Advances in power smoothing techniques in renewable microgrids: a comprehensive review of the state of the art

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Context and motivation

The transition toward a more sustainable and diversified energy matrix has driven the growth of renewable energies, such as wind, solar, and hydrokinetic, in modern electrical systems (Barra et al., 2021). However, the intermittent and variable nature of these sources presents significant challenges for the stability and reliability of energy systems (Zhou et al., 2013). Variability in energy generation can cause fluctuations in frequency and energy quality in electrical grids, underscoring the urgent need to develop effective power smoothing strategies. Recent research has shown that power smoothing techniques play a crucial role in mitigating power fluctuations, thus ensuring the operational stability of electrical systems. A variety of approaches have been developed to address this challenge, with a growing emphasis on the use of high-power energy storage systems (ESSs) (Barra et al., 2021).

In the realm of grid-connected residential microgrids, which integrate renewable generation and storage capacity, energy management strategies based on fuzzy logic have been designed to smooth the network power profile (Arcos-Aviles et al., 2019). Additionally, the utilization of kinetic energy from wind turbines for grid connections has been explored as a promising strategy for smoothing wind power (Wang et al., 2018). Kinetic ESSs, such as flywheel storage systems, have emerged as an attractive option for enhancing stability and energy quality in power systems and microgrids (Zhou et al., 2013). By leveraging advances in energy storage technologies and control strategies, it is possible to address challenges associated with renewable generation variability, thus advancing toward a more sustainable and reliable energy future (Jarnut et al., 2017; Mansouri et al., 2020; McCarthy et al., 2016). All of this, together with the increasing adoption of renewable energies such

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as solar and wind, has posed significant challenges to the stability of electrical systems due to the inherent variability of these energy sources. To address this variability and ensure the reliability of electrical systems, further research into effective power smoothing strategies, especially in isolated and renewable-based systems, is required (Zhou et al., 2013). The study of energy storage technologies has become a key area of research in this field. Electrochemical supercapacitors, for example, have proven to be rapidly rechargeable energy storage devices used in a variety of applications, from pulse technology to electrical energy storage (Volfkovich, 2021). Research has also demonstrated the potential of porous media in improving the performance of photovoltaic (PV) thermal systems (Sangtarash et al., 2024).

However, the proper selection and comparison of these technologies are key aspects that require comprehensive and global assessment to determine their effectiveness and viability in different environments (Barra et al., 2021; Sebastián, 2021; Wang et al., 2018). Additionally, the study of island systems presents particular challenges in terms of energy stability and reliability due to their geographic isolation and dependence on external energy sources. Therefore, research on power smoothing techniques adapted to these specific conditions is essential to ensure a successful transition to more sustainable and autonomous electrical systems (Jarnut et al., 2017; Mansouri et al., 2020; Tripathy et al., 2017). In this context, this review study aims to provide a comprehensive and comparative overview of the different power smoothing techniques available globally, with a specific focus on their application in island systems. By analyzing and comparing the results of previous research, we hope to identify the most promising technologies and best practices for improving the stability and reliability of renewable energy-based electrical systems, thus contributing to a more effective transition towards a sustainable and reliable energy future.

Literature review

The existing literature provides a comprehensive insight into power smoothing strategies applied to various renewable energy sources. For instance, studies such as Barra et al. (2021) offer a thorough review of high-power ESSs specifically used for wind power smoothing, highlighting the increase in publications on this topic in recent years and the need for further research to address wind energy fluctuations. Furthermore, research like that presented in Arcos-Aviles et al. (2019) explores fuzzy logic-based energy management strategies to smooth the power profile of grid-connected residential microgrids, emphasizing fuzzy logic-based control design and its effectiveness in improving the power profile of residential microgrids. The utilization of kinetic energy from wind turbines for grid connection has also been investigated, as described in Wang et al. (2018), where emerging technologies for frequency regulation and low-voltage ride-through capability utilizing kinetic energy stored in wind turbines are analyzed, emphasizing applications of this energy for wind smoothing.

Likewise, the use of flywheel-based ESSs has been extensively researched, as presented in Zhou et al. (2013), where the structures and applications of these systems in power systems and microgrids are examined, highlighting their role in improving energy quality, supporting renewable energy integration, and enhancing system stability. Studies like Zhou et al. (2013) offer an overview of energy storage technologies used in marine current energy systems, emphasizing the importance of high ESSs for long-term energy fluctuations smoothing due to tidal phenomena. Within the same context, research on electrochemical supercapacitors, as presented in Volfkovich (2021), provides a detailed review of these rapidly rechargeable energy storage devices, highlighting their application in electrical energy storage and peak load mitigation in electrical grids.

The presented works address various crucial aspects in renewable energy integration, energy storage, and energy system stability. Beginning with the analysis of short-term solar variability in Rajasthan, India, the importance of understanding and managing this variability for efficient large-scale solar energy integration into grids is highlighted. Utilization of ground-measured solar irradiation data allows for quantification of the impact of this variability and assessment of the effectiveness of spatial smoothing techniques in reducing fluctuations, which is fundamental for successful solar energy implementation in the region (Menadi et al., 2024). Furthermore, deeper dives into energy storage technology and applications recognize their vital role in energy system operation to mitigate renewable energy source intermittency and enhance system stability. From biomass and gas storage to more advanced technologies like zinc-bromine flow batteries, performance characteristics are examined, and future development trends, challenges, and opportunities in energy storage are identified (Tripathy et al., 2017).

Isolated microgrids with wind and diesel power are also under study, with a focus on dynamic simulation to evaluate system quality and stability. The review highlights different operation modes of these microgrids as well as the role of various energy storage technologies in improving their quality and stability. Dynamic simulation examples are provided to illustrate microgrid behavior under wind speed variations and load consumption (Sebastián, 2021). On the other hand, the selection of energy storage technologies for prosumer microgrids is also examined, emphasizing the importance of location and technical characteristics of storage devices to optimize renewable energy integration and increase locally generated energy self-consumption. Comparison of different technologies, such as lithium batteries and vanadium flow batteries, provides a comprehensive view of available options and their potential applications in prosumer microgrids (Jarnut et al., 2017).

Some authors have conducted review studies discussing the importance of ESSs in improving system quality and stability, as well as providing ancillary services for grid support (Mansouri et al., 2020). Additionally, the potential of flutter-based energy harvesting devices in fluid streams is explored, highlighting research approaches and potential applications of this emerging technology. Key challenges, such as low power density and structural fatigue issues, requiring further research to overcome, are identified (McCarthy et al., 2016). The review on battery storage utilization in the value chain of energy systems underscores the increasing importance of this system in addressing congestion and imbalances in conventional electrical grids. An exhaustive analysis of various battery technologies, from well-known lithium-ion and lead-acid batteries to emerging technologies like vanadium flow batteries, is conducted. Operational principles, control strategies, and technical characteristics of each technology are highlighted, as well as their application in ancillary services for microgrids and large-scale energy systems (Ratshitanga et al., 2024).

Research gaps

Despite the exhaustive research provided by scholars, several criteria remain to be studied regarding the advancement in power smoothing techniques, some of which are enumerated below:

- Despite the diversity of energy storage technologies mentioned in the literature (Barra et al., 2021; Volfkovich, 2021; Zhou et al., 2013), such as flywheel storage systems, electrochemical supercapacitors, and vanadium flow batteries, there is still a lack of comprehensive comparative evaluation of these technologies in terms of effectiveness and specific applicability for smoothing power generated by renewable sources. This gap can help guide the appropriate selection of storage technologies for different power smoothing applications.
- Current research highlights the need for strategies tailored to the particular conditions of island systems, such as their geographic isolation and dependence on external energy sources. However, there is a gap in the development and evaluation of specific power smoothing strategies for these systems, considering the integration of multiple renewable energy sources and storage systems, and partial research on this topic is presented in the literature (Benavides et al., 2024; Villa-Ávila et al., 2024; Zhou et al., 2013).
- Despite the variety of energy storage technologies currently available and studied in the literature (Gao et al., 2024; Wu et al., 2024; Zhou et al., 2013), there is a lack of research on how to integrate these technologies synergistically to maximize power smoothing efficiency, especially in microgrid systems or island environments. This could explore the potential of combining different technologies to enhance energy supply stability and reliability.
- A significant gap lies in the optimization of ESSs for particular applications, such as residential microgrids or marine current energy systems presented in the literature (Arcos-Aviles et al., 2019; Jarnut et al., 2017; Wang et al., 2018). Further research is required to understand how to design and operate these systems optimally, considering the variability of renewable generation and specific environmental characteristics.
- Although some emerging technologies are mentioned, such as flutter-based energy harvesting devices (McCarthy et al., 2016; Ratshitanga et al., 2024), deeper research is needed on these technologies. This includes their technical feasibility, implementation challenges, and potential applications in power smoothing, which could contribute to the development of innovative and effective solutions to address renewable generation variability.

Contributions and chapter organization

To address the identified research gaps in the field of power smoothing techniques, several key contributions are proposed. Firstly, a comprehensive comparative evaluation of various energy storage technologies mentioned in the literature, such as flywheel storage systems, electrochemical supercapacitors, and vanadium flow batteries, is suggested to better understand their effectiveness and specific applicability for smoothing power generated by renewable sources. Additionally, the development of specific power smoothing strategies adapted to the unique conditions of island systems is proposed, considering the integration of multiple renewable energy sources and storage systems. Furthermore, investigating how to synergistically integrate different energy storage technologies to maximize power smoothing efficiency, especially in microgrid systems or island environments, is suggested. Research is also proposed to optimize ESSs for particular applications, such as residential microgrids or marine current energy systems. Finally, deeper research into emerging technologies, such as flutter-based energy harvesting devices, is suggested to explore their technical feasibility, implementation challenges, and potential applications in power smoothing. The subsequent sections of this chapter are structured as follows: Section "Contextualization and state of the art" provides a thorough contextualization and state of the art, offering a comprehensive overview of the current landscape. Following this, Section "Power smoothing techniques" delves into the intricacies of power smoothing techniques, detailing various methodologies and their applications. Section "Current challenges and future directions" addresses the contemporary challenges and outlines future directions, presenting an analysis of the obstacles ahead and potential avenues for advancement. Lastly, Section "Conclusion" encapsulates our findings and deductions in a concise conclusion.

Contextualization and state of the art

Definition of power smoothing

"Power smoothing" refers to the action of reducing fluctuations in energy generation, especially in systems incorporating renewable energy sources. The goal is to maintain a more stable and uniform power output, which is essential for preserving the stability and reliability of electrical systems, particularly in situations where energy generation is intermittent and variable. This process relies on various techniques and strategies designed to smooth variations in generated power. It involves the use of high-power ESSs, as well as the application of adaptive control techniques and the integration of different storage technologies. The implementation of these techniques allows for the optimization of renewable energy utilization and reduces dependence on conventional energy sources, contributing to a more effective transition toward a sustainable and reliable energy future (Barra et al., 2021; Jarnut et al., 2017; Mansouri et al., 2020; Sebastián, 2021; Wang et al., 2018). In Fig. 11.1, the methodology used in this chapter is depicted.

History and evolution of power smoothing technique

Indeed, the history of power smoothing in renewable energy is marked by a series of technological advancements and contributions from various researchers over time. Although there are no exact data on its inception or who specifically is

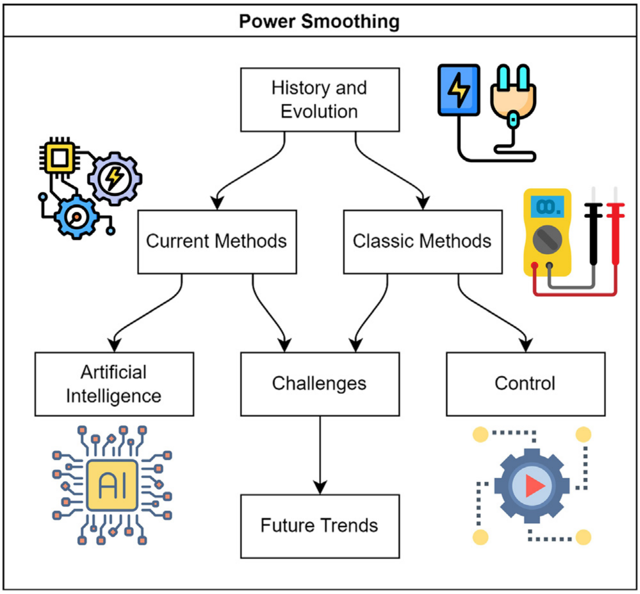

Figure 11.1 Proposed methodology overview. Theoretical framework.

credited with inventing this technique, it can be said that the earliest works in the field of power smoothing in renewable energy likely date back to the 1970s and 1980s when the first commercial applications of wind and solar technologies began to emerge. Authors and pioneers in the field of renewable energy, such as William Heronemus (Manwell, et al., 2001; Prof Dr & Goetzberger, 2023), may have contributed to laying the groundwork for research in this field. As research in renewable energy progressed and challenges associated with variability in energy generation were identified, other researchers and scientists began to explore solutions to mitigate these fluctuations. Researchers such as Daniel Kirschen, Goran Strbac, and Jianzhong Wu have made significant contributions to the development of control techniques and ESSs for power smoothing in electrical systems. In recent decades, the field of power smoothing has experienced significant growth, with a wide range of research and technological developments conducted by scholars, engineers, and scientists worldwide. Scientific and technical literature on this topic has increased considerably, addressing aspects such as control algorithms, ESSs, renewable integration into the grid, and specific applications in island systems (McCarthy et al., 2016).

In the current energy landscape, power smoothing techniques have become crucial due to the growing dependence on renewable sources and the urgent need to maintain stability in electrical grids. With the expansion of wind and solar energies, whose generation is inherently variable and intermittent, significant challenges arise to ensure a constant and reliable electricity supply. In the case of wind systems, fluctuations in wind speed can result in drastic variations in power production. Recent research has shown that integrating technologies such as lithium-ion batteries and blade angle regulation can mitigate these fluctuations, improving supply quality and reducing the associated economic impacts (Galli et al., 2024). Similarly, in PV solar systems, the use of advanced ESSs alongside control algorithms can smooth power fluctuations, ensuring grid stability even under variable solar irradiance conditions. The combination of storage technologies, such as lithium-ion batteries and supercapacitors, has been shown to significantly reduce power oscillations while extending system lifespan (Yan et al., 2024).

Furthermore, the development of predictive control techniques based on neural networks has opened up new possibilities for reducing energy fluctuations and optimizing battery state of charge, outperforming conventional power smoothing methods (Cano et al., 2024). In microgrids, innovative control strategies, such as the use of multiple hydrogen storage tanks and hierarchical control systems, can significantly improve stability and responsiveness to load demand, enabling efficient autonomous operations (Pelosi et al., 2024).

It is also crucial to consider the evaluation of storage requirements for power smoothing applications in PV plants. Detailed methodologies for determining the optimal size of storage systems, considering technical and economic aspects, can result in significant reductions in required storage volume (Amorim et al., 2024). Similarly, the implementation of sensorless controllers and the use of multistage flying capacitor inverters are technological advancements that allow for the optimization of energy extraction and smoothing of power injection into the grid, increasing reliability and reducing system costs (Khlifi et al., 2024). In an increasingly renewable energy-focused world, power smoothing techniques are essential to ensure effective integration, improve grid stability, and offer significant economic and environmental benefits. Their relevance in the current context is undeniable, as they address critical challenges on the path toward a sustainable energy future (Abdelghany, Al-Durra, et al., 2024).

Currently, when performing a search with the term "power smoothing" in Web of Science, the results shown in Fig. 11.2 are obtained and Fig. 11.3 illustrates the quantity of publications per country, delineating the primary keywords preceding a deeper exploration of the topic.

Power smoothing techniques

A comprehensive classification of various power smoothing techniques encompasses a wide range of methods aimed at stabilizing energy generation and consumption in renewable energy systems. In this chapter, these techniques will be classified under certain indices that are important within the field of electrical microgrids specifically. These techniques fall into different categories, including control strategies, objective function optimization methods, and energy conversion

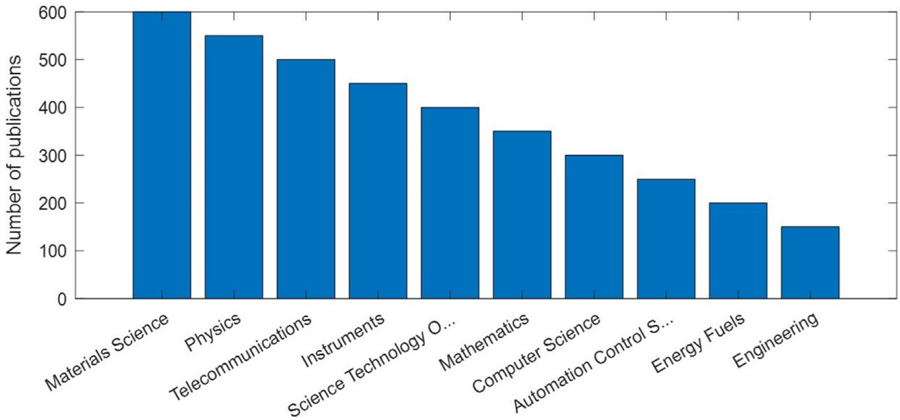

Figure 11.2 Analysis of publication distribution by area.

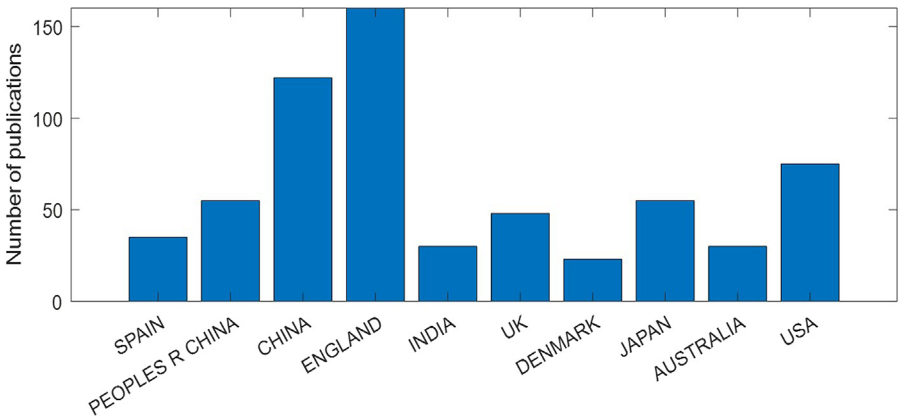

Figure 11.3 Analysis of publication distribution by country.

approaches, among others. To better understand what the power smoothing technique entails, Fig. 11.4 displays the PV output power without applying any power smoothing method and applying the moving average method. It is noticeable that the reduction in peaks is significant despite it being a basic technique.

Adaptive control

Adaptive control emerges as an essential component in the landscape of power smoothing, offering adjustable dynamics to balance energy supply with demand in real-time. Strategies such as adaptive control, discussed in Wu et al. (2024), allow for dynamic allocation of power among different energy storage devices, such as batteries and supercapacitors, thus optimizing energy flow according to real-time

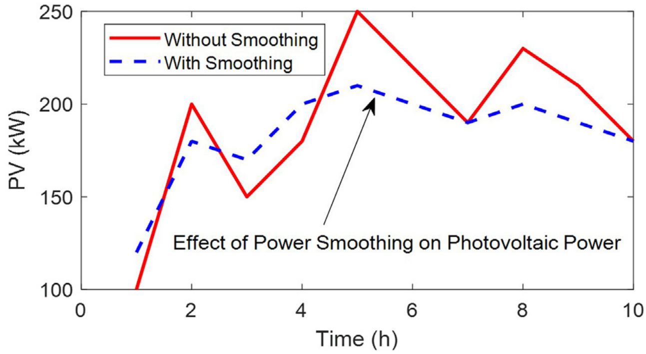

Figure 11.4 Effect of power smoothing on PV output power.

conditions. This type of control is based on learning from past errors, continuously adjusting the system based on the amount of wasted or surplus energy, which may be related to the intermittency of renewable sources. Various research works explore adaptive approaches to enhance system efficiency, ranging from the use of adaptive affine projection algorithms in superconducting energy storage units to adaptive fuzzy logic control techniques in hybrid microgrid energy management.

For instance, Hasanien (2014) presented an adaptive control scheme for superconducting energy storage units aimed at smoothing the power output of wind farms. This technique, based on the Set-membership Affine Projection Algorithm, allows for faster adjustment and lower computational complexity, demonstrating its effectiveness in improving grid stability. On the other hand, Ambia and Al-Durra (2015) introduced an innovative adaptive power smoothing control technique for hybrid microgrids, incorporating an adaptive fuzzy logic control algorithm to efficiently manage energy during transitions between grid-connected and islanded modes, demonstrating its ability to maintain energy balance even under extreme conditions. Similarly, Meng et al. (2018) proposed an adaptive control design for autonomous operation of multiple ESSs in power smoothing applications, using an adaptive cutoff frequency method to optimize the operation of distributed systems autonomously and without the need for external communication. Jamsheed and Iqbal (2022) investigated the use of a battery-based ESS to improve the stability of wind energy systems through a smart control approach based on neural identification and simultaneous control, highlighting the controller's adaptability to changing operating conditions.

Predictive control

Predictive control, using advanced algorithms such as neural networks, is employed to anticipate energy fluctuations and proactively adjust energy production. This approach is crucial for managing the variable generation of renewable sources such as PV systems, especially with the increasing demand for fast charging stations for electric vehicles. To effectively manage power fluctuations in wind-solar microgrids, a cascaded predictive control is proposed, integrating multiple hydrogen storage tanks. This method allows the microgrid to operate autonomously without connection to the electrical grid. An innovative approach combines neural predictive control and exponential moving average to smooth power, optimize battery charging, and mitigate ramp rates. This system outperforms conventional methods.

Feedback output control in PV systems, using a multilevel flying capacitor inverter, ensures maximum power and corrects power factor. To smooth wind power, a dynamic approach based on dynamic waves, using a hybrid ESS, is proposed. This method addresses uncertainty in wind energy through robust predictive control. Additionally, frequency control mechanisms monitor and regulate grid frequency.

To delve deeper into these techniques, the most significant studies have been analyzed from the perspective of relevance in the Web of Science. For example, in the study presented in Khalid and Savkin (2010), a model-based predictive control approach is proposed to smooth the output of wind energy using controlled battery storage. Similarly, Di Cairano et al. (2013) described a model predictive control (MPC) approach to smooth motor transitions in a hybrid powertrain, using battery storage. Furthermore, Khalid and Savkin (2014) focused on minimizing distributed battery storage capacity in a wind farm using predictive control and wind energy prediction. Meanwhile, Liu et al. (2017a, 2017b) presented an operation model of a hybrid ESS based on wavelet dynamic decomposition and predictive control to smooth wind energy output. Other studies, such as Meng et al. (2017), proposed a flexible control strategy for maximum power point tracking in wind turbines, considering both conversion efficiency and power smoothing. On the other hand, Bo and Johansen (2017) described a power variation smoothing method using batteries in a marine power plant, with nonlinear predictive control. Similarly, Lei et al. (2018) presented an MPC-based energy storage control method to smooth PV energy output. Nasiri et al. (2019) discussed predictive control of a CHB STATCOM in a wind farm application to smooth active and reactive power. In the field of PV energy, Han et al. (2020) proposed a dual regulation control method for a distributed ESS in smoothing PV power fluctuations. Meanwhile, Shaltout et al. (2020) presented an economic MPC control approach to smooth wind power and mitigate tower loading.

For wind energy, Wu et al. (2021) described a stochastic predictive control approach for wind energy smoothing using ESSs. On the other hand, Park and Zadeh (2021) proposed a predictive control approach for onboard dc energy hybrid systems in ships to improve voltage regulation and power smoothing. Additionally, Syed and Khalid (2021) described a neural network-based predictive control approach for PV power smoothing with battery energy storage. Meanwhile, Syed and Khalid (2023) presented an IMPC control strategy for stable dispatch of solar-wind renewable energy with battery energy storage and hydrogen electrolysis. In the transportation field, Lian et al. (2023) proposed a real-time energy management strategy for hybrid fuel cell electric buses using short-term power smoothing prediction. Finally, Abdelghany, Mariani, et al. (2024) described a unified control platform for integrating wind-hydrogen systems into the electrical grid using predictive control and mixed-logical dynamic modeling, while Lin, Cao, et al. (2024) proposed an MPC and WMA control approach for energy management and HESS capacity allocation in wind farms.

Objective function optimization

On the other hand, objective function optimization methods focus on maximizing energy efficiency and minimizing fluctuations through mathematical modeling and algorithmic optimization. These techniques involve formulating optimization problems to determine the optimal size and operation of ESSs. By defining objective functions that prioritize factors such as energy quality, system stability, and profitability, these methods allow for the design of robust and efficient power smoothing solutions.

Specifically, objective function optimization methods aim to maximize energy efficiency and minimize fluctuations through the use of mathematical modeling and algorithmic optimization techniques. This approach stands as a cornerstone in the quest for solutions that enable more effective management of ESSs, addressing crucial aspects such as energy quality, system stability, and profitability. In a recent study on wave energy conversion for generator sizing optimization and hybrid system integration, the importance of smoothing power variations in wave energy converters to optimize generator size and associated converters is highlighted. This study reveals the need to understand the impact of mechanical ESSs on the performance of wave energy converters, leading to the proposal of a method for selecting the optimal generator capacity based on different wave climates.

Furthermore, technology and applications of ESSs have been thoroughly reviewed, recognizing their crucial role in grid operation to smooth the intermittency of renewable energy generation and improve system stability. This analysis covers a variety of ESS technologies, from biomass storage to gas storage, highlighting their historical evolution, performance characteristics, and advanced materials. Additionally, applications of these technologies in short, medium, and long-term power systems are identified, ranging from energy generation to distribution and final consumption.

On the other hand, the use of battery-based ESSs has emerged as a key solution to address instability challenges in conventional power grids. This study details the global landscape of integrating battery technologies into renewable energy production systems and utility power grids. A comparative analysis of various battery technologies, such as lithium, lead-acid, sodium-sulfur, and vanadium flow batteries, is conducted, highlighting their application in ancillary services and control techniques that improve the performance of microgrids and conventional power grids. These studies are focused on renewable energy microgrids, within a world with similar studies that are widely studied in the literature review.

Power smoothing techniques using energy storage and energy conversion systems

Lastly, energy conversion techniques play a crucial role in transforming energy from variable renewable sources into stable electricity compatible with the grid. Hybrid optimization methods combine different energy conversion technologies to maximize energy capture and utilization in variable environmental conditions. Additionally, innovative approaches such as using electric vehicle batteries for power smoothing leverage the existing infrastructure to store and distribute energy efficiently, reducing dependence on traditional grid resources. To delve into the details of these power smoothing techniques, energy conversion techniques play an essential role in the process of transforming variable renewable sources into a form of electricity stable and compatible with the power grid. These methodologies not only address the capture and efficient utilization of energy in changing environmental conditions but also explore new innovative ways to improve energy system stability and efficiency.

A key strategy in this regard is hybrid optimization, which merges various energy conversion technologies to maximize the utilization of energy resources in variable environments. This approach, supported by research such as that conducted by Menadi et al. (2024) and Pelosi et al. (2024), aims to combine, for example, wind and solar energy with storage systems such as electric vehicle batteries. The latter point is particularly relevant given the increase in electric vehicle adoption and associated charging infrastructure. As mentioned in Villa-Ávila et al. (2024), the strategic use of these batteries not only contributes to smoothing energy fluctuations but also optimizes system efficiency by innovatively leveraging the existing infrastructure. A notable example is the power smoothing method presented in the study titled "Innovative Power Smoothing Technique for Enhancing Renewable Integration in Insular Power Systems Using Electric Vehicle Charging Stations." This approach proposes an improved "ramp-rate" technique that incorporates fuzzy logic to control the ramp rate in real time, using electric vehicle batteries to optimize self-consumption and reduce power fluctuations. Experimental validation of this technique demonstrates a significant 14% reduction in energy generation variability, resulting in a more stable and reliable power supply profile.

Additionally, the importance of real-time implementation of hybrid approaches is highlighted, as discussed in Menadi et al. (2024), where the implementation of a hybrid ESC control approach to maximize PV power extracted under partial shading conditions is analyzed. This study demonstrates how the combination of methods such as super twisting control and modified extreme control can improve the efficiency of solar energy generation systems by optimizing maximum power point tracking, even under adverse conditions. Then, the integration of hybrid ESSs, as described in Pelosi et al. (2024), offers a promising solution to smooth power oscillations in energy production from sources such as wave energy. By combining technologies such as lithium-ion batteries and supercapacitors, the stochastic nature of wave energy generation is mitigated, thus improving the quality and stability of the energy delivered to the power grid.

Lastly, hydrogen plays a crucial role in power smoothing in PV generation systems, as described in several studies. For example, in Takahashi et al. (2019), a novel power smoothing control method for a PV generation system using a water electrolyzer is proposed. This method distributes the long and short-term components of PV power fluctuations, supplying the long-term components to the power grid and the short-term components to the electrolyzer, which converts energy into hydrogen for fuel cell vehicles. On the other hand, Kong et al. (2021) focuses on the technoeconomic analysis of hydrogen energy for power smoothing in renewable energies, optimizing the capacity of electrolyzers and fuel cells to maximize system benefits. Additionally, Huang et al. (2021) presented a wind−hydrogen− superconducting magnetic energy storage (SMES) hybrid system to improve power smoothing and system reliability, using an alkaline electrolyzer and SMES to provide a cost-effective solution. On the other hand, Mariani et al. (2022) proposed a model-based predictive control to operate hydrogen-based ESSs in wind farms, allowing for smooth power injections and avoiding penalties for contracted power deviations. Likewise, Rufer (2023) described a new experimental power smoothing method using supercapacitors and hydrogen for PV/HKT hybrid systems, demonstrating a significant reduction in power fluctuations and an improvement in hydrogen production. Finally, Behera and Saikia (2023) presented a hybrid ESS including a hydrogen/bromide redox flow battery and a supercapacitor, controlled by an adaptive energy management system to enhance energy and power support in PV systems. Table 11.1 provides a brief summary of the different existing power smoothing methods classified according to the methodology of the algorithm used in each case.

Current challenges and future directions

The current challenges of power smoothing span a wide range of areas and technologies. These details are shown in Table 11.2. Among these challenges are the significant costs associated with battery maintenance and replacement, as well as the storage of chemical fuels, which represent a major economic obstacle to the implementation and maintenance of ESSs. The integration of hybrid systems with the existing infrastructure presents technical and compatibility difficulties that must be overcome to ensure smooth operation. Another crucial challenge is user acceptance, as users often show resistance to adopting new technologies without clear incentives. Concerns about reliability and associated costs also play a significant role in users' perception of these technologies.

The complexity in algorithm control is another prominent challenge, with high computational capacity requirements and large volumes of data needed to train advanced algorithms. Additionally, uncertainty in prediction models and prediction accuracy represent a constant challenge in the energy smoothing process. Numerous proposals and technical and operational improvements are being made to address these challenges, from intelligent control of battery state of charge to the development of

Table 11.1 Classification of the most important power smoothing methods, according to the methodology used.

Method	Description	References
Autoadaptive control	Uses electric vehicle batteries to smooth energy fluctuations with fuzzy logic.	Villa-Ávila et al. (2024)
	Autoadaptive approach to allocate power between grid, battery, and supercapacitor.	Wu et al. (2024)
Predictive control	Innovative method using hybrid energy storage to smooth energy fluctuations.	Benavides et al. (2024), Mansouri et al. (2020), Ratshitanga et al. (2024), Abdelghany, Al-Durra, et al. (2024), Cano et al. (2024), Khlifi et al. (2024), Guo et al. (2020), Arévalo et al. (2023), Benavides et al. (2023), Khalid and Savkin (2010), Abdelghany, Mariani, et al. (2024), Lin, Cao, et al. (2024), Takahashi et al. (2019), Kong et al. (2021), Huang et al. (2021), Mariani et al. (2022), Rufer (2023), Behera and Saikia (2023)
	Reduction of fluctuations in renewable sources through predictive control with neural networks.	Cano et al. (2024), Guo et al. (2020), Arévalo et al. (2023), Benavides et al. (2023), Reihani et al. (2016), Nempu et al. (2021), Hadi et al. (2021), Cao, Wu, Zhang and Li (2022), Cao, Wu, Zhang, Li, and Zhang (2022)
	Combines techniques to maximize energy under partial shading conditions.	Menadi et al. (2024)
	Hybrid storage combined with wave energy converter to smooth power oscillations.	Pelosi et al. (2024)
Objective function (optimization)	Proposes a method to optimize marine wind and wave generator sizing.	Gao et al. (2024)
	Energy storage to smooth fluctuations in renewable energy generation.	Tripathy et al. (2017), Ratshitanga et al. (2024), Benavides et al. (2022), Shim et al. (2019), Anwar et al. (2017), Zhang et al. (2017)
	Uses multiple storage technologies to provide greater flexibility in energy management.	Tripathy et al. (2017), Kong et al. (2021), Behera and Saikia (2023)

(*Continued*)

Table 11.1 (Continued)

Method	**Description**	**References**
	Short-term energy storage to mitigate energy fluctuations in short periods.	Tripathy et al. (2017)
	battery energy storage system (BESS) efficiency in Maui, Hawaii, through nonlinear programming and real-time control.	Reihani et al. (2016)
	Power variability smoothing with Li-Ion battery.	Galli et al. (2024)
	Algorithm to reduce necessary storage capacity in photovoltaic systems.	Yan et al. (2024)
	Improves energy quality in hybrid microgrids.	Nempu et al. (2021)
	Peaks reduction in machining processes without productivity loss.	Hadi et al. (2021)
	Balances power smoothing and frequency regulation.	Cao, Wu, Zhang and Li (2022)
	Addresses uncertain power fluctuations and frequency deviation.	Cao, Wu, Zhang, Li, and Zhang (2022)
	Enhances stability in renewable systems.	Benavides et al. (2022)
	Optimizes size and operability of supercapacitors.	Arévalo et al. (2023)
	Enhances battery lifespan.	Benavides et al. (2023)
Dynamic simulation	Dynamic simulation of renewable energy generation systems to understand and optimize energy quality and stability.	Sebastián (2021), Mansouri et al. (2020)
Adaptive frequency control	Maintains grid frequency within acceptable limits by adjusting instantaneous power generation.	Mansouri et al. (2020), Ratshitanga et al. (2024)
Power reduction	Controlled reduction of active power generated by renewable energy facilities to maintain grid stability.	Mansouri et al. (2020)
Restrictive control	Controlled injection of reactive power into the grid to maintain voltage quality within acceptable limits.	Mansouri et al. (2020), Ratshitanga et al. (2024)
	Sensorless control of photovoltaic systems with a flywheel inverter.	Khlifi et al. (2024)
Frequency control	Integration of wind turbine pitch regulation with a battery to avoid ramp-up violations.	Galli et al. (2024)

Table 11.2 Current challenges of the power smoothing method for electrical systems including renewable sources and microgrids.

Current Challenges	References	Description
Costs	Cunha and Pereira (2024), Fan et al. (2024), Liu and Peng (2024), Syed et al. (2024), Yu et al. (2024), Zhang et al. (2024)	High costs due to battery maintenance and replacement, and chemical fuel storage. Economic challenges in implementing and maintaining energy storage systems.
Integration with Infrastructure	Hou et al. (2024), Li, Wang, et al. (2024), Li, Ding, et al. (2024), Shi et al. (2024), Syed et al. (2024), Wang, Zhou, et al. (2024), Ye et al. (2024), Yu et al. (2024), Zhang et al. (2024)	Difficulty in integrating hybrid systems with existing infrastructure. Technical and compatibility challenges.
User Acceptance	Liu and Peng (2024), Shi et al. (2024), Yu et al. (2024), Zhang et al. (2024)	User resistance to new technologies without clear incentives. Concerns about reliability and costs.
Control Complexity and Algorithms	Li, Wang, et al. (2024), Li, Ding, et al. (2024), Wang, Zhou, et al. (2024), Ye et al. (2024)	High computational complexity and large data volumes needed for training advanced algorithms.
Inaccurate Models and Prediction of Errors	Li, Wang, et al. (2024), Li, Ding, et al. (2024)	Uncertainty in wind predictions and variability in generation models.
System Security and Stability	Hou et al. (2024), Wang, Zhou, et al. (2024)	Need for real-time monitoring and proper parameter adjustment to ensure stability.
Selection of K-means Clusters	Hu et al. (2024)	Optimization using Pearson correlation coefficient and greedy algorithm.
Spectral Comparison between Locations	Bel and Bandi (2024)	Systematic decomposition of solar irradiance time series needed.

(*Continued*)

Table 11.2 (Continued)

Current Challenges	References	Description
Technical and Operational Proposals and Improvements	Deng et al. (2024), Jena and Ray (2024), Lei et al. (2024), Li, Ding, et al. (2024), Li, Wang, et al. (2024), Liang et al. (2024), Lin, Lin, et al. (2024), Wang, Cui, et al. (2024)	Various proposals and improvements related to energy smoothing.
Prediction of Lithium-ion Battery Health	Fauzi et al. (2024)	SGEformer model improves prediction accuracy, setting a new standard.
Battery State of Charge Control	Lin, Cao, et al. (2024), Syed and Khalid (2023)	Intelligent control to extend battery life and stabilize wind power.
Real-time Energy Management Strategy	Lian et al. (2023), Mariani et al. (2022)	Real-time strategy for electric buses and energy storage system operation in wind farms.
Power Smoothing Method for PV Systems	Behera and Saikia (2023), Takahashi et al. (2019)	Control for PV systems to smooth fluctuations and experimental method with supercapacitors and hydrogen.
Techno-economic Analysis of Hydrogen Energy for Renewable Energy Smoothing	Kong et al. (2021), Rufer (2023)	Economic analysis of electrolyzer optimization and gas reinforcements for renewable energy smoothing.
Cooperative Control of Wind-hydrogen Hybrid Systems	Arevalo, Cano, et al. (2023), Huang et al. (2021)	Cooperative strategy to enhance resilience and smoothing in wind-hydrogen systems. Experimental method to reduce fluctuations with supercapacitors and hydrogen.
Integration of Renewable Energy Prediction Systems into Power Smoothing Controllers	Khalid and Savkin (2010), Syed and Khalid (2021), Wu et al. (2021)	Development of controllers using energy prediction systems to smooth renewable energy output.
Optimization of Energy Management Strategies for Hybrid Electric Vehicles	Di Cairano et al. (2013)	Proposal of energy management strategies to enhance efficiency in hybrid vehicles.

(*Continued*)

Table 11.2 (Continued)

Current Challenges	**References**	**Description**
Battery Storage Capacity Minimization for Cost Reduction	Khalid and Savkin (2014), Benavides et al. (2022)	Development of schemes to minimize battery storage capacity in distributed configurations.
Optimal Coordination of Energy Storage Systems for Wind Power Smoothing	Liu et al. (2017a, 2017b), Wu et al. (2021)	Development of operation models to smooth wind power output.
Conversion Efficiency and Power Smoothing Balance in Large Inertia Wind Turbines	Meng et al. (2017)	Methods proposed to balance conversion efficiency and power smoothing in wind turbines.
Fatigue Mitigation in Wind Turbine Towers through Economic Wind Energy Control	Shaltout et al. (2020)	Economic control methods proposed to reduce fatigue load on wind turbine towers.
Uncertainty Management and Energy Storage Capacity Planning in Wind Energy Systems	Wu et al. (2021)	Methods developed to manage uncertainty and plan energy storage capacity in wind systems.
Voltage Regulation and System Stability Improvement in Hybrid Energy Systems on Vessels	Bo and Johansen (2017), Park and Zadeh (2021)	Methods proposed to improve voltage regulation and stability in hybrid energy systems on vessels.
Utilization of Neural Networks for Solar Energy Fluctuations Smoothing with Energy Storage Systems	Bo and Johansen (2017), Syed and Khalid (2021)	Development of controllers based on neural networks to smooth solar energy fluctuations with energy storage.
Optimal BESS Configuration with Frequency Constraints	Cao, Wu, Zhang, Li, and Zhang (2022), Cao, Wu, Zhang and Li (2022)	Proposal of optimal configuration for battery energy storage systems (BESS) to maintain power fluctuations and frequency deviation within predefined limits, improving system stability.

(*Continued*)

Table 11.2 (Continued)

Current Challenges	References	Description
Experimental Study of Power Smoothing Methods	Arevalo, Benavides, et al. (2023), Benavides et al. (2022, 2023)	Evaluation of power smoothing algorithms for renewable systems, combining solar, wind, and hydrokinetic energy with hybrid storage systems, showing reduction in energy fluctuations and increased self-consumption.
Adaptive Control for Power Smoothing in Wind Farms	Hasanien (2014)	Adaptive control scheme proposed for energy storage units (SMES) to smooth power output from wind farms, improving grid stability through fuzzy learning algorithms and adaptive proportional-integral control.
Adaptive Control Design for Autonomous ESS Operation	Ambia and Al-Durra (2015)	Proposal for adaptive control method for energy storage systems (ESS) operating autonomously and without external communication, using an adaptive high-pass filter to smooth power and maintain state of charge within safe limits.
Improvement of Dynamic Stability in Wind Systems	Meng et al. (2018)	Examination of how energy storage systems (BESS) can enhance stability of wind systems through intelligent control based on neural identification and simultaneous control.

real-time energy management strategies for electric vehicles and wind farms. Furthermore, innovative approaches are being explored, such as the use of neural networks to smooth solar energy fluctuations and the design of optimal configuration schemes for ESSs with frequency constraints.

After a comprehensive analysis of the literature, several future research directions can be identified, guiding technological development in the field of power smoothing. Below is a concise summary of potential future trends in power smoothing methods for renewable systems. Additionally, Table 11.3 provides an overview of these future trends in a more concise format.

Energy storage systems

The development of efficient ESSs emerges as a key trend in power smoothing. Advancing storage technologies to store excess energy during high generation periods and release it during low generation intervals stabilizes the grid (Barra et al., 2021; Benavides et al., 2024; Menadi et al., 2024; Pelosi et al., 2024; Ratshitanga et al., 2024; Tripathy et al., 2017; Wu et al., 2024; Zhou et al., 2013).

Control and energy management

Effective control and management of energy resources are crucial for ensuring grid stability. Sophisticated control algorithms dynamically adjusting energy flow, optimizing

Table 11.3 Key trends and future challenges of power smoothing techniques in renewable systems.

Future challenge	References
Development of adaptive strategies for renewable energy storage system control	Benavides et al. (2024), Khlifi et al. (2024), Shim, Kim, and Hur (2019), Guo et al. (2020), Nempu et al. (2021)
Optimization of integrated hybrid renewable energy systems	Anwar et al. (2017), Guo et al. (2020)
Advancement of predictive control techniques	Benavides et al. (2024), Hadi et al. (2021)
Investigation of load management strategies for high penetration renewable energy networks	Reihani et al. (2016), Zhang et al. (2017)
Optimization of energy storage system size and placement	Reihani et al. (2016), Zhang et al. (2017)
Research on robust methods for wind power smoothing	Guo et al. (2020)
Development of power smoothing strategies using superconductors for AC-DC hybrid microgrids	Nempu et al. (2021)

energy utilization, and responding to grid disturbances are needed (Abdelghany, Al-Durra, et al., 2024; Arcos-Aviles et al., 2019; Benavides et al., 2024; Villa-Ávila et al., 2024; Wang et al., 2018; Wu et al., 2024; Yan et al., 2024).

Integration of renewable technologies

Seamless integration of various renewable energy sources is essential for achieving a reliable and sustainable energy mix. Optimizing the integration of solar, wind, and other renewables to maximize system efficiency is emphasized (Barra et al., 2021; Benavides et al., 2024; Galli et al., 2024; Mansouri et al., 2020; Menadi et al., 2024; Pelosi et al., 2024; Sebastián, 2021; Villa-Ávila et al., 2024; Wang et al., 2018; Zhou et al., 2013).

Optimization of photovoltaic systems

Optimizing PV systems plays a critical role in improving their performance and reliability. Enhancing the design and operation of PV systems to maximize energy yield and mitigate grid disturbances is a focus (Galli et al., 2024; Jarnut et al., 2017; Menadi et al., 2024; Yan et al., 2024).

Advanced predictive control

Predictive control techniques based on neural networks are gaining prominence in improving the stability and efficiency of renewable energy systems. The potential of predictive control algorithms to anticipate grid conditions and optimize energy management accordingly is highlighted (Cano et al., 2024).

Microgrid and vehicle-to-grid applications

Microgrids and vehicle-to-grid (V2G) systems offer innovative solutions for decentralized energy management. The applications of microgrids and V2G technologies in optimizing energy utilization and grid stability are explored (Abdelghany, Al-Durra, et al., 2024; Arcos-Aviles et al., 2019; Benavides et al., 2024; Mansouri et al., 2020; Prof Dr & Goetzberger, 2023; Villa-Ávila et al., 2024; Wu et al., 2024).

Robust wind power smoothing

Robust methodologies utilizing hybrid ESSs are essential for mitigating wind generation variability. Developing robust control strategies to ensure reliable and consistent integration of wind energy is emphasized (Guo et al., 2020).

Power smoothing in microgrids with superconductors

Utilizing superconductors in AC-DC hybrid microgrids presents a promising pathway for power smoothing. Exploring the potential of superconductor technologies in improving grid stability and efficiency is discussed (Nempu et al., 2021).

Conclusion

The transition toward a more sustainable and diversified energy matrix has increased the demand for power smoothing techniques due to the intermittent and variable nature of renewable energies. The need to maintain stable and uniform energy generation to ensure the operational stability of electrical systems is becoming increasingly crucial. Over the decades, the field of power smoothing has experienced significant growth, with contributions from various researchers and technological advancements. From early work in the 1970s and 1980s to recent developments in adaptive and predictive control, the historical evolution highlights continuous progress in this field. This chapter provided a comprehensive review of these techniques applied to renewable energies. The following conclusions are drawn:

Although there is a wide variety of power smoothing techniques, ranging from adaptive and predictive control strategies to objective function optimization methods and energy conversion approaches, this diversity reflects the complexity of the challenge and the need for innovative and adaptive solutions. Power smoothing techniques are applied in a variety of contexts, from wind and solar systems to microgrids and transportation applications. Each application has its own challenges and specific requirements, underscoring the importance of adapting power smoothing techniques to the conditions and needs of each environment.

Technological advancements, such as the development of adaptive and predictive control algorithms, advanced ESSs, and optimization techniques, are continually driving the field of power smoothing forward. These advancements are enabling more efficient and effective solutions to address the variability of renewable energy generation. Objective function optimization methods focus on maximizing energy efficiency and minimizing fluctuations through mathematical modeling and algorithmic optimization. This demonstrates a comprehensive approach to addressing the challenges associated with renewable energy generation variability.

Various energy storage technologies, such as electric vehicle batteries, hydrogen storage, and hybrid storage systems, are highlighted. These technologies offer innovative solutions to address power fluctuations and improve electrical system stability. Hybrid approaches, which combine different energy conversion technologies, are critical for maximizing energy capture and utilization in variable environmental conditions. These approaches allow for the optimal use of available energy resources and improve overall energy efficiency.

Further research is needed to optimize ESSs for particular applications, such as residential microgrids or energy systems based on marine currents. Understanding how to design and operate these systems optimally is crucial to ensuring energy supply stability and reliability. Additionally, it is essential to continue exploring emerging technologies, such as aerodynamic flutter-based energy harvesting devices, to drive the development of power smoothing and improve overall energy efficiency.

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