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Microgrid supervisory controllers and energy management systems: A literature review

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ABSTRACT

Microgrids (MGs), featured by distributed energy resources, consumption and storage, are designed to significantly enhance the self-sustainability of future electric distribution grids. In order to adapt to this new and revolutionary paradigm, it is necessary to control MGs in intelligent and coordinated fashion. To this aim, a new generation of advanced Microgrid Supervisory Controllers (MGSC) and Energy Management Systems (EMS) has emerged. The aim of this paper is to summarize the control objectives and development methodologies in the recently proposed MGSC/EMS. At first, a classification of control objectives is made according to the definition of hierarchical control layers in MGs. Then, focusing on MGSC/EMS related studies, a detailed methodology review is given with emphasis on representative applications and research works. Finally, the conclusions are summarized and the proposals of future research directions in this area are given.

Contents

1. Introduction 1264
2. Hierarchical control – definitions and issues 1264
   2.1. Hierarchical control for microgrids 1264
   2.2. Centralized and decentralized management 1265
3. Centralized MGSC/EMS 1266
   3.1. Power management 1266
   3.2. Economic dispatch and unit commitment 1266
   3.3. Decision making strategies in UC and ED 1267
   3.4. Genetic algorithms and swarm algorithms 1268
   3.5. Mixed integer linear and non-linear optimizers 1269
   3.6. Rule based systems and machine learning systems 1269
4. Multi-agent system based MGSC/EMS – recent applications 1269
5. Conclusion and future trends 1271
References 1271

Abbreviations: (ANN), Artificial Neural Networks; (CR), Compensation References; (DM), Decision Making; (DSM), Demand Side Management; (DER), Distributed Energy Resource; (DNO), Distribution Network Operator; (ED), Economic Dispatch; (EMS), Energy Management System; (ESS), Energy Storage System; (GTA), Generator Agent; (GA), Genetic Algorithm; (ICT), Information and Communication Technology; (LA), Load Agent; (LB), Local Bus; (LC), Local Controller; (MLS), Machine-Learning system; (MO), Market Operator; (MPPT), Maximum Power Point Tracking; (MG), MicroGrid; (MIA), MicroGrid Intelligent Agent; (MGM), MicroGrid Manager; (MGSC), MicroGrid Supervisory Controller; (MILP), Mixed Integer Linear Program; (MINLP), Mixed Integer Non-Linear Program; (MAS), Multi-Agent System; (PC), Power Converter; (RES), Renewable Energy Source; (RH), Rolling Horizon; (RBS), Rule Based system; (SC), Schedule Coordination; (SLB), Sensitive Load Bus; (SCADA), Supervisory Control And Data Acquisition; (TCG), Tertiary Compensation Gain; (UC), Unit Commitment

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1. Introduction

The primary traits of sustainability in electrical power and energy field are environmental influence, economic operation and social convenience. A MicroGrid (MG) [1–3], as shown in Fig. 1, is a small scale grid that can integrate distributed Renewable Energy Sources (RES), conventional generators, Energy Storage Systems (ESS) and consumption, forming a flexible, self-sufficient, and more environmentally friendly system than individual unit. It can be operated in either grid-connected or islanded mode in case of grid faults or planned islanding. The new paradigm of flexible distribution systems includes the widespread adoption of MGs.

During last decades, a large number of MG related research programs and projects [2–7] have been established in cooperation between prominent universities and companies all over the world. By now, total installed MG capacity has well passed 4 GW throughout the world, with North America leading the world market with a capacity share of 67% [8].

A multi-layer block diagram is a common way of representing the MG systems [9–13], as shown in Fig. 2(a). The field layer integrates all the physical components, including: 1) Distributed Energy Resources (DER), which can be RES, ESS or conventional generators; 2) Power Converters (PC), which act as interface between DER and the grid; 3) grid components, such as transformer, switchgears, transmission lines, etc.; 4) power consumers (loads).

The local control layer includes the basic functions like local generation/consumption control and ESS management. It normally follows the instructions from upper level controllers. The top level of MG control system performs the functions of Supervisory Control And Data Acquisition (SCADA). This layer is also sometimes called the Energy Management System (EMS), MG Supervisory Controller (MGSC) or MG central controller. For clarity, the term MGSC/EMS is used in the remainder of this paper.

The aim of MGSC/EMS is to provide necessary functions like power quality control, ancillary services, participation in the energy market, and to optimize the operation of the system by enhancing its intelligence level [9]. Influence from higher level operator, such as Distribution Network Operator (DNO) and Market Operator (MO), may also be taken into account. Naturally the availability of Information and Communication Technology (ICT) is of utmost importance for realizing these functions.

Ever increasing demands on desirable characteristics for future MGs bring more challenges to MGSC/EMS [9–11]. For instance, it should be possible to achieve smooth transition between islanded and grid-connected modes under either intentional or unintentional conditions, integrate demand side strategies, and handle increasing penetration of renewable energy by developing advanced scheduling and dispatching strategies considering prediction errors. Motivated by the intensification of EMS research and applications in recent years, this paper presents a general overview of MGSC/EMS related definitions, functions and methodologies. It is organized as follows. Section 2 gives a detailed definition of possible roles and objectives of MGSC/EMS in a MG system on the basis of classical hierarchical control structure. The methodologies applied in MGSC/EMS for real-time power regulation and short-/long-term energy management are reviewed in Section 3 with emphasis on representative research works. Section 4 generalizes the agent based EMS research and applications. Section 5 gives the summary and future trends.

2. Hierarchical control – definitions and issues

This section gives a brief overview of a classical MG hierarchical control and is followed by the elaboration of principles about how MGSC/EMS part can be incorporated in the respective structure.

2.1. Hierarchical control for microgrids

Overall MG management is a complex multi-objective control system that deals with issues from different technical areas, time scales and physical levels. The domains of interest include load power sharing, voltage/frequency and power quality regulation, market participation, short-/long-term scheduling etc. In order to properly handle these issues, a hierarchical control scheme has been proposed and widely accepted as a standardized solution for efficient MGs management [9,12–14]. It should be noted that terminology used herein is different from the one used in some recent works. For instance, [14] places energy management functions into secondary control, while tertiary control is defined for multiple MGs coordination. This paper takes the standardized definition introduced in [9,12,13], and taken from conventional power systems.

It comprises three principal levels:

- Primary level: primary control performs the control of local power, voltage and current. It normally follows the setting

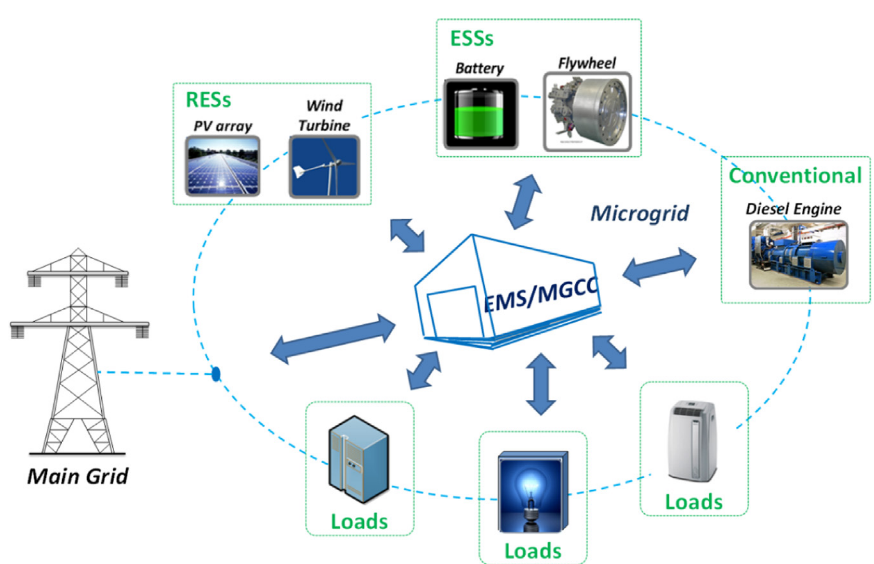
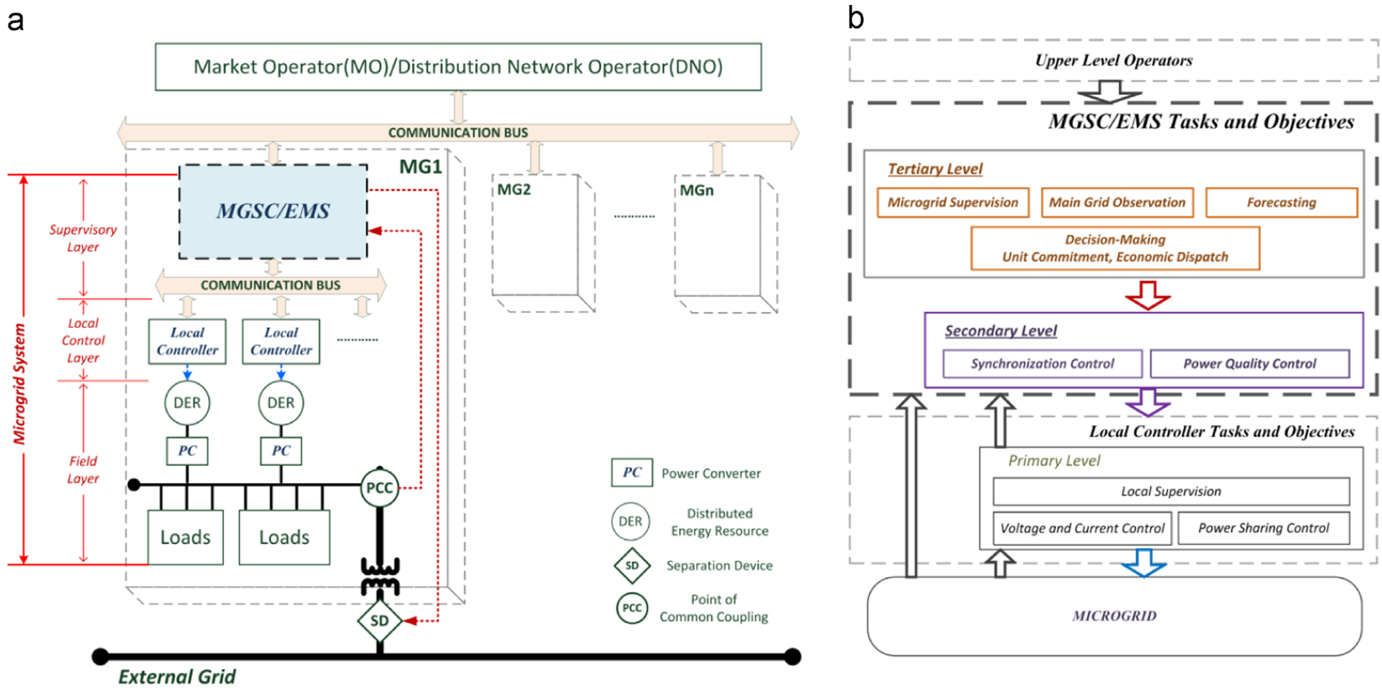


Fig. 1. Microgrid infrastructure.



General structure of microgrid control systems *Hierarchical control in Microgrids*

Fig. 2. MG system and hierarchical control scheme.

points given by upper level controllers and performs control actions over interface PCs.

- Secondary level: in the existing hierarchy, secondary control appears on top of primary control. It deals with power quality control, such as voltage/frequency restoration, as well as voltage unbalance and harmonic compensation. In addition, it is in charge of synchronization and power exchange with the main grid or other MGs.
- Tertiary level: the aim of tertiary control is to introduce intelligence in the whole system. To that end, tertiary control will attempt to optimize the MG operation based on merits of interests, mostly efficiency and economics. Knowledge from both MG side and external grid are essential to execute the optimization functions and ICT is a key enabling technology for that matter. Decision making (DM) algorithms are employed to process the gathered information and take proper actions.

In this conventional control structure, both tertiary and secondary control is implemented in MGSC/EMS. The bandwidths of different control levels are normally separated by at least an order of magnitude, implying the decoupling of the dynamics in different levels. This feature simplifies the modeling and analysis for MG systems. As we move towards higher control levels, regulation speed becomes slower; e.g. droop control in primary level has typically a response within 1～10 ms, secondary control speed can reach up to 100 ms～1 s depending on the speed limit of underlying communication technology, while tertiary control executes DM in discrete time steps ranging from seconds to hours.

2.2. Centralized and decentralized management

Based on the same hierarchy shown in Fig. 2(a), the functions of MGSC/EMS can be implemented in centralized or decentralized way. The level of decentralization is defined by the intelligence of Local Controllers (LC), which can be used just to execute commands from upper level or make their own decisions. A general comparison is made concerning different aspects and levels of decentralization of MGSC/EMS, as shown in Fig. 3.

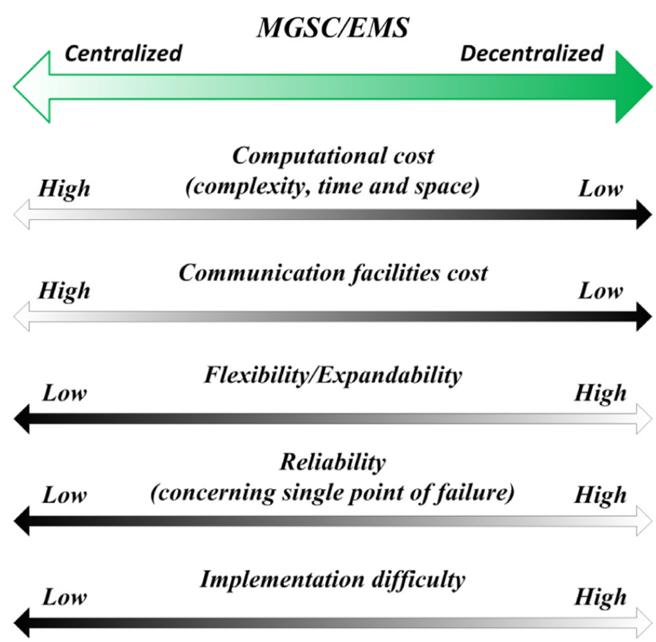


Fig. 3. MGSC/EMS in different levels of decentralization.

Either way has advantages and disadvantages, which determine its appropriateness of application on the specific MG type (residential, commercial or military), and the legal and physical feature (location, ownership, size, topology, etc.).

Centralized control and management systems [15–45] usually require data collection from both MG components and external grid. Based on the gathered information, scheduling and optimization procedures can be executed to achieve economic and efficient operation. Obviously, the advantages of centralized MGSC/EMS include real-time observability of the whole system and straightforward implementation. If designed properly, it provides a strong supervision and wide control over the entire system. Also confidential and private information can be protected within the central unit. However, from another point of view, those features also indicate that the MGCC needs to be highly powerful so as to process considerable amount of data and make proper decisions. High bandwidth communication is required in order to exchange information timely. Moreover, the centralized management entails a single point of failure, and central unit fault will cause the breakdown of the entire system. Low flexibility/expandability is another critical limit of centralized management.

Considering above discussion, centralized MGSC/EMS is usually more suitable for the following MG cases [16,22,29,30,44]:

- Small scale MGs where centralized information gathering and DM can be realized with low communication and computation cost;
- All the properties within the MG have a common goal so that the MGSC/EMS can operate the MG as a unity;
- Military MGs where high privacy/confidence is required;
- System configuration is almost fixed which does not require high flexibility/expandability.

On the other hand, in order to achieve more flexible operation and avoid single point of failure, decentralized control systems have been brought to stage [9,46,47]. Recent progress in alternative communication technologies [48] (WiFi, Zigbee, etc.) and information exchange algorithms [49–53] (Peer-To-Peer, Gossip, Consensus etc.) enable the possibility of decentralized control and management in practical applications. In that sense, functions provided by conventional centralized control mechanism, such as frequency and voltage regulation, DER coordination, energy management, can also be realized in a decentralized way, while the level of decentralization can range from centralized to fully decentralized [54]. Multi-Agent System (MAS) based MGSC/EMS has indeed become a prominent research direction as it provides the possibility to actualize decentralized management functions. It can have the same hierarchy and functions as centralized ones, but transferring the DM authority to local side by increasing the intelligence level of LCs. ICT again plays a decisive role since the local decisions are made based on necessary information from the environment and neighborhood.

In summary, decentralized control and energy management can, to some degree, reduce the computational burden, since the DM is processed locally and MGSC/EMS only needs to perform information sharing/coordination. The system can keep normal operation even after loss of MGSC/EMS functions which avoid the single point of failure. Another advantage is that the realization of plug-and-play functionality is much easier, which considerably enhances MG flexibility/expandability. However, on the other hand, the decentralized operation requires well synchronization among the units, communication system starts to play pivotal role on system safety and stability which requires extensive study and analysis. Information security becomes another critical issue.

Generally speaking, decentralized tertiary control and energy management can be more desirable when [20,26,27,55–57]:

- The size of the MG is large or the generation, consumption and storage are widely dispersed which makes centralized data acquisition difficult or costly;
- The resources are owned by different entities who have their own operation goals and require local decision making (DM) schemes;
- Periodical fast reconfigurations of the systems like adding or removing existing units are required.

The following two sections assess the applications of centralized and decentralized EMS systems in MGs, respectively.

3. Centralized MGSC/EMS

This section reviews the application of MGSC/EMS in MG power/energy management field with more focus on optimal dispatching and scheduling of energy units, and the relevant DM strategies.

3.1. Power management

MGSC/EMS can improve accuracy of load power sharing and efficiency of the whole system. In particular, although droop control typically achieves proper active power sharing among DERs, reactive power cannot be accurately shared due to mismatches of the parameters of transmission lines between DERs. Under these situations, additional power control loop can be implemented in MGSC/EMS for achieving desirable reactive power sharing among DERs, as presented in [58–65]. Moreover, adaptive droop method was proposed and applied in [32,45,66–68] to realize accurate power sharing while ensuring the system stability at the same time. The authors in [67,68] integrate optimization functions for enhancing system efficiency and obtaining desirable system dynamics.

On the other hand, due to the rise in share of power electronic equipment, more and more attention in MG area is paid to the power quality issues. These issues typically include: 1) voltage/frequency deviation caused by the droop control method, 2) voltage unbalance caused by non-symmetrical loads or imbalances in transmission lines; 3) voltage and current harmonics. Instead of using dedicated compensation devices, recent research works tend to employ DERs as distributed compensators and make them share the compensation efforts [69–74]. The authors in [72–74] have proposed a centralized controller for the power quality enhancement on Sensitive Load Bus (SLB), as shown in Fig. 4. The MGSC/EMS measures the power quality on SLB and generates Compensation References (CR) to local control systems. This method realizes selective compensation of negative sequence SLB fundamental voltage ($V^{+/-}$) as well as positive and negative sequence SLB voltage harmonics ($V^{h+/-}$). Furthermore, considering the transmission line differences and different power quality limits in Local Buses (LB), a tertiary control approach is presented in [74] in which an optimization method is proposed and implemented to the MGSC/EMS as tertiary power quality controller aiming at finding the optimal sharing proportion of compensation efforts among DERs (see Fig. 4). It sends Tertiary Compensation Gains (TCGs) as adjusting variables to lower level controllers in order to adjust the compensation effort of each DER considering the DER compensation capability and LB power quality requirements. Based on this scheme, an improved approach is also proposed in [75] to achieve better current sharing and system stability.

The design and implementation of MGSC/EMSs for test-bed MG systems have been reported in [45,63,64,76–79], which show the hardware integration and signal interfacing of MGSC/EMS with other MG components.

3.2. Economic dispatch and unit commitment

Taking inspiration from terminology used in conventional power systems, some authors have proposed the EMS functions to be divided into two categories [15–31,80–85]: Unit Commitment (UC) and Economic Dispatch (ED). According to the time scale of the management cycle, day-ahead scheduler and short-term/real-time dispatcher can be differentiated, as shown in Fig. 5. Day-ahead

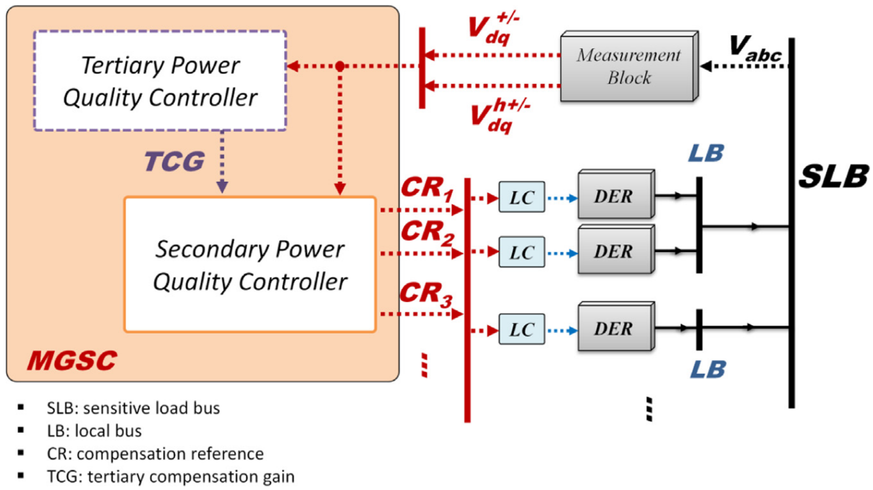


Fig. 4. MGSC for enhanced power quality.

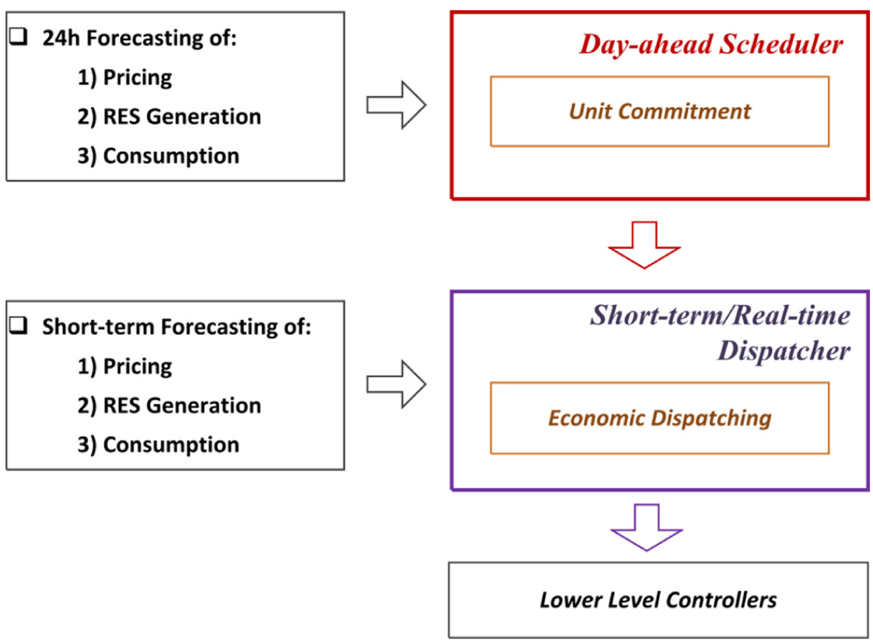


Fig. 5. Energy management in microgrids.

scheduler can offer UC solutions based on 24-h generation and consumption forecasting aiming to find the most cost-effective combination of generating units to meet forecasted load and reserve requirements. This commitment schedule takes into account the inter-temporal parameters of each generator (minimum run time, minimum down time, notification time, etc.) but does not specify production levels, which are determined a few minutes before delivery by the Short-term/Real-time Dispatcher. In Short-term/Real-time Dispatcher, based on the short-term forecasting information, the solution of ED problem is given. The latter is actually the least-cost usage of the committed assets during a single period to meet the demand, while adhering to generator and transmission constraints.

The coordination of UC and ED can be intuitively understood from Fig. 6 [22]. Such classification derives from the main underlying issues affecting the energy management problem including the response time of the different involved DERs; the requirement for different resolution times and dispatch time frames affecting the management of each DER (e.g. up/down times, charge/discharge cycles, etc.); the uncertainty about the power production from renewables. Although strongly interlinked, these issues are rarely considered as a whole in the existing literature [22,36,86–88].

Further on, a supervisory control is applied in a MG system in [18] using a UC with a Rolling Horizon (RH) strategy. The UC-RH is considered for reducing the effect of the uncertainties of the estimated or forecasts data used by MGSC/EMS. The data include ESS state of charge estimation, predictions of electric-load/water consumption and RES power generation. The UC function in the MGSC/EMS provides the optimal set-points for one prediction horizon (T=2 days) with a sampling time of 15 min. An ED function is applied for adjusting the set-points for a shorter update period (i.e. 1–5 min) based on the current measurement of electric-load/water consumption and RES generation. The update period of ED is rolling after each step which helps to reduce the effect of uncertainties and forecasting errors.

3.3. Decision making strategies in UC and ED

Both the UC and ED are essentially the solution of a Decision Making (DM) problem, which may be considered as, for instance:

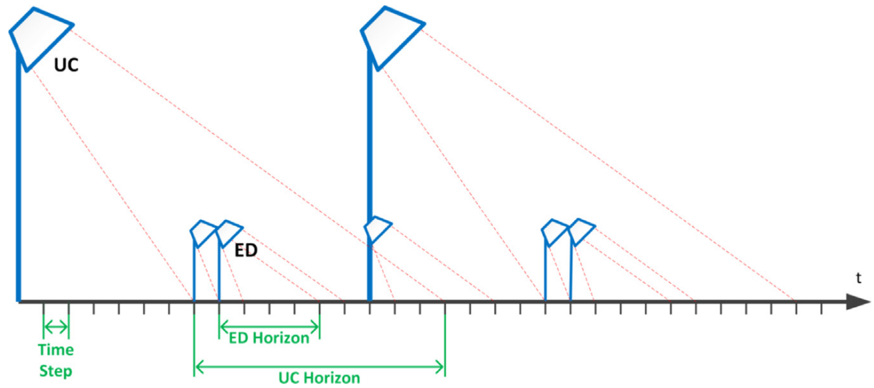


Fig. 6. Coordination of UC and ED.

- an optimization problem with either discrete or real valued variables [21,86–93];
- a Rule Based system (RBS) (fuzzy-logic based [93] or standard [16,44]);
- a Machine-Learning system (MLS) (Neural Network based) [41,94]; etc.

Such solution of a DM problem provides of a set of operation points for the various energy resources along different time frames. The set of operation points should be chosen so as to minimize or maximize one or more objective functions, namely so as to 'optimize' one or more objective functions under one or more constraints. The set of operation points are therefore the variables from which such objective functions depend and they may take real and/or discrete values giving rise respectively to real, mixed integer, or integer optimization problems. For the same aim, RBS can provide a solution. They are Artificial Intelligence reasoning systems, that provide a solution based on the inference mechanism. Such inference is either based on precise reasoning and classifications such as it happens in Expert Systems or on approximated classifications (fuzzy-logic based systems). Artificial learning is however an interesting opportunity for machines as it allows adaptation to changing environments and improvement of performances based on a feedback from the environment. In this field, both fuzzy RBS and Neural Network can serve as DM systems or also for modeling and prediction purposes.

In all cases, optimization problems for UC and ED are widely formulated as constrained multi-objective in MG applications [21,36,85–88,91,92,95,96]. The common objectives include line loss, carbon emission, profit, cost, power quality, demand balance, etc. They can be pursued as a whole, or partly and with a different priority, both in grid connected and in isolated operation modes.

The EMS must solve an optimization problem whose complexity depends on imposed objectives, considered uncertainties, the complexity of constraints and the decision variables types.

In general, EMSs aim at finding techno-economic and environmental optimum over a time-scale that varies from several minutes up to 24 h. Depending on the type of objective functions (i.e. market dependent) or on the constraints over the variables (i.e. Battery Energy Storage Systems), it may be required to consider a 24-h time frame for UC or ED.

On the other hand, executing short-term (e.g. 1-h ahead) dispatch would produce more reliable results in terms of precision since some input parameters are generated by power production, power consumption or cost parameters forecast algorithms. An interesting review in the problem of uncertainty over data management is proposed in [97].

The time frame to which such forecast is referred to is one of the basic influencing factors on the precision of results. In light of the above, different types of long term dispatch can be envisioned [37,98] either carried out every 24 h or adjusting the set points based on closer predictions about loads and generations [88]. Therefore, a broad classification of EMSs based on optimization can be carried out looking at the time scale which also bounds admissible calculation times.

One of the features that affect the choice of the optimization algorithm is the consideration of the power losses within optimization formulation. Such an objective function depends on the solution of the load flow equations that are highly nonlinear, increasing the complexity and calculation time of the overall optimization procedure. For this reason, some authors prefer the use of Artificial Neural Networks (ANN) to produce optimal layouts after a suitable training phase [41,94]. ANN can also account for uncertainty in input parameters such as fuzzy systems [93]. Other systems can be adopted to tackle the problem of uncertainty [86] as well.

Other classifications based on EMS optimization in the existing literature concern the problem formulation. It may include the thermal units management as in [99], giving rise to a more efficient costs reduction. Besides, most papers explicitly account for environmental objectives together with cost minimization [33,90,100] not translating them into cost terms as non-commensurable objectives. On the other hand, when this is not the case, letting some fuel based generation units work at maximum efficiency also implies a strong reduction of carbon emissions as shown in [17].

Based on the above devised classifications, the optimization algorithms applied in centralized EMS are reviewed here. The objectives can be optimized by using a single or combined techniques, such as ration questioning technique, genetic algorithms (GAs), multi-attribute DM, and so on. A number of research works with applications of different optimization algorithms have been selected and reviewed here. Comparison and analysis are conducted to show the advantages and disadvantages of such kinds of algorithms implemented in MGs with different operation modes and objectives.

3.4. Genetic algorithms and swarm algorithms

These methods are largely employed in the power systems literature due to their flexibility and the possibility to use complex formulations of the problem at hand. No matter what is the nature of variables and constraints, they will end up with one or more solutions. However, no guarantee is given to the user about its optimality. Many population based and evolutionary algorithms take their inspiration from Genetic Algorithms introduced by John Holland in the early 1970 s and developed by D. E. Goldberg [101]. The basic mechanism of initial population generation, selection and recombination can indeed be recognized in almost all these algorithms. Many commercial packages can be employed for the DM process for EMS, although their use does not allow the designer of the DM for the EMS to elaborate on variables coding [21], more refined perturbation mechanisms or over constraints handling [87,88]. The drawbacks however reside in the long calculation times and in the inherently uncertain behavior leading to different results at each run. By now not many authors have reported about the statistical behavior of the outcome of these algorithms although this is one of the most important elements for their real implementation in MGs applications. GAs and many other swarm algorithms have the possibility to handle many objectives and to face constrained formulations [87] and robustness issues [86].

3.5. Mixed integer linear and non-linear optimizers

This class of optimizers is quite often employed [87,102] for DM processes for EMS in MGs due to their commercial availability in efficient software packages such as GAMS and CPLEX [89]. On the other hand, the formulation of the problem is hardly conditioned, i.e. quantities are linearized [37] to use Mixed Integer Linear Program (MILP), and the variables nature is sometimes forced to be changed to accomplish the requirements. Especially Mixed Integer Non-Linear Program (MINLP) optimizers combine the numerical difficulties of handling nonlinear functions with the challenge of optimizing in the context of non-convex functions and discrete variables. Although it is one of the most flexible modeling paradigm available for optimization, in the most general cases it is hopelessly intractable. For complex problems and large number of variables, calculation times can be a problem.

3.6. Rule based systems and machine learning systems

Both RBS and MLS find their motivation in their intrinsic ability to produce results in limited calculation times. RBS may either use fuzzy systems [36] or standard RBS [15,16,44]. On the other hand, in all cases, the system must be suitably trained either based on the designer's knowledge or using an optimization algorithm [94]. Fuzzy RBS and Neural Networks are certainly more flexible, but still, they can easily produce unreliable results.

As a conclusion, deterministic algorithms such as MILP and MINLP are an interesting option when energy management can be carried out without minimizing power losses (i.e. in very small MGs) or optimizing other highly non-linear operational parameters. If this is not possible, then evolutionary methods or rule based systems can offer a viable alternative. Also, according to the calculation times required by the chosen approach and the response time of the DERs involved, a hybrid DM approach can be designed separating the main problem into sub-problems as suggested in [22]. Another challenging issue concerns the uncertainty about power production from renewables, related with weather and load; such terms are parameters of the DM problem and should be suitably handled.

4. Multi-agent system based MGSC/EMS – recent applications

Within the higher control and management levels of MG, distributed approaches have been explored to increase reliability, security, and situational awareness. Despite a distinction of those distributed techniques for MGSC/EMS is not always clear, [103] classifies them into four groups: Distributed Model Predictive Control-Based Techniques, Consensus-Based Techniques, Multi Agent-Based Techniques, Decomposition-Based Techniques. To illustrate the difficulty on their sorting, in [56] a MAS architecture is deployed but the information is shared by using an optimized average consensus algorithm.

For the enhanced robustness, reliability and flexibility of MGs, MAS based decentralized control has been recently proposed for MG management [46,47,54]. Moreover, MASs have become the major trend of energy management research and development in recent years due to their interesting properties [104]. They have been used to deal with economical power coordination, voltage coordination among other issues both in MGs [105] and in networks of MGs [104].

Generally speaking, a MAS can be regarded as a computerized system composed of multiple interacting intelligent agents within a given environment. Extending this definition, MAS can be defined as a system composed of two or more interacting agents and each of them has its own goals and performs its function autonomously [106]. MASs can be used to solve problems that are difficult or impossible for an individual agent or a monolithic system to solve. Intelligence may include some methodic, functional, procedural or algorithmic search and processing approach. The notions of an agent, intelligent agent and MAS are elaborated in [46]; here, the authors essentially devise three basic properties that distinguish an intelligent agent from a software or hardware automated system:

- Reactivity: ability to react to changes in the environment in a timely manner;
- Pro-activeness: goal-directed behavior;
- Social-ability: interaction with other agents.

Extending this definition, MAS can be defined as a system composed of two or more interacting agents. Due to the interesting properties, MASs have become the major trend of energy management research and development in recent years [104]. The engineering applications of MAS are comprehensively reviewed in [46,47], including the concept, definition, technologies, standards and development tools.

In recent years, a number of MAS based MGSC/EMSs have been proposed. The author of [104] has sought to establish an open source operation platform for MAS based real-time emulation of MG management and control. Three basic types of agents are defined: producer, consumer and observer agents, which are consistent with MG assets. The interaction framework and the constitution of each agent are shown in Fig. 7. Within the proposed framework, each element of the MG has three layers: the component layer, the control layer, and the agent layer. Each element can interact through electrical connection (wires) and a communication interface (telecommunication system between agents). The component layer implements the physical component interface to the MG (e.g. wind turbine generator, load bank, or battery system). The operation of the component are controlled at the control layer through governors, maximum power point tracking (MPPT) devices, tripping mechanisms, charge controllers, and so on. Typically, these control sub-systems have set points and characteristics that can be modified. The reference control signals are locally exploited by the agent layer to manage the component. For each element, the agent can interpret local conditions, affect

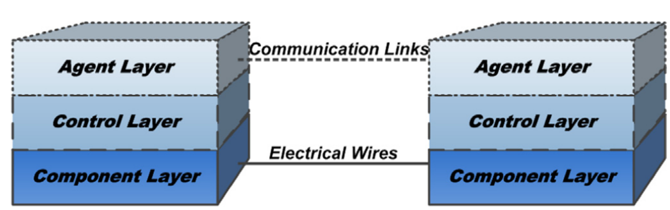


Fig. 7. MAS multi-layer interaction framework.

action on the MG by controlling the component, interact with other agents, and optimize the attached component operation. Each agent performs the local supervisory control and energy management functions, and the agent layer, as a whole, provides the overall management for MG system.

A MAS for real-time MG operation is presented in [107] mainly focusing on generation scheduling and demand side management. A layered architecture of MAS is proposed with a number of dedicated agents defined in each layer. Among those agents, MG manager (MGM) agent, schedule coordination (SC) agent and demand side management (DSM) agent perform the role of MGSC/EMS. MGM is responsible for monitoring and scheduling the operation of DERs and loads, while SC and DSM act as coordinator and interface between MGM and DER/load agents.

In order to realize fully decentralized energy management, a heterogeneous cellular wireless network based MAS is established in [108]. The authors first demonstrate that solving the ED problem is equivalent to achieving average consensus in MG system. Then consensus algorithm is implemented for achieving global information discovery and local decision-making.

The general architecture of a MG EMS based on MAS is described in [109], as shown in Fig. 8. Several different sorts of agents are defined in MGSC and LCs including: Database Gateway agent for storing and retrieving information with databases; Data Monitor agent for obtaining real-time operation data from DER and feed essential information to databases; MG Operator agent for optimizing the operation of the whole system; DER Gateway agent for interfacing other agents and control system with DER devices; Schedule Tracker agent for following the schedule from MG Operator agent and sending set-point to DER; DER Operator agent for locally optimizing the operation of DER and response with MG Operator agent. Based on this scheme, a secondary control is implemented for regulating MG frequency and power flow in islanded and grid-connected mode.

A hierarchical framework of MAS is presented in [27], as shown in Fig. 9. The MAS structure proposed recalls the hierarchical control structure proposed in [12,13]. The upper level agent is designed in a centralized manner providing MGSC/EMS functions, the middle level agents are organized in a coordinated manner to achieve coordination among DERs. The lower level agents are decentralized for local recognition, learning and evaluation aiming at autonomous and stable operation. The combination of the three levels formulates a hybrid control for MG system. In [106] a three-level hierarchical energy management strategies are presented, consisting in a multiagent-based hybrid EMS-MG (HEMS-MG) with centralized and decentralized energy control functionalities.

Focusing on MG operation in a market environment, a MAS architecture is proposed in [19], as shown in Fig. 10. Two basic sorts of agents, Load Agent (LA) and Generator Agent (GTA), are employed in both MG level and market level for demand and generation side management respectively. MG Intelligent Agent (MIA) exists at the top level of each MG agent system, which has the responsibility to decide how the MG will participate in market, as a load or as a generator, according to the mismatch of local demand or supply. In this case, MIA performs the MGSC/EMS role

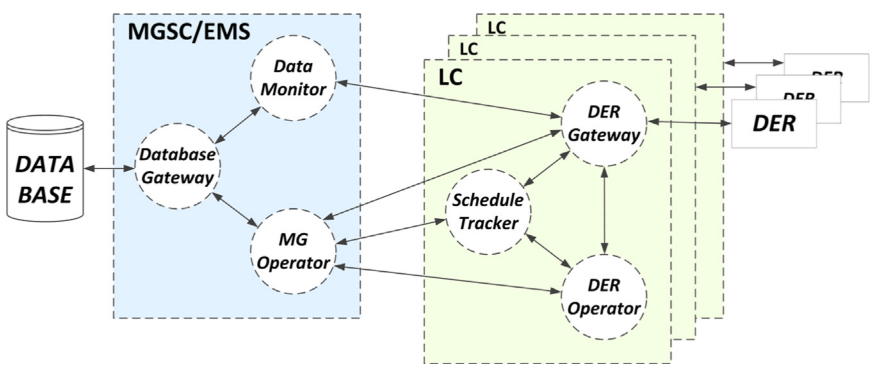


Fig. 8. A general architecture of a MAS based MG EMS.

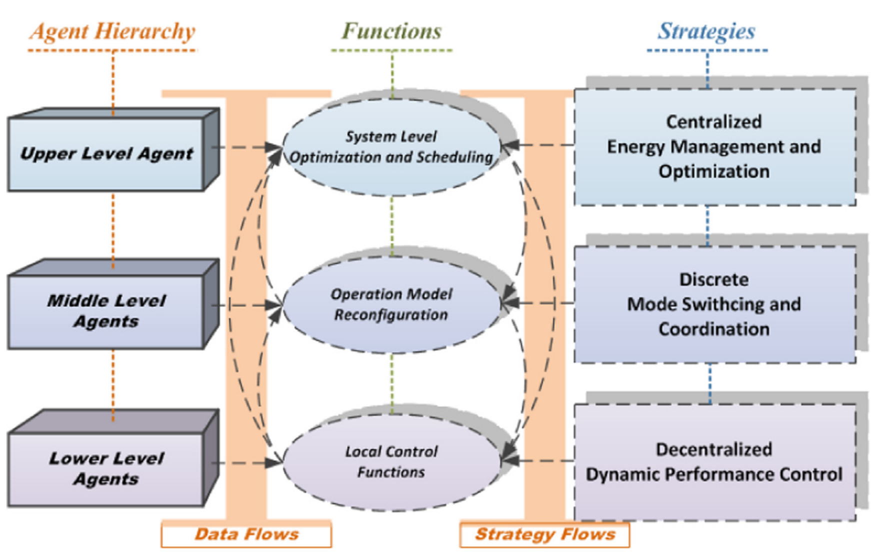


Fig. 9. Hierarchical framework of a MAS application.

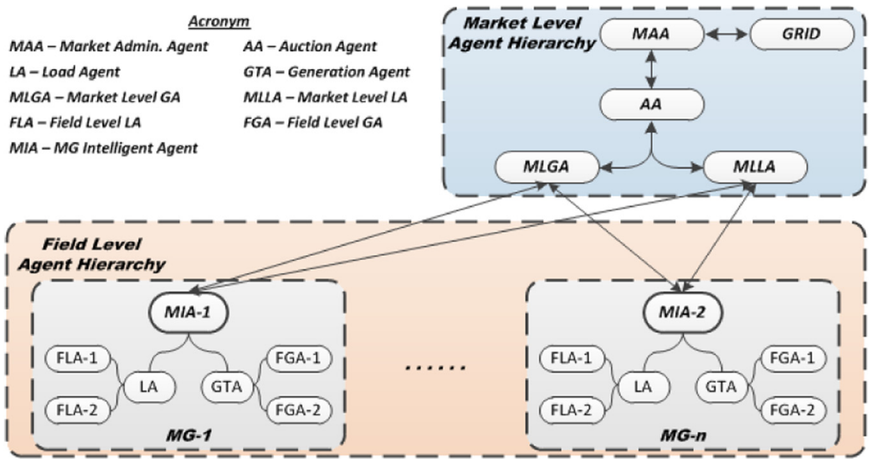


Fig. 10. MAS application for MG operation in a market environment.

and helps the optimal participation of a MG unit to the energy market environment.

Decentralized control of networks of microgrids (SMGs) has also been address by using MAS techniques. In [105], different agents, one for each microgrid and one for each power line, agree on a saddle point of a local function satisfying the internal demand, and exchanging power between locally stored, the main grid, and other microgrids.

More recently, following the architecture proposed in [104] and further developed in [26], the inherent multi-objective problem of Energy/Power Management is considered using a MAS architecture. In this case, else than best compromise solutions also in situ goals are incorporated in the local Agent DM process. Each Agent is called to solve locally a multi-objective optimization problem and to implement the relevant trade-off solutions accounting both for costs and for emissions. A weighted sum approach allows the user to define preferences through numerical weights.

Regarding the challenges ahead, [103] exposes that the convergence analysis of distributed control and management schemes to get optimal operational modes is still a trendy research area regarding algorithms and communication topologies. Similarly, stability analysis has been done in control area but it is required to apply to power system applications. Taking into account that those techniques rely on communication infrastructures to be developed, cybersecurity, requirements, delays and other restrictions have to be addressed. Besides, nonmodel-based approaches should be used in microgrids since they not require a detailed model. Also, regulatory considerations should be considered to follow policies and adopt or create standard. Furthermore technological restrictions and current developments have to be considered to diminish existing gaps between research and industrial fields.

5. Conclusion and future trends

This paper reviews the strategies and technologies applied in MGSC/EMS on the basis of standardized hierarchical control. The definitions and tasks of each level are summarized. MG energy management is actually multi-objective and inter-disciplinary topic handling not only electrical but also economic and environmental issues. The way of realizing MGSC/EMS can be centralized or decentralized. Up-to-date applications of both types of strategies are reviewed, indicating also their suitability for different sorts of MGs.

The sustainable utilization of energy resources requires environmentally friendly and economic operation of the whole system. Up-to-date research works and technologies provide many solutions and possibilities to achieve the objectives in different areas while the project-based study, development and integration demonstrate the suitability and practicability of different methods. For the basic requirements of continuous and reliable operation, simple and autonomous coordination strategies of different DERs are gaining more and more interests. The choice of centralized or decentralized architecture requires MG designer to make a tradeoff option between them. Although decentralized management offer enhanced flexibility, comprehensive analysis is necessary to ensure the secure and reliable operation of the system. Moreover, the handling of variable energy generation and consumption is still demanding proper solutions involving active participating of consumer side.

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