energies

Editorial

Recent Developments and Trends in Energy Management Systems for Microgrids

Maria Carmela Di Piazza

Consiglio Nazionale delle Ricerche (CNR), Istituto di Ingegneria del Mare (INM), Via Ugo La Malfa 153, 90146 Palermo, Italy; mariacarmela.dipiazza@cnr.it

Citation: Di Piazza, M.C. Recent Developments and Trends in Energy Management Systems for Microgrids. *Energies* **2022**, *15*, 8226. https://doi.org/10.3390/en15218226

Received: 29 September 2022
Accepted: 27 October 2022
Published: 4 November 2022

1. Introduction

Energy transition is the path toward transforming the global energy sector from being fossil-based to being zero-carbon, driven by the need to reduce energy-related CO_2 emissions so as to counteract climate change. Although environmental sustainability and climate neutrality are the leading goals of this process, energy transition is a more complex paradigm shift that aims to provide global economical and societal benefits.

Future trend forecasts show an increase in global energy demand, which is projected to be about 47% by 2050, according to the U.S. Energy Information Administration's latest International Energy Outlook [1]. In addition, improved access to energy is needed worldwide. All such motivations, as well as the need for the increased resilience of power systems, are fostering the establishment of a new energy ecosystem whose basic idea relies on decentralization. According to this approach, energy challenges can be tackled by creating privileged solutions with which to access dependable, green, and resilient energy. In this scenario, microgrids have been identified as the appropriate electrical power system model to achieve the goals related to energy transition.

A microgrid is a small-scale and self-controlled electrical power system that interconnects generators and loads within given electrical boundaries. It can interact with an upstream main grid and can be operated in either a grid-connected mode or in an isolated mode. The principal features of microgrids are as follows: the presence of multiple distributed generators, with a high proportion of renewables (e.g., photovoltaic panels, wind generators, etc.); the presence of energy storage systems (ESSs), frequently based on batteries; and the presence of advanced communication infrastructures [2].

Energy storage systems (ESSs) in microgrids are used to perform multiple functions that address the management of generation and demand variability. The typical uses of ESSs in microgrids include providing services such as voltage support, frequency regulation, synthetic inertia, renewable firming and time shift, arbitrage, and distribution system upgrade deferral. Additionally, the extensive use of information and communication technology (ICT) allows a microgrid's components to exchange information with each other in a bidirectional way [3].

As far as control and management are concerned, microgrids are usually governed according to a multilevel approach covering different time horizons and physical levels. This control approach, known as hierarchical control, allows for the achievement of the most significant microgrid objectives, such as voltage/frequency regulation, power sharing, synchronization, and resilient as well as profitable operation. All of the described characteristics permit electrical power flows in microgrids to be modulated, following defined optimization objectives, as well as allowing the final users of electrical energy to actively participate in the electrical market [4].

The energy management systems (EMSs) used in microgrids are supervisory control systems operating at higher levels of hierarchical control for dispatching power sources and ESSs according to defined objectives, such as cost optimization, energy efficiency improvement, demand profile shaping, price stabilization, reducing pollutant emissions, and so on.

EMSs play a pivotal role in microgrids by managing power balance in highly volatile conditions, due to uncertainties of power generation from renewables and demand, often taking advantage of artificial intelligence (AI)-based forecasting techniques. They allow microgrids to be operated in an optimized fashion and support distributed system operators (DSOs) in decision making, contributing to increasing microgrids' reliability, sustainability, efficiency, and economy [5].

Recent technical literature exhibits numerous technical contributions dealing with the development of EMSs for microgrids and highlights the need for the further investigation of some specific technical aspects, such as the development of effective and reliable forecasting techniques in addition to the definition of proper usage patterns for battery energy storage systems (BESSs) to prolong batteries' lives [6].

Manifold strategies and tools for pursuing EMSs' objectives have also been proposed; they embrace classical optimization methods in addition to metaheuristic techniques and solutions based on machine learning and artificial intelligence. Finally, different specific applications have been explored, including, for example, grid-connected, isolated, and residential microgrids.

The significance and the volume of recent scientific productions on EMSs for microgrids testify to the topicality of and interest in the issue by the international scientific community, as well as to the need for emphasizing scientific advances in this subject. With this in mind, this editorial provides a survey of selected articles recently published in *Energies* that focus on the considered topic and identify the most relevant key areas of interest, technology trends, and open technical challenges.

2. Brief Review of the Selected Contributions

The short survey proposed in this editorial considers ten articles focused on EMSs for microgrids authored by international research teams from different geographical areas and published in *Energies* between 2020 and 2021.

For the sake of the reader's convenience, the selected articles have been roughly classified and grouped into the following themes:

- Centralized EMSs.
- Decentralized EMSs.
- EMSs for residential microgrids.
- Deep learning (DL)- and AI-based techniques for energy management and forecasting in microgrids.

Among the papers referable to the first theme, an interesting review is proposed by Espín-Sarzosa et al. in [7]. This review explores a complete paper database to identify the main technical trends in the domain of centralized EMSs for microgrids. On such a basis, it provides outcomes for a more in-depth understanding of the specific challenges, opportunities, technical barriers, and open issues on future centralized EMS developments. In detail, several EMS attributes related to its features have been considered in the study, e.g., the formulation of objective functions, resolution techniques, operating models, the handling of uncertainties, time horizons, and the level of modeling detail. Four prevalent research trends have been determined: uncertainty-related issues (33% of the total references analyzed), multi-objective strategies (29%), traditional paradigms (21%), and P-Q challenge (17%). No evidence of a research trend where all EMS development issues are dealt with simultaneously has been detected. On the contrary, in most cases, research focused on the improvement of specific areas, while introducing simplifications in others. According to [1], it can be envisaged that a centralized approach in EMS requires a proper representation of the stability aspects related to the microgrid operating transitions, for example, from a grid-connected to an isolated mode. From this point of view, the effects of operating transitions should be integrated into the EMS optimization strategy. Important considerations of storage systems are also given in the review. It is illustrated that, as a key component for EMS operation, an energy storage system should be fully considered in the EMS mathematical optimization problem, taking into account the evolution of both state of charge (SoC) and state of health (SoH). In particular, since it has been discovered that SoH is not yet frequently considered, additional research efforts should focus on developing effective and general SoH models suitable to be included in the EMS mathematical problem.

Gil-González et al. in [8], propose an EMS that addresses the economic dispatch of renewable generators (wind and solar power) and BESSs in DC microgrids using second-order cone programming (SOCP). The proposed SOCP formulation makes possible the conversion of the non-convex economic dispatch model into a convex approach via performing a mathematical relaxation. According to this approach, the achievement of a global optimum and simple implementation are ensured. The accuracy and efficiency of the proposed solution are validated against the non-convex model and semidefinite programming (SDP) under different simulation scenarios. The SOCP model includes dynamic energy purchase prices, which makes the formulation suitable for implementation in real-time operation. Finally, an artificial neural network (ANN) is used to forecast the primary sources of renewable energy to reduce the error due to the uncertainties of generation.

The contribution proposed by Silva et al. [9] deals with optimal day-ahead scheduling in microgrids in a real energy market scenario. The study focuses its efforts on detailed mathematical modeling of a microgrid's main components while preserving the linearity of the problem to simplify the implementation. Accurate models of the following components are provided: a BESS; a photovoltaic (PV) system; and directly controllable loads (i.e., shiftable and interruptible ones). The EMS in [9] also considers PV and battery availability costs, as well as the possibility of PV curtailment and load shedding. Furthermore, the proposed modeling also allows for the consideration of scheduled intentional islanding events. The obtained results show the following: 1. Energy arbitrage has an impact on the reduction in microgrid costs in a time-of-use tariff. 2. The BESS capacity can impact a microgrid's energy bill. 3. Scheduled islanding events may be needed to pursue day-ahead optimization.

Two interesting contributions focused on centralized EMSs for isolated microgrids are given in [10,11]. It is worth noting that isolated microgrids pose significant technical challenges related to stability and optimal design for ensuring technical and financial viability [7,10].

Cecilia et al. in [10], develop an EMS for a standalone microgrid that includes PV generation, a BESS, and hydrogen production. The EMS aims to optimize the design performance and the microgrid's operation by a) minimizing the amount of energy cycled in the battery (so that the battery size and associated losses are reduced); b) exploiting the long-term surplus energy for producing hydrogen to be used in fuel-cell-powered hybrid electric vehicles. The proposed EMS relies on a model predictive control (MPC) scheme that provides appropriate matching between demand and supply. The model includes a solar irradiance prediction algorithm and considers the battery behavior; however, the findings in [10] do not allow for the quantification of the benefits in terms of battery life extension. The energy management strategy leads to an improved reliability with a reduced battery effort; indeed, the system acquires more robustness to an unexpected increase in system demand or unexpected decrements in produced solar energy. As a result, a stable and efficient supply is also envisaged with a relatively small battery.

García-Vera et al. in [11], focus on the topical issue of battery optimal operation in isolated hybrid microgrids. The authors stress the importance of battery life estimation as a key factor in the optimization of the electrical system, since battery life duration has a significant impact on the microgrid's final costs. On such a basis, they propose a comparison of different technologies and battery models and identify the most battery-related influential factors in microgrid operation. The authors provide evidence that the conventional models used for the estimation of battery life are not realistic enough, and that the effect of temperature should be included in such models. The superiority of lithium-ion batteries with respect to their lead–acid counterparts is also evidenced, based on the consideration that the former give rise to lower costs throughout the life of the microgrid due to lower maintenance costs and a longer lifespan. Finally, according to [11], in isolated microgrids an optimal dimensioning of the system components is identified as the favored solution to achieve significant energy and economic benefits.

Despite the amount of publications on centralized EMSs for microgrids being prevalent, decentralized approaches are also gaining momentum in recent years thanks to their higher flexibility and resilience. As far as decentralized EMSs are concerned, Alhasnawi et al. in [12], propose a new robust control strategy for microgrids governed by multi-agent systems (MASs). The proposed strategy is based on a consensus algorithm (CA) applied with microgrids' connected distributed generators in the Energy Internet paradigm. This work addresses some gaps in the technical literature, such as simultaneous voltage/frequency regulation in addition to active and reactive power sharing. In detail, it proposes a distributed secondary control enabling group plug-and-play features, implements a control framework based on MASs and cloud servers, defines communication protocols at the different levels of hierarchical control, and implements a two-layered communication architecture based on the MQTT protocol and on a cloud-based server called ThingSpeak.

The obtained results show that the proposed energy management strategy correctly regulates both frequency and voltage under diverse fault events. Additionally, active and reactive power are equally shared among distributed power sources. Finally, the flexibility and scalability of the proposed method are assessed in the case of a microgrid with eight distributed generators.

Considering the theme of residential microgrids, an interesting contribution has been proposed by Dey et al. in [13]. Here, the impact of residential loads in raising the generation cost of the electrical system is investigated for the case of a low-voltage grid-connected microgrid; furthermore, the active and passive roles of the utility in realizing the optimal scheduling of the distributed resources are studied. The authors of [13] emphasize the need for developing efficient and fast optimization techniques; to this end they propose a hybrid optimization technique to reduce the generation cost of the residential microgrid. In particular, the proposed hybrid optimization technique was the Modified Grey Wolf Optimization-Sine Cosine Algorithm-Crow Search Algorithm (MGWOSCACSA), and the developed EMS has been tested and assessed under different operating scenarios. An increase of 50% in generation costs when the residential loads were included in the analysis has been observed. In addition, it has been noted that the active participation of the utility determined 9–17% savings in the generation cost with respect to the cases when the microgrid was operated in a stand-alone mode.

Increasing interest is being found in the use of DL- and AI-based techniques in the technical domain of the control and management of microgrids in recent years. These techniques are prevalently applied to the forecasting of generation from renewables and electrical demand. As for this last theme, Lan et al. in [14], introduce a centralized operation/management framework for reconfigurable microgrids that encompasses hybrid electric vehicles (HEVs), shiftable/curtailable loads, batteries, and renewable generation (wind units and solar panels). A comprehensive model is developed to describe all of the components of a microgrid and optimize its operating cost over a 24 h horizon. An advanced machine learning method, based on support vector regression (SVR), has been proposed for predicting the charging demand of HEVs. This method allows for accurate and reliable prediction without the risk of overfitting due to the complexity of the data. Furthermore, for tackling the complexity of the optimization problem, a novel optimization algorithm based on the dragonfly algorithm (DA) is developed to manage the optimal scheduling of a microgrid's loads, ESSs, and switches operation. The accurate estimation of the HEVs' total charging demand allows for the set-up of coordinated charging schemes, providing more economical operation of the microgrid. A reduction in cost in the order of about 3–4%, along with a reduction in the CPU time between 7% and 23%, have been obtained with the use of a modified dragon fly algorithm (DMA) compared to other methods, such as genetic algorithms (GAs), particle swarm optimization (PSO), and the original DA. Finally, the optimal switching and reconfigurability of the microgrid's feeders, realized by the proposed method, also contribute to diminishing the system power losses.

The forecasting of renewable generation is a crucial issue in the development of EMSs for microgrids; it allows for the effective planning and scheduling of optimal power flows in addition to having a significant impact on EMSs' performance. Starting from this consideration, Aslam et al. in [15], propose a comparative study on different DL approaches used for performing hourly and daily solar radiation in a very-long-term time horizon, i.e., one year ahead. Different kinds of applications are envisaged for the proposed study, such as microgrid design, installation, and planning; moreover, it can be useful to estimate the degradation-rate-influenced energy potential of PV generators. According to [15], DL-based models outperform traditional probabilistic approaches. Long short-term memory (LSTM) and gated recurrent units (GRUs) have been proven to be more effective than other DL approaches, due to their capability of carrying significant information over a long distance. Of the two selected methods, GRUs showed slightly better behavior in terms of accuracy and performed relatively faster due to having fewer gates compared to LSTM. From the observed results, overall, LSTM and GRUs are individuated as very promising DL-based approaches for long-term solar radiation forecasting.

Finally, still considering the topic of forecasting for EMSs applied to microgrids, contribution [16] is worth being cited. Here, La Tona et al. propose a method for selecting the frequency of forecasting execution within an energy management algorithm. A sample two-stage EMS, conceived to pursue minimum electricity while reducing power demand uncertainties, has been considered as case study. This EMS uses neural-based day-ahead forecasting based on a non-linear autoregressive network with exogenous inputs (NARX) ANN and is executed according to different frequencies in the day. The findings of [16] exhibit the existence of a representative relationship between the forecasting execution frequency and the reduction in uncertainty in the electrical demand pursued by the EMS. Specifically, a reduction in the demand uncertainty is observed for an increased forecasting execution frequency of up to half an hour in the 24 h time horizon. Simulation results allow for the assessment of to what extent is repeating the forecasting task advantageous for obtaining still noticeable improvements in the EMS performance.

3. Conclusions

This editorial briefly summarizes the content of ten articles, recently published in the journal *Energies*, which are focused on EMSs for microgrid applications. The reviewed research offers novel contributions in the considered technical area, outlining recent developments, key open issues, and promising future trends.

Funding: This research received no external funding.

Conflicts of Interest: The author declares no conflict of interest.

References

1. U.S. Energy Information Administration. *U.S. Energy Information Administration, International Energy Outlook with Projection to 2050*; U.S. Energy Information Administration: Washington, DC, USA, October 2021. Available online: https://www.eia.gov/outlooks/ieo/pdf/IEO2021_Narrative.pdf (accessed on 15 September 2022).
2. Fang, X.; Misra, S.; Xue, G.; Yang, D. Smart Grid—The New and Improved Power Grid: A Survey. *IEEE Commun. Surv. Tutor.* **2012**, *14*, 944–980. [CrossRef]
3. Vazquez, S.; Lukic, S.M.; Galvan, E.; Franquelo, L.G.; Carrasco, J.M. Energy Storage Systems for Transport and Grid Applications. *IEEE Trans. Ind. Electron.* **2010**, *57*, 3881–3895. [CrossRef]
4. Meng, L.; Shafiee, Q.; Trecate, G.F.; Karimi, H.; Fulwani, D.; Lu, X.; Guerrero, J.M. Review on Control of DC Microgrids and Multiple Microgrid Clusters. *IEEE J. Emerg. Sel. Top. Power Electron.* **2017**, *5*, 928–948. [CrossRef]
5. Ma, G.; Li, J.; Zhang, X.-P. A Review on Optimal Energy Management of Multimicrogrid System Considering Uncertainties. *IEEE Access* **2022**, *10*, 77081–77098. [CrossRef]

6. Morin, D.; Stevenin, Y.; Brault, P. Energy Management of isolated DC microgrids with hybrid batteries-hydrogen storage system using Model Predictive Control and Wavelet Neural Networks based forecasts. In Proceedings of the 2019 21st European Conference on Power Electronics and Applications (EPE '19 ECCE Europe), Genova, Italy, 3–5 September 2019; IEEE: New York, NY, USA, 2019; pp. 1–10. [CrossRef]
7. Espín-Sarzosa, D.; Palma-Behnke, R.; Núñez-Mata, O. Energy Management Systems for Microgrids: Main Existing Trends in Centralized Control Architectures. *Energies* **2020**, *13*, 547. [CrossRef]
8. Gil-González, W.; Montoya, O.D.; Grisales-Noreña, L.F.; Cruz-Peragón, F.; Alcalá, G. Economic Dispatch of Renewable Generators and BESS in DC Microgrids Using Second-Order Cone Optimization. *Energies* **2020**, *13*, 1703. [CrossRef]
9. Silva, V.A.; Aoki, A.R.; Lambert-Torres, G. Optimal Day-Ahead Scheduling of Microgrids with Battery Energy Storage System. *Energies* **2020**, *13*, 5188. [CrossRef]
10. Cecilia, A.; Carroquino, J.; Roda, V.; Costa-Castelló, R.; Barreras, F. Optimal Energy Management in a Standalone Microgrid, with Photovoltaic Generation, Short-Term Storage, and Hydrogen Production. *Energies* **2020**, *13*, 1454. [CrossRef]
11. García-Vera, Y.E.; Dufo-López, R.; Bernal-Agustín, J.L. Optimization of Isolated Hybrid Microgrids with Renewable Energy Based on Different Battery Models and Technologies. *Energies* **2020**, *13*, 581. [CrossRef]
12. Alhasnawi, B.N.; Jasim, B.H.; Sedhom, B.E.; Hossain, E.; Guerrero, J.M. A New Decentralized Control Strategy of Microgrids in the Internet of Energy Paradigm. *Energies* **2021**, *14*, 2183. [CrossRef]
13. Dey, B.; García Márquez, F.P.; Basak, S.K. Smart Energy Management of Residential Microgrid System by a Novel Hybrid MGWOSCACSA Algorithm. *Energies* **2020**, *13*, 3500. [CrossRef]
14. Lan, T.; Jermsittiparsert, K.; Alrashood, S.T.; Rezaei, M.; Al-Ghussain, L.; Mohamed, M.A. An Advanced Machine Learning Based Energy Management of Renewable Microgrids Considering Hybrid Electric Vehicles' Charging Demand. *Energies* **2021**, *14*, 569. [CrossRef]
15. Aslam, M.; Lee, J.-M.; Kim, H.-S.; Lee, S.-J.; Hong, S. Deep Learning Models for Long-Term Solar Radiation Forecasting Considering Microgrid Installation: A Comparative Study. *Energies* **2020**, *13*, 147. [CrossRef]
16. La Tona, G.; Di Piazza, M.C.; Luna, M. Effect of Daily Forecasting Frequency on Rolling-Horizon-Based EMS Reducing Electrical Demand Uncertainty in Microgrids. *Energies* **2021**, *14*, 1598. [CrossRef]