Multi-Agent Systems and Demand Response: A Systematic Review

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***Abstract*—The mismatch between electricity supply and demand in power system and the management of it using response loads leads to the notion of Demand Response. In this paper, a comprehensive review of Multi-Agent System is carried out along with works in the space of demand response and power system operation. Factoring from different scopes, two aspects are thereafter highlighted – MAS-based DR in market systems and distribution network assets, respectively. Alongside, a comparison of popular tools used for demand response and impact analysis is also addressed since proper tools can be more beneficial and recognizable to effective implementation. The benefits of the various actors towards MAS technology in the transition towards Smart Grid are also highlighted. Finally, some unsolved questions and remaining challenges are explictly identified.**

***Index Terms*—Multi-Agent Systems, Demand Response, Energy Market, Smart Home, Smart Grid.**

I. Introduction

THE increasing interest in integrating intermittent renewable generation, electric vehicles and other technologies into smart electricity network presents major challenges from the viewpoints of economic and reliable operation of the electric power system. In order to transition the existing electricity grid towards the Smart Grid, new functionalities and capabilities are expected to emerge and being deployed. Amongst them, demand response(DR) has been widely accepted as a potentially impactful and promising solution. Various pilot programs and research have been conducted around the world, such as US[1][2], Europe[3], UK[4], China[5], Australia[6], New Zealand[7]–[10], and Singapore[11].

Traditionally, residential customers, located at downstream end of the electricity grid with strictly hierarchical generating-delivering-consuming architecture, have limited capabilities to participate in the system operation but to react to dynamic environment or accept proposals from upstream end passively. Therefore Demand Side Management(DSM), specifically Demand Response(DR), has drawn massive attention for decades due to the fact that it enables end-users to strategically respond to the change of consumption in order to maximize network benefit or minimize electricity cost.

Demand response, in general, provides customers the opportunity to respond to supply conditions and participating in power system operation. By reducing their electricity consumption at peaking hours and responding to higher market prices, consumers can change and reschedule their appliance patterns so as to lower and save their power cost and bills. Hence, different ways, such as incentive-based DR, priced-based DR, are developed to achieve this goal. In incentive-based DR program, consumers are able to respond to system operator's request by reducing some loads during the peaking demand hours and receive some monetary bonus offered by operator in return. Whereas customers, in priced-based DR, will voluntarily adjust or shift the schedule of their appliances due to the variation of electricity price[12]. By shifting their consuming patterns from high price to the low, customers expect to have an appropriate reduction of electricity cost. Nevertheless, the surging penetration of distributed generation(DG) and Electric Vehicles(EVs) in the form of Micro-Grids(MGs) enables customers, instead of simply responding to the dynamics, to actively participate in the economic operation of whole electricity market, which brings great complexity and challenges to the existing power system.

Multi-agent systems(MASs) are computational systems in which a collection of loosely coupled autonomous agents interact with each other so as to solve a specific problem[13]. Agents, with capabilities to communicate, cooperate, coordinate and negotiate with others, can choose not only to work together in a form of teamwork but also to fight or conflict with one another in order to maximize benefit. Figure1 shows the generic architecture of an intelligent agent. Generically, agents have the capabilities to respond or communicate with external environment and other agents. Additionally, information interpretation, response analysing, knowledge updating as well as decision making play essential roles in reacting and effecting the exterior circumstance autonomously. For decades, MAS has been widely used in research of electric power system, from Micro-Grid control[14] to the reliability of Smart Grid[15], from power generation[16] to transmission[17] and distribution system[18], from power system state estimation[19], communication security[20], system protection[21], fault location and system restoration[22][23], optimal power flow[24][25], electric vehicle charging[26], to demand side response[27]–[29]. Moreover, the IEEE Power Engineering Society(PES) has formed a MAS Working Group to investigate the issues and challenges in using MAS in the field of power engineering[30][31].

The purpose of this paper is to present an overview of the existing MAS technologies deployed in the field of demand response in power system. The increasing penetration of DG and EVs enables residential customers to take part in the operation of electricity market, where they can not only perform the reaction to upper-level system but also actively offer the ability to generate and control. Hence in this paper the interests of DR are drawn from the level of power system

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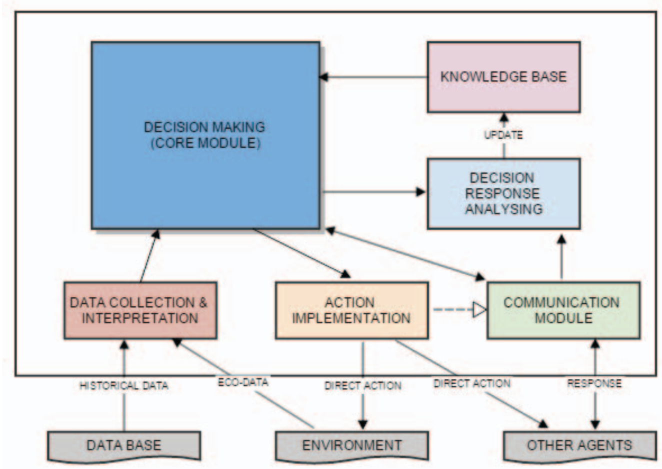

Fig. 1. Generic architecture of intelligent agents

as well as electricity market respectively. The contributions of this paper are threefold:

- Reviewing MAS-based demand side response in terms of residential distribution system and electricity market;
- Comparing several favourable tools used in DR and highlighting their appropriate deploying fields;
- Giving a highlight of the benefits of deploying MAS technology in both physical and economic perspectives;

The rest of this paper is organized as follows: Section II illustrates generalized MAS architecture. Section III reviews the MAS techniques applied in DR in terms of the electricity market. In section IV, an overview of existing MAS programs for smart home, building, community and load management is presented. Section V lists the tools used in simulation of demand side response. In Section VI, the potential benefits of MAS are highlighted from different perspectives. In addition, some remaining challenges and unsolved questions are raised in Section VII. Last, some conclusions are drawn.

II. MAS Architecture

MAS, as a combination of several agents working in collaboration to achieve the desired goal, has become an increasing powerful tool to develop complex systems that take advantages of agent properties such as autonomy, sociality, reactivity and pro-activity[32]. In power distribution level, the generalized agent-based coordination approach, acting as a hierarchical architecture, consists of three levels of control(shown in Figure2) – coordination agent(coordinates the consumption of several local controller agents), local controller agent(controls the sub-group of devices), and device controller agent(controls specific appliances by simple on/off switches or complex energy consumption rescheduling)[33].

Due to the variety of power resources(such as solar and wind generation units acting as stochastic resources, diesel generators acting as controllable resources, batteries functioning as storage units) and loads(e.g., shiftable operation devices, thermal buffer devices, user action devices, etc.), different demand supply matching schemes based on MAS have been presented. In [33], categorized coordination techniques are

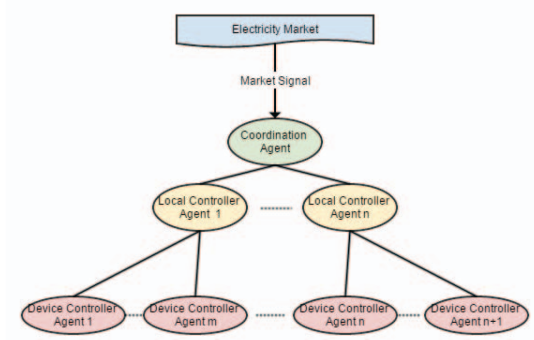

Fig. 2. Structure of MAS coordination approach

reviewed – market-based and non-market. Further, in the category of market coordination, the capability of altering demand in order to match the supply is also classified. Instead of solely depending on the price, the non-market-based techniques concern multi-objective functions combined with system stability. It has been revealed that decentralized approaches have the natural advantage in terms of computational cost when the system experiences an increasing number of resource agents. Whereas fully distributed non-market-based algorithms suffer from the sub-optimality.

III. MAS-based DR in Electricity Market

Traditional power system was composed of electric companies vertically, in which power monopolies took the responsibilities of producing, transporting, and distribution without any competition[34]. Moreover, the market price and system reliability were far from the suitable level of consumer satisfaction. Owing to the liberalization taken place from the nineties, electricity market was separated from the natural monopoly functions of transmission and distribution to competing generation and retail sections[35]. Increased competition of both generation and retail sectors has dramatically curtailed the net cost, hence the electricity price has experienced a significant decrease. Consumers, in retail market, can also benefit from the competition of diverse retailers by choosing their suppliers based on the best offer.

Electricity markets(EMs) are essential systems where buyers and sellers participate to trade electricity using supply and demand to set agreeable prices. During the trading process, several parties, including generators, independent system operators(ISOs), regional transmission operators(RTOs), retailers, aggregators, regulators, and consumers, etc., in the system will negotiate, bid, cooperate, compete, or even regulate to maximize one's benefit or maintain reasonableness and effectiveness of the whole electric market. Therefore, the autonomous and heterogeneous participants can be modelled as agents which perform specific and strategic actions in the electricity market.

Originated from natural phenomena, MAS technology plays an increasingly important and active role in electricity market modelling. With attractive features such as autonomy, negotiability, and communicability, agents, in electricity market, can either cooperate or compete with others in terms of electricity price and market share. Hence, game theory, a decision-making process where each agent's payoff depends on the decision of others[36], is widely used in the research of multi-party electrical system[17], [26], [37]–[39].

A. Market Modelling

Electricity market, in which electricity producers, retailers and aggregators compete with others strategically to motivate consumers to connect to them so as to maintain profit and customer satisfactory whereas customers, with the capability to offer their remaining demand or supply and trade with others in need, can maximize benefit as well.

Several MAS-based EM models, such as strategic competition among producers, retailers and aggregators[37], elastic and inelastic power supply deficit[40], volume and price management strategies[34], and market tariff decisions[41] are proposed.

In addition, contract and price design, faced by the electricity retailers, is also a vital aspect of residential demand response in market modelling since appropriate price signals, which can indirectly trigger the curtailment of power consumption during peaking demand hours, can relieve the burden of supply-demand matching from the viewpoints of electricity suppliers. Therefore research with regard to ancillary service contract design[42], active and fixed price mechanism[43] and real-time price design[44] are carried out respectively. In [42], consumers, rather than communicating and negotiating with aggregators individually, cooperate with others in a form of community. Then aggregators send contract proposals directly to the community and purchasers can decide to accept or reject the contract accordingly. Furthermore, different pricing mechanisms are carried out in view of the effectiveness[43]. Results reveal that active market mechanism, compared with fixed price, will cause spikes easily since some responsive loads will begin operating immediately once the decrease of price has been sensed, which ends up with the failure of peak demand management.

B. Demand Side Modelling

Traditionally, the majority of customers in deregulated markets do not directly participate in the market[45]. Instead of contracting with aggregators without access to hourly or daily price information, Thimmapuram[45] demonstrated the benefit of utilizing consumers' price elasticity of demand to limit the power consumption and reduce the energy prices and congestion charges. Moreover, agent-based modelling of demand elasticity[46] as well as price elasticity[47] are also presented due to their essence in residential demand forecasting and energy market pricing. Yang[47] presented an analytic price responsive behaviour model on the basis of demand theory. It has been proved that complex household electricity consumption behaviours can be modelled by the combination of conventional ones, which provides much more flexibilities for the analysis of residential electricity consumption under dynamic pricing response. In [48], a complex bid model, based on the demand and states of devices, for time-shifting loads to dynamically respond to the market is proposed as well.

C. Demand Exchange

Instead of simply reacting to the price signal from retailers, DR can also be treated as public goods. In [49], a Demand Response Exchange competitive market scheme is proposed. Acting in the market as intelligent agents, buyers will require and are willing to pay for DR in order to compensate their energy consumption, whereas DR sellers are capable to supply DR on request by curtailing consumer loads. Furthermore, Walrasian auctions, imported from microeconomics, is deployed in the market clearing scheme for DR scheduling. By this, the presented clearing scheme will reach the Pareto optimal in which no agent can increase its benefit by adjusting the schedule without reducing benefits from other agents. Similar results are addressed in [50].

IV. MAS-based DR in Smart Distribution Network Operation

Conceptually, the consumption patterns of end-user in response to the variation of power supply and real-time price fluctuate dynamically. In order to save the cost of electricity, residential customers, instead of manually turning appliances on and off, prefer appliances to automatically change or reschedule their running time under certain constraints(e.g., household temperature, EV charging time span, dishwasher functioning time span)[51]. Hence the concept of Automatic Load Management or Smart Home/Building/Community emerged. Combined with the attractive features of MAS, smart distribution systems in view of demand response receive more and more attention in scientific research area.

A. DR in Smart Home/Building/Community

In [52], four different optimization strategies of smart home energy management(i.e., comfort preferred, cost preferred, energy efficiency preferred, and demand side management) are proposed and explained. Deployed in a decentralized manner, a MAS is introduced to cope with these strategies in order to provide customers with flexibility and control over their energy use. Alternatively, focuses on the scope of commercial building are considered in [10], [12], [53], [54]. Further, [55] considers electricity consumption and supplies in terms of communities where different kind of users(e.g., price sensitive users, price insensitive users, constant electricity consumption users, and load serving entities) are treated as intelligent agents. In place of treating users as agents, [56] presents a MAS where utilities and communities are treated as autonomous agents. By interacting with each other through limited information exchange, agents will reach an agreement in the form of a Nash equilibrium iteratively.

B. DR with DG and EVs

The surging fraction of renewable sources and EVs brings massive challenges to traditional distribution network as well. In [57], a MAS based feeder-side load management scheme was proposed. Considering factors of minimum price, maximum possible generation of renewable sources, and demand reduction in decision making process, the presented system is

Features	GridLAB-D	OpenDSS	AMES	MASCEM	EMCAS	MATLAB/SIMULINK+JADE
Num of Devices/Players	Simultaneously Millions	N/A	Limited	Limited	Limited	Limited
Time Scale	Sub-seconds to Many Years	N/A	Days	Short- and Medium- Term	Long-Term	Short- and Medium- Term
Centrality of Architecture	Decentralized; Agent-based; Information-based	Centralized	Agent-based; Role-player-based	Agent-based; Role-palyer-based	Agent-based; Role-player-based	Decentralized; Agent-based
Distributed Generation Supported	YES; Used to evaluate the cost/benefit trade-off of investment	YES; Well-supported	N/A	YES; Included in Virtual Power Player; Used in contribution analysis	YES; Thermal & Renewable generation; Energy Storage; EV	YES; Limited to wind turbine
Market Interaction/Bussiness Systems	YES	NO	YES	YES	YES	N/A
Unique Features	Integrates supply, demand, power flow, load and market modeling, residential appliances, distributed generations, population growth, etc.	Multiple simulation modes; Faster sequential-time simulation; Stronger electrical system modeling	Focuses on the strategic trading in restructured wholesale market with congestion managed by locational marginal prices	Focuses on key players in real markets competing, learning, adapting strategies to establish their own objectives and rules	Multi-dimensional environment model, including physical layer, several business layers, and a regulatory layer	Wide range of common and domain-specific alogrithms and support; Easily integrated with other softwares; Powerful agent platform
GUI	NO	YES	YES	YES	YES	YES
Integration with other Softwares	Easily	Easily	Easily	Easily	Easily	Easily
Programming Language	C/C++	Delphi	Java	Java	Java	Matlab+Java
Developer	PNNL	EPRI	Iowa State University	Polytechnic Institute of Porto	Argonne National Laboratory	The MathWorks, Inc; Telecom Italia

Fig. 3. Tools used in DR research

capable to forecast the daily load profile by utilizing Artificial Neural Network (ANN) on historical data. Another version of load forecasting with penetration of DGs, based on Reinforcement Learning(RL), is in [58]. In addition, Logenthiran[59] introduced a MAS based smart charging and discharging scheme for plug-in EVs, which will reduce the operational cost and lower the peaking system demand. Similar system considering PEVs and batteries is in [60].

V. Tools used in DR

In this section, a comparison of different yet popular tools in research of MAS in demand response of power system will be drawn since proper tools can be much beneficial and recognizable to one's research outcome. Hence a focus on widely used tools, such as GridLAB-D[61], OpenDSS[62] , MATLAB/SIMULINK + JADE[63], AMES[64], MASCEM [65], and EMCAS[66], will be addressed in this paper. The attention for several aspects(e.g., the number of devices or players supported for running simultaneously, the time scale of simulation, the centrality of proposed architecture, the support of distributed generation, the internal action of market participants, the unique features compared with other software, etc.), which are essential attributes for MAS deployed in demand response analysis, are drawn.

From Fig.3 we can conclude that GridLAB-D and OpenDSS are suitable for the research in terms of appliances and physical systems whereas AMES, MASCEM and EMCAS are more appropriate for the simulation of market role player or policy participants. On account of the fact that both GridLAB-D and OpenDSS are well-supported for the physical electrical system modelling, researchers, focusing on the dynamics of power system with regard to actual demand response action, will benefit from these two tools. Between them, GridLAB-D has considered the specific models of daily appliances as well as the weather condition and population growth, while OpenDSS is better at electrical system modelling and faster converging during simulations. In spite of some common features(e.g., market interactions, GUI, programming language, etc.) among the three market tools, EMCAS is advantageous from others in some aspects for instance the time scale, supported distributed generators as well as multidimensional environment model. Last, MATLAB/SIMULINK, combined with Java Agent DEvelepment Framework(JADE), can be applied in the study of smart home in respect of the actual demand response from a specific customer.

VI. Potential Benefits of MAS

It has been widely highlighted that MAS, with the features of flexibility and extensibility, has the tendency to be exploited as system construction and modelling approach. Apart from the scientific viewpoints, MAS also provides attractive benefits to the participants of wholesale market, retail market as well as distribution network.

- For the system operators, MAS, combined with Game Theory, Demand Theory, or Microeconomics, is naturally capable to model the operation of wholesale market, which helps to facilitate the effective operation of the power system and electricity markets and curtail the possibility of extreme cascade failure and blackouts.
- From retailer's perspective, agent concept can be deployed in the modelling of demand side response. End-users, acting as autonomous agents, will diversely react to the dynamic change of price signal on the basis of some features such as personal income, residential area, and specific power reliance. Hence this modelling approach will be helpful for the contract design and ancillary service design.
- For the distribution companies, utilizing MAS in the distribution network can bring more intelligence to the existing one. Combined with advanced sensing technologies, control techniques, and integrated communications technologies, MAS-based distribution network is able to perform self-healing, attack resistance, accommodation of generation and storage options, and optimization of assets[32].
- Customers, laying at the bottom of the power chain, are expected to benefit from this technology as well. Concepts of Smart Home/Building/Community enable consumers to strategically participate in the market operation and provide ways to maximize their profit or

minimize the cost. The intermittent renewable resources, EVs, and storage elements, deployed in the residential level, also have the necessity to act in a plug-and-play manner which is one of the several unique features of MAS.

VII. Unsolved Questions and Challenges

In spite of the fact that numerous research outcomes from demand response have been gained from the deployment of MAS, there are still some questions and challenges remaining unsolved.

- The increasing penetration of stochastic and intermittent renewable resources bring massive uncertainty to the whole power system, which desperately requires more robust control structures and advanced forecasting techniques to handle these highly type-dependent variables.
- The introduction of EVs in residential level will pave the way for promoting DR to inject the power back to grid rather than simply acting as a load. Therefore proper facilitation mechanisms in EM will be required.
- Hierarchical MAS structure[67] has proved its effectiveness over the purely centralized or decentralized ones in terms of fast convergence. However present MAS architectures are usually fixed and not suitable to the dynamically changing power environment. As a result, more suitable MAS structures are expected to realize their potential in demand side response.
- ”Intelligent” agents in existing MAS structures are not that intelligent at all since they simply perform some basic communication and control schemes. This is due to the fact that complex functions will require massive computational and communicational cost, which consequently delay the speed of system convergence. With the development of information communication technologies, agents are expected to gain more intelligence and perform more complex yet effective actions.

VIII. Conclusion

A thorough bibliographic review of Multi-Agent System (MAS) and its implementation for demand side response in power systems has been carried out. Different scopes, i.e., MAS for electricity market services and MAS for smart grid distribution asset management, where demand response combined with MAS are comprehensively identified. In addition, a comparison of popular tools used in DR analysis is presented to highlight the unique features applicable to the particular objective sought. This paper has also identified some unsolved questions and remaining challenges for future research in the direction of MAS in electrical power systems.

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