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Review

A Survey of Recent Advances in the Smart Management of Microgrids and Networked Microgrids

Romain Mannini [1,2], Julien Eynard [1,2] and Stéphane Grieu [1,2,*]

[1] PROMES-CNRS (UPR 8521), Rambla de la Thermodynamique, Tecnosud, 66100 Perpignan, France
[2] Physical and Engineering Sciences Department, University of Perpignan Via Domitia, 52 Avenue Paul Alduy, 66860 Perpignan, France
* Correspondence: grieu@univ-perp.fr

Abstract: Microgrids (MGs) and networked (interconnected) microgrids (NMGs) are emerging as an efficient way for integrating distributed energy resources (DERs) into power distribution systems. MGs and NMGs can disconnect from the main grid and operate autonomously, strengthen grid resilience, and help mitigate grid disturbances and maintain power quality. In addition, when supported by sophisticated and efficient management strategies, MGs and NMGs have the ability to enhance power supply reliability. However, their deployment comes with many challenges, in particular regarding the efficient management of DERs. That is why a survey of recent advances in the smart management—the term refers to a variety of planning and control tasks—of MGs and NMGs is presented in this paper. It aims at establishing a picture of strategies and identifying trends in methods. The reader is provided with an in-depth analysis of a variety of papers recently published in peer-reviewed journals: the way the methods are used and the common issues addressed by the scientific community are discussed. Following this analysis, one can especially observe that (1) model-based predictive control (MPC) is emerging as a competitive alternative to conventional methods, in particular in voltage and frequency regulation and DER management (2) due to their ability to handle complex tasks, data-driven strategies are getting more and more attention from the scientific community (3) game theory (GT) is a very good candidate for efficient management of complex systems as NMGs (4) MPC and artificial intelligence are increasingly being used for proper MG islanded operation or to manage electric vehicles (EVs) efficiently.

Keywords: microgrid; networked microgrid; power distribution grid; energy management system; management strategy

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1. Introduction

This section first endeavors to describe the context leading to the deployment of microgrids (MGs) and networked (interconnected) microgrids (NMGs) (Section 1.1). Such a deployment comes with many challenges, in particular regarding the efficient management of distributed energy resources (DERs). The pursued objectives can be technical, ecological or economical oriented [1]. Review papers are presented (Section 1.2) and the review methodology is explained (Section 1.3). The paper's aim is first to identify current trends in management methods. This section ends with the paper's organization (Section 1.3).

1.1. Context

World demand in electricity is expected to double by the end of 2050 [2] while the world is facing two main challenges: the global warming [3,4] and the depletion of fossil and fissile resources [5–7]. A possibility for power generation with low carbon emissions and minor impact on the environment is having recourse to renewable energies [8]. Resorting to this kind of energy resource in a distributed way is more and more frequent [9,10]. However, renewable energies may have a negative impact on the main grid, in particular regarding stability, reliability, and power quality. The deployment of MGs—low-voltage power distribution networks of interconnected DERs, controllable loads, and critical loads, which can operate in either grid-connected or islanded mode and are subject to operational characteristics of the main grid—and NMGs enables high penetration of distributed energy resources in the main grid. A MG, through optimal operation, is able to handle intermittent energy resources [11]. Additionally, other benefits can be reached: ecological benefits [12], self-sufficiency, self-healing, islanding ability, reliability, flexibility and robustness [13]. In addition, power losses can be lowered thanks to the proximity between distributed generators and power consumption spots. Availability of power sources can also be improved [13,14]. When supported by management strategies that take advantage of sophisticated tools—model-based predictive control, multi-agent systems, game theory or artificial intelligence, to name some of these tools—MGs and NMGs enable high penetration of locally available DERs and enhance power supply reliability and resiliency in a significant way. In this context, MGs and NMGs are being deployed all over the world, especially in Asia and North America [15–18]. European countries are also involved in MG development [17]. From 2015 to 2020, the global installed power in MGs has doubled to reach 3 TW [15,16]. During the fourth quarter of 2018, the number of MGs has culminated to 2258 [19]. This trend is expected to continue over the next years at the same rate as the one observed between 2015 and 2019 [15,16]. In some countries, politics influence the deployment of MGs [20–23]. Germany and Italy are two good examples of the influence of politics in the domain, with a growth of local energy communities (LECs), which typically refer to cooperating consumers (or prosumers) in order to satisfy energy needs using DERs, and a change in the paradigm of power generation, from a centralized power generation to a distributed one [24,25]. According to the EU package entitled "Clean Energy for All Europeans", there is a particular concern to pose European citizens as the key players into the energy markets future, as part of the EU decarbonization effort and targets of year 2050. Towards these efforts, the LEC concept can drive and empower the end-users to consume energy in a more responsible manner, contribute to energy savings and steer the power distribution grid to become more flexible.

In this context, the need for efficient management strategies (i.e., decision-making strategies) for MGs and NMGs is high. The control and planning tasks behind managing such systems are, among others, voltage and frequency regulation, power flow management, DER management, reactive power compensation, and optimal operational planning. These tasks go with the deployment of MGs and NMGs. As a result, this paper provides a survey of recent advances in the smart management of MGs and NMGs. Its main purpose is to identify current trends in the methods used. The reader is provided with an in-depth analysis of a variety of papers recently published in peer-reviewed journals from the leading publishers of scientific content. Thus, far, NMG management is little discussed in the literature, that is why this paper aims at establishing a picture of management strategies for this kind of interconnected system, in light of the methods used.

1.2. Review Papers

This section is dedicated to review papers (Table 1). In [18], Hirsch et al. define the concept of MG and provide a multi-disciplinary portrait of MG drivers, real-world applications, challenges, and future prospects. In [26], Eid et al. review the classification of MGs and discuss their control objectives, in particular in islanded mode. The most common problems and solutions are summarized. In [27], a review of experimental MGs and test systems around the world (Europe, North America and Asia) is conducted. This review paper is focused on the available MG control options and is concluded by highlighting possible research areas that could enhance the practical use of MG facilities. In [28], a comprehensive literature review of the most relevant research works on NMGs is conducted. The major benefits and challenges related to NMGs are analyzed.

Table 1. Review papers. AC stands for alternative current. DC stands for direct current. DER stands for distributed energy resource. EMS stands for energy management system. EV stands for electric vehicle. MAS stands for multi-agent system. MG stands for microgrid. MPC stands for model-based predictive control. NMG stands for networked microgrid. RES stands for renewable energy system.

Paper	Brief Description
[18]	A multi-disciplinary portrait of MG drivers, real-world applications, challenges, and future prospects is provided
[26]	MG control objectives, in particular in islanded mode, are discussed
[27]	A review of experimental MGs and test systems around the world is conducted
[28]	A review of the most relevant research works on NMGs is conducted
[29]	Control strategies for DC MGs are discussed
[30]	An overview of solutions evaluated during the last years by the scientific community for MG optimal management is given
[31]	A review of optimization techniques for the management of isolated MGs with hybrid renewable sources is conducted
[32]	An analysis of decision making strategies and their solution methods for MG energy management systems is performned
[33]	An overview of primary and seconderay control approaches for DC MGs is provided
[34]	A review of EMS control strategies for MGs with DERs is conducted, with a focus on energy storage
[35]	A review of energy management in renewable energy based MGs is conducted
[36]	Smart approaches for power grid monitoring and control, in a context of prolific distributed generation, are discussed
[37]	The application of MPC to MGs and NMGs is reviewed, from the point of view of their main functionalities
[38]	A review of MPC applied toward the control of MGs and NMGs is conducted
[39]	Coordination strategies and protection schemes that have been proposed for MGs in the last few years are reviewed
[40]	A review of compensation methods against power quality issues in MGs is conducted
[41]	An overview of control approaches for inverter-based MGs operating in islanded mode is given
[42]	A review of droop control techniques to coordinate distributed generators in MGs is conducted
[43]	Voltage and frequency control strategies of hybrid AC/DC MGs are reviewed
[44]	A review of AC/DC MGs in connection with RES-based distributed generators, ESSs and loads is conducted
[45]	A survey of the latest analytical and approximation techniques to model the uncertainties in MGs is presented
[46]	A survey on hybrid renewable energy system is presented
[47]	A review of optimization objectives, constraints, tools and algorithms for energy management in MGs is conducted
[48]	Control objectives and development methodologies in MG supervisory controllers are summarized
[49]	The major issues and challenges in considering multi-agent systems for MGs are discussed
[50]	A review of approaches and techniques used to establish an efficient energy management strategy is conducted
[51]	Optimization techniques applied to MG planning are reviewed and guidelines for innovative planning are defined
[52]	A review of optimal control techniques for energy management and control in MGs is conducted
[53]	A survey of multi-agent systems for MG control is presented
[54]	An overview of MAS-based distributed coordinated control and optimization in MGs and NMGs is given
[55]	A review of power management and control strategies for MGs is conducted
[56]	A review of recent trends in power management strategies for optimal operation of DERs in MGs is conducted

Table 1. *Cont.*

Paper	Brief Description
[57]	A review of the modelling and implementation of flexible ramping products is conducted
[58]	A survey of control strategies for grid-connected EVs is presented

Taking a look at review papers dealing with the management—the term is used in a broader sense here, covering various control and planning tasks—of MGs and NMGs, published in the last few years in peer-reviewed journals, one can first highlight the work done by Al-Tameemi et al. [29] which is focused on control strategies for DC MGs. Centralized, decentralized, distributed, and hierarchical control strategies are discussed in this review paper. In [30], Topa Gavilema et al. give an overview of different solutions evaluated during the last few years by the scientific community to manage MGs. The review shows the variety of mature and tested solutions for managing MGs with different configurations. The main conclusion which is deduced from this review is that a technique for energy management is mandatory when operating a MG. In [31], a review of optimization techniques for the management of isolated MGs with hybrid renewable sources is conducted. The authors highlight the relevance of using artificial intelligence tools to optimize MG operation. In [32], a comparative analysis of decision making strategies and their solution methods for MG energy management systems is performed. Various uncertainty quantification methods are summarized in order to manage both the volatility and intermittency of renewable energy resources and load demand. In addition, a comparative analysis of communication technologies is discussed. In [33], Gao et al. provide an overview of primary and secondary control approaches for DC MGs. Inner loop and droop control approaches for primary control are reviewed. Centralized, distributed, and decentralized secondary control approaches are discussed in detail. In [34], a review of EMS control strategies for MGs with DERs is conducted, with a focus on energy storage. ESSs can be supported by appropriate controllers in order to increase MG reliability and efficiency. As highlighted by the authors, both the lifetime and efficiency of ESSs are greatly influenced by the chosen control strategy. In addition, this strategy has an impact on economic viability. In [35], a literature review of energy management in renewable energy based MGs is conducted, along with a comparative analysis of optimization objectives, constraints, solution approaches, and simulation tools. Isolated and interconnected MGs are considered. Due to increased technological maturity and because it can provide grid services, energy storage is highlighted as an attractive option to manage the intermittent nature of renewable energies. In [36], Dkhili et al. discuss smart approaches for power grid monitoring and control, in a context of prolific distributed generation. Two methods are showcased by the authors in terms of efficiency: multi-agent systems and model-based predictive control. In [37], Garcia-Torres et al. review the application of MPC to MGs and NMGs, from the point of view of their main functionalities, describing the design methodologies and the main current advances. Challenges and future perspectives of MPC and its applications in MGs and NMGs are described and summarized. In [38], a comprehensive review of MPC applied toward the control of MGs and NMGs, including both converter- and grid-level control, is conducted. This review shows that MPC is emerging as an interesting alternative to conventional methods in different aspects of MG/NMG management. In addition, some of the most important trends in MPC development are identified and discussed.

In [39], coordination strategies and protection schemes that have been proposed for MGs in the last few years are reviewed. The advantages and limitations of existing MG protection schemes are discussed. Future directions for research in the protection system design for MGs and NMGs are also outlined. In [40], a review of compensation methods against power quality issues in MGs is conducted. Various control techniques, algorithms, and devices are discussed. In [41], an overview of control approaches for inverter-based MGs operating in islanded mode is given. MG control objectives are summarized. In [42], a review of droop control techniques highlights the benefits of using those techniques to coordinate distributed generators in MGs. In [43], voltage and frequency control strategies of hybrid AC/DC MGs are reviewed. Various interlinking converter strategies based on droop and communication control are presented. Some recommendations are given for future work in this research field. In [44], a review of AC/DC MGs in connection with RES-based distributed generators, energy storage systems, and loads is conducted. A thorough comparison between the two types of MGs is realized, from economical, technical and environmental points of view. Possible control and energy management strategies for the two types of MGs are also investigated. In [45], Prakash Kumar and Saravanan present a survey of the latest analytical and approximation techniques reported in the literature to model the uncertainties in a MG environment. The authors highlight the inadequacy of uncertainty modelling methods applicable to RESs, both in terms of number and accuracy.

In [46], Hina Fathima and Palanisamy bring to light the concept of hybrid renewable energy system (HRES). A literature survey on HRES is presented. In addition, a review of modelling and applications of renewable energy generation sources and energy storage systems is presented. Metrics, which entail the technical and economic performance of the system, are enlisted. In [47], a review of optimization objectives, constraints, tools and algorithms for energy management in MGs equipped with heterogeneous energy resources and energy storage devices—small scale distributed energy management (DEM)—is conducted. This work provides foundation for further investigation in the field of cost effective energy management techniques for NMGs. In [48], Meng et al. summarize the control objectives and development methodologies in MG supervisory controllers. A classification of control objectives is proposed according to the definition of hierarchical control layers in MGs. Proposals of future research directions in this domain are given. In [49], the major issues and challenges in considering multi-agent systems for MGs are discussed. The authors present a comprehensive review of state-of-the-art applications and trends. In [50], a comprehensive review of approaches and techniques used to establish an efficient energy management strategy is conducted. These approaches include standalone and grid-connected hybrid renewable energy systems for power generation. In [51], optimization techniques applied to MG planning are reviewed and guidelines for innovative planning focused on economic feasibility are defined. Some trending techniques and new MG planning approaches are pointed out. In [52], a review of optimal control techniques for energy management and control in MGs is conducted. A general architecture for optimal EMSs is provided and analyzed in detail. The authors highlight that EMSs based on a hierarchical control architecture are the most commonly found in the literature. In [53], a survey of multi-agent systems for MG control and operation is presented. MAS concepts, architectures, platforms and processes are reviewed. Limitations are discussed. In [54], a comprehensive overview of MAS-based distributed coordinated control and optimization in MGs and NMGs is given. Topology models and mathematic models are summarized. The merits and drawbacks of these control methods are evaluated.

In [55], a review of power management and control strategies for MGs is conducted. In [56], Rangu et al. present a comprehensive review of recent trends in power management strategies for optimal operation of DERs in MGs. First, deterministic and probabilistic approaches, as well as stochastic programming and robust optimization strategies are discussed. Furthermore, the optimal scheduling problem of DERs in MGs is presented. Advanced control and demand response strategies are also presented. In addition, multi-agent-based distributed and decentralized control strategies are reviewed. In [57], an in-depth review of the modelling and implementation of flexible ramping products is conducted by Wang et al. A survey of cutting-edge charging–discharging methods and optimization strategies and objectives for grid-connected EVs is presented in [58]. Several controlled charging–discharging issues with respect to system performance, such as overloading, power quality deterioration and power loss, are reviewed. The challenges and issues faced by EV applications are also discussed from the aggregator's point of view. The authors highlight that uncontrolled charging–discharging may result in grid stability, power quality or operational efficiency issues.

1.3. Review Methodology and Organization of the Paper

A research with the following keywords (in the paper's title and abstract) was performed on ScienceDirect, IEEE Xplore and Google Scholar, among other sources for research papers: microgrids, interconnected microgrids, networked microgrids, multi-microgrids, management, control, planning, model-based predictive control, multi-agent systems, game theory, stochastic programming, robust optimization, artificial intelligence, droop control. As highlighted in Figure 1, the number of research papers dealing with MG/NMG management published in peer-reviewed journals owned by the leading publishers of scientific content (Elsevier, IEEE, MDPI and Springer) has increased a lot in recent years, from almost nothing in the early 2000s (one paper in 2002) to about 1600 (1609) in 2021. This increase is reflective of a booming interest in MGs and NMGs, which can be seen as an efficient way of integrating DERs into power distribution systems. Because the need for efficient management strategies is high, this paper focuses on the most popular methods—model-based predictive control, multi-agent systems, game theory, stochastic programming, robust optimization, artificial intelligence, and droop control—used in recent times for MG/NMG management. The term "management" is used in a broader sense, thus covering various control and planning tasks. So, these research papers address different aspects of MG/NMG management, for example voltage or frequency regulation, power flow management, distributed generation management or MG/NMG optimal planning. This survey paper aims at establishing a picture of management strategies for MGs and NMGs, in light of the methods used, the way these methods are used and the issues addressed by the scientific community (the reader is provided with an in-depth analysis of a variety of papers recently published in peer-reviewed journals in Section 3).

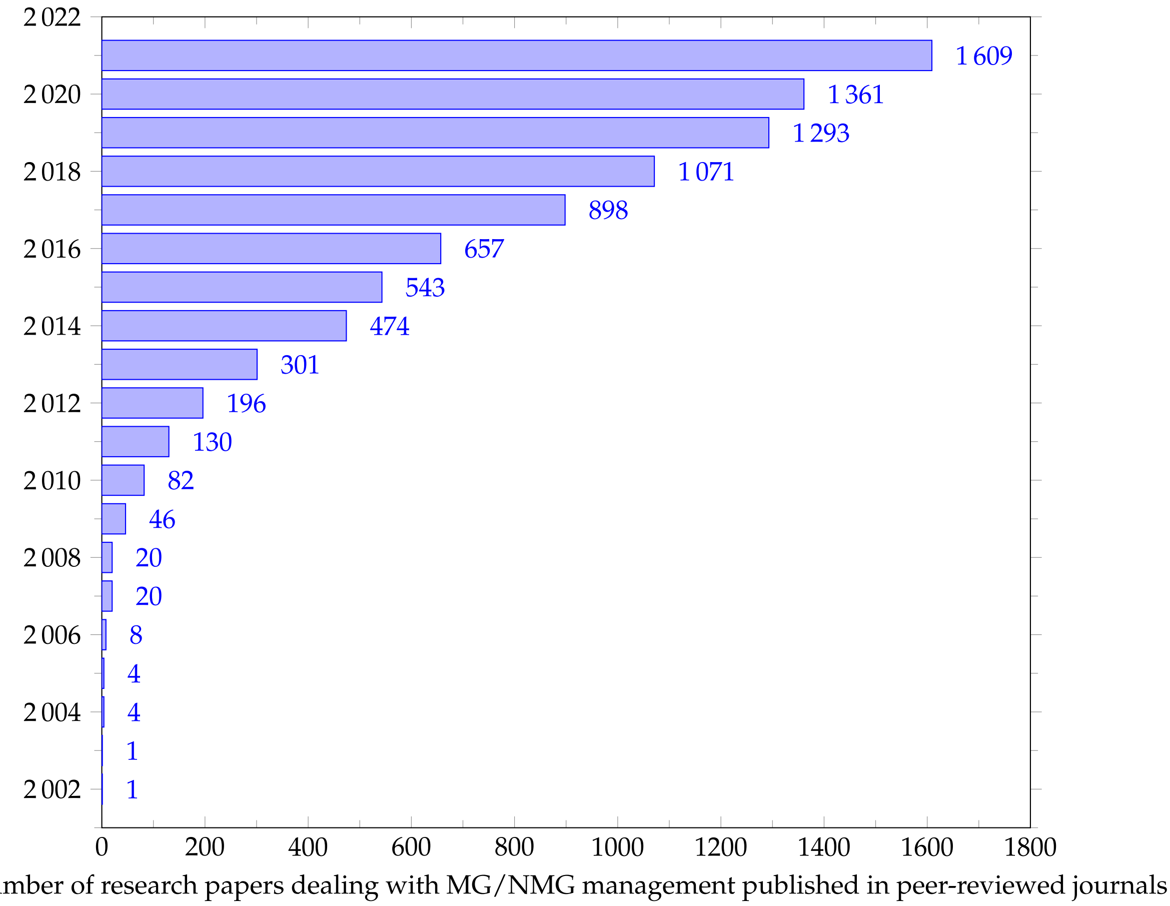

Figure 1. Number of research papers dealing with MG and NMG management published in peer-reviewed journals owned by the leading publishers of scientific content from 2002 to 2021.

In Figure 2, the focus is put on years 2011, 2016 and 2021. Trends in methods are identified. First, one can observe that droop control is still a popular method for MG/NMG management, although its influence decreases: the method is used in 63 papers (48% of the total number of papers considered in this study) in 2011, 334 papers (51%) in 2016, and 533 papers (33%) in 2021. Artificial intelligence, model-based predictive control, robust optimization and, to a lesser extent, stochastic programming are gaining in popularity. Artificial intelligence was used in 14 papers (11%) in 2011, 28 papers (4%) in 2016 and 244 papers (15%) in 2021. Thus, the popularity of artificial intelligence methods, in particular reinforcement learning, in the field of MG/NMG management is relatively new. That being said, machine and deep learning tools, in particular convolutional and recurrent neural networks (long short-term memory networks), are widely used for time series forecasting and, as a result, can be involved in the implementation of predictive strategies. Regarding MPC, it was used in very few papers (3) in 2011 but the number of papers dealing with MPC-based strategies for MG/NMG management has increased to 88 (14%) in 2016 and 226 (15%) in 2021. A similar trend can be observed for robust optimization: the method was used in 9 papers (7%) in 2011, 51 papers (8%) in 2016, and 216 papers (15%) in 2021.

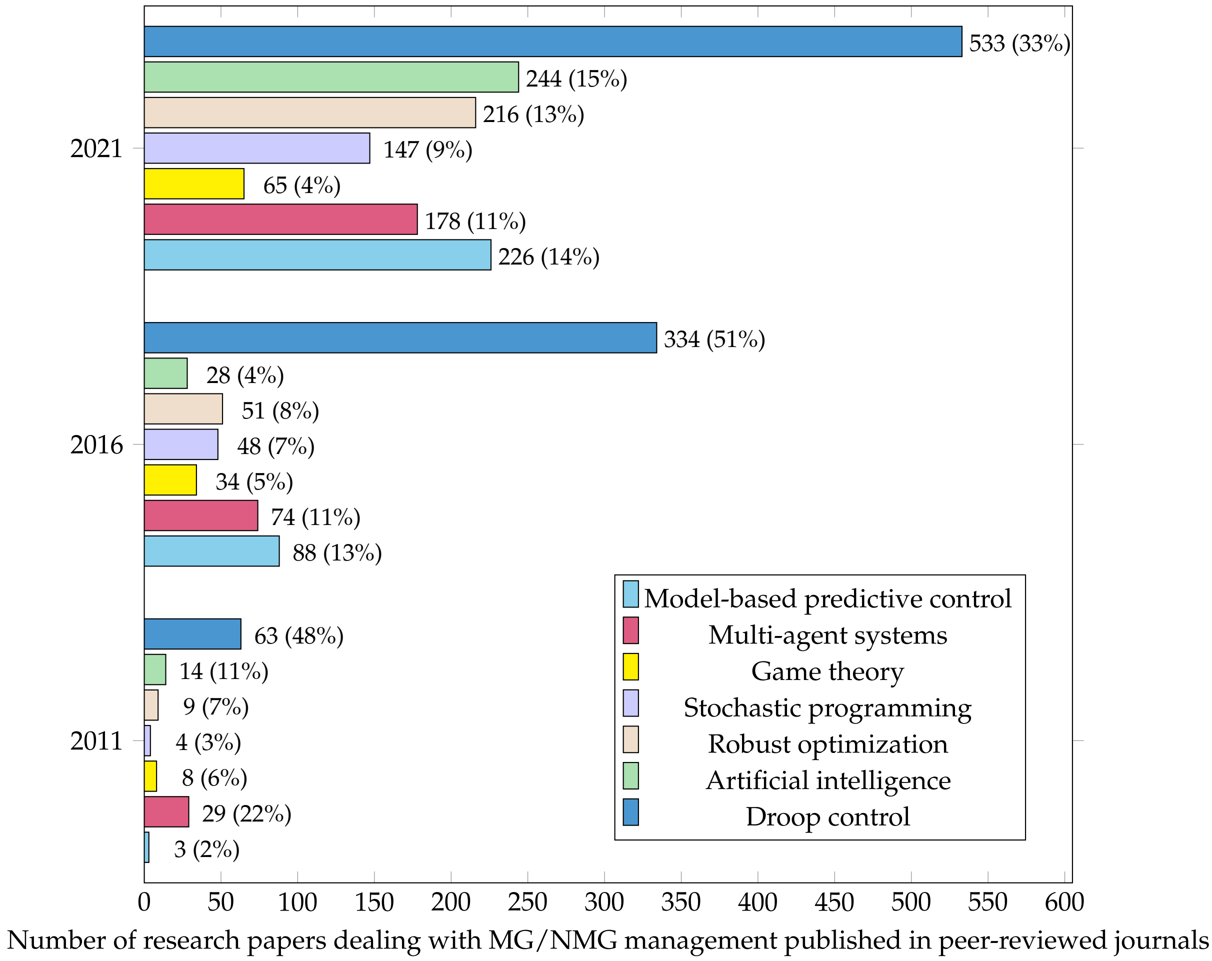

Figure 2. The methods used for MG/NMG management with a focus on years 2011, 2016 and 2021. The research papers considered here—these papers deal with different aspects of MG/NMG management—are published in peer-reviewed journals owned by the leading publishers of scientific content.

Figure 3 is about the number of papers addressing the management of MGs vs. the number of papers addressing the management of NMGs in 2011, 2016 and 2021. Taking a look at this figure, one can clearly see that NMG management is still little discussed by the scientific community in comparison with MG management. Only 15 papers (4%), 67 papers (4%) and 184 (5%) papers address the management of NMG in 2011, 2016 and 2021, respectively. However, the number of papers addressing the management of NMGs has increased tenfold between 2011 and 2021, which reflects a growing interest for efficient strategies dedicated to the management of this kind of interconnected system.

The paper is organized as follows: in Section 2, MGs and NMGs are defined. MG/NMG components are listed and explained. Because the energy management system is a key MG/NMG component, the focus is put on it. Then, Section 3 focuses on research papers recently published in peer-reviewed journals, identifying advances in MG/NMG management, according to the addressed issues. Table 2 summarizes the papers discussed in Section 3. Note that to improve the readability of the paper, for all the highlighted works, their main features, the MG/NMG resources and the noticeable results are summarized in tables. The section ends with a discussion. The paper ends with a conclusion (Section 4).

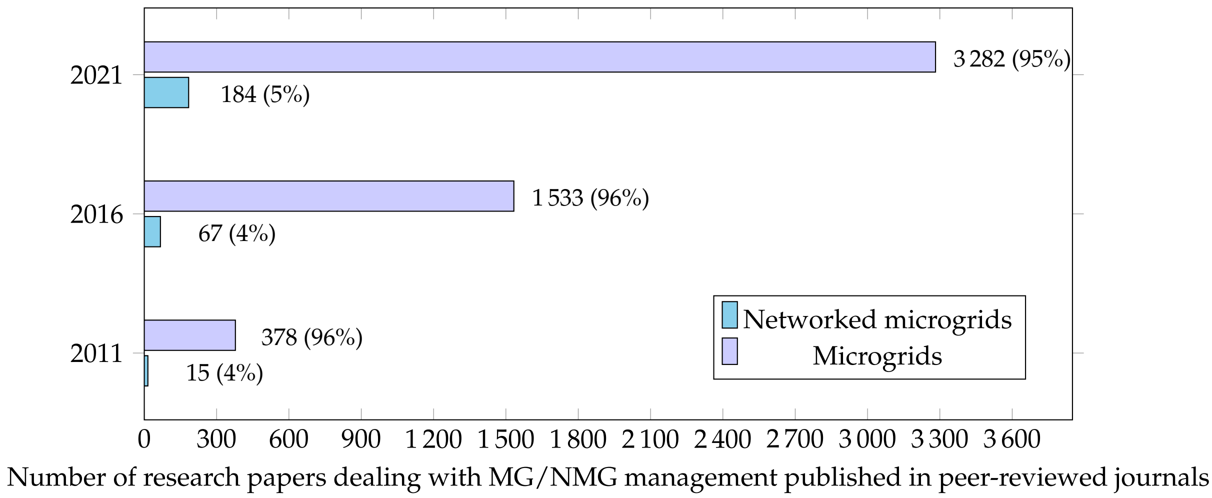

Figure 3. MG management vs. NMG management with a focus on years 2011, 2016 and 2021. The research papers considered here—these papers deal with different aspects of MG/NMG management—are published in peer-reviewed journals owned by the leading publishers of scientific content.

Table 2. Discussed papers highlighting recent advances in MG/NMG management, according to the method used (see Section 3).

Method	Discussed Papers	Section
Model-based predictive control	[59–71]	Section 3.1
Multi-agent systems	[72–81]	Section 3.2
Game theory	[82–90]	Section 3.3
Stochastic programming	[91–98]	Section 3.4
Robust optimization	[99–105]	Section 3.5
Artificial intelligence	[106–118]	Section 3.6
Droop control	[119–128]	Section 3.7
Other programming methods	[129–138]	Section 3.8

2. Microgrids and Networked Microgrids

In this section, microgrids and interconnected (networked) microgrids are first defined (Section 2.1). The different components of a MG are then listed and explained (Section 2.2). In Section 2.3, the focus is put on a key MG/NMG component in the implementation of a management strategy: the energy management system (EMS).

2.1. Definitions

Regarding MGs, several definitions can be found in the literature [21,139–143]. First, MGs can be seen as multiple parallel-connected distributed generators with coordinated control strategies, which are able to operate either in grid-connected or islanded mode. According to Energuide [141], a MG is a small power distribution grid connected to the main grid on a single point acting as a switch. In other words, a MG can simply be defined as a means to integrate distributed generators into the power system [1]. A MG has a power comprised between some kilowatts and some megawatts [139,144,145]. The U.S. Department of Energy [21] defines a MG as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the main grid. A microgrid can connect and disconnect from the grid and, as a result, can operate in grid-connected or islanded mode. A remote microgrid is a variation of a microgrid that operates in islanded conditions". The International Council on Large Electrical Systems (CIGRE) and the Consortium for Electric Reliability Technology Solution (CERTS) define MGs as "electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded". The French Energy Regulation Commission (CRE) [23,143] defines MGs as "small-scale power grids designed to provide a reliable power supply to a small number of consumers. Microgrids combine multiple local and diffuse production facilities, consumption facilities, storage facilities and supervision and monitoring tools for demand management. Microgrids can be directly connected to the power distribution grid (i.e., the main grid) or operate disconnected from the grid (islanding mode). The microgrid concept, likely to concern different system scales (i.e., a building, a district, an industrial or a craft zone, a village, etc.) is being extended to heat and natural gas networks, and can thus be thought out in a multifaceted manner".

In recent years, interconnected (networked) microgrids have emerged as one of the best successors to the current power distribution system. In NMGs, local resources are shared between MGs and cooperative power exchange management is carried out [82]. According to Alam et al. [28], "networked MGs is referred to the interconnection of two or more MGs with an ability to connect distribution system to exchange power among the microgrids and/or the distribution system at the point of common coupling (PCC)". The deployment of NMGs is an interesting way to improve security, efficiency, durability, robustness, reliability, economic profitability and carbon footprint aspects [28,134,146]. In networked MGs, a MG can be islanded for independent operation, along (or not) with other MGs. In this case, energy management systems (EMSs) seek to maximize energy self-sufficiency [28,139].

2.2. MG Components

A MG (or a NMG) is composed of the following components (Figure 4) [32,147]:

- Distributed generators. Sources of distributed generation include on-site renewables, such as wind and solar, waste-to-energy and combined heat and power (CHP). Conventional generation sources (diesel generator for example) may be used for emergency situations or in case MGs are isolated.
- Loads. As highlighted by Gavilema et al. [30], loads, which are critical or not, can be classified into different categories: non-controllable loads, shiftable loads, controllable comfort-based loads and controllable energy-based loads.
- Energy storage systems (ESSs). ESSs—correct sizing of these systems is crucial [148]—are needed to store renewable energy, to perform load shifting or to assist during black starts [149]. In MGs, energy storage systems can either be mechanical, electrochemical or electrical [34,150].
- Electric vehicles (EVs). Because of an acceleration in the adoption of EVs, EV integration in a MG (or in a NMG) environment is critical. There is a need for efficient vehicle-to-grid technologies and optimization techniques.

- An energy management system (EMS) (Section 2.3). The EMS coordinates energy demand and supply between the dispatchable generators and the different loads, while aiming at the fulfilment of technical, economical, and environmental objectives. Supervisory control and data acquisition (SCADA) systems, which can help improving microgrids' reliability, safety and economic benefits [151], are closely linked to EMSs [13]. If the EMS is a predictive one—i.e., a predictive energy management system (PEMS)—a forecast module is involved to predict loads, power generation and energy prices, among the quantities of interest. Accurate forecasts are needed to achieve efficient flux management in MGs and NMGs [152].

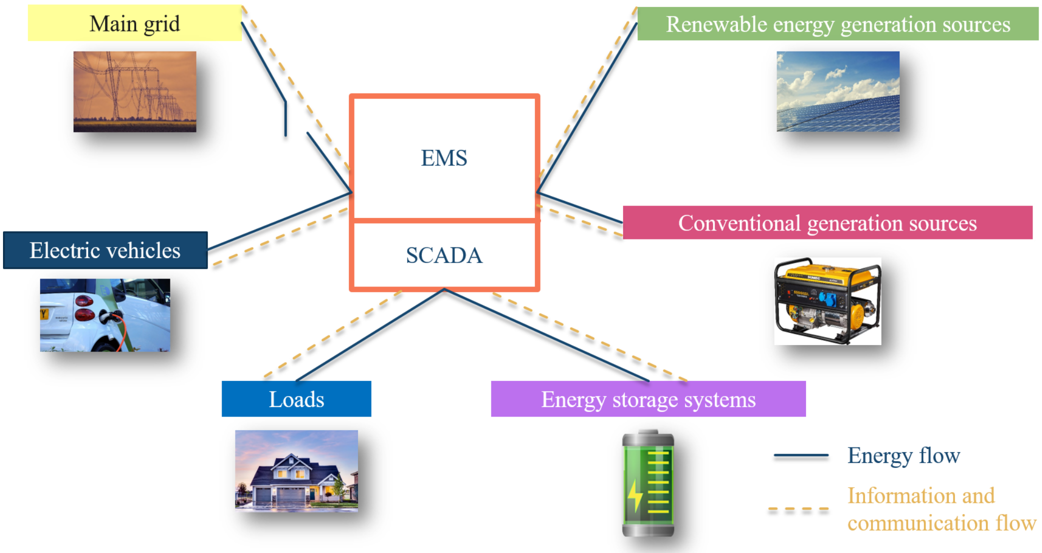

Figure 4. MG components: loads, renewable energy generation sources, conventional generation sources, energy storage systemms, and eletric vehicles. The EMS/SCADA coordinates energy demand and supply between the dispatchable generators and the different loads [32].

2.3. Energy Management System

According to the International Electrotechnical Commission (IEC), an energy management system is "a computer system comprising a software platform providing basic support services and a set of applications providing the functionality needed for the effective operation of electrical generation and transmission facilities so as to assure adequate security of energy supply at minimum cost" [32]. According to the International Organization for Standardization (ISO), "an energy management system involves developing and implementing an energy policy, setting achievable targets for energy use, and designing action plans to reach them and measure progress. This might include implementing new energy-efficient technologies, reducing energy waste or improving current processes to cut energy costs" [153].

EMSs have several functions among which data monitoring, data analytics, and real-time control. EMSs can also account for data uncertainties: for example, Carli et al. [154] propose an EMS based on a robust MPC approach, allowing the consideration of data uncertainties, to minimize the total economical cost, while satisfying comfort and energy constraints; Karimi and Jadid [155] propose a cooperative multi-objective optimization approach for energy management in NMGs, where the renewable generation uncertainty is modeled as a stochastic component. Benefits of EMSs are: power generation dispatch, reactive power support, detecting power quality problems, frequency regulation, energy savings, and reduction of carbon dioxide emissions, to name a few [32,156]. EMSs play a key role in the management of distributed generators and energy storage systems during grid-connected and islanded operation modes. Islanding is an interesting option in case of emergency, for example when an extreme climatic event occurs or if a cyber attack happens, or when power demand is too high and, as a result, consumers can be asked to disconnect from the main grid. In the first case, voltage or frequency is greatly affected [157]. When a fault is detected, smooth transition and synchronization between grid-connected and islanded operation modes has to be achieved [1,119,158,159].

SCADA systems, which consist of both software and hardware components, first enable remote and on-site gathering of data. SCADA systems play also a key role in data visualization, storage, monitoring, and control [36,160]. In addition, SCADA systems can contribute to solving protection and communication issues [55]. A special attention is paid in [161] to security. A possible evolution path towards dynamic MGs is highlighted in [162], in the light of SCADA systems. In this context, new-generation peer-to-peer communication systems are needed. In addition, due to the cyber vulnerabilities introduced by digitalization and an increasing dependency on ICT systems, looking into MG security becomes crucial. One of the newest ways to solve security-related issues is through blockchain. Blockchain is a powerful trustworthy platform for peer-to-peer transaction based on distributed data storage, enabling to keep track of the exchanged data. A review of challenges and opportunities in the energy sector for blockchain is conducted in [163]. As highlighted in the literature, the decentralized structure of blockchain is particularly suitable for implementing control and business processes in MGs, using smart contracts and decentralized applications. In [164], an overview of projects and concepts in relation with blockchain applications in MGs is given. The authors conclude that the most promising use case from the MG perspective is peer-to-peer trading, where energy is locally exchanged and traded between consumers and prosumers. In [165], Canaan et al. address the existing approaches attending to cyber-physical security in MGs, including blockchain. In [166], the possibility of customizing blockchain technologies to satisfy socio-economic requirements of transactive energy management in NMGs is evaluated. In [167], an enhanced blockchain-based data management scheme for MGs is proposed. The aim is to counteract possible false data injection (FDI) attacks. In [168], a hierarchical bidding and transaction structure based on blockchain (HBTS) for MGs is proposed. The bidding strategy effectiveness is verified through experiments. In [169], a blockchain-based energy trading platform for smart homes in a MG is proposed.

In MGs, EMSs can be centralized, decentralized, distributed or hierarchical [29]. Hierarchical control [120,170–173] is commonly used to manage MGs. It consists of different layers to ensure voltage/frequency stability, power sharing and optimal operation. Hierarchical control is defined as having the following four levels, from the fastest to the slowest level [11,29,38,52,56,170,174–176]:

- Level 0, i.e., the inner loop control. This level, which consists of voltage and current loops, deals with managing the output power of renewable energy sources (operation time is in milliseconds).
- Level 1, i.e., the primary control. This level consists of an independent local control for increasing power reliability. It aims at stabilizing frequency and voltage using droop controllers [176] (operation time is in milliseconds to seconds).
- Level 2, i.e., the secondary control. This level deals with monitoring and supervising the MG in order to collect the necessary information from distributed generators and regulating these generators. It compensates the voltage and frequency steady state deviations caused by the primary control [176,177] (operation time is in seconds, minutes, even hours).
- Level 3, i.e., the tertiary control. This level, which deals with managing power fluxes, consists of an interface between the MG and the main grid. It takes into consideration economic factors and determines power flow between the MG and the main grid in order to achieve optimal operation or to minimize power losses when the MG is islanded [176] (operation time is in minutes, hours, even days).

For NMGs, in a centralized structure, all MGs are controlled thanks to a single energy management system, which optimize the operating costs of each MG through preventing load shedding of critical loads [1,32]. Although such an EMS has an uncomplicated implementation with acceptable reliability in islanded mode, it can lead to heavy costs as the structure requires communication infrastructures, and has low flexibility. In a decentralized structure, each MG is equipped with a local control center and operated independently of the other MGs [178]. A MG fulfills its generation and load balance through sharing energy with the main grid or other MGs in its vicinity. In islanded mode, the main objective of each MG is to maintain a reliable power supply to its customers [178,179]. A local generator may export electricity and will enter either in the competitive or collaborative mode with other local generators [1,32]. In comparison with the centralized structure, a decentralized EMS is well-suited to MGs. This kind of EMS, however, is highly dependent on the main grid in interconnected mode, which results in high operating costs. Moreover, such a structure is not beneficial and flexible in islanded mode. The centralized and decentralized approaches have different drawbacks. Centralized EMSs are easier to implement but are cost expensive (due to the communication structure) and difficult to manage [34]. In a decentralized approach, the MGs are more dependent on the main grid as local controllers do not communicate and the quantity of electricity bought from the grid is generally higher [34,180].

In order to tackle these drawbacks, distributed energy management systems have emerged [82,180–182]. Distributed EMSs are defined as a combination of a number of local EMSs and a central EMS. Local EMSs optimize their own resources and inform the central EMS of their needs or if a surplus of energy is available [82,180]. Distributed EMSs have the ability to make mitigating operating cost savings. A central EMS along with local energy management systems perform scheduling, monitoring and rescheduling, and benefits distribution processes. In [82], a hybrid EMS based on canonical coalition games is proposed for cooperative power exchange management of NMGs.

3. MG/NMG Management Strategies

In this section, research papers recently published in peer-reviewed journals, dealing with various aspects of MG/NMG management, are presented and discussed. The main applications and issues addressed by the scientific community are identified. Works concerned by (1) MGs and NMGs operated in islanded mode and (2) MGs and NMGs equipped with EVs are highlighted. Model-based predictive control (Section 3.1), multi-agent systems (Section 3.2), game theory (Section 3.3), stochastic programming (Section 3.4), robust optimization (Section 3.5), artificial intelligence (Section 3.6) and droop control (Section 3.7) are the main considered methods. The way these methods are used to solve complex control and planning tasks is analyzed. The section ends with a discussion (Section 3.9).

3.1. Model-Based Predictive Control

In recent years, model-based predictive control (MPC), an advanced method of process control used to control a process while satisfying a set of constraints, is getting more and more attention from the scientific community. As the deployment of renewable energy-based distributed generators increases, energy management becomes more complex and efficient tools are needed to handle such a complexity. An overview of MPC in a MG context is given in [38]. As highlighted by the papers previously mentioned, MPC is used in recent years for voltage and frequency regulation, distributed generation management, EV and ESS management, or power flow management. Some recent papers are highlighted in the followings in order to give to the reader an overview on how MPC is used for MG/NMG management [59–71].

In [59], a novel cooperative MPC framework is proposed for urban districts comprising multiple MGs sharing certain distributed energy resources. Each MG is equipped with an MPC-based energy management system, responsible for optimally controlling flexible loads, heating systems, and local power generators. The proposed coordination algorithm is distributed and guarantees constraints satisfaction. Each MG achieves cost savings. In addition, the quantity of electricity extracted from the main grid is lowered. In [60], a genetic algorithm is used by Yang et al. to optimize the ESS schedule in a NMG composed of 321 households in Norway (the *Demo Steinkjer*). Using MPC, a compromise has been entered between two objectives, maximizing the economic cost and extending the battery's lifetime. Cost savings have been realized whereas the battery's lifetime has been preserved. In [61], a model predictive controller is proposed to regulate frequency fluctuations in a grid-connected MG. In order to mitigate power fluctuations caused by energy demand and renewable energy sources, a dynamic energy interaction scheme is also proposed. As stated by the authors, a stable system frequency is hard to achieve. In comparison with a PI (proportional–integral) controller, the MPC controller is faster and achieves better results. In [62], an MPC-based decentralized control scheme is proposed for hybrid source converters and parallel-connected voltage source inverter (VSI) in an islanded MG. As an interesting result, fluctuations in PV power generation can be smoothened by controlling the PV converter. In addition, the strategy maintains the DC-link voltage and state of charge balancing among batteries. The active and reactive power sharing between distributed generators can be achieved by the proposed control scheme under fluctuating power generation, various load conditions and mismatched feeder impedance. Wu et al. [63] have used MPC to enhance robustness to multi-uncertainty of electric vehicles in a MG, in coordination with wind energy. Feedback from aggregated EVs is used for higher forecasting accuracy. In a standalone MG equipped with an energy storage system, Ryu et al. [64] have used MPC to improve hosting capacity of solar photovoltaics and EV integration. The effectiveness of the proposed controller is demonstrated via numerical simulations. Using MPC, frequency deviation has been reduced to zero by [65] in an islanded MG. Diesel generators and EVs has been put to good use. In [66], a new control strategy based on MPC with seamless transfer characteristics for a grid-connected voltage-source inverter is presented. The objectives of the proposed MPC controller are decoupled power control in grid-connected mode, load voltage control in islanded mode, and seamless transition between modes of operation. The effectiveness of the proposed control strategy has been validated. In [67], a robust MPC-based energy management system, which is formulated using a fuzzy prediction interval model as prediction model, is proposed for MGs. A MG in Chile (Huatacondo) has been used as a test bench. The results highlight that the proposed MPC-based energy management system increased the robustness of the MG by using a diesel generator as a spinning reserve. However, the operating costs are slightly increased. In a MG composed of a large number of power generators, Nozal et al. [68] have decided for a genetic algorithm as an optimizer for the proposed MPC controller in order to reduce operating costs in this complex system. Good results are achieved. In [69], Gust et al. compare two different strategies for MG management. The first one is a reactive strategy where no forecast is required, a greedy heuristic is used. The second one is an MPC-based strategy. The total economic cost is significantly reduced with the MPC-based strategy. In the InterFlex H2020 research project framework, Bogdabovic et al. [70] have demonstrated an MPC-based approach for MGs with an important proportion of renewable energy sources. Artificial neural networks were used as forecasting tool. A central battery system is used as grid-forming unit in order to balance the MG. Simulation results show the effectiveness of the proposed approach. In particular, smart management of energy storage allows reducing exchanges with the main grid and, as a result, smooth islanding (with no voltage or frequency disturbances). The demonstration is based on E.ON's MG in Simris (Sweden). Finally, a coordinated optimization framework embedded in an MPC scheme is proposed by Ouammi et al. [71] for power flow management in a cooperative NMG with multi-greenhouses. As an interesting result, the MPC scheme is capable of ensuring the power supply without any support from the main grid, reaching the objective of net zero energy greenhouses.

For all the papers highlighted in this section, the main features, MG/NMG resources, and noticeable results are summarized in Table 3. If a paper deals with MG islanded operation, this is highlighted in the table.

Table 3. A focus on papers dealing with model-based predictive control (MPC) for MG/NMG management. CHP stands for combined heat and power. EMS stands for energy management system. ESS stands for energy storage system. MG stands for microgrid. NMG stands for networked microgrid. PCC stands for point of common coupling. PI stands for proportional integral. RES stands for Renewable energy source. VSI stands for voltage-source inverter. WT stands for wind turbine.

Syst.	Main Features	MG/NMG Resources	Islanded Op.	Noticeable Results	Ref.
NMG	A cooperative MPC framework is proposed for energy management; each MG is equipped with a local MPC-based EMS	Heat pumps, CHP plants, ESSs	-	Cost savings are achieved; the amount of electricity extracted from the main grid is lowered	[59]
NMG	MPC is used for ESS management, a genetic algorithm enables optimizing the ESS schedule	PV solar panels, WTs, ESSs	-	Economic cost is maximized; battery's lifetime is extended	[60]
MG	MPC is compared with PI control for regulation of frequency fluctuations	WTs, diesel generators	-	Frequency regulation is improved using MPC	[61]
MG	A decentralized MPC control scheme is proposed for hybrid source converters and parallel-connected VSIs	PV solar panels, ESSs	✓	Voltage quality, load sharing at the PCC and load conditions are enhanced	[62]
MG	MPC is used for EV management; feedback from aggregated EVs is used for higher forecasting accuracy	WTs, EVs	-	Robustness to multi-uncertainty of EVs is enhanced	[63]
MG	A 2-level MPC-based EMS is proposed	PV solar panels, diesel generators, ESSs, EVs	✓	Hosting capacity of solar PV, EV integration, and voltage quality are improved	[64]
MG	MPC is used for frequency regulation in a MG equipped with EVs	Diesel generators, EVs	✓	Frequency deviation is reduced to nearly zero	[65]
MG	MPC with seamless transfer characteristics is proposed for VSIs	-	✓	Voltage regulation is improved	[66]
MG	A robust MPC-based EMS is proposed	PV solar panels, WTs, diesel generators, ESSs	✓	Robustness is improved	[67]
MG	MPC is used for MG management; a genetic algorithm is used as an optimizer for the proposed MPC controller	PV solar panels, WTs, microturbines, diesel generators	-	Operating costs are reduced; the ESS is better managed	[68]
MG	An MPC-based strategy is proposed to improve MG operation under real-world conditions	PV solar panels, WTs	-	Total economic cost is significantly reduced	[69]
MG	MPC is used in a MG demonstration project with an important proportion of renewable energy sources	PV solar panels, WTs, diesel generators, ESSs	✓	RESs are favoured; islanding operation time is extended	[70]
NMG	MPC is used for power flow management in a highly constrained NMG	PV solar panels, WTs, water tanks, ESSs	-	Power supply is ensured without any support from the main grid	[71]

3.2. Multi-Agent Systems

As stated by Dkhili et al. [36], numerous definitions have been given to explain multi-agent systems. An agent is "a free-standing entity situated in a partially or totally observable environment to which it is able to react. An agent is, controversially so, characterized as "intelligent". This refers to its ability to perceive changes in its environment and make decisions autonomously". An agent will percept a situation, take a decision and act from its own drawback. However, when the problem is too complex, a single agent will not be able to solve it: several agents, acting as a multi-agent system are needed. We can distinguish three MAS architectures: a centralized architecture where each agent is controlled by a single control center, a distributed architecture where each agent handles its own part of the network, and a hierarchical architecture where some agents are above the command chain, over other agents [53]. MAS has been vastly used and has the following features: flexibility, extensivity, fault tolerance, communication and cooperation. A comprehensive review of MAS-based distributed coordinated control and optimization in MGs and NMGs is proposed by Han et al. [54]. Some recent papers are highlighted in the followings in order to give to the reader an overview on how MAS is used for MG/NMG management [72–81].

In [72], MAS is introduced for intelligent scheduling of NMG autonomy-cooperative operation. A 3-layer coordinate control system framework is designed. Results suggest that the proposed strategy can be applied to the optimal scheduling of MG operation, both in grid-connected and islanded modes. In addition, the authors highlight on one hand that energy storage affects MG scheduling and on the other hand that price-based demand response can smooth the load demand curve and improve MG operation. In [73], Kong et al. establish a multi-agent bidding and trading mechanism of distributed energy resources in a commercial MG connected to the main grid. In addition, an artificial immune algorithm is improved to search for the optimal strategy. The strategy provides an effective coordination and interaction between the main grid and the NMG. Resource and benefit distribution is improved. In [74], a multi-agent approach to modeling and simulation of MG operation with vehicle-to-grid system included is presented by Egbue et al. The authors looked for the minimization of the electricity extracted from the main grid. Finally, Khan et al. [75] have proposed an MAS-based technique for electrical power delivering and electricity price uncertainties control to attain robust energy scheduling of the domestic loads and EV aggregator. Local agents operate and accomplish their respective tasks in an autonomous way, making the MG smarter and reliable. The trading of electrical power and energy balancing jobs over the required load demand has also been accomplished. MG reliability has been significantly improved. In [76], a distributed hierarchical control framework based on MAS with coordinated secondary and tertiary levels is proposed for islanded MGs. The multi-agent system is designed to cover both control levels for cyber–physical implementations. The proposed control framework has been validated in real time and under hardware-in-the-loop conditions using a cyber–physical MG platform. In [77], Morstyn et al. propose the use of a novel multi-agent sliding mode control for state of charge balancing between distributed DC MG battery energy storage systems. The strategy (1) ensures the battery energy storage systems are either all charging or all discharging, thus increasing efficiency and reducing degradation of battery lifetime (2) achieves faster state of charge balancing and (3) avoids overloading the batteries during high-load periods. In [78], a MAS-based decentralized approach with fault tolerance control is proposed for NMGs. The results show that the frequency and voltage stay at the prescribed values and the system is more tolerant to failures than in a centralized approach. In [79], a 3-layer MAS architecture is established by Chen et al. for NMG coordinated operation. A multi-time scale energy optimization scheme, including day-ahead scheduling and real-time dispatch, is proposed by the authors. Real-time dispatch aims at minimizing the regulation cots of each MG, with the help of the fast tracking ability of controllable distributed generators and energy storage systems. Results show that a cooperative strategy is better for reducing regulation costs in a NMG than a non-cooperative one. A multi-agent (model-free) reinforcement learning approach is proposed by Fang et al. [80] to achieve distributed energy scheduling and strategy-making in the case of a regional NMG. An independent market strategy is learnt. In [81], a demand response (DR) strategy built on an incentive-based demand response (IBDR) model is proposed to minimize the daily operating costs of hybrid MGs. Three case studies were considered to derive the most reduced daily operating costs. A MAS is used to make sure that all the MG energy sources are properly managed. Using smart agents enables the MG to perform optimally.

For all the papers highlighted in this section, the main features, MG/NMG resources, and noticeable results are summarized in Table 4. If a paper deals with MG islanded operation, this is highlighted in the table.

Table 4. A focus on papers dealing with multi-agent systems (MASs) for MG/NMG management. DER stands for distributed energy resource. DR stands for demand response. ESS stands for energy storage system. IBDR stands for incentive-based demand response. MG stands for microgrid. NMG stands for networked microgrid. WT stands for wind turbine.

Syst.	Main Features	MG/NMG Resources	Islanded Op.	Noticeable Results	Ref.
NMG	MAS is introduced for intelligent scheduling of NMG; a 3-layer coordinate control system framework is designed	PV solar panels, WTs, gas turbines, ESSs	✓	Optimal scheduling of MG operation both in grid-connected and islanded modes is achieved	[72]
NMG	A MAS-based bidding and trading mechanism of DERs is proposed	PV solar panels, WTs, diesel generators, microturbines, ESSs	-	Coordination and interaction between the NMG and the main grid are effective	[73]
MG	A MAS-based approach for MG operation with included vehicle-to-grid system is proposed	PV solar panels, WTs, ESSs, EVs	-	The amount of electricity extracted from the main grid is minimized	[74]
MG	An MAS-based EMS with a virtual bidding strategy is proposed	PV solar panels, hydro generator, diesel generator and batteries	-	Energy sources are optimally dispatched, economic viability and secure operation are achieved	
MG	A MAS-based technique for electrical power delivering and electricity price uncertainties control is proposed	PV solar panels, WTs, fuel cells, ESSs, EVs	-	MG reliability is improved; robust energy scheduling is achieved	[75]
MG	A 3-layer MAS for distributed hierarchical control is proposed for islanded MGs	Cyber-physical MG platform	✓	Effectiveness of the method is validated in real time and under hardware-in-the-loop conditions	[76]
MG	A MAS-based sliding mode control for state of charge balancing is proposed	PV solar panels, ESSs	✓	Current balance and power quality are improved	[77]
NMG	A MAS-based decentralized approach with fault tolerance control is proposed	PV solar panels, ESSs, microturbines	-	Frequency and voltage control is efficient; fault tolerance is improved	[78]
NMG	A 3-layer MAS architecture is proposed for NMG coordinated operation; a 2-level optimization with cooperation is done	PV solar panels, WTs, ESSs, fuel cells, microturbines	-	Regulation costs are reduced	[79]
NMG	A MAS-based reinforcement learning approach is proposed for distributed energy scheduling in NMGs	PV solar panels, WTs	-	Economical profits are increased	[80]
MG	A MAS-based DR strategy built on an IBDR model is proposed	PV solar panels, WTs, ESSs	-	Daily operating costs are reduced; the strategy enables all the energy sources to be properly managed	[81]

3.3. Game Theory

As NMGs emerge, energy management evolves. The aim of NMGs is to achieve both resilience and stability through power exchange among the MGs and to smooth the penetration of distributed generation into the power distribution grid. According to Dkhili et al. [36], "game theory is a branch of applied mathematics used to tackle a multitude of problems where the components of the system have evolving interdependent relationships". Game theory (GT) allows modeling the behavior of subsystems' agents involved in strategic situations where the outcome of a player's actions is function of its choices, these of other players, and exterior factors. Different kinds of cooperation might be used in the context of NMGs:

- Selfish mode: every MG only considers the main grid as an auxiliary aid, MGs do not share their respective resources.
- Selfish cooperation: energy exchanges between MGs exist, but only when a MG has power surplus and if these exchanges do not have any effect on management. A MG pursues its own interest first.
- Collective cooperation: the NMG is considered as a whole, optimization is done for the system and benefits will be shared proportionally to the respective contributions of the MGs.

Some recent papers are highlighted in the followings in order to give to the reader an overview on how GT is used for MG/NMG management [82–90]. First, a hybrid EMS architecture based on canonical coalition games for cooperative power exchange management in NMGs, interconnected with the main grid via a macro station, is proposed by Querini et al. [82]. A central EMS and local EMSs perform three main processes: a scheduling process, a monitoring and rescheduling process, and a benefits distribution process. By comparing the proposed architecture with a coalition formation game-based algorithm, the authors have concluded that the problem of power exchange management in NMGs should be modeled as a canonical coalition game and not as a coalition formation game. In [83], two techniques based on game theory, i.e., Shapley values and Nash equilibrium, are proposed by Ali et al. for correct sizing of a networked grid-connected MG. System optimization is based on a multi-objective imperialistic competition algorithm (ICA). The NMG is composed of two different grid-connected MGs with common electrical load and might have different combinations of generation resources including wind turbine, photovoltaic panels, and batteries. Different kinds of cooperation are studied in the paper and the best results were obtained when considering the Shapley values and if actors play in a cooperative way. In another paper from the same authors [84], the selected technique for optimal planning of a networked grid-connected MG (i.e., for capacity allocation of generation resources and batteries and to maximize the annual profit of each MG) is the Nash bargaining game. A particle swarm optimization (PSO) algorithm is used to find the most feasible Nash bargaining solution. According to the authors, the proposed technique provided the best results (among the different techniques the authors have tried). A coalitional-game-theory-based local power exchange algorithm is proposed by Mei et al. [85] to identify incentives for coalitional operation. The proposed method also helps MGs trade power locally with neighboring MGs, in order to meet their own power requirements while achieving higher expected individual utility. Simulation results show that the proposed coalitional-game-theory-based local power exchange algorithm is capable of increasing individual MG utility in the network. In [86], a strategy for day-ahead economic dispatch based on game theory, capable of solving mixed integer programming problems, is proposed by Sun et al. As an interesting statement, the price of electricity is considered as an independent variable in the optimization process. A case study (i.e., a MG with one utility and two users who want to lower costs) allows assessing the effectiveness and practicability of the strategy. The latter ensures that each actor achieves its own economic goals. Hu et al. [87] introduce a novel multi-energy management framework for pelagic islanded MG clusters (PIMGCs). In this framework, the operators on “resource” islands sell energy resources while the aggregators and users on “load” islands dispatch and consume energy resources, respectively. The operators determine their daily optimal energy supply in a distributed collaborative way, each aggregator determines its daily optimal energy demand and hourly optimal energy usage, and each user determines its hourly optimal energy consumption. A hierarchical day-ahead distributed algorithm is proposed to obtain the Nash equilibrium strategy: the operators minimize their aggregate operational cost, each aggregator maximizes its revenue and each user maximizes its payoff. Simulation results show the effectiveness and benefits of the proposed multi-energy management framework for the PIMGCs. In [88], Yu et al. propose a MG energy trading Bayesian game (METBG) for time-of-use price based energy trading between MGs. The utility model of players is established using a Bayesian-Stackelberg game. The price mechanism solution has been rigorously derived and an iterative algorithm is presented to achieve the equilibrium solution. As interesting results, the METBG-based scheme is capable of guiding the EVs to operate as an energy storage system. The price mechanism of METBG makes MGs willing to participate in the power exchange with more surplus energy and the energy storage’s charging/discharging capacity is increased. In [89], Javanmard et al. present a 2-stage framework in which distribution feeder reconfiguration is implemented in order to satisfy technical and security constraints. In addition, MG day-ahead scheduling is carried out by a game-theoretic approach in order to avoid market power. A shiftable-load demand response program is implemented. The optimization problem is modeled as a mixed-integer quadratically constrained programming (MIQCP) problem. Results indicate reduced market power and operating costs. In [90], Aziz et al. present a game theoretic analysis for community MGs including a coalition of prosumer households with photovoltaic solar panels. Using an application of mean field game theory, the authors highlight that Nash equilibrium strategies enable minimizing both the households' energy generation cost and the energy consumption cost.

For all the papers highlighted in this section, the main features, MG/NMG resources, and noticeable results are summarized in Table 5. If a paper deals with MG islanded operation, this is highlighted in the table.

Table 5. A focus on papers dealing with game theory (GT) methods for MG/NMG management. EMS stands for energy management system. ESS stands for energy storage system. MG stands for microgrid. MIP stands for mixed integer programming. NMG stands for networked microgrid. PSO stands for particle swarm optimization. WT stands for wind turbine.

Syst.	Main Features	MG/NMG Resources	Islanded Op.	Noticeable Results	Ref.
NMG	A hybrid EMS based on canonical coalition games for cooperative power exchange management is proposed	PV solar panels, WTs	-	Power exchange management in NMG should be modeled as a canonical coalition game	[82]
MG	Two GT techniques are proposed for sizing and comparative analysis of a grid-connected NMG	PV solar panels, WTs, ESSs	-	Shapley values provide the best results; actors have to play in a cooperative way	[83]
MG	The Nash bargaining game is selected for MG optimal planning; a PSO algorithm is used	PV solar panels, WTs, ESSs	-	Optimal planning is achieved	[84]
NMG	A coalitional-game-theory-based local power exchange algorithm is proposed	PV solar panels, WTs	-	Individual MG utility in the network is increased	[85]
NMG	A GT-based strategy for day-ahead economic dispatch capable of solving MIP problems is proposed	PV solar panels, ESSs	-	Each actor achieves its own economic goals	[86]
NMG	A multi-scale energy management strategy and a hierarchical day-ahead distributed algorithm are proposed	PV solar panels, WTs, ESSs	✓	Operating costs are reduced; each aggregator maximizes its revenue; each user maximizes its payoff	[87]
NMG	A MG energy trading Bayesian game is proposed	PV solar panels, WTs, ESSs, EVs	-	Total economic cost is reduced; energy storage's charging and discharging capacity is increased	[88]
NMG	A game-theoretic approach is used for day-ahead scheduling; a shiftable-load demand response program is implemented	PV solar panels, WTs, gas turbines, ESSs	✓	Market power, operating costs, losses, and voltage deviations are reduced	[89]
MG	A game theoretic analysis for community MGs is proposed	PV solar panels, ESSs	-	Nash equilibrium strategies minimize both the energy generation and energy consumption costs	[90]

3.4. Stochastic Programming

Stochastic programming (SP) is an optimization framework dealing with decision-making under uncertainty [183]. Some recent papers are highlighted in the followings in order to give to the reader an overview on how SP is used for MG/NMG management [91–98].

In [91], a mixed integer nonlinear programming (MINLP) model is presented for the optimal operation of islanded droop-based MGs. A scenario-generation approach is used for uncertainty consideration in the optimization model. Results have shown that the total operating costs are reduced. Reference is a deterministic approach. In [92], a combined stochastic programming and receding horizon control strategy is proposed by Li et al. for energy management under uncertainty in MGs. A proper strategy is also proposed by the authors in order to maintain the SP model as a mixed integer linear constrained quadratic programming (MILCQP) problem. The problem is solvable without resorting to any heuristics algorithms. Results demonstrate the superiority of the proposed strategy for both islanded and grid-connected operating modes. The work presented in [93] by Guo et al. focuses on the optimal risk assessment of a MG equipped with a parking lot of EVs. A DR program and high penetration of wind and solar energies are considered for enhancing financial and environmental goals. The proposed model is formulated as a mixed-integer linear 2-stage stochastic model. Results indicate that the integration of EVs and demand response reduces the MG total operating cost. Besides, CO_2 emissions and renewable power curtailment are reduced. In [94], a mixed-integer linear programming framework-based model is proposed for optimal operation of a grid-connected smart building. Results confirm that the proposed stochastic approach is capable of lowering the total expected daily cost. In [95], the operation of a MG with dispatchable generators is formulated as a 2-stage stochastic optimization problem, wherein day-ahead (DA) and real-time (RT) stages are seen in one shot. DA and RT decision variables are determined in order to minimize the MG operating costs. Flexibility resources are used to increase MG flexibility. In [96], a regret-based risk-averse stochastic production task and energy management (PTEM) model for industrial MG is proposed. The model is formulated as a mixed-integer linear programming problem based on stochastic programming considering uncertainties of day-ahead electricity market prices and PV power generation. Results highlight that the proposed PTEM approach is effectively risk-averse. In [97], a novel aggregate production planning model with onsite renewable energy (APPM-RE) is proposed. The model is a 2-stage stochastic program considering uncertainties (in particular in power generation). The results show that the model can assist firms in accurately anticipating the effect of transitioning to wind- and solar-based MGs. In addition, numerical experiments show that the most affordable manner to decarbonize production, transportation, and warehousing is through prosumer MG operation. In [98], a chance constrained stochastic conic program model for NMG planning is proposed. Stochastic scenarios are used to capture randomness and a joint chance constraint is proposed to control the operational risks. Numerical results demonstrate the effectiveness of the proposed planning model and the superior performance of the developed algorithm.

For all the papers highlighted in this section, the main features, MG/NMG resources, and noticeable results are summarized in Table 6. If a paper deals with MG islanded operation, this is highlighted in the table.

Table 6. A focus on papers dealing with stochastic programming (SP) for MG/NMG management. APPM-RE stands for aggregate production planning model with onsite renewable energy. DG stands for distributed generator. ESS stands for energy storage system. MILCQP stands for mixed integer linear constrained quadratic programming. MILP stands for mixed-integer linear programming. MINLP stands for mixed-integer nonlinear programming. MG stands for microgrid. NMG stands for networked microgrid. PTEM stands for production task and energy management. WT stands for wind turbine.

Syst.	Main Features	MG/NMG Resources	Islanded Op.	Noticeable Results	Ref.
MG	A stochastic MINLP model is proposed for optimal operation of islanded droop-based MGs	DGs, WTs, ESSs	✓	Total operating costs are reduced	[91]
MG	A combined SP and receding horizon control strategy is proposed; the problem is formulated as a MILCQP one	PV solar panels, WTs, ESSs	-	The strategy is efficient for islanded and grid-connected modes; operating costs are reduced	[92]
MG	An optimal risk assessment strategy is proposed, the model is formulated as a MILP 2-stage stochastic one	PV solar panels, WTs, diesel generators, EVs	✓	Integration of EVs and demand response reduce total operating costs	[93]
MG	A MILP framework-based model for optimal operation of a MG is proposed	PV solar panels, ESSs, EVs	-	Total expected daily cost is lowered	[94]

Table 6. *Cont.*

Syst.	Main Features	MG/NMG Resources	Islanded Op.	Noticeable Results	Ref.
MG	The operation of a MG equipped with dispatchable generators is formulated as a 2-stage stochastic optimization problem	PV solar panels, WTs, ESSs, EVs	-	MG flexibility is increased; operating costs are reduced	[95]
MG	A regret-based risk-averse stochastic PTEM model for industrial MG is proposed; the model is formulated as a MILP SP-based problem	PV solar panels, microturbines	-	The proposed PTEM approach is effectively risk-averse; economic cost is reduced	[96]
MG	An APPM-RE model is proposed; the model is a 2-stage SP considering uncertainties	PV solar panels, WTs, ESSs	-	The model can assist firms in accurately anticipating the effect of transitioning to wind- and solar-based MGs	[97]
NMG	A chance constrained stochastic conic program model for NMG planning is proposed	PV solar panels, microturbines, ESSs	✓	Operational risks are controlled; the proposed planning model is effective	[98]

3.5. Robust Optimization

Robust optimization (RO) methods are used to solve functions with random parameters and uncertainties that can vary over time. In such methods, values of the uncertain parameters are defined by a continuous set [30]. Some recent papers are highlighted in the followings in order to give to the reader an overview on how RO is used for MG/NMG management [99–105].

In [99], a 2-stage robust optimization model is established, considering uncertainties. It aims to find a balance between economy and robustness of MG operation. The robust equivalent representation proposed by Yang et al. includes the robust equivalent characterization of both photovoltaic power generation and wind power generation outputs. In order to solve the problem, the Benders dual algorithm is used by the authors. The simulation results show that the system's robustness can be achieved by solving the robust adjustment parameters, while the operating cost can be reduced. In [100], the impact of two representative demand response programs, i.e., price-based and incentive-based demand response programs, and batteries sizing on the operation of NMGs is analyzed by Hussain et al. Robust optimization is used to realize forecast uncertainties. In addition, worst-case scenarios of renewables, loads, and prices are considered. Operating costs of the considered NMG have been reduced for increases in both demand response intensity and batteries' size. In [101], a robust distributed energy management scheme for NMGs is proposed. It aims to optimize the total operating cost of NMGs through the trading of energy with neighboring MGs and the main grid. Uncertainties are handled using an adjustable robust optimization technique. A 4-MG case study is considered in order to validate the proposed approach. Operating costs are reduced. In [102], a two-stage robust scheduling model is proposed to reduce the operating cost of NMGs and optimize electric power dispatch. The uncertainties associated with existing loads, renewable energy sources, and EV usage are taken into consideration. The optimization problem is formulated as a MILP problem and solved using a column and constraint generation algorithm. The feasibility of the proposed approach is demonstrated. Its superiority in terms of economic cost and convergence performance in comparison with existing robust optimization methods is demonstrated thanks to numerical case studies. In [103], Adineh et al. propose a method based on robust optimization to reduce voltage harmonic distortion. A central controller receives voltage harmonic distortion measurements, optimizes the global information and sends back the optimal voltage harmonic components to the local controller of each distributed generator. The results highlight the robustness and efficiency of the controller. In [104], a robust game-theoretic optimization model is developed for NMG economical operation by considering the renewable-based distributed generators uncertainty. The batteries' charging and discharging power is predicted using the column and constraint generation algorithm, particle swarm optimization, and a Markov decision process model of random variables. Suggestions regarding the battery operation mode are given by the authors. Simulation results show the ability of the proposed approach to tackle the uncertainty of renewable-based distributed generators. In [105], a two-stage robust day-ahead optimization model, in which a hierarchical frequency control structure is defined, is proposed for resilient MG operation. The MG operating costs are reduced while sufficient primary and secondary reserves are scheduled to restrict frequency deviations and avoid load shedding under the worst-case realization of islanding events. A column-and-constraint generation algorithm is used to solve the problem. Numerical test cases show the effectiveness of the proposed approach.

For all the papers highlighted in this section, the main features, MG/NMG resources, and noticeable results are summarized in Table 7. If a paper deals with MG islanded operation, this is highlighted in the table.

Table 7. A focus on papers dealing with robust optimization (RO) for MG/NMG management. DG stands for distributed generator. DR stands for demand response. ESS stands for energy storage system. MG stands for microgrid. NMG stands for networked microgrid. WT stands for wind turbine.

Syst.	Main Features	MG/NMG Resources	Islanded Op.	Noticeable Results	Ref.
MG	A 2-stage RO model is proposed for balancing economy and robustness of MG operation	PV solar panels, WTs, microturbines, ESSs	-	System's robustness is achieved; operating costs are reduced	[99]
NMG	The impact of price-based and incentive-based DR programs and batteries sizing on NMG operation is analyzed	PV solar panels, WTs, ESSs	-	Operating costs are reduced	[100]
NMG	A robust distributed energy management scheme is proposed	PV solar panels, WTs, diesel generators, ESSs	-	Operating costs are reduced	[101]
NMG	A 2-stage robust scheduling model is proposed	PV solar panels, WTs, fuel cells, microturbines, EVs	-	Operating costs are reduced; electric power dispatch is optimized	[102]
MG	A RO-based method is proposed to reduce voltage harmonic distortion	DGs	✓	The developed controller is robust and efficient; voltage harmonic distortion is reduced	[103]
NMG	A robust game-theoretic optimization model is proposed for NMG economical operation	PV solar panels, WTs, ESSs	-	The uncertainty of renewable-based distributed generators is tackled	[104]
MG	A 2-stage robust day-ahead optimization model is proposed for resilient MG operation	DGs, ESSs	✓	Operating costs are reduced; load shedding is avoided during islanding events	[105]

3.6. Artificial Intelligence

Artificial intelligence (AI) methods are nowadays very popular methods. As previously stated in the paper, artificial intelligence—mainly machine and deep learning—is used in forecasting. As highlighted in the following papers [106–118], artificial intelligence, in particular artificial neural networks and fuzzy/neuro-fuzzy systems, can also be used in the management of MGs and NMGs. These papers are highlighted in the followings in order to give to the reader an overview on how AI is used in the domain.

In [106], a novel strategy, which combines an analysis of power consumption with a model for anomaly detection, is proposed for addressing the energy shortages in rural areas of Africa and the low energy efficiency of off-grid solar power systems. Machine learning is used to detect anomalies. The model is nonintrusive and zero-training-cost. The proposed approach increases the utilization of local renewable energy sources and improves residents' experience. In [107], a 2-stage reconfigurable framework is proposed for near real-time MG operational planning. An artificial neural network is used to predict energy dispatch decisions. It demonstrates robust predictive performance. In [108], a decision-tree-based peak shaving algorithm is proposed for islanded MGs. Simulation case studies are conducted under various load conditions and the results are compared with those of conventional techniques. The peak load demand is effectively mitigated while generation units are efficiently operated. In [109], a deep reinforcement learning-based secondary control algorithm is proposed for MGs in islanded mode. The deep deterministic policy gradient controller decides for the output power of the storage systems to guaranty voltage and frequency stability. The performance of the controller is compared to the one of droop controllers, considering a short-circuit event, feeder and load disconnections. Results show an important reduction of voltage and frequency deviations. In [110], multi-agent reinforcement learning is used to control a MG in a mixed cooperative and competitive setting. The agents control a hybrid energy storage system; the aim is to maximize the utilization of renewables and reduce the energy costs. Moreover, an aggregator agent trades with external MGs competing against one another and competing against the aggregator in order to reduce their own energy bills. Renewable energy utilization is increased and energy bills are reduced. In [111], both the design and validation of an online-trained ANN-based control system for AC/DC MGs are investigated. Adaptive artificial neural networks are used to track the maximum power point of distributed generators and to control the power exchanged between the front-end converter and the main grid. In addition, a fuzzy logic-based power management system is proposed. Results demonstrate the effectiveness, robustness, and self-adaptation ability of the proposed control approach. In [112], a flexibility based operational planning paradigm is applied to MG energy dispatch. A decision tree-based dispatch strategy, which can provide feasible and near optimal decisions, is proposed by the authors. Its computational efficiency is very high.

In [113], a knowledge-based neuro-fuzzy system, i.e., an adaptive neuro-fuzzy inference system (ANFIS), is used to control frequency and power sharing among distributed generators in a full renewable energy based MG while working in different areas of the operating points. The ANFIS rules and configuration are introduced to handle the complexity of larger MGs. Effectiveness of the proposed approach is demonstrated thanks to two case studies. Results suggest that the developed ANFIS controller, in comparison to conventional controllers such as proportional–integral (PI) controllers, is able to satisfy power sharing among distributed generators while better regulating frequency. In [114], Cheng et al. propose the concept of small-type DC MG as well as control methods for power converters and generators. A DC-MG-based power generation system which is connected to the main grid is considered. The system is composed of a photovoltaic array, a wind generator, fuel cells and an energy storage system. Fuzzy controllers and a dynamic programming method are suggested by the authors in order to increase the injected power and balance the power flow and the voltage level of the distributed generators. Energy storage enables overcoming power flow issues and stabilizing the voltage level. Results show that good operation performance for different load conditions is provided by the proposed control method. In [115], an approach for MG management in islanded conditions is proposed by Oliveira et al. Its aim is to maximize the duration of power supply taking into consideration the availability of renewable sources and stored energy. Load shedding, dispatch of expensive fossil fuel sources, and demand response actions are taken with the help of fuzzy logic. Because voltage/frequency regulation is one of the main challenges for proper operation of isolated MGs, a MG and simulation-based control structure including voltage and current control feedback loops is proposed for MG inverters in [116]. A PI controller is implemented along with the hybrid multi-objective symbiotic organism search algorithm to control the voltage deviation due to load variations. A fuzzy decision maker is proposed for optimal solution in voltage controller. A performance comparison is done with particle swarm optimization or multiple objective particle swarm optimization. With the proposed approach, voltage/frequency regulation is improved. In [117], Mohamed et al. propose a stochastic fuzzy-based framework based on cloud theory and swarm optimization (polar honeybee mating algorithm) for optimal scheduling and management of MG units. The simulation results on a typical case study (a

MG equipped with PV solar panels, a wind unit and plug-in hybrid EVs) demonstrate the efficiency of the proposed optimization method. The method shows good performance by reducing system costs. In [118], Jiao et al. propose a multi-objective optimization energy management model for MGs with plug-in EVs and distributed generators. An improved gray wolf algorithm is proposed to solve this model. Compared with both particle swarm optimization and traditional gray wolf algorithm, the proposed model improves accuracy and convergence speed. Besides, the model is applied to three scheduling schemes and results show that, in some particular cases, plug-in hybrid EVs favor energy economy.

For all the papers highlighted in this section, the main features, MG/NMG resources, and noticeable results are summarized in Table 8. If a paper deals with MG islanded operation, this is highlighted in the table.

Table 8. A focus on papers dealing with artificial intelligence (AI) methods for MG/NMG management. ANFIS stands for adaptive neuro-fuzzy inference system. ANN stands for artificial neural network. DG stands for distributed generator. DR stands for demand response. DSM stands for demand side management. ESS stands for energy storage system. MG stands for microgrid. NMG stands for netwoked microgrid. RL stands for reinforcement learning. WT stands for wind turbine.

Syst.	Main Features	MG/NMG Resources	Islanded Op.	Noticeable Results	Ref.
MG	A DSM machine-learning-based strategy for off-grid MGs is proposed	PV solar panels, ESSs	✓	Utilization of local renewable energy sources is increased	[106]
MG	A 2-stage reconfigurable framework is proposed for near real-time MG operational planning; an ANN is used to predict energy dispatch decisions	PV solar panels, WTs, ESSs	-	The ANN demonstrates robust predictive performance	[107]
MG	A decision-tree-based peak shaving algorithm is proposed for islanded MGs	Gas turbines, ESSs	✓	Peak load demand is effectively mitigated; generation units are efficiently operated	[108]
MG	A deep RL-based secondary control algorithm is proposed for MGs in islanded mode	PV solar panels, synchronous generators, ESSs	✓	In comparison with droop control, voltage/frequency deviations are reduced	[109]
MG	Multi-agent RL is used to control a MG in a mixed cooperative and competitive setting	PV solar panels, WTs, hybrid ESSs	✓	Renewable energy utilization is increased; energy bills are reduced	[110]
MG	An online-trained ANN-based control system for hybrid MGs is designed and validated; a fuzzy logic-based power management system is proposed	PV solar panels, WTs, fuel cells, ESSs	-	The control approach is effective, robust, and has self-adaptation ability	[111]
MG	A flexibility-based operational planning paradigm is applied to MG energy dispatch; a decision tree-based control mapping method is proposed	DGs, WTs, ESSs	-	Efficiency of the decision tree-based dispatch strategy is very high	[112]
MG	An ANFIS is used to control frequency and power sharing among distributed generators	PV solar panels, WTs	✓	Power sharing among distributed generators is efficient; frequency deviation is reduced	[113]
MG	Fuzzy controllers and a dynamic programming method are proposed	PV solar panels, WTs, fuel cells, ESSs	✓	Energy storage enables overcoming power flow issues and stabilizing the voltage level	[114]
NMG	Load shedding, dispatch of expensive fossil fuel sources, and DR actions are taken in islanded mode with the help of fuzzy logic	PV solar panels, WTs, diesel generators, microturbines, ESSs, EVs	✓	Duration of power supply is maximized	[115]
MG	A control structure including voltage and current control feedback loops for MG inverters is proposed; A fuzzy decision maker is used	PV solar panels, WTs, ESSs	✓	Voltage/frequency regulation is improved	[116]
MG	A stochastic fuzzy-based framework based on cloud theory and swarm optimization is proposed	PV solar panels, WTs, EVs	-	System costs are reduced	[117]

Table 8. *Cont.*

Syst.	Main Features	MG/NMG Resources	Islanded Op.	Noticeable Results	Ref.
MG	An improved gray wolf algorithm is proposed to solve a multi-objective optimization energy management model	PV solar panels, WTs, diesel generators, EVs	-	Accuracy and convergence speed are improved; EVs favor energy economy	[118]

3.7. Droop Control

According to Li [184], "droop control refers to a method of simulating the drooping characteristics of a traditional generator set. This control method is generally applicable to occasions where multiple communication line-free inverters are connected in parallel. The working principle is as follows: each inverter self-detects its own output power and then adjusts the same against the reference output voltage amplitude and the frequency obtained by carrying out droop control, so as to realize reasonable allocation of active power and reactive power of the system". Some recent papers are highlighted in the followings in order to give to the reader an overview on how droop control is used for MG/NMG management [119–128].

In [119], MG coordinated controllers are designed for enhancing the MG reliability by protecting it against unintentional islanding instability. In this strategy, the DC link voltage is used as a feedback parameter in the droop control loop. This leads to reliable operation. Stability is enhanced. The validity of the proposed strategy is verified by software simulations. A hierarchical control strategy is proposed by Zhao et al. [120] to maintain frequency stability in an islanded medium-voltage MG. The proposed architecture divides the system frequency in three zones: the stable zone, the precautionary zone, and the emergency zone. For both the stable and precautionary zones, a rule-based controller is proposed. For the emergency zone, droop control is used. Theoretical analysis, time-domain simulations, and field test under various conditions and scenarios prove the validity of the control strategy. In [121], a distributed hierarchical control with three levels is proposed for AC MGs. The primary control is a basic droop control, the secondary control is based on a distributed control with a leader-follower consensus protocol and the tertiary level is a mode-supervisory control, which manages the control targets of four operation modes. Frequency/voltage recovery and accurate power sharing are achieved in islanded mode. In grid-connected mode, flexible power flow regulation is achieved. In [122], a distributed hierarchical control framework is formulated as a 3-layer structure. Droop control is chosen for the first layer and leaderless consensus-based control is chosen for the second layer (active power regulation). The same method is used in the third layer for power dispatch. The results show improved economic dispatch and frequency regulation. In [123], an average power sharing control strategy for parallel operation of voltage source inverter based on modular uninterruptible power systems is proposed. The strategy relies on a modified droop control that can quickly adjust the voltage of local modules and the average power of parallel modules. Simulation results confirm the effectiveness of the strategy. Power sharing performance is improved and circulating currents in the parallel modules are eliminated. In [124], power sharing among distributed generators in islanded MGs is addressed. An enhanced droop control strategy is proposed. A first controlled voltage source is inserted into the conventional droop control loop to compensate the feeder voltage drop. Because droop control leads to voltage and frequency deviations in case of load variations, a secondary controlled voltage source is also inserted in the loop. Thanks to the proposed strategy, power sharing performance is improved and unmatched feeder impedances are eliminated. In [125], a state-of-charge (SOC) balancing and coordinated control strategy based on the adaptive droop coefficient algorithm for multiple energy storage units is proposed. In case of a slight SOC deviation, a fuzzy logic-based algorithm dynamically adjusts the droop coefficient and changes the power distribution. In addition, a bus voltage recovery control scheme is used to regulate the bus voltage, thus improving voltage quality. Thanks to the proposed approach, SOC balance is achieved in a fast and precise way while regulating bus voltage. In [126], an enhanced Newton–Raphson (NR) approach for power flow analysis in droop-controlled islanded MGs is proposed. The approach is NR-based but a more comprehensive model that considers different droop schemes is used. Results show that this approach has excellent accuracy and low computational time. In [127], a novel pre-synchronization control strategy based on improved droop control for MG connections is proposed. An improved droop control strategy adjusts the MG output voltage and frequency automatically. A pre-synchronization controller compensates for the angular frequency during droop control. Results suggest that the proposed control strategy is highly effective and reliable: accuracy and stability of voltage and frequency are improved, the harmonics provoked by inverters are suppressed, and the control errors are reduced. In [128], a novel decentralized adaptive droop control approach for DC MGs is proposed. The approach aims at enhancing the current sharing performance and provides superior DC bus voltage regulation. A decentralized bus voltage control method based on local measurements only is first introduced. Second, the droop coefficient value is adaptively changed. Results show that the current sharing error and voltage variations are reduced.

For all the papers highlighted in this section, the main features, MG/NMG resources, and noticeable results are summarized in Table 9. If a paper deals with MG islanded operation, this is highlighted in the table.

Table 9. A focus on papers dealing with droop control for MG/NMG management. DC stands for direct current. DG stands for distributed generator. ESS stands for energy storage system. MESU stands for multiple energy storage unit. MG stands for microgrid. NMG stands for networked microgrid. NR stands for Newton–Raphson. SOC stands for state-of-charge. UPS stands for uninterruptible power system. WT stands for wind turbine.

Syst.	Main Features	MG/NMG Resources	Islanded Op.	Noticeable Results	Ref.
MG	MG coordinated controllers are designed, the DC link voltage is used as a feedback parameter in the droop control loop	PV solar panels, WTs, microturbines, ESSs	✓	Reliable operation is achieved; stability is enhanced	[119]
MG	A hierarchical control strategy is proposed to maintain frequency stability in an islanded medium-voltage MG	DGs, WTs, ESSs	✓	Validity of the control strategy is proved by theoretical analysis, time-domain simulations, and field tests	[120]
MG	A distributed hierarchical control with three levels is proposed for AC MGs	DGs	✓	Voltage/frequency recovery and accurate power sharing are achieved in islanded mode; flexible power flow regulation is achieved in grid-connected mode	[121]
MG	A distributed hierarchical control framework is formulated as a three-layer structure	Diesel generators, microsources, ESSs	-	Improved economic dispatch and frequency regulation are achieved	[122]
MG	An average power sharing control strategy for parallel operation of voltage source inverter based on modular UPSs is proposed	DGs	-	Power sharing is improved; circulating current in the parallel modules are eliminated	[123]
MG	A 2-level controlled voltage source is inserted into the conventional droop control loop	DGs	✓	Power sharing is improved; unmatched feeder impedances are eliminated	[124]
MG	A SOC balancing and coordinated control strategy based on the adaptive droop coefficient algorithm for MESUs is proposed	PV solar panels, MESUs	✓	SOC balance and bus voltage stability are achieved	[125]
MG	An enhanced NR approach for power flow analysis in droop-controlled islanded MGs is proposed	DGs	✓	The proposed approach has excellent accuracy and low computational time	[126]
MG	A pre-synchronisation control strategy based on improved droop control is proposed	DGs	✓	Voltage/frequency accuracy and stability are improved; harmonics provoked by inverters are suppressed	[127]
MG	A decentralized adaptive droop control approach for DC MGs is proposed	DGs	-	Current sharing error and voltage variations are reduced	[128]

3.8. Other Programming Methods

In this section, some recent papers are highlighted in order to give to the reader an overview on how other programming methods than the ones considered in the previous sections are used for MG/NMG management [129–138].

First, an energy management strategy based on demand side management is proposed by Pascual et al. [129] for a residential MG equipped with photovoltaic solar panels, a small wind turbine and solar thermal collectors. The power exchanged with the main grid is controlled thanks to batteries and a controllable electric water heater. By using forecasted data and controlling the electric water heater, a better grid power profile is achieved while reducing the overall cost of the system (in particular, thanks to a smaller battery). In [130], the impact of utility induced flexible load shaping on non-dispatchable energy sources is investigated by Kumar et al. A 3-stage stochastic energy management system framework is proposed for solving optimal day-ahead scheduling and minimizing the operating cost of grid-connected MGs. Four scenarios for solar and wind power generation are created in the first stage in order to address the uncertainty problem by considering real-time meteorological data. The second stage deals with the MG configuration, the operational constraints and demand side management. The quantum particle swarm optimization (QPSO) is devised at the third stage in order to obtain the optimal power dispatch configuration for distributed generators. Thanks to the proposed stochastic framework, operating costs are significantly reduced. In [131], a new statistical method is proposed for assessing the impact of distributed energy reliability and variability on the performance of MGs. In addition, a novel use of the optimization platform REopt to explore multiple cost savings and revenue streams is provided. Distributed energy resources are selected by evaluating their life cycle costs and the resilience of islanded MGs. The authors highlight that hybrid MGs—equipped with a combination of solar panels, batteries and networked emergency diesel generators—are more resilient and cost-effective than diesel-only systems. In [132], an adaptive optimal defense mechanism is proposed to establish secure MG islanding, without acquiring fast response energy resources. The dynamics involved in the islanding transition are considered into the search for optimal defense measures by using the "simulation optimization" technique. Effectiveness of the proposed adaptive defensive approach when the islanding occurs is demonstrated. Such an approach can help to improve system performance. In [133], a new Monte-Carlo-based model taking into consideration uncertainties on the charging station's load of EVs and on operating parameters. Operating parameters uncertainties are energy market prices, photovoltaic power generation and loads is presented for MG's day-ahead operation optimization. Various stochastic scenarios are generated and involved in a mixed-integer linear programming (MILP) cost minimization problem. Results show that total operating costs are decreased by applying the proposed model. In [134], considering reliability and resilience enhancement, an optimal energy storage sizing approach is proposed for networked and non-networked MGs. A 2-level optimization model is proposed for energy storage sizing. The upper-level deals with the sizing problem, aiming at maximizing annual profit. The lower-level is aimed at operation optimization for profit maximization under various operating scenarios. The problem is converted into a MILP. Results highlight on the one hand that the energy storage size can be reduced while the operating profit is improved by interconnecting MGs. On the other hand, results show that energy interaction between NMGs allows enhancing both reliability and resilience in case of grid outages. In [135], an annealing mutation particle swarm optimization algorithm is proposed for minimizing the operating cost and the cost of environmental protection of MGs. The authors conclude that the orderly charging and discharging mode guided by electricity prices can effectively reduce these costs. Reliability of MG operation is improved. Mobile emergency resources are critical to the resilience of power distribution systems in case of natural disaster [136]. As a result, a distributed secondary control algorithm is designed to regulate frequency and voltage in islanded MGs. Case studies are used to demonstrate both the effectiveness and robustness of the proposed control algorithm to switching communication topologies. In [137], an autonomous smart

MG is designed and simulated for energy independence. Its automatic control system is rule-based. Results show that the MG can adequately supply power to its community, without relying on a utility power grid. In [138], an exact feedback linearization method based on the nonlinear differential geometry theory is proposed to realize the linearization of bi-directional DC/DC converters. The nonlinear property of these converters cause large voltage disturbances. In addition, considering the approaching speed of the linearized Bruno standard model, a sliding mode controller is designed by using the exponential approach law. Simulation results show that the proposed method has fast response, strong anti-interference ability and good steady-state characteristics.

For all the papers highlighted in this section, the main features, MG/NMG resources, and noticeable results are summarized in Table 10. If a paper deals with MG islanded operation, this is highlighted in the table.

Table 10. A focus on significant papers dealing with other programming methods than the ones considered previously for MG/NMG management. DC stands for direct current. DG stands for distributed generator. DSM stands for demand side management. ESS stands for energy storage system. EWH stands for electric water heater. MG stands for microgrid. MILP stands for mixed-integer linear programming. NMG stands for networked microgrid. WT stands for wind turbine.

Syst.	Main Features	MG/NMG Resources	Islanded Op.	Noticeable Results	Ref.
MG	A rule-based strategy is proposed for DSM in a residential MG	PV solar panels, solar thermal collectors, WTs, EWHs, ESSs	-	Overall cost of the system is reduced	[129]
MG	A 3-stage stochastic EMS framework is proposed for solving optimal day-ahead scheduling with the use of quantum particle swarm optimization	PV solar panels, WTs, microturbines, gas turbines	-	Operating costs are reduced	[130]
MG	The optimization platform REopt to explore multiple cost savings	PV solar panels, diesel generators, ESSs	✓	Hybrid MGs are more resilient and cost-effective than diesel-only MGs	[131]
MG	An adaptive optimal defense mechanism is proposed to establish secure islanding	PV solar panels, microturbines	✓	Effectiveness of the proposed approach when islanding occurs is demonstrated	[132]
MG	A Monte-Carlo-based model is proposed for optimization of MG's day-ahead operation, the problem is formulated as a MILP	PV solar panels, WTs, ESSs, EVs	-	Total operating costs are reduced	[133]
NMG	A 2-level optimization model is proposed for ESS sizing, the problem is formulated as a MILP	DGs, ESSs	✓	Operating profit is improved by interconnecting MGs, reliability and resilience in case of grid outages are enhanced	[134]
MG	An annealing mutation particle swarm optimization algorithm is proposed	PV solar panels, WTs, diesel generators, microturbines, ESSs, EVs	-	Operating costs and environmental protection costs are reduced; MG operation reliability is improved	[135]
NMG	A distributed secondary control algorithm is designed to regulate frequency and voltage in islanded MGs	DGs	✓	The proposed control algorithm is efficient and robust to switching communication topologies	[136]
MG	An autonomous smart MG is designed and simulated for energy independence, the automatic control system is rule-based	PV solar panels, diesel generators, ESSs	✓	Power is adequately supplied by the MG to its community	[137]
MG	An exact feedback linearization method based on the nonlinear differential geometry theory is proposed to linearize bi-directional DC/DC converters	DGs, ESSs	-	The proposed method has fast response, strong anti-interference ability and good steady-state characteristics	[138]

3.9. Discussion

Conclusions are drawn from the papers discussed in the previous subsections (from Section 3.1 to Section 3.8). The following applications and issues addressed by the scientific community are identified:

- model-based predictive control is emerging as a competitive alternative to conventional methods in voltage and frequency regulation, power flow management, distributed energy resource management or MG/NMG operation optimization;
- machine learning tools are getting more and more attention from the scientific community as they can be used in the development of efficient forecasting algorithms but also in the development of smart control approaches for MGs and NMGs, in particular based on reinforcement learning, which is emerging as an interesting solution; fuzzy logic and neuro-fuzzy systems—these systems combine fuzzy logic with artificial neural networks—are still popular in the domain;
- multi-agent systems are widely used in the management of distributed systems and are still attractive in the management of MGs and NMGs equipped with multiple distributed generators and/or EVs; multi-agent systems have proven to be a useful tool to emphasize the autonomous behavior of members in an energy community;
- due to its ability to handle cooperation efficiently, game theory is a very good candidate for efficient management of NMGs, as highlighted by several research papers included in this survey;
- although its popularity seems to be decreasing, droop control is still used widely in a MG context for frequency and voltage regulation or power flow management.

As the interest for EVs is growing—this interest is evidenced by the number of papers sourced for this survey—a lot of challenges are still ahead, particularly in the management of the batteries these vehicles are equipped with. The integration of EVs in power systems impacts power demand, which leads to uncertainties. These uncertainties may have different influences on the performance of the implemented energy management strategies. EV batteries will play a key role in balancing energy supply and demand and have the potential to contribute to optimal operation in islanded MGs and NMGs. As a result, novel and efficient strategies are needed to take advantage of these flexible storage capacities, in a context of increasing penetration of distributed generation in the power systems. Strategies for EV management based on MPC (see Table 3), stochastic programming (see Table 6) or artificial intelligence (see Table 8) are gaining in popularity these past few years.

The feasibility of management strategies to be adopted for the operation of MGs and NMGs when they become isolated is also evaluated. As proper (i.e., stable and autonomous) islanded operation is crucial, strategies based on load shedding (to improve voltage stability) and capable of efficiently managing ESSs are needed. As highlighted in Section 3, MPC (see Table 3) and artificial intelligence (in particular, reinforcement learning) (see Table 8) are increasingly being used for this purpose. Droop control (see Table 9) is still an interesting option for proper islanded MG/NMG operation, as evidenced by certain papers recently published in peer-reviewed journals.

Furthermore, even though theoretical aspects of MG management have been vastly studied over the years, there is a lack of in situ implementations. Demonstration projects are relatively few in number. As a result, there is still an important gap to cover between research work and in situ implementation of the developed strategies. This can be explained, at least partially, by the heavy computational cost of the solutions relying on an optimization. Solutions like the ones based on MPC have to offer an acceptable compromise between performance and computational cost in order to be implemented in situ. The increasing number of distributed generators in MGs as well as the deployment of EVs and hybrid energy storage systems increase the overall complexity to handle. This complexity is also increased by the deployment of NMGs. That is why strategies capable of accounting for complex (distributed) systems and increasing uncertainties are needed. The literature lacks frameworks incorporating this kind of strategy. In this context, game theory (see Table 5) is a promising tool. In addition, let us mention that both the development and implementation of efficient energy management strategies require data and, as a consequence, an exhaustive MG/NMG instrumentation as well as efficient data acquisition systems and transmission protocols.

4. Conclusions

An efficient way for integrating distributed energy resources into power distribution systems is emerging: microgrids (MGs) and networked (interconnected) microgrids (NMGs). These systems can disconnect from the main grid and operate autonomously, strengthen grid resilience, and help mitigate grid disturbances and maintain power quality. When supported by sophisticated and efficient management strategies, MGs and NMGs have the ability to enhance power supply reliability. Benefits from organizing power distribution systems through MGs and NMGs are also related to reducing carbon dioxide emissions and operating costs, but also improving the robustness to failures. However, the deployment of MGs and NMGs, which is ongoing in many countries, comes with many challenges, in particular regarding the efficient management of distributed energy resources or electric vehicles (EVs). That is why a survey of recent advances in the smart management of MGs and NMGs is presented in this paper. A variety of planning and control tasks are discussed. The paper aims at establishing a picture of strategies and identifying trends in methods. To this end, the reader is provided with an in-depth analysis of papers recently published in peer-reviewed journals, highlighting the way the methods are used and the common issues to be resolved. Following this analysis, one can especially observe that (1) despite its heavy computational cost, model-based predictive control (MPC) is emerging as a competitive alternative to conventional methods in voltage and frequency regulation or distributed energy resource management (2) machine learning tools (in particular, reinforcement learning) are getting more and more attention from the scientific community as they can be used in the development of smart control approaches for MGs and NMGs (3) due to its ability to handle cooperation, game theory (GT) is a very good candidate for efficient management of complex systems as NMGs, which is still little discussed in the literature (4) MPC and artificial intelligence (in particular, reinforcement learning) are increasingly being used for proper MG islanded operation or to manage a fleet of EVs in an efficient way.

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Abbreviations

The following abbreviations are used in this manuscript:

AC/DC	Alternative current/direct current
ANFIS	Adaptive neuro-fuzzy inference system
ANN	Artificial neural network
APPM-RE	Aggregate production planning model with onsite renewable energy
ARIMA	Autoregressive integrated moving average
ARMA	Autoregressive moving average

BESS	Battery energy storage system
CES	Community energy storage
CHP	Combined heat and power
DER	Distributed energy resource
DP	Dynamic programming
DG	Distributed generator
DR	Demand response
DSO	Distribution system operator
DSM	Demand side management
EMS	Energy management system
ESS	Energy storage system
EV	Electric vehicle
G2V	Grid-to-Vehicle
GT	Game theory
HMA	Honeybee mating algorithm
IBDR	Incentive-based demand response
ICA	Imperialistic competition algorithm
MAS	Multi-agent system
MESU	Multiple energy storage unit
METBG	Microgrid energy trading Bayesian game
MG	Microgrid
MILCQP	Mixed-integer linear constrained quadratic programming
MILP	Mixed-integer linear programming
MINLP	Mixed-integer nonlinear programming
MIP	Mixed-integer programming
MIQCP	Mixed-integer quadratically constrained programs
MOSOS	Multi-objective symbiotic organism search
MPC	Model-based predictive control
NG	Nanogrid
NMG	Networked microgrid
NR	Newton–Raphson
P2P	Peer-to-peer
PCC	Point of common coupling
PI	Proportional integral
PSO	Particle swarm optimization
PTEM	Production task and energy management
PV	Photovoltaic
QPSO	Quantum particle swarm optimization
RES	Renewable energy source
RL	Reinforcement learning
RO	Robust optimization
SARIMA	Seasonal autoregressive integrated moving average
SCADA	Supervisory control and data acquisition
SOC	State-of-charge
SP	Stochastic programming
SG	Smart grid
UPS	Uninterruptible power system
V2G	Vehicle-to-grid
VSI	Voltage-source inverter
WT	Wind turbine

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