in [8]. Chanda *et al.*, [9] suggested an optimization model for maximizing social welfare by standardizing the operating conditions with an overall enhancement of dynamic stability of power markets, keeping in mind the communication technologies in smart grid. The role of users in the demand side management of smart grids with the help of a smart design has been presented in [10]. A direct load control (DLC) method based on multi-objective particle swarm optimization algorithm used for load control in smart grids has been reported in [11]. Karimi *et al.* [12] presented a study of the smart meter message concatenation problem for efficient concatenation of multiple small smart metering messages reaching data concentrator units to reduce protocol overhead, resulting in network utilization. A

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wide-area measurement-based, dynamic, stochastic, optimal power flow control algorithm using adaptive critical designs to achieve a high penetration level of intermittent renewable energy into the smart grids has been proposed by the authors in [13]. Milioudis *et al*. [14] presented a method that deals with the exact location of high impedance faults in the smart grids. A comparative analysis of tertiary control systems for smart grids using the flex street model has been reported in [15].

MASs have drawn attention for utilization in many real-world applications from mobile robot group coordination to unmanned aerial vehicle formations. In the past ten years, MASs have drawn the attention of researchers due to the possibility of their potential applications in different fields like biology, physics, system engineering, control systems, smart grid, etc. [16]. Extensive literature has been reported on use of the concept of MASs in various fields [17]. Jing *et al*. [18] presented two non-smooth leader-following formation protocols for non-identical Lipschitz nonlinear MASs with directed communication network topologies. Collision-free consensus problem in an agent network single-integrator dynamics has been reported in [19] and [20]. Wu *et al*. [21] investigated the distributed exponential consensus of stochastic delayed MASs with nonlinear dynamics under asynchronous switching. Implementation of context-aware workflows with MASs is reported in [22]. The concept of MASs has also been applied in the field of smart grids and researchers are exploring their broad use in this field.

Recently, improved intelligent evolutionary algorithms supported by MAS have been explored for smart grid scheduling to save costs. Wang *et al*. [23] introduced an algorithm for the economic load dispatch problem of a large-scale hydropower station using multi-agent glowworm swarm optimization (MAGSO). A detailed study on MASs for allocation of resources and scheduling in a Smart Grid is available in [24]. MASs have been used to decentralize the traditional centralized resource allocation in the smart grid. In [25], the authors introduced an algorithm for non-convex economic load dispatch in smart grids using distributed pattern search algorithm (DPSA).

This paper presents a comprehensive review on the topic of MASs for control of smart grids, and is of relevance to researchers, engineers, designers, and manufacturers working in the field of smart grids. Over 120 publications [1]–[126] are critically reviewed and classified into five categories. The first category [1]–[25] is based on the general concepts of smart grids and MASs. The second category [26]–[49] focuses on the smart grid concepts, technologies, and standards. The third category [50]–[70] deals with architecture and agents used in MASs. The fourth category [71]–[78] covers the intelligent agents used in smart grids. The fifth and final category [79]–[128] deals with the implementation of MASs in smart grids. Figure 1 depicts the pie-chart indicating the share of each the above-mentioned topics in the present review of MASs for control of smart grids.

This paper has seven sections. After the introduction in Section I, the general concepts of smart grids and their standards as well as smart grid technologies are described in Section II. Section III presents MASs and related works reported in literature. Multi-agents that have been used in smart grids are covered under Section IV. Implementation of the concept of MASs into the smart grid has been detailed in Section V. The future scope of research on application of MASs for future smart grid development has been provided in Section VI. Finally, Section VII concludes the review.

II. SMART GRID

The smart grid is a combination of information technology, communication technology, and power system engineering, to provide an efficient and robust power system [26]. A smart grid is basically an intelligent electrical network deployed to improve efficiency, reliability, sustainability, security, and flexibility of the electrical power network by making it automated, observable, controllable, and fully integrated. This grid has a digital structure, different types of sensors, and two-way communication, is self-monitoring, provides pervasive control, and self-healing capabilities, supports remote checks, remote tests, and distributed generation, and has a variety of customers [27].

A. Smart Grid Architecture

The architecture of the smart grid with respect to the energy and applications has three components, namely, power generation, transmission, and distribution, as illustrated in Fig. 2 [28]. Different aspects of the smart grid are described

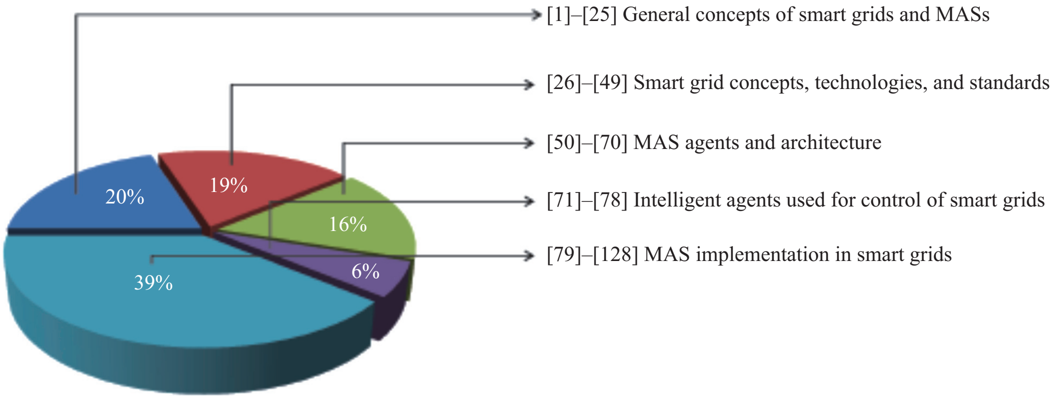

Fig. 1. The pie-chart of topics reviewed in literature, and their share in the present review of MAS-based control of smart grids.

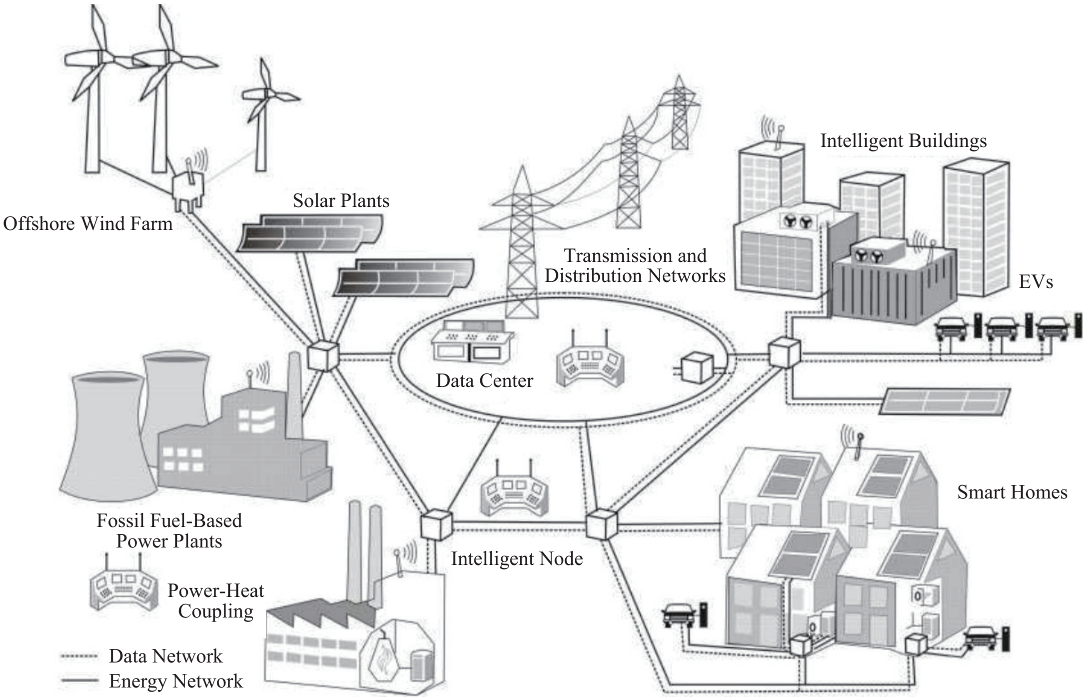

Fig. 2. Smart grid architecture with all components.

in Fig. 3 [29]. Solutions for smart grid aspects that use a MAS are included in Fig. 3, and have been discussed in this paper. Smart power production is related to forecasting demand and controlling power generation with the objective of decreasing costs while satisfying the demand for energy at load plants and consumers [30]. To achieve smart control of the smart grid, the distributed energy sources (DGs) are integrated and operated jointly with a capacity similar to conventional generators within the concept of virtual power plants (VPP) [31]. The smart grid enables the integration of DGs at transmission and distribution layers. Hence, these layers require high power reliability and efficiency for which static VAR compensator (STATCOM) is widely used [32]. A conventional power generation system includes centralized power generators with unidirectional power flows from these centralized plants to loads. There is weak market integration in a conventional system. In a smart generation system, the distributed power generation is integrated in addition to the centralized generators. Storage and electricity vehicles are also integrated into the grid. Further, generation is managed according to the actual demand using forecasting techniques. Smart grids can be characterized using controlled generation looking at demand and multi-directional power flow [29].

Integrating existing transmission-distribution utilities into the smart grid requires the digital platform to cope with communication protocols. It provides increased controllability, data management, and flexibility [33]. Smart energy infrastructure includes a microgrid with renewable energy sources (RES), hydrogen energy, energy storage systems, smart home, and interaction with electrical vehicles known as grid-to-vehicle (G2 V) and vehicle-to-grid (V2G). They include individual customer DGs such as combined heat and power (CHP) sources, fuel cells, and RES at the distribution level [34].

B. Smart Grid Standards

The definitions of the smart grid formulated by organizations such as the Institute of Electrical and Electronics Engineers (IEEE), International Electro-Technical Commission (IEC), European Technology Platform (ETP), and National Institute of Standards and Technology (NIST) have widely been adopted in practice [35]. IEEE 1547 standards provide the standard technical requirements for the integration of DG sources to the smart grid. Recently the following newer standards have been introduced [36]:

- **IEEE-1547.1**: Standards for conformance test procedures for equipment interconnecting distributed resources with an electric power system.
- **IEEE 1547.2**: An application guide for IEEE-1547 standard for interconnecting distributed resources with an electric power system.
- **IEEE-1547.3**: Draft guide for monitoring, exchanging information, and controlling distributed resources interconnected with the electric power system.

C. Smart Grid Deployment in Existing Grids

Using a smart grid in large countries such as India requires large investment in terms of technical foundation and in human resources. It also takes a long time, in the order of decades, to be fully realized.

The evolutionary process for the deployment of the smart grid is depicted in Fig. 4 [27]. A present-day grid is transformed into a smart grid by deploying a communications system, advanced control system, electric vehicles, energy storage, smart energy management schemes, etc. A smart grid deployment methodology using fuzzy logic based on the priority factor has been proposed by the authors in [37]. The

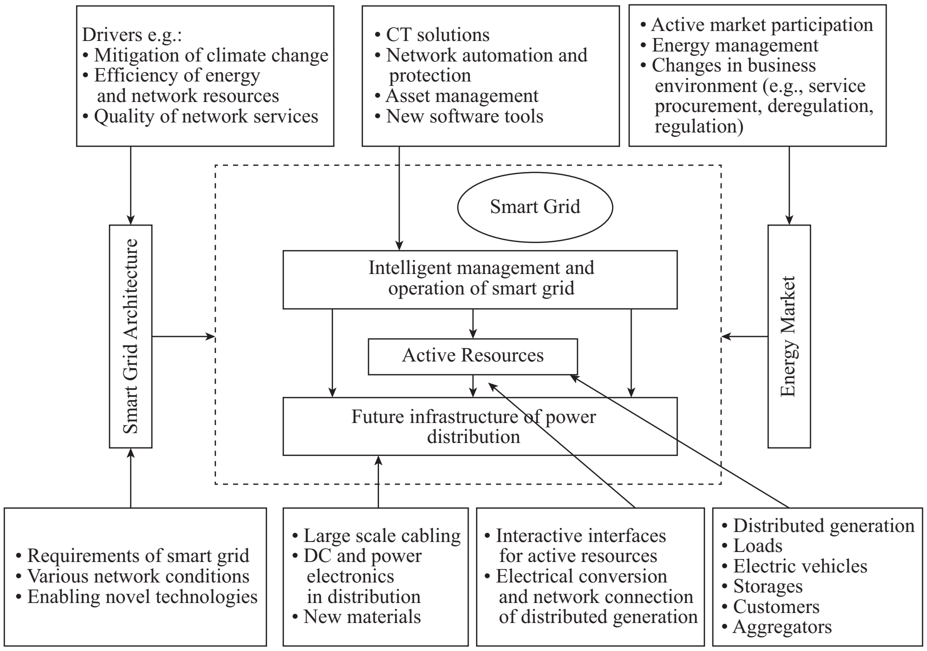

Fig. 3. Different aspects of smart grid [29].

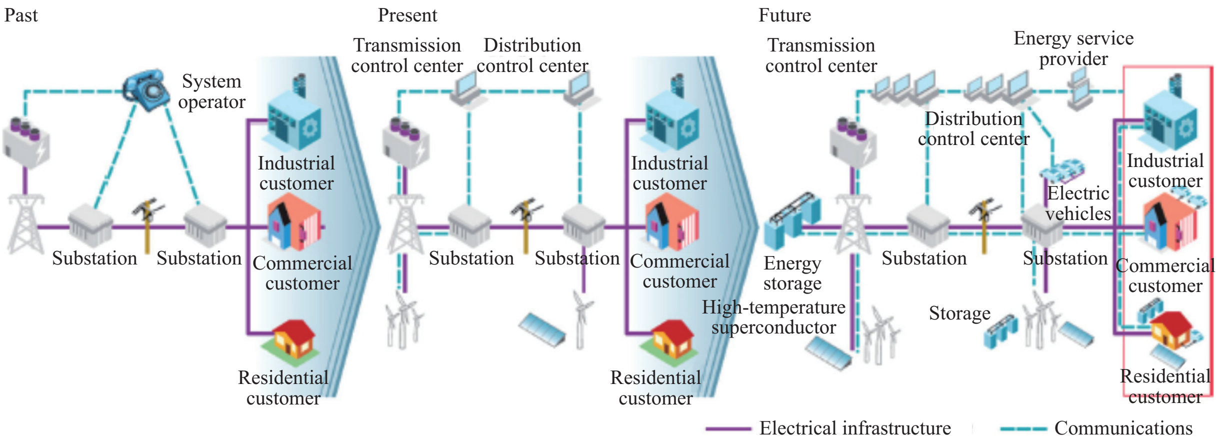

Fig. 4. The process of smart grid deployment [27].

use of particular variables for smart grid deployment needs an evaluation of electrical system conditions wherever promotion to smart grid environment is under consideration.

D. Related Research Work

A volume of work is reported on the various aspects of the smart grid. An overview of smart grid concepts is presented by the authors in [38]. Tenti et al. [39] presented a conservative power theory, which provides a suitable control of smart microgrids to meet out characterization needs. This also provides the ground for developing cooperative control methods for distributed switching power processors and static reactive power compensation devices. An information flow security properties-based confidentiality model that can mitigate event confidentiality violation in smart grids has been proposed by the authors in [40]. This algorithm has been tested on various physical systems including the IEEE-118 bus test system. A detailed study of development in the field of smart grid technologies has been provided in [41]. Irfan *et al.* [42] introduced two protocols to address data-prioritization and delay-sensitive data transmission for wireless sensor and actor networks (WSANs) that are used for smart grid communication. These protocols are based on the delay response cross-layer (DRX) and fair and delay response cross-layer (FDRX) data transmission schemes, respectively. A prioritized traffic-scheduling procedure considering the heterogeneous characteristics for cognitive radio communication-based smart grid system according to the different traffic types, such as multimedia sensing data, control commands, and meter readings, has been reported in [43]. Zhou *et al.* [44] proposed an optimal power allocation design for downlink capacity in a heterogeneous home area network (HAN) with application in a smart grid using beamforming to the smart meter. A thorough overview of routing protocols for smart grid applications with the critical analysis of their advantages and potential limits has been presented in [45]. An online load scheduling approach, for mitigating price prediction error impact and constraints, which are temporally coupled in smart grids, has been proposed by the authors in [46]. A system of energy expenditure management for the heterogeneous demand of smart grids based on queuing has been proposed in [47]. Ding *et al.* [48], developed a comprehensive real-time interactive structure for smart grid customers and utilities, which ensures grid stability and quality of service. A virtual ring structure capable of privacy protection by symmetric and asymmetric encryption of customer requests in the smart grids has been proposed in [49].

An in-depth study of different concepts related to smart grids has been carried out based on critical reviews of the publications [26]–[49]. Various variables required to be evaluated in a smart grid have been illustrated by Table I. The demand side management (DSM) benefits of customers, the utility, and society with respect to the smart grid are illustrated in Table II. A comparative study between the traditional power grid and the smart grid has been provided in Table III. An overview of control strategies adopted in smart grids has been illustrated in Table IV. The intelligent automation functional elements to be considered in the design of smart grids have been illustrated pictorially in Fig. 5. The benefits and drawbacks of important communication technologies deployed in smart grids are listed in Table V.

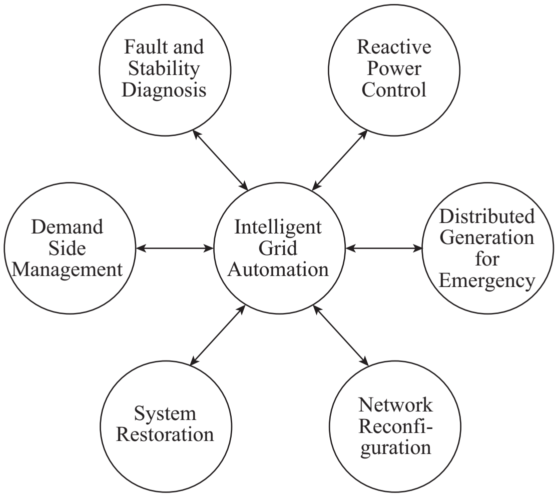

Fig. 5. Smart grid intelligent automation functions.

III. III. Concept of Multi Agent System

A multi-agent system (MAS) is a system consisting of two or more intelligent agents; it is linked to the subject of distributed problem-solving. A MAS does not have any general system goal but has local goals to be achieved by the individual agents separately.

A. Intelligent Agents

The overall goal of the system can be realized by the involvement of MASs with local goals [50]. Intelligent agents are used to solve a problem collectively based on the behavior implemented by each agent. They work together and exchange information to achieve the targeted solution. An agent receives its environment sensor inputs and accordingly generates an output action. The agent-environment interaction is a cyclic interaction between the two. It can be represented as Agent → Environment → Agent. Sensory input is taken by the agents from their environment, and they produce output actions that affect the environment. It is also possible to design an autonomous system with the help of agents that has properties such as resilience, robustness, and fault tolerance. Communication between agents is the most important part that helps to achieve the targeted solution [51]. Intelligent agents should have the following features [52]:

- **Autonomous**: They exercise partial control of their internal state and actions. They influence system outputs without the interference of people or any external means.
- **Reactivity**: They have the capability of timely reaction to all environment changes. They also take action based on these changes and achieve the targeted functions.
- **Pro-activeness**: Intelligent agents exhibit dynamically changing behavior, which is directed to achieve the targeted goals. The pro-activeness of an agent may be defined as its ability to take the initiative.

TABLE I
Variables Used for Smart Grid Deployment [37]

Conditions of electrical systems	Indicators (Variables)
Technical features	Importance of supplied load. Power factor of the system. Level of technical and non-technical losses. Load factor of the system. Electric system infrastructure. Telecommunication infrastructure. Failure rate. Integration potential of DG sources. Deployment potential of energy efficiency programs. Life time of assets. Technical sources of operation and maintenance. System load level.
Economic characteristics	Invoicing of electrical system including the delivery cost as well as cost of maintenance and operation.
Installation Location	Underground installation. Distance from research and center of operation. District of growth prediction. District of government-social policies. Regions of historical relevance or tourist towns. Nearby natural resources. Being of interest to large companies. Districts with difficult climatic conditions.
Human resources	Availability of skilled professionals. Technical persons having in depth knowledge in the area and possessing the capabilities for training in the area.
Environmental condition	Energy sources of fossil fuel. Environmental incentives program. Districts with potential of weather disasters impacting electric systems.
Possibility of partnership	Electric utilities. Telecommunications operators. Research institutions. Manufacturers of equipment and software developers.
Socioeconomic conditions of consumers	Human Development Index of the community. Purchasing power of the community. Records of involving in community projects. Districts with progress of social programs. Community bonds for new services.

TABLE II
DSM BENEFITS TO THE UTILITY, SOCIETY, AND CUSTOMERS

Utility	Society	Customer
Lower cost of service	Reduced environmental degradation	Satisfy electricity demand
Reduced capital cost	Conserve resources	Reduced costs
Improved operating efficiency	Protect global environment	Improved lifestyle
Flexible operation	Maximum customer welfare	Improved value of services

TABLE III
COMPARISON BETWEEN TRADITIONAL GRID AND SMART GRID

Traditional Power Grid	Smart Grid
Centralized power generation	Distributed power generation
One-way communication	Two-way real time communication
Radial networks are dominant	Dispersed networks are dominant
Mechanical technology dominated	Digital technology dominated
Small number of sensors in the network	Large number of sensors and monitors
Slow response to emergencies	Fast response to emergencies
Manual control is dominant	Automatic control
Less data involved	Large volume of data involved
No storage system	Storage systems are used

- **Social ability**: They have the ability of negotiation and interaction while cooperating with other agents, devices, and humans to set their actions and fulfill their goals.

B. Multiple Agent System Architecture

The cooperative control of MASs has drawn attention of researchers working on control theory and applications for the last two decades due to their potential applications in many areas such as unmanned aerial and underwater vehicles, collision avoidance, scheduling of automated highway systems, distributed optimization of multiple mobile robotic systems, flocking of mobile vehicles, etc. [53]. A basic architecture of MAS can be broadly classified into three categories. These are centralized, distributed, and hierarchical architectures. The third category may be further classified as two-level and hierarchical architectures [52].

Centralized structure is via the control of agents by one control center, as in a relationship between a master and slave. The agents may be homogeneous and non-communicative in nature [54]. The distributive structure is defined by a group of agent intercommunications handled via a single-layer control structure [55]. In the hierarchy architecture, some of the agents have authority over the other agents [56].

C. Related Works

The MAS concept has been implemented in different industrial processes. This subsection outlines MAS-based control of different systems reported in literature. Consensus control of MASs has attracted the attention of the control community in the recent past due to broader use of these systems in civil and military applications. It has been used for the establishment of control over a fleet of surface vehicles, in wireless sensor networks, and in robot-based systems [57]. Various aspects about the consensus of MASs have been reported in literature. Huang *et al.* [58] investigated the problem of distributed average consensus over general directed digital networks with limited data transmission rate in the communication channels. A distributed dynamic encoding and decoding scheme with a finite-level uniform quantizer has been used for the communication between the agents. The distributed

TABLE IV
CONTROL STRATEGIES USED IN SMART GRIDS

Control Strategies	Features	Complexity	Communication type and expense
Centralized control	Control signals	High for controller	Two/one way
	Decision by high-level controller	Low for controlled object	High
Control of price	Generated by high-level controller & sent to units	Relatively high for controller	One way
	Low-level units do not need to respond	Low for controlled object	Low
Transactive control	Low-level units' response is with power scheduling	Low for controller	Two-way
	The price is generated and sent by high-level controller in multiple iterations	Quite high for controlled object	Relatively high

TABLE V
BENEFITS AND DRAWBACKS OF COMMUNICATION TREND APPLIED FOR SMART GRIDS

Communication Technology	Advantages	Disadvantages
Power line communication (PLC)	Wide communication infrastructure is already available Lower operation and maintenance costs	Significant interference of channel and signal loss Complex routing Disruptive effect due to appliances
Digital subscriber line (DSL)	Wide communication facilities already available Most widely distributed broadband	Not suitable for long distance networks Operators charge more to utilities that use the networks
Fiber optic	Far-distance communication Ultra-high bandwidth Robustness from electromagnetic and radio interference	Costly installation Costly terminal equipment Not suitable for upgrading/metering
Wireless personal area network (WPAN)	Low power consumption Low deployment cost Ipv6-based network compatibility	Limitation for building large networks Low bandwidth
Worldwide interoperability for microwave access (WiMAX)	Supports huge group of users concurrently Long distance communication is possible Channel bandwidth connection-oriented control	Licensed spectrum required High cost of terminal equipment Network management is complicated
Global system for mobile communications (GSM)	Open industry standards Supports millions of devices Terminal equipment low power-consumption User flexibility and suitability	Costly use of service-provider networks Increased cost due to network being licensed
Satellite	Highly reliable Long distance communication possible	High latency High cost of terminal equipment

protocols parametrized by scaling function, control-gain, and several levels for quantization have been designed and detailed in mathematical models. The essential and comprehensive requirements of consensus ability concerning the admissible agreement protocols for the descriptor MASs with determined agents and topology, as specified by general linear-time-invariant systems, have been detailed in [59]. Wen *et al.* [60] investigated the consensus of second-order MASs without the measurement of states of velocity of the agents. These can be either a double integrator or a harmonic oscillator. The authors proposed a distributed observer-based protocol for solving the second-order consensus problem of MAS with/without delay by utilizing the position information of agents. A leader-following consensus problem for a MAS with directed-communication topology and nonlinear dynamics has been dealt with by the authors in [61]. The controlling input of the leader agent is supposed to be unknown to its following agents. A distributed nonlinear adaptive control that solves the problem of leader-following consensus by using the relative state information among adjacent agents has been proposed in this paper. A study considering the observer-based consensus tracking problem of linear MASs with saturation of input has been presented in [62]. In this study, an adaptive consensus protocol using just the dynamics of an agent with the relative output of its neighboring agents has been proposed. This protocol is fully distributed and is also independent of any global information. Ma *et al.* [63] presented a study of the consensus problem of nonlinear MASs with control gain error. The consensus of a category of nonlinear MASs has been realized with assistance of impulsive consensus conditions using the algebraic graph, impulsive differential equations, and Lyapunov stability theories. Jin *et al.* [64], presented a distributed adaptive iterative learning control for controlling high-order nonlinear MAS under non-parametric and parametric system uncertainty alignment condition.

A discussion of research work related to control design of linear and nonlinear architecture of MASs using artificial intelligent and neural network-based techniques follows. Shahvali *et al.* [65] proposed a distributed neural-network-based adaptive control of stochastic nonlinear MASs possessing feedback design. This study deploys a radial-basis feed-forward neural network for approximating nonlinear functions with uncertainty, while a linear observer is used to account for unmeasured states. Using the common Lyapunov function for guaranteeing the switching stability of a MAS network with unbalanced describing graphs and bidirectional communication links, has been given in [66]. In [67], the authors present a technical note on the adaptive cooperative output arrangement for a variety of nonlinear MASs.

In this study, a distributed adaptive control rule with multiple functions of Nussbaum-type is outlined, in which the closed-loop system achieves global stability, and each agent tracks a class of prescribed signals asymptotically. Peng *et al.* [68] investigated the problem of cooperative controlling high-order nonlinear uncertain MASs on a directed graph, which has firm topology. The problem to track and control a networked MAS with impulsive influences and multiple delays has been examined by the authors in [69]. These results have been applied to mechanical robotic systems. Fu et al [70] proposed a four observer-based distributed controller for general linear MASs to achieve finite time-coordinated tracking under different situations. Numerical simulations have also been provided for illustrating the effectivity of the proposed controllers.

A summary of MAS architectures based on detailed study and critical reviews of the publications [50]–[70] has been provided in Table VI.

IV. MULTI AGENTS IN SMART GRID

The regular performance of the power system depends on the control structure. This comprises software and hardware protocols to exchange control/status signals. In a modern power system, this is performed by a SCADA (supervisory control and data acquisition) system [71]. A smart grid integrates various types of generators and loads. Therefore, it requires fast and advanced sensing, control, and communication technologies. A MAS that stands a few steps ahead of the SCADA is used to manage the grid. It is used as a development tool and helps the designers to create sophisticated supervisory and control applications for the smart grid.

A. Smart Grids and MAS

Smart grid intelligent agents are classified into two groups. One group includes the agents embodying the management of energy, marketing of energy, and pricing and scheduling of energy, whereas, the other group focuses on efficiency, reliability, network security, fault-handling, etc. These agents are designated based on their function in smart grids such as Distributed Resource (DR) agents, consumer agents, device agents, intelligent response control agents, intelligent prevention control agents, and graphical user interface (GUI) agents [72]. Unified-energy agents are the base for the systematic advancement of energy grids of the future. Their

TABLE VI
BRIEF SUMMARY OF MAS ARCHITECTURE

Architecture	Type of Agent	Role of agents
Centralized	Cognitive and reactive	Cognitive agents help in high level decisions and fast communications. The reactive agents give fast response.
Distributed	Local	Discovery of local communications and information.
Two leveled hierarchical	High-level and low-level	High-level agents are responsible for managing infrastructure, low-level agent scheduling, and inter-system communication. The low-level agents accept schedules and assist in managing the assets.
Three leveled hierarchical	High-level, mid-level, and low-level	High-level agents help in the critical decisions as well as in data and policy management. The mid-level agents help in the location of faults in the systems such as smart grids. These agents also help in data and policy management. Low level agents are responsible for sensor management as well as the management of hardware and input/output devices.

classification and structure have been provided in detail by the authors in [73]. An agent of energy is a software system that manages energy expenditure, generation, transformation and energy storage in the smart grids. Their control may be central, distributed, or local. These may be classified depending on the level of integration (IL0, IL1, …, IL5). The possible integration levels of the energy agents in the smart grid, their control topologies, and detailed description are illustrated in the Table VII.

B. Agent-Based Control Structure of Smart Grid

To achieve the coordinated control of the smart grid, the agents work in hierarchical fashion. A detailed architectural study of electricity agents in smart grid markets has been provided in [74]. The intelligent agents used in the smart grids have system for decision-making, input and output interfaces, and system for communication. A seven-layered structure for smart grid agent-based control is provided in Fig. 6. A brief description of each layer is given below [72], [75]:

- Lowest layer includes the component level and load level agents. These are responsible for the task of measurement monitoring, equipment control and load switching.
- Prosumer agents are responsible for coordination between the upper- and lower-level agents. These agents forecast expected energy generation and anticipated demand. These agents make decisions about the purchase or sale of energy from the distribution network.
- DER agents predict future energy pricing based on expected generation by interacting with other DER agents.
- Microgrid agents control the loads and generation units including micro and macro.
- Distribution level agents act as a bridge between the micro grid and the main utility grid through the transmission system organization (TSO) agents.
- TSO agents take important market decisions utilizing the information related to energy demand. They also convey energy requirements to generation plants.
- Main grid agents monitor the complete system status. In the event of any problems that have not been resolved by lower-level agents, the TSO give major decisions to achieve the overall goal.

A distributed secondary cooperative scheme for the current-controlled PWM inverters based on networked MASs with accurate power sharing between the DER units has been provided in [76]. Capriglione *et al*. [77] presented the experimental characterization of consensus protocol for decentralized smart grid metering.

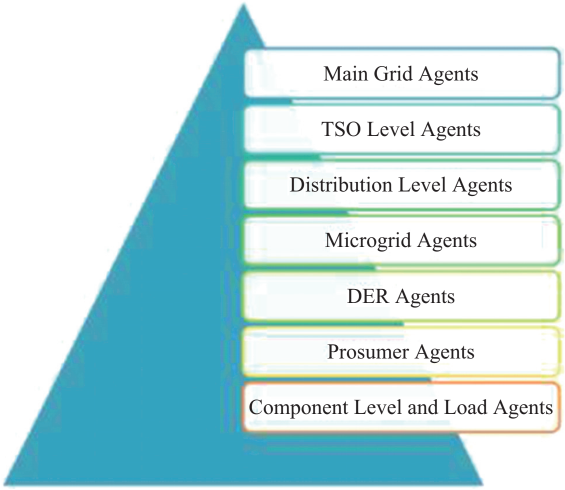

Fig. 6. Seven layered agent-based control structure of smart grid (TSO: transmission system operator).

C. Intelligent Agents and Electric Vehicle Charging System

Intelligent agents play an effective role in the smart charging of electric vehicle charging systems. Unda *et al*. [78] described how to manage battery-charging distribution networks for electrical vehicles by MASs, which are based on three types of agents: electric vehicle (EV), local area, and coordinator agents. The hierarchical architecture of these agents is described in Fig. 7. The EV agent sends the preference to the local area agent. In return, the local area agent sends the charging setpoint. Furthermore, the local area agent sends aggregated EV demand to the coordinator agent. The coordinator agent sends the aggregated demand to the operator of the distribution system. The operator is responsible for distribution network operation within technical limits.

V. IMPLEMENTATION OF MULTI AGENT SYSTEM CONCEPT IN SMART GRID

The increasing employment of smart grid technologies in future power systems, such as automatic voltage regulators, smart meters and sensors will enhance the capabilities of the grid, such as grid optimization, self-recovery, dynamic

TABLE VII
INTEGRATION LEVEL, CONTROL ARCHITECTURE, AND DESCRIPTION OF ENERGY AGENTS IN SMART GRID

Integration Level	Type of overall Control	Description
IL0	Central	This corresponds to the initial development around the 1980 s. Includes Bakelite-ferrite electric meters and some newer versions without information exchange.
IL1	Central	Meters enabling energy usage information transfer. This requires central data analysis.
IL2	Central	Advanced metering systems that have prediction capability. These meters enable the obtaining of energy consumption information with locally aggregated data, with overall centralized control.
IL3	Local and central	Advanced local area controller that can act on the underlying local system and react autonomously to external signals such as price signals, for local optimization.
IL4	Local, central, and distributed	Advanced local area controller that is restricted to its area but independent on the local systems that can dynamically build coalitions, to keep track of optimization goals, e.g., intelligent local power transformers responsible for one network segment.
IL5	Distributed and local	Fully distributed control of energy production, distribution and supply.

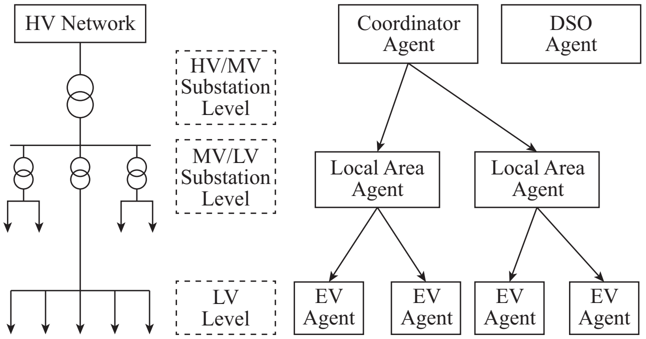

Fig. 7. Intelligent agent hierarchy in electric vehicle charging system (DSO: distribution system operator).

pricing, integration of renewable energy sources, and storage devices [79]. Control of these grids is achieved by upgrading the communication and information systems. MASs play an effective role in the coordinated control of smart grids. This section presents the implementation of MASs to achieve the concept of the smart grid.

A. MAS Architecture for Control of Smart Grids

This section explains in detail the classification of MAS agents according to their application in a smart grid. The architecture and control approaches of MAS for smart grids are also discussed in detail. The classification of the MAS approach in smart grids is illustrated in Fig. 8. In smart grids, the agent-based approach helps in achieving control of the system, meeting technological requirements, information processing, participating in competitive wholesale markets, analyzing electricity consumer behavior, deploying decentralized structures, market integration, and in agent-based decision support [80]. Albana [81] introduced the concept of Link in the smart grid to secure the decentralized operation structure. The Link architecture such as Grid-Link, Producer-Link, and Storage-Link have been used in the proposed architecture in his paper. A MAS for the improvement of transient stability of smart grids, to avoid the loss of synchronous operation in the power system, is introduced in [82]. In [83], a conceptual MAS design is introduced for interconnected power system restoration based on a dynamic team-forming mechanism. The proposed MAS system contains three layers; a proactive layer, a reactive layer, and a social layer as well as two agents, namely bus and coordination agents. The bus agent controls every single bus of the power system. The coordination agent manages the behavior of the bus agents.

Research related to the use of MAS-based approaches in smart grids for management of energy dispatch, unit commitment, reactive power control, security, communication, and improvement of voltage profile, is given in detail in the succeeding paragraph.

Dayong [84], introduced a decentralized multi-agent coalition formation-based energy dispatch mechanism, which enables agents to autonomously find partners via negotiation under determined protocols. This mechanism does not need a central controller or any other global information. A hierarchical distributed structure based on holonic concept for reactive power control in smart grids has been proposed in [85]. Holons can negotiate with each other, change limits and modify their roles. Keith et al. [86] advanced the application of an agent-based decentralized security system using reputation-based trust, peer-to-peer communications, and a data transfer design, to defend against malicious attacks and other Byzantine failures. Fuzzy logic and fuzzy agent-based self-organizing architecture to address voltage control in the smart grids have been proposed in [87]. The distributed agents are treated by a fuzzy-based solution algorithm to classify proper actions pointed at enhancing the bus voltage magnitude profile. Dibangoye *et al.* [88] investigated the unit commitment problem and economic dispatch that search for the optimal plans and amount of power generation by distributed units in response to electricity demand, in the context of smart grids.

Research work related to MAS-based control of smart micro-grids, generation control, identification of optimal policies, and load classification is discussed in this paragraph. Kremers *et al.* [89] presented a simple case study for the MAS-based model and simulation of a simple smart microgrid. The microgrid model processes both electrical and communication flows for the management of dynamic load through an integrated approach. A MAS smart generation control scheme for the automatic generation of control coordination in interconnected complex power systems has been presented in [90]. A decentralized MAS with the successful performance of a fast policy hill climbing algorithm with eligibility trace

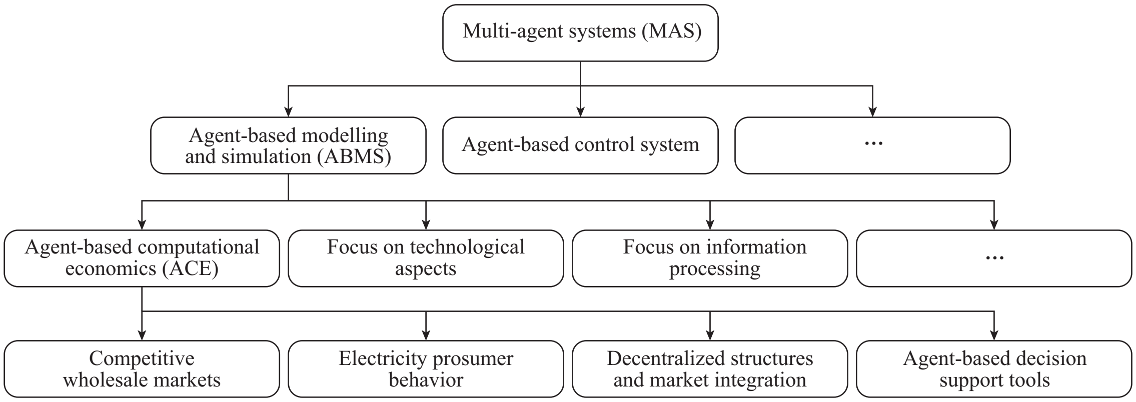

Fig. 8. Classification of multi agent system-based approaches in smart grid.

has been developed. The algorithm effectively identifies the optimal average policies using a variable learning rate under different operational circumstances. Its implementation is in a flexible MAS with a stochastic dynamic game-based smart generation control simulation platform. Saraiva *et al.* [91] proposed a general structure using an artificial neural network (ANN) and MAS. MAS is utilized to manage the functions for load classification. Here, two agents are used where the first agent is termed as a Smart Meter Agent and used for simulating a consumer side smart meter, to use load demand measurements. The second agent is the Substation Agent, which receives the data from the Smart Meter Agents. This agent is used to store the nature, quantity and behavior of loads, which are utilized for classification of nonlinear loads in smart grids by ANN. Hence, input to the ANN is received from a MAS. Here, ANN architecture with Multi-layer Perceptron is utilized for classifying the loads. Here, the classification tool is controlled by the Smart Meter Agent, and data of identified consumer nonlinear load that are fed from the smart grid are held by the Substation Agent. The different load classes in the study and corresponding neurons for ready reference are provided in Table VIII. Here, the output results are indicated using 1-of-CL encoding to represent CL classes. Eight different classes are designated for representing various combinations of use of equipment/loads. Hence, the output layer has 8 nodes where each output pattern indicates a load class.

TABLE VIII
SMART GRID LOAD CLASSIFICATION USING MAS-SUPPORTED ARTIFICIAL NEURAL NETWORK

Load class	Description	Output neurons							
		1	2	3	4	5	6	7	8
Class-1	X-ray equipment	1	0	0	0	0	0	0	0
Class-2	HCT	0	1	0	0	0	0	0	0
Class-3	HRS	0	0	1	0	0	0	0	0
Class-4	X-ray equipment + HCT	0	0	0	1	0	0	0	0
Class-5	HCT + HRS	0	0	0	0	1	0	0	0
Class-6	X-ray equipment + HCT on standby	0	0	0	0	0	1	0	0
Class-7	HCT on standby + HRS on standby	0	0	0	0	0	0	1	0
Class-8	X-ray equipment + HCT + HRS on standby	0	0	0	0	0	0	0	1

Research work related to the use of MAS-based approaches in smart grids for management of electric vehicle charging; hierarchical and distributed cognitive radio architecture; active demand; and cloud architecture is discussed in this paragraph. In [92], the hierarchical and distributed cognitive radio architecture management (HDCRAM), originally aimed for cognitive radio operations, has been proposed by the authors for management of smart grids. This architecture has been applied partially (distribution network, production network, microgrid) and over the whole smart grid. The simplified cognitive cycle used in the architecture works in a cyclic manner and can be represented as Decision Making → Adaptation → Sensing → Decision Making. This illustrates that a Cognitive Radio equipment performs three important activities, including a sensing activity, an intelligent activity (decision-making), and a reconfiguration activity (adaptation). All these are interrelated. First of all, the information is sensed and then a decision is taken for reconfiguration. Mocci *et al.* [93] proposed a decentralized MAS to coordinate active demand and plug-in electric vehicles in the smart grids based on a low voltage network. An analysis of the cloud computing feasibility for the construction of smart grid has been presented in [94]. The multi-agent technology was used to control each node in the network based on the cloud architecture of the smart grid. An agent-based model for a hybrid car energy network integrated with the smart grid has been proposed by the authors in [95]. A two-leveled hierarchical control methodology for integration of electric vehicles into the distribution network has been proposed in [96]. It coordinates operational constraints and self-interests of the car owner while the distribution system operator (DSO) is facilitated by a fleet operator (FO) and grid capacity market operator. Yigit *et al.* [97] presented a cloud computing-based architecture for smart grids. Saba *et al.* [98] proposed a solution by the integration of a multi-agent system with the smart grids for energy management. The optimized performance and energy management of electric vehicles on the microgrid have been presented in [99].

B. Communication Between Smart Grid Agents

Smart grid communications between different agents require a two-way data flow for emerging applications of the grid. These applications include distributed generation, wide area situational awareness, demand response (DR), and advanced metering infrastructure (AMI). These applications perform on communication networks like neighborhood area networks, wide area networks, and local (home) area networks [100].

Note: HCT: Helical computed tomography; HRS: Hemodynamic recording system.

The working of these networks is based on various infrastructures and standards. The communication languages, standards, and technologies of MAS implementation in the power networks have been provided in detail by the authors in [101]. The standards of the Foundation for Intelligent Physical Agents (FIPA) are widely used by MAS developers. A technique of message interchange between grid agents and FIPA agents has been provided in Fig. 9. Common Information Model (CIM) uses software applications for exchange of information related to the configuration and status of an electrical network. The IEC 61850 standard is focused on standardizing the design of the automation system for an electric substation. The nodes of intelligent smart grid communicate with the electrical equipment and multi-agent platforms using the multi-agent communication language (FIPA ACL). Message communication between the grid agents is achieved by the use of CIM/IEC 61850 message. Nieves *et al.* [102] presented semantic and syntactic interoperability to the smart grid vision. Various standards as well as communication methodologies are discussed in detail. Misra *et al.* [103] presented a learning automata-based multi-constrained fault-tolerance method for efficient management of energy in the smart grid communication network.

C. Electrical Vehicles and Smart Grids

This section details the research work related to use of MAS for electrical vehicle charging stations that are integrated with

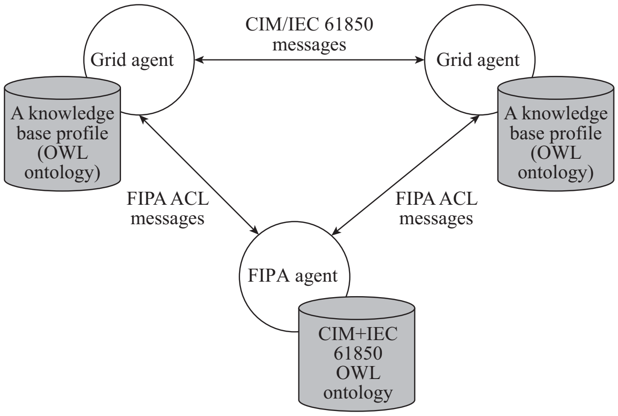

Fig. 9. Message interchange between grid agents and FIFA agents. (Note: ACL- agent communication language, CIM- common information model).

smart grids. Habibidoost et al. [104] investigated the capability of an electric vehicle (EV) for being a source of power in an emergency as a way for a Smart Grid to support itself. For that purpose, a MAS involving micro-grid, home, and EV agents is defined to manage EV battery sources. In [105], the authors presented the multi-agent modelling and microgrid vehicle-to-grid (V2G) simulation, while considering different requirements like plug-in electric vehicles (PEVs), distributed renewable energy resources (DERs), and non-PEVs. Pang *et al.* [106] demonstrated in detail the potential advantages of battery electric vehicles (BEVs) and plug-in-hybrid electric vehicles (PHEVs) being considered as dynamically configurable dispersed energy storage, acting in a vehicle-to-building (V2B) operating mode. Junjie *et al.* [107] presented a detailed study of methods for smart grid charging of electric vehicles for fleet operators.

D. Integrated Structure of Smart Grid and Building Energy Systems

This section details the research work related to use of MAS for integrated structure of smart grid and building energy systems. Hurtado *et al.* [108] proposed an agent-based particle swarm optimization (PSO) technique for optimization of the inter-operation of building energy management systems (BEMS) and smart grid (SG), which requires the facilitation of the complicated relationship of the two environments. The PSO is utilized to maximize both comfort and energy efficiency. The SG-BEMS framework domains are explained with the help of Fig. 10. The two main domains of this framework are the distribution network building (consumer premises). There is continuous exchange of information between the BEMS and SG, which is based on a common ontology allowing the exchanged messages to be understood by both domains. However, exchange information is kept at the lowest level allowing both systems to operate for achieving their own goals. Power circuits of the distribution system and building domains are designed using four different layers. The operation layer is linked to the SG-BEMS and hosts the Distribution Management Systems (DMS) and the Energy Management System (EMS). It also manages the building controls, which includes the centralized management systems (CMS), zone management system (ZMS), and the device management system (DMS). The field layer of the SG-BEMS system contains the equipment for monitoring, control, and protection of the power network and building installation. These equipment are intelligent in nature and use communication-supported controllers. The distribution network is operated with an objective to provide power supply to the customers with high reliability. Conventionally, controls of

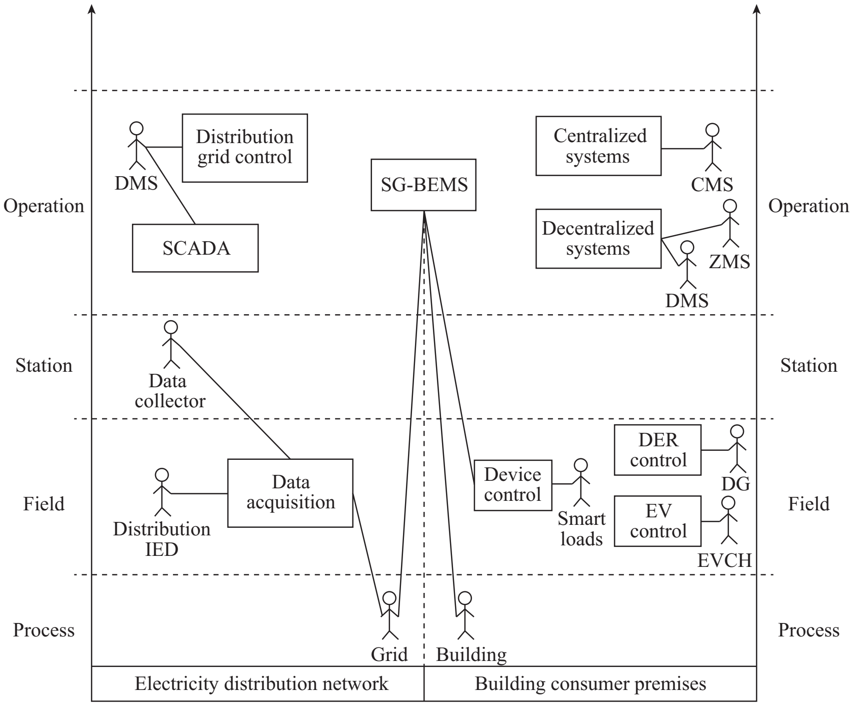

Fig. 10. SG-BEMS framework domains. (Note: DMS- Distribution management system).

the distribution system prevent overloading, regulate voltage magnitude, maintain power quality, and ensure grid security. In this system, the voltage variations over a network feeder are formulated by the following relation:

$$\Delta u=\frac{(P.R+Q.X)+j(P.X+Q.R)}{u_{\text{base}}} \tag{1}$$

where P–active power; Q–reactive power; X–reactance; R–resistance; u_{base}–reference voltage; Δu–voltage variation. It is clear from the above equations that voltage variation is depended on the flow of power in the feeder and network impedance. The nature of power (active or reactive) is defined by the X/R ratio, which has a great impact on the voltage level. Hence, voltage variations can be controlled effectively through the control of active and reactive power in the SG-BEMS framework.

A detailed study on MAS applications of improved building procedures in interaction with the smart grid has been provided in [109]. Wang *et al.* [110] proposed a model for management of indoor energy and comfort in a smart building using information fusion, in an ordered weighted averaging aggregation.

E. Soft Grids and MAS

Utilities are upgrading the communication and information systems for effective control of smart grids. This is achieved by end-to-end coordinated control using software; a new smart grid concept referred to as the “soft grid”. Integration of MASs in grid management will ensure that the requirements of the soft grid are achieved [111], [112]. In [113], the authors used the concept of software technology integration with web technology for designing a grid architecture. This approach overcomes the limitations of existing web architecture-based grids. In [114], the authors introduced a LABVIEW software-based multi-agent approach for control and restoration of the grid during faulty and outage events. In [115], the authors developed a MAS for smart management of energy in an IoT-based system. The soft grid is motivated by design to accept the best offers. Thus, it proposes a negotiation system amongst agents for reducing the demand. Howell *et al.* [116] elaborated the energy system generation through a critical review of the relevant authoritative research works. It covers concepts of multi-energy systems and interrelations, smart grids and microgrids, and virtual power plants, and involves interoperability and distributed intelligence.

F. Miscellaneous Application Scenarios

This section details the application of MAS for voltage control, power market, demand-side response, etc. Ren *et al.* [117] proposed an agent-based technique for the optimization of system reliability in the restoration process, by taking load balancing as the constraint condition. A novel wolf pack algorithm was developed to modify the restoration strategy. Klaimi et al [118] developed a solution for minimizing the smart grid users’ loss in a multi-agent context. In the first step, power loss effects on the cost of energy are reflected, while in the second step, a novel technique that aims to meet the customers daily energy demands by using the energy storage system is presented. Santos *et al.* [119] proposed a hierarchical centralized MAS, which coordinates different monitoring steps and decision making processes to enhance the conventional contingency response techniques like load-shedding schemes. Gomes *et al.* [120] proposed an entire architecture for a micro-grid management system, relying on the multi-agent strategy for easy realization of various energy strategies. Chang *et al.* [121] proposed an agent-based middle-ware framework (AMF) that deploys a distributed cyber-physical system (CPS) to improve communication reliability in a smart city. Keshta *et al.* [122] developed a MAS for achieving the optimal management of energy for voltage regulation, and to improve the stability of a system under different weather conditions and load perturbations for the two connected microgrids. A direct-current MAS deploying hybrid hydrogen fuel cells and renewable energy system is reported in [123]. Furthermore, the application of distributed generation consisting of traditional and renewable energy sources, as well as accumulators and static converters is presented. Mishra *et al.* [124] introduced multi-agent based coordinated decision-making for optimally investing in expansion of distribution network generation and transmission. Kong *et al.* [125] proposed a MAS-based optimal bidding procedure using the artificial immune system (AIS) for optimizing the power output coordination in DERs with different owners affected by commercial microgrid uncertainties. Xie *et al.* [126] developed an agent-based design for distribution of under-frequency load shedding (UFLS). The consensus weighting protocol (CWP) plays the key role in making agreements amongst the agents. Xiong *et al.* [127] proposed a renewable energy multi-objective management scheme for satisfying the requirements of diversities in the customers’ community. Their approach is via a MAS that coordinates and controls the generation of the power and consumption units. Adjerid and Maouche [128] proposed a multi-agent system-based decentralized state estimation method for active distribution networks.

A filtering technique to estimate the states and unknown inputs of a class of nonlinear discrete-time heterogeneous multi-agent systems is designed in [129]. Taylor approximation of the nonlinear multi-agent system is applied to develop a distributed semi-cooperative switch-mode filter. This is effective to obtain minimum-variance unbiased (MVU) evaluation of unknown inputs and states. In [130], authors introduced a comprehensive market framework which helps the residential consumers to obtain proactive residential demand response actions in the day-ahead market (DAM). An agent-based interaction platform is designed for effective interaction between the generators, retailers, residential consumers, and independent system operator (ISO).

G. Performance Improvement in Smart Grid Using MAS

Performance of smart grids improve significantly by the use of MASs. A detailed study to show the improvement in smart grids by the use of MASs is reported in [92]. Table IX presents a comparative study between a system in a conventional mode of grid operation and the same system under a smart grid with MAS. It is observed that the variability and the maximum/minimum power levels in conventional power grid are much higher compared to the smart grid with MAS. Using

TABLE IX
PERFORMANCE OF A SMART GRID WITH CLASSICAL APPROACH AND MAS

Mode of Smart Grid Operation	Peak Power consumption (W)	Peak power generation (W)
MAS	850	800
Conventional	5500	7000

a MAS, additional generation is stored in battery systems and utilized when the need arises. Hence, load and generation scenarios are balanced in such a manner that continuous load is maintained and the generation is accordingly balanced. In the conventional mode of operation, the load should preferably be when generation is available. In a similar manner, the performance of the grid improves in all aspects when a MAS is used.

VI. FUTURE SCOPE

The present thrust is to boost the penetration of intermittent low carbon energy sources as well as the integration of loads (electric vehicles, heat pumps, etc.) into the smart grids. This is expected to pose a serious challenge to the grids in terms of perturbation of power flow and variations in voltage conditions to the customers and utility equipment. Furthermore, ensuring proper operation while restricting the negative impact of increased energy sources and loads is also a challenging task. There is a need for coordinated control of the smart grids. MAS is a better solution than the existing SCADA systems. There is a need to investigate the prospective use of MAS to provide optimized coordinated control of smart grids looking at improving the different complex variables in the networks. MAS is a better candidate to manage voltage variations, smart grid power market, demand-side response in smart grid, load forecasting, generation forecasting, and generation scheduling during the high RE integration to the smart grid scenario. Furthermore, the concept of soft grid can be realized using MAS. Hence, implementation of the MAS concept for control of smart grids with a high penetration level of RE sources may be considered for future investigation, with the aim of effectively coordinating the above discussed smart events/processes. The employment of the MAS concept to manage flexibility of the smart grids to mitigate RE variability may also be explored. This will help to improve the performance of smarts grids in the future and increase the level of RE sources in the grids.

VII. CONCLUSION

A comprehensive literature review of the multi-agent systems (MASs) was carried out. This is an attempt to summarize and categorize the research on the topic of MASs and their use in the development of future smart grids. The review concentrated on smart grids, MASs, intelligent agents used in smart grids, and implementation of the concept of MASs in smart grids. A study to show the performance improvement of a grid made smart due to use of MAS is also included. Finally, at the end of paper, the future scope for research to increase the controllability of the future smart grid using MASs has been provided.

From this review, it is concluded that the smart grid is the next generation of conventional grids based on its two-way power and information flow capability. It incorporates smart metering infrastructure capable of sensing and measuring the power consumption of users by integrating advanced communication and information technologies. Overall control of the smart grid is still a challenging task. The cooperative control of the multi-agent system has attracted researchers working in the field of smart grids to integrate the concept of smart grid, to achieve smart control of smart grids. A significant work in this field has been reported and this paper collects the research that has already been done, which helps to direct future research. In conclusion, the present day conventional grid is attaining a digital structure, different types of sensors, two-way communication systems, self-monitoring systems, pervasive controls, and distributed generation, which upon deployment, render that grid as smart. Various consumers are connected to smart grids. Smart grids also have significant self-healing capacity. Standards such IEEE, IEC, ETP, and NIST are effective in providing procedures and protocols for efficient operation of smart grids. Various intelligent agents have been used for control of smart grids; MAS is the most effective means of control of the various aspects of smart grids. MASs help in embodying the management of energy, marketing energy, as well as pricing and scheduling energy. MAS also improves efficiency, reliability, network security, fault-handling capability of smart grids, communication between agents, SG-electrical vehicles, and SG-building energy systems. Soft grids can be developed using MAS. It is hoped that this review on MASs and their integration with smart grids will be of use to consumers, designers, manufacturers, researchers, and engineers who are working in the field of future smart grid development.

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