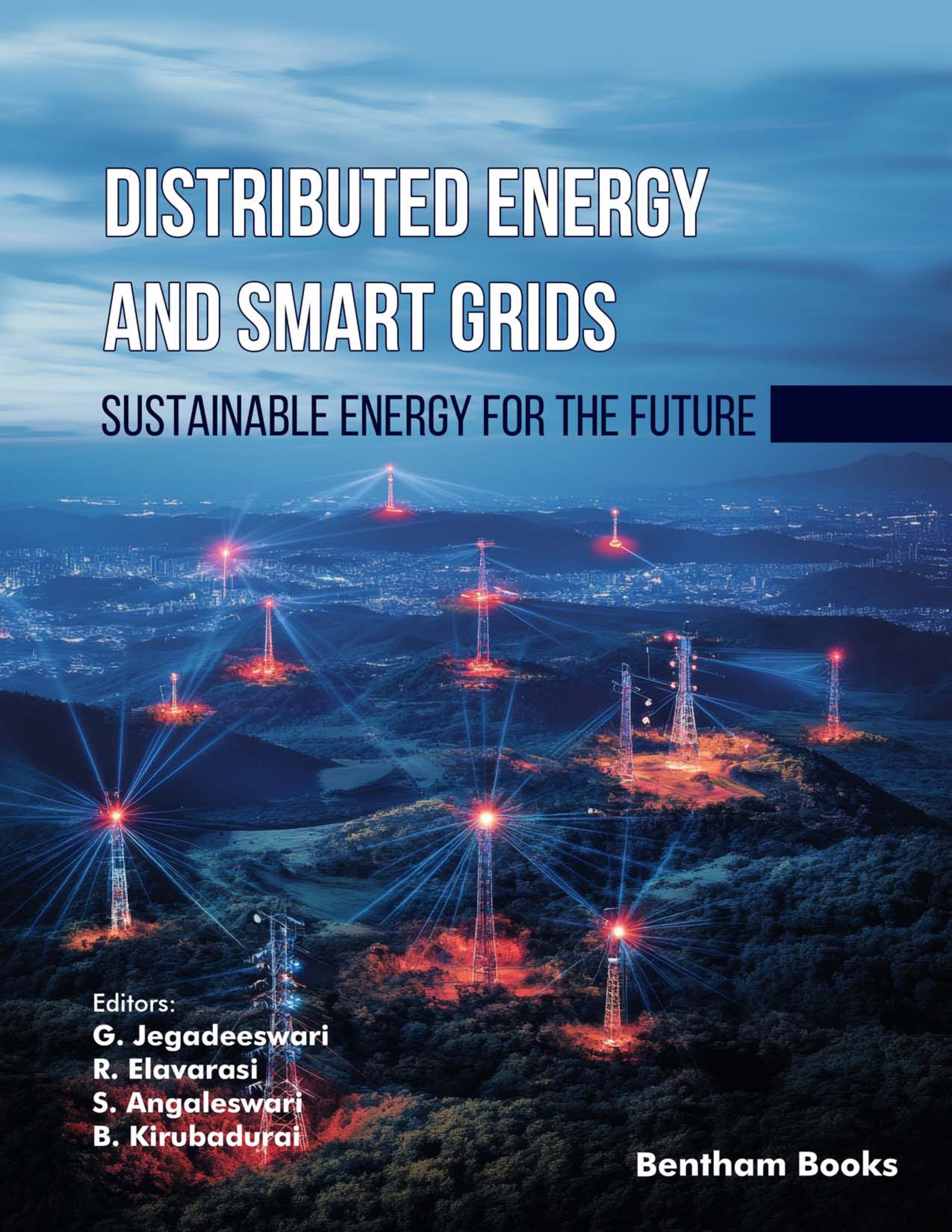
DISTRIBUTED ENERGY AND SMART GRIDS

SUSTAINABLE ENERGY FOR THE FUTURE



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Distributed Energy and Smart Grids: Sustainable Energy for the Future

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ISBN (Online): 979-8-89881-339-0

ISBN (Print): 979-8-89881-340-6

ISBN (Paperback): 979-8-89881-341-3

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First published in 2026.

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FOREWORD

Energy is the backbone of modern civilization. From the moment we wake up and switch on a light to the devices that power industries, transportation, and homes, our lives are intricately woven with energy consumption. For decades, we have relied on large, centralized power plants, often fueled by non-renewable resources, to supply our electricity needs. While this model has served us well, it is no longer sustainable in the face of rising energy demands, climate change, and the need for energy security.

A new era of energy innovation is upon us. Today, distributed energy resources (DERs) and smart grids are transforming the traditional energy landscape, offering a future that is more decentralized, efficient, resilient, and environmentally friendly. This transition is not just an advancement in technology; it is a fundamental shift in the way we generate, manage, and distribute power.

As a researcher, deeply involved in the study of energy systems, I have witnessed firsthand how cutting-edge technologies are reshaping industries and societies. The need for smarter, cleaner, and more adaptive energy solutions has never been greater. My own work has led me to explore how emerging energy technologies can bridge the gap between conventional power infrastructure and modern, sustainable solutions.

Throughout my journey, I have observed how renewable energy sources, such as solar and wind, are no longer just alternative options but mainstream power sources. However, these sources bring inherent challenges intermittency, storage limitations, and integration complexities, which demand innovative solutions. This is where smart grids come into play.

A smart grid is more than just an improved electrical network; it is a dynamic system that integrates digital intelligence, automation, and real-time data analytics to optimize energy distribution and consumption. It enhances grid stability, reduces energy losses, supports decentralized energy production, and empowers consumers to participate in the energy market actively. Imagine a world where homes generate their own electricity, store excess energy, and trade it within a community microgrid. This is no longer science fiction but an emerging reality.

This book, Distributed Energy and Smart Grids: Sustainable Energy for the Future, is a culmination of research, technological advancements, and visionary ideas that aim to redefine the future of energy. It delves into the principles, challenges, and opportunities presented by decentralized energy generation, smart grid implementation, energy storage solutions, and digital transformation in the power sector.

The content within these pages is designed to offer a comprehensive understanding of how distributed energy and smart grids are shaping the next generation of power systems. Whether you are a researcher, engineer, policymaker, energy professional, or simply an enthusiast eager to understand the energy revolution, this book serves as a guide to help navigate the evolving landscape of modern energy solutions.

Each chapter is structured to provide insightful discussions, real-world applications, and technological advancements that drive the adoption of sustainable and resilient energy systems. By addressing key challenges such as grid modernization, cybersecurity, policy frameworks, and economic feasibility, this book offers a roadmap for the future of energy.

The global energy transition is not just about technology; it is about people, policies, and collective action. The shift toward distributed energy and smart grids requires collaboration among researchers, industries, governments, and consumers. By embracing these advancements, we can build an energy system that is not only reliable and efficient but also sustainable and accessible to all.

As we move forward, we must continue to innovate, challenge conventional paradigms, and invest in future-ready energy solutions. The insights presented in this book aim to spark new ideas, encourage meaningful discussions, and inspire practical implementations that contribute to a greener, smarter, and more resilient world.

I extend my gratitude to the authors, editors, and all those who have contributed to this remarkable volume. Their dedication to advancing the discourse on technology and sustainability is a beacon of hope for a brighter future. As you read these pages, I encourage you not only to absorb the knowledge but also to be inspired to take action, for it is through collective effort and shared vision that we will turn the promise of these technologies into a reality that benefits us all. The time for change is now. Let us work together to reshape the future of energy, ensuring a sustainable planet for generations to come.

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PREFACE

The global energy sector is undergoing a profound transformation, driven by technological advancements, environmental concerns, and the need for energy security. The traditional model of centralized power generation, which has dominated for over a century, is no longer sufficient to meet the demands of an increasingly electrified and interconnected world. In its place, a new paradigm is emerging, one that leverages distributed energy resources (DERs) and smart grid technologies to create a more sustainable, resilient, and intelligent energy infrastructure.

This book, Distributed Energy and Smart Grids: Sustainable Energy for the Future, is the result of our extensive research and exploration into the next generation of energy systems. As researchers and professionals working in this field, we have seen firsthand how advancements in renewable energy, energy storage, and digital grid technologies are reshaping the way we produce, distribute, and consume electricity. This shift is not merely a trend; it is an essential step toward a cleaner, more efficient, and more decentralized energy future.

The idea for this book stemmed from a fundamental question: How can we create an energy system that is both sustainable and reliable while meeting the demands of an evolving world? As we delved deeper into this question, we realized that the answer lay in the synergy between distributed energy systems and smart grids.

• Distributed energy resources (DERs), such as solar panels, wind turbines, and energy storage systems, empower consumers and communities to generate their own power, reducing reliance on traditional fossil fuel-based grids.

• Smart grids, equipped with digital intelligence and real-time analytics, optimize electricity distribution, enhance grid stability, and facilitate seamless integration of renewable energy sources.

Together, these innovations offer a transformative solution to some of the biggest challenges facing our energy infrastructure today: climate change, grid inefficiencies, energy access, and resource scarcity. This book is designed to provide a comprehensive overview of the technological, economic, and policy aspects of distributed energy and smart grids.

This book also explores real-world case studies and the latest research on successful implementations of smart grids and decentralized energy systems worldwide. By presenting both technical insights and practical applications, this book aims to provide valuable knowledge for researchers, engineers, policymakers, and energy professionals.

This book is intended for a broad audience, including:

• Researchers and Academics – Those seeking to explore advanced concepts in distributed energy and smart grids.

• Engineers and Energy Professionals – Individuals involved in energy system design, grid management, and renewable energy integration.

• Policymakers and Regulators – Decision-makers looking for insights on policies that can facilitate the transition to smart and distributed energy systems.

• Students and Enthusiasts – Anyone interested in learning about the future of energy and how technology is reshaping the power industry.

The world is at a pivotal moment in the evolution of its energy infrastructure. With growing environmental concerns, the increasing demand for energy, and rapid technological advancements, the transition to distributed energy and smart grids is not just an opportunity, it is an imperative.

It is our hope that this book will serve as a valuable resource in understanding the complexities, opportunities, and challenges of modern energy systems. More importantly, we hope it will inspire new ideas, encourage innovation, and foster collaborations that contribute to a sustainable and resilient energy future.

The journey toward a cleaner, smarter, and more inclusive energy system is one that requires commitment, research, and innovation from all of us. Let us move forward together in shaping an energy future that is efficient, intelligent, and sustainable for generations to come.

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CHAPTER 1

An Overview of Technologies, Energy Management Systems, and Challenges in Integrating Solar Energy Systems for Energy Transition

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Abstract: A key component of the Sustainable Development Goals is the switch to renewable energy sources in order to attain a net-zero global energy system. RESs, energy efficiency, and electrification are three important areas that need to be addressed right away. There are other routes as well, all of which call for a major rise in regulatory frameworks, policies, and investments in research. In this sense, attaining a net-zero global energy system remains greatly aided by solar energy. The most plentiful and accessible resource is solar power, and its price has dropped dramatically in recent years. To increase the effectiveness and economy of PV systems as well as their integration with other energy systems, there is an urgent need for ongoing technological advancements and innovations. Additionally, integrating various energy systems can lead to emissions reductions and energy savings. This chapter will examine the various energy system types that can be combined with PV systems in urban settings, as well as the energy balance calculation of each system. It will also examine the technologies and techniques employed, the difficulties encountered, and the solutions and approaches taken to overcome these difficulties. Furthermore, we will talk about smart energy management solutions for demand-side management, energy storage, and distributed generation that integrate various technologies more effectively and sustainably.

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Keywords: Clean energy transition, Demand-side management, Energy storage system, Smart energy management systems, Solar energy, Zero energy neighborhood.

INTRODUCTION

In order to solve the pressing energy and resource restrictions, environmental risks, global challenges of climate change, and other sustainable development concerns, it is imperative to explore a new route *via* the global energy transition. There are several scenarios based on various energy transition paths in DNV's Energy Transition Outlook 2024 [1]. The forecast that by 2050, renewable energy sources like wind and solar will provide 64% of the world's power is one of the possibilities that is highlighted. The fastest-growing renewable energy source is solar, with PV system capacity expected to increase by more than 22 times between 2018 and 2050. As a result, by 2050, solar energy will dominate the RES mix, making up over 70% of it. Furthermore, according to the report, by 2050, 80% of passenger cars will be electric vehicles (EVs). They are thus emerging as a new prospect in the integration of PV systems.

Solar energy systems come in a wide variety and can be integrated with other energy systems to optimize the benefits of solar radiation. Nowadays, the combination of solar energy with other sources or grid systems has become more popular. The main objectives of optimizing storage and energy production efficiency are to provide clean energy and reduce energy costs. The first grid-connected photovoltaic systems were installed in the 1970s, marking the beginning of SESI’s long history. Since then, it has expanded to encompass a wide range of applications, from small-scale systems to large-scale utility projects. With over 800 GW of solar energy capacity installed globally by 2020, SESI has emerged as a crucial component of the renewable energy sector [2].

The significance of SESI in achieving a sustainable energy future is emphasized in the World Energy Outlook 2021 [3]. The report highlights the necessity of regulatory frameworks and policies that support the integration of power systems with solar energy networks, as well as the development of technologies such as demand-side management and energy storage to facilitate this integration. Additionally, the report underscores the importance of collaboration among stakeholders, including consumers, industry, and policymakers, to support the integration of other renewable energy sources alongside solar power (Fig. **1**) [4].

Fig. (1). PV systems integration.

To ensure a reliable and affordable electricity supply, it is essential to address the integration of solar power into power systems and networks as its role becomes increasingly significant. This chapter provides a concise and comprehensive review of the various studies published on photovoltaic (PV) systems, aiming to help researchers understand the importance of PV energy systems, the types of solar systems available, and the different SESI techniques and technologies. Section **2** describes various Distributed Energy Resource (DER) technologies, followed by an explanation of the energy balance formulation. Section **3** covers SESI methods and approaches, while Section **4** introduces the concept of a Smart Energy Management System (SEMS). Finally, Section **5** briefly discusses the challenges associated with solar systems and possible solutions.

TECHNOLOGIES ENABLED FOR DISTRIBUTED ENERGY SYSTEM

Solar system integration can be optimized through various methods and technologies, including batteries, electric vehicles (EVs), and Smart Energy Management Systems (SEMSs). Excess solar energy can be stored in batteries for use during periods of high demand or low solar output. EVs can also be considered mobile energy storage units, capable of shifting energy demand from peak to off-peak periods, thereby reducing greenhouse gas emissions and energy costs. SEMSs enhance the utilization of renewable energy sources (RES), minimize energy expenses, and optimize solar energy production and storage by leveraging machine learning and data analytics. This section explores various distributed energy technologies, including energy storage systems (ESSs) and

CHAPTER 2

Enhancing Sustainability: Integrating Renewable Energy Sources into Smart Grids for Efficient and Resilient Energy

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Abstract: The integration of renewable energy sources into smart grids is essential for achieving sustainable, efficient, and resilient energy systems. With increasing global demand for cleaner energy and the rapid development of renewable technologies, smart grids offer a flexible infrastructure that can accommodate the unique characteristics of renewables, such as variability and decentralization. This chapter reviews key challenges and solutions for integrating solar, wind, and other renewable sources into smart grids. Key topics include demand response, energy storage, grid stability, and real-time energy management, along with the role of Internet of Things (IoT) and artificial intelligence (AI) in enabling adaptive and predictive grid operations. Furthermore, the chapter explores case studies that demonstrate the successful implementation of renewable-smart grid integration and highlights future directions for research. The findings underscore the critical importance of advanced control systems, dynamic pricing, and regulatory support in maximizing the reliability and efficiency of renewable energy within smart grids, contributing to a sustainable energy future.

Keywords: Internet of Things (IoT), Artificial Intelligence (AI), Renewable Energy Sources (RES), Smart grids.

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INTRODUCTION

As countries work to cut carbon emissions and switch to cleaner energy sources, the global energy scene is changing dramatically [1, 2]. Integrating Renewable Energy Sources (RES), including solar, wind, and hydropower, into smart networks is essential to this shift [3]. Because renewable energy is intermittent, smart grids offer a flexible and intelligent energy infrastructure that can balance supply and demand. Building a durable, effective, and sustainable energy infrastructure requires integrating renewable energy sources into smart networks [4, 5]. This procedure entails utilizing cutting-edge technologies to connect renewable energy sources, such as hydropower plants, wind turbines, and solar panels, to the electrical grid for maximum efficiency. We can start by evaluating the energy demand, grid capacity, and available renewable resources [6 - 8] and conduct feasibility studies to determine suitable renewable technologies and installation sites [9, 10]. Also, we need to develop a comprehensive integration plan addressing technical, economic, and regulatory aspects. In order to accommodate variable energy sources, we need to upgrade the grid infrastructure. Moreover, sensors, smart meters, and cutting-edge communication systems need to be installed to facilitate data sharing and real-time monitoring [11]. Make sure that power from decentralized renewable sources may flow both ways through the grid [12, 13]. To handle supply-demand imbalances, there is a need to implement energy storage technologies like batteries, pumped hydro, or thermal storage. Storage systems aid in supplying excess energy during times of low output and storing it during times of peak production [14-16]. Machine learning (ML) and artificial intelligence (AI) are used to implement sophisticated grid management systems [17, 18]. These systems control grid stability, forecast consumption trends, and improve energy distribution [19]. Consumer participation is encouraged through demand response programs that incentivize reducing electricity use during peak periods [20, 21]. Smart appliances and home energy management systems can automate these adjustments [22]. Supportive regulatory frameworks, incentives, and policies must be in place [23, 24]. Also, clear interconnection standards must be established to streamline permitting processes for renewable installations and enhance cybersecurity to protect the smart grid from potential cyber threats [25 - 27]. Robust data encryption, secure communication protocols, and continuous system monitoring need to be implemented [28, 29]. This chapter examines key challenges, enabling technologies, and innovative solutions for integrating RES into smart grids, emphasizing demand response, energy storage, real-time management, and advanced control mechanisms. Fig. (**1**) shows how the smart grids are integrated with renewable energy for efficient and resilient energy.

KEY CHALLENGES IN RENEWABLE ENERGY INTEGRATION

Variability and Intermittency

Because of seasonal variations and weather, renewable energy sources are inherently unpredictable. Grid stability is hampered by this intermittency, necessitating real-time supply and demand balancing systems.

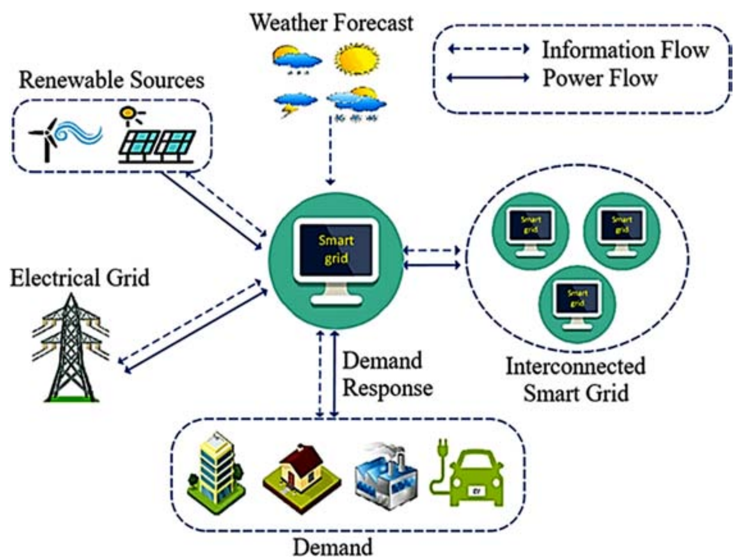

Fig. (1). Integrating renewable energy sources into smart grids for efficient and resilient energy.

Decentralization of Energy Production

A decentralized generation paradigm is introduced by distributed energy resources (DERs), such as community wind farms and rooftop solar panels. This calls for improvements to communication protocols and grid infrastructure.

Grid Stability and Security

Fluctuations in renewable energy output can destabilize power grids, causing voltage and frequency variations [30, 31]. Ensuring grid resilience requires robust control systems and fast-acting response mechanisms.

Regulatory and Market Barriers

Policy and regulatory frameworks often lag behind technological advancements, creating obstacles for widespread renewable energy integration [32, 33]. Fig. (**2**) shows the key challenges of renewable energy integration.

CHAPTER 3

Grid Automation Technologies and Control Mechanisms

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Abstract: This chapter examines technologies and strategies to improve the efficiency, reliability, and adaptability of the modern power grid. As global energy demand increases, grid automation has become essential for integrating renewable energy sources, effectively managing electricity loads, and quickly resolving system issues. By implementing advanced technologies and automated control mechanisms, grid automation enables a resilient and intelligent infrastructure that can easily cope with day-to-day operations and unforeseen challenges. Such adaptation is critical in supporting a changing energy landscape where traditional approaches are no longer sufficient. This chapter focuses on these advances and how automated power grids can contribute to a stable, flexible, and sustainable electricity supply.

Keywords: Automation, Advanced metering infrastructure (AMI), Artificial intelligence (AI), machine learning (ML), Smart grid, Supervisory control and data acquisition (SCADA).

INTRODUCTION

Grid automation represents a fundamental cornerstone in the modern energy landscape. As global energy demand continues to increase, the traditional power grid was designed for simple one-way transmission. This design is no longer adequate. With the rise of renewable energy sources like solar and wind, and the integration of advanced digital technologies, the traditional power grid is transforming into a smart grid. Grid automation acts as the driving force behind this evolution by making the grid more efficient. It also helps the grid become more adaptable and resilient in response to modern challenges [1].

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Grid Automation and its Main Objectives

Power grid automation involves the use of digital technology to monitor and control the power grid. It also helps optimize its performance in real time. This capability is essential to respond to the dynamic nature of the current energy environment [2]. Through automated systems, operators gain access to real-time data related to current flow, equipment status, and network performance. This access allows them to make quick and informed decisions. It reduces the chance of outages. It also minimizes downtime and enables proactive maintenance. These improvements enhance the overall reliability of the power grid [3].

One major benefit of grid automation is increased efficiency. Automated systems help improve power distribution by balancing loads more effectively. They also minimize energy losses [4]. This efficient use of resources ensures that energy reaches the areas where it is needed the most. It avoids unnecessary waste. In addition, automation supports better resource management. It also helps in the integration of renewable energy sources. Renewable energy depends on weather conditions and can fluctuate without warning [5]. Automated control systems handle these changes by adjusting power supply levels in real time. This action ensures a stable power supply. It also maintains a balanced power grid [4].

Another important benefit of automation is access to real-time data for grid operators. Automated systems monitor the health of the grid continuously. They collect data on important factors such as voltage, frequency, and load conditions. This data is useful for identifying problems before they become serious. It also supports fast adjustments when sudden changes occur. This proactive strategy prevents service disruptions. It strengthens the grid and helps it adapt to unexpected demand [6].

Security and resiliency are also central benefits of grid automation. Automatic fault detection and isolation tools help operators find problems immediately. They also isolate affected sections to avoid large-scale outages. In addition, automatic response systems help the grid recover quickly after interruptions. This ability is important for maintaining a stable power supply [7].

This chapter now builds on these advantages. It explains the specific technologies and control systems that make grid automation possible. This overview shows that grid automation is not just a temporary shift. It is a necessary step as the power grid develops into a smarter and more reliable system. This development is needed to meet the complex energy demands of today and the future.

KEY COMPONENTS OF GRID AUTOMATION SYSTEMS

The basic components of an automated grid system include technologies that support monitoring, communication, and control functions. These functions are essential to create a grid that is responsive, efficient, and resilient. Important technologies such as advanced metering infrastructure, supervisory control and data acquisition systems, and distribution management systems form the foundation of grid automation. Each of these systems performs a specific role. They support real-time data collection. They also enable continuous communication and allow dynamic management of grid operations [8].

Advanced Metering Infrastructure (AMI)

AMI enables two-way communication between utilities and consumers, collecting detailed consumption data to analyze usage patterns, optimize demand response, and improve load forecasting [9]. This supports efficient power flow management, informed energy choices for consumers, and energy efficiency, leading to cost savings.

SCADA Systems

SCADA systems provide real-time monitoring of grid assets by collecting data from sensors on parameters such as voltage, frequency, and current. This enables operators to monitor grid health, detect faults, and take corrective action to ensure grid stability, especially as renewable energy sources continue to increase [4, 8].

Distribution Management Systems (DMS)

The distribution management system improves the performance of the distribution network by carrying out automated tasks. These tasks include voltage regulation, load balancing, and fault detection and isolation. The system helps improve grid reliability. It also reduces downtime caused by faults and increases the resilience of the entire network [10].

These technologies work in coordination. Each one adds a layer of intelligence and automation to the grid. The supervisory control and data acquisition system collects data that can be used by the distribution management system for informed decision-making. The advanced metering infrastructure supports both systems by providing detailed data about electricity usage. When combined, the advanced metering infrastructure, the supervisory control and data acquisition system, and the distribution management system allow for a coordinated method of grid management. This setup supports proactive maintenance. It enables fast responses to faults. It also helps in the efficient distribution of energy [8].

CHAPTER 4

Smart Energy Management and Optimization: Data-Driven Approaches for Sustainable Energy Systems

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Abstract: By combining advanced metering, data analysis, and machine learning technology, smart grids have revolutionized energy management systems. This chapter explores the key components of energy management and optimization in smart grids, with an emphasis on anomaly detection, secure communications, and the utilization of renewable energy sources. The first stage is investigating methods for gathering and processing data using smart meters in order to examine variables including power, voltage, current, and power factor. Machine learning models are used to identify abnormalities, including contextual and point anomalies, as well as cybersecurity risks, to preserve grid stability and dependability. The chapter also covers optimization techniques that improve resource use and lower energy expenses, enabling a dynamic balance between supply and demand. In order to give consumers relevant information and suggestions, secure communication protocols are emphasized, underscoring the significance of cybersecurity in contemporary power grids. In the end, integrating demand-responsive renewable energy sources is suggested as a workable way to address future energy requirements. This thorough analysis shows how intelligent energy management systems might revolutionize the development of an energy landscape that is robust, sustainable, and efficient.

Keywords: AI, Anomaly prediction, Energy management, Machine learning, Smart city, Smart energy, Smart grids.

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INTRODUCTION

Overview of Smart Grids

Smart grids, which combine traditional power systems with cutting-edge information and communication technology, represent a substantial advancement in the energy industry. Smart grids provide for two-way communication between utilities and customers, allowing for real-time monitoring and management, in contrast to traditional networks that rely on a one-way flow of power. To encourage efficient energy distribution, reduce transmission losses, and adapt to shifting supply and demand, these systems make use of automation, sensors, and advanced metering infrastructure (AMI). A sustainable and reliable energy future is made possible by smart grids, which integrate renewable energy sources and utilize cutting-edge technologies like artificial intelligence (AI) and machine learning (ML) [1, 2].

Importance of Energy Management in Modern Power Systems

Meeting the growing demand for power worldwide while reducing environmental damage requires efficient energy management. The goal of energy management in modern power systems is to maximize the production, transmission, and consumption of electricity. Smart grids are essential because they make it easier to gather and analyze data in real time, which helps utilities predict demand patterns, reduce peak loads, and maximize energy use. Furthermore, advanced energy management techniques enable the more seamless integration of renewable energy sources, hence reducing reliance on fossil fuels. These developments not only increase grid efficiency and stability, but they also help achieve climate goals and promote sustainable growth [3, 4].

Challenges and Opportunities

Despite its potential, the adoption of smart grids faces several challenges. Key issues include:

Data Security and Privacy

Protecting sensitive consumer data and ensuring secure communication channels.

Integration of Renewables

Managing the intermittent nature of renewable energy sources like solar and wind.

High Implementation Costs

The initial investment required for deploying smart grid infrastructure is significant.

Regulatory and Policy Barriers

Inconsistent regulations and a lack of policy support can hinder widespread adoption.

Despite these challenges, opportunities for innovation exist. Advances in big data analytics and machine learning provide us with the means to estimate demand, carry out predictive maintenance, and spot abnormalities. Peer-to-peer energy trade and safe energy transactions are made possible by new technologies like blockchain. A more robust and sustainable energy system is also being promoted by government policies and incentives that accelerate the transition to smart grids by integrating renewable energy.

DATA COLLECTION AND PREPROCESSING

Role of Smart Meters in Data Acquisition

The foundation of data collection in smart grids is smart meters. These sophisticated metering systems allow for the detailed, real-time collection of vital energy production and consumption data. Smart meters regularly capture and send data, providing comprehensive insights into energy trends, in contrast to standard meters that give cumulative energy use statistics [5]. Smart meters' primary functions include:

Monitoring Usage Patterns

Providing detailed data on household or industrial energy consumption over time.

Enabling Dynamic Pricing

Facilitating real-time pricing models by supplying precise usage data to utilities.

Detecting Anomalies

Identifying irregularities like energy theft, equipment malfunctions, or unusual consumption trends.

CHAPTER 5

Performance Analysis of Control Schemes for Doubly Fed Induction Generator-based Wind Energy Conversion Systems in Stand-alone DC Microgrid

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Abstract: In areas of surplus wind availability, wind becomes an imperative source, and wind power generation at all possible conditions of wind velocity is a confronting task. This study emphasizes the evaluation of various control methods for the Rotor Side Converter (RSC) in a standalone Doubly Fed Induction Generator (DFIG) based Wind Energy System (WES). The stator voltage and frequency are regulated by controlling the RSC. Voltage control, Cascaded Voltage-Current Control, and Sequence-based Voltage-Current Control are deployed for RSC, and the performance is compared. The primary merit of this work, along with its comparative analysis, lies in ensuring efficient power transmission within the system across all operational modes, regardless of fluctuations in wind velocity. The comparative analysis is conducted using the Simpower Systems toolbox of MATLAB, and the validation, along with effective power transfer in various modes, is performed in real time using the Software-in-Loop (SIL) OPAL-RT (OP4510) real-time simulator. The findings demonstrate the effective performance of the DFIG-based WECS within a standalone DC microgrid across various operational modes, employing different control strategies.

Keywords: Cascaded current control, Cascaded voltage - current control, DFIG, voltage control, DC microgrid, Sequence-based voltage – current control, OPAL-RT, Voltage control.

INTRODUCTION

In recent years, the environment and humans have been affected by global warming. The power system energy production sector accounts for about 75% of overall CO_2 emissions worldwide. This contributes to the increase of Greenhouse Gas (GHG) emissions together with global warming [1]. Renewable Energy

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Sources replace fossil fuel power production, thereby addressing global warming, energy crises, and energy costs as an alternative and effective mode of power production [2]. Among various non-conventional energy sources, energy extracted from the wind plays an important role due to the availability of wind in different geographical localities. Since variable speed generator is widely employed for wind-based energy systems, DFIG is extensively utilized owing to its unique capability to operate at various speeds while maintaining a constant frequency, smaller converter rating, and flexible power control. This sets it apart from synchronous generators or fixed-speed induction generators commonly found in wind power systems [3, 4].

Owing to the extensive installation of wind turbine generating systems in offshore and remote locations, extensive transmission lines are needed to transport electricity. This variability may occasionally result in voltage instabilities or disturbances at the point of common interconnection, preferably referred to as PCC. The voltage imbalances are the ones that the wind turbine experiences most often and severely [5]. Various traditional control methods have been applied to the RSC and the Stator Side Converter (SSC) of a DFIG to address voltage imbalances and disturbances. The commonly used conventional Proportional Integral (PI) controller to manage the voltage disturbances under different grid conditions is analysed [6]. The DFIG's RSC utilizes a vector control method, featuring inner current loops and outer voltage loops to effectively control active and reactive power. This setup aims to mitigate inter-area oscillations within extensive transmission systems [7]. A Direct Power Control (DPC) strategy, designed for regulating active and reactive power, employs a nonlinear sliding mode control technique to regulate the rotor voltage directly. This DPC method eliminates instantaneous active and reactive power components without the need for synchronous coordinate transformations, as outlined in a study [8]. Additionally, a Direct Torque Control (DTC) technique for maintaining DC voltage in an autonomous system is explored [9]. Additionally, the incorporation of a battery into a standalone WES is analysed [10], where control strategies are implemented on both the Rotor Side Converter (RSC) and the Grid Side Converter (GSC) to maintain stable voltage and frequency under varying speed conditions. A sensorless control method to eliminate the rotor position sensor, using a Model Reference Adaptive System in a standalone system, is given in a study [11]. The paper suggests a method for evaluating the efficient power transfer of WES operated in both isolated and grid-tied configurations [12]. In another study [13], a current controller is based on the integration of a PI controller and a Resonant controller RC, implemented in either an RSC or a load-side converter. LSC compensates all the distorted and unbalanced stator currents, whereas RSC eliminates distorted harmonic voltages and unbalanced voltages at the PCC. The current control uses the main and auxiliary controllers for RSC and

GSC to obtain the required positive and negative sequences. Thus, the torque oscillations due to unbalanced stator supply and active power oscillations are eliminated by ensuring that constant active power is delivered throughout the DFIG system [14]. A coordinated control strategy is implemented to manage the RSC and GSC of the DFIG, effectively eliminating the negative sequence components, as outlined earlier [15].

To implement islanded operation while ensuring stable stator voltage and frequency *via* RSC, a sequence-based voltage-current control method is utilized. This strategy facilitates the system to handle dynamics with limited overshoot. Validation of the system is carried out using a Software-In-Loop (SIL) technique employing an Opal RT (OP4510) real-time controller. The outcomes demonstrate successful regulation of the stator's frequency and voltage, bidirectional slip power transfer, and versatile power transfer operations in multiple modes, which is the novelty of this paper. This paper delves into the effective power transfer across various modes between generation and load.

SYSTEM DESCRIPTION

The proposed isolated DFIG-based WECS encompasses RSC and associated connective elements feeding three-phase unbalanced loads and non-linear loads. The system interfaces with a standalone DC microgrid, incorporating various renewable energy sources and DC loads, including electric vehicles, solar panels, batteries, and motor-driven applications. Fig. (**1**) provides a schematic representation of the proposed system, where the RSC is configured to enable bidirectional slip power flow and ensure accurate control of the stator's voltage and frequency. Comprehensive system specifications and power from the wind characteristics are detailed in Appendices A and B, respectively.

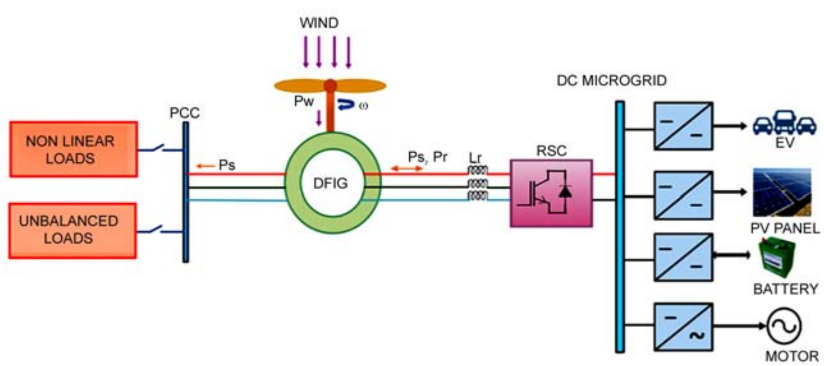

Fig. (1). Overall schematic DFIG-based WECS in a stand-alone DC microgrid.

CHAPTER 6

Photovoltaic-Powered Underwater Propulsion System with Improved Power Quality Using a Shunt Active Power Filter

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Abstract: Systems for underwater propulsion are essential to military applications, research, and marine exploration. In order to improve overall system performance and power quality, this study suggests an underwater propulsion system driven by solar photovoltaics with an incorporated Shunt Active Power Filter. Through the use of a photovoltaic array, the device effectively collects solar energy and stores it in a battery bank, guaranteeing uninterrupted function even when submerged. By successfully reducing power quality problems, including transient disturbances, harmonics, and voltage sags, an SAPF ensures steady and effective propulsion system operation. The Maximum Power Point Tracking approach is used to maximize the solar PV system's energy harvesting. The purpose of the Shunt Active Power Filter is to improve the system's efficiency by reducing harmonics produced by nonlinear loads. It functions using a hysteresis controller and the instantaneous reactive power theory. The system can maintain voltage stability and produce minimum Total Harmonic Distortion under a variety of operating situations, according to simulation findings. The suggested method offers a dependable and environmentally responsible substitute for traditional propulsion methods, opening the door for cutting-edge and sustainable undersea technology.

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Keywords: Marine technology, Maximum power point tracking (MPPT), Power quality, Shunt active power filter (SAPF), Solar photovoltaic (PV), Total harmonic distortion (THD), Underwater propulsion.

INTRODUCTION

The search for renewable energy sources for underwater applications has been driven by the increasing demand for propulsion systems that are both energy-efficient and environmentally sustainable. Conventional underwater propulsion systems that rely on fossil fuels or batteries face several limitations, such as limited endurance, high operational costs, and environmental concerns. Solar photovoltaic (PV) systems offer a clean and sustainable energy source that can potentially power underwater vehicles.

However, integrating solar PV systems with underwater propulsion introduces several technological challenges, particularly in ensuring system reliability and maintaining consistent power quality. The performance of such systems can be adversely affected by harmonics, voltage fluctuations, and power losses, which often arise from dynamic operating conditions and nonlinear load behavior. To address these challenges and enhance both power quality and system efficiency, Shunt Active Power Filters (SAPFs) are proposed as an effective power conditioning solution.

This study presents a novel underwater propulsion system powered by solar photovoltaics, where a Shunt Active Power Filter is employed to improve power quality. The SAPF reduces harmonics and stabilizes voltage, while a Maximum Power Point Tracking (MPPT) algorithm ensures optimal energy extraction from the solar PV array. This integrated approach not only guarantees reliable and efficient propulsion but also supports the global shift toward clean and green energy sources. By combining renewable energy technologies with advanced power quality management, the proposed system initially introduced by Qian Liu *et al.* in 2014 [1] has the potential to revolutionize submarine propulsion. A detailed modeling, design, and performance evaluation of the system is provided in their study.

Power engineers today face significant power quality challenges due to nonlinear loads in distribution systems. The advancement of semiconductor technologies has led to a sharp rise in the use of power electronic devices by end-users. While essential, these devices often introduce issues such as reactive power disturbances, harmonic distortion, reduced system efficiency, poor power factor, and excessive device heating. These problems, if unaddressed, are expected to worsen in the coming years, as described by Anand Singh *et al.* in 2014 [2]. To tackle power quality issues, two primary strategies are employed:

Load conditioning makes the load less sensitive to harmonics and power fluctuations. However, this isn't easy to implement due to the complexity and variability of modern loads.

Power line conditioning, which involves installing conditioning systems at the Point of Common Coupling (PCC) to mitigate or eliminate the adverse effects caused by nonlinear, harmonic-generating loads.

Traditionally, passive filters have been used to address reactive power disturbances and harmonic problems. However, these filters suffer from significant drawbacks such as resonance issues, fixed compensation characteristics, large physical size, and performance dependence on source impedance. To overcome these limitations, Machida and Sasaki introduced the concept of the Active Power Filter in 1971. Since then, active power filters, particularly SAPFs, have proven to be far more effective in mitigating harmonic distortion and reactive power disturbances compared to traditional passive filters.

OBJECTIVE

The primary objective of this study is to design and develop a solar photovoltaic-powered underwater propulsion system integrated with a Shunt Active Power Filter (SAPF) to enhance power quality and operational efficiency. The specific goals include:

- Utilizing solar PV technology to provide a sustainable and eco-friendly power source for underwater propulsion.
- Integrating a SAPF to mitigate power quality issues such as transient disturbances, harmonics, and voltage fluctuations caused by nonlinear loads.
- Employing a Maximum Power Point Tracking (MPPT) algorithm to maximize energy extraction from the solar PV array.
- Developing a robust system capable of maintaining stable operation under dynamic and varying underwater conditions.
- Advancing the application of green energy solutions for marine exploration, research, and defense purposes.

The development of sustainable underwater propulsion systems has garnered significant attention in recent years. A comprehensive review of existing studies reveals both the challenges and advancements in utilizing renewable energy sources and improving power quality for underwater applications.

Solar PV technology has been widely investigated for marine applications. Research by *Jeevananthan K.S. (2014)* [3] demonstrated the feasibility of

CHAPTER 7

Double Quadratic Boost Converter Technology in Modern EV Energy Systems with BLDC Motors

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Abstract: The increasing energy demand in the transport sector is stimulating a transition towards Electric Vehicles (EVs). For the propulsion of EV, an advanced Brushless Direct Current (BLDC) motor is integrated. To power the BLDC motor, instead of using the conventional energy that emits greenhouse gases and affects human health, sustainable energy is essential. Henceforth, renewable energy, such as Photovoltaic (PV) based Double Quadratic Boost Converter (DQBC), is proposed. DQBC efficiently boosts the voltage of low output power from the PV system, achieving higher efficiency and voltage gain. The Chicken Swarm Optimization (CSO) algorithm is integrated to tune the parameters of the Proportional-Integral (PI) controller to maximize energy flow and ensure system stability under dynamic conditions. The Bidirectional converter promotes efficient energy transmission between the battery and the EV motor. Moreover, a 3-phase Voltage Source Inverter (3Φ VSI) converts the Direct Current (DC) voltage source to Alternating Current (AC) for regulating the BLDC motor. The proposed system highlights the advancements in optimization techniques like CSO and integrating DQBC to enhance the energy efficiency, reduce losses, and improve the overall system performance for EV energy systems. The experimental verification of the presented model is implemented in MATLAB/Simulink, which shows a higher efficiency of 96.01%. Overall, the proposed model significantly boosts the system's reliability, making it suitable for EV applications.

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Keywords: 3Φ VSI EV, Battery, Bidirectional converter, BLDC motor, CSO, DQBC, PI controller, PV system, RES.

INTRODUCTION

The demand for energy conversion is high due to the exponential growth of the population. The increased population leads to the extensive use of conventional resources that are confined and reflect substantial residues in human health and the environment. The usage of fossil fuels has been significantly reduced by RES in the past few years [1]. The energy generation from RES is environmentally friendly and is sustained over a long period because it is widely available. Solar energy is one of the RES, and it is the primary energy source for PV-based applications. The light energy from the sun is converted into electrical energy. The population expands, thus the requirement for transport facilities also increases. By using conventional vehicles, the emission of CO_2 greatly affects the atmospheric condition, as illustrated in Fig. (**1**). The conventional vehicles are replaced with vehicles energized by renewable sources [2, 3].

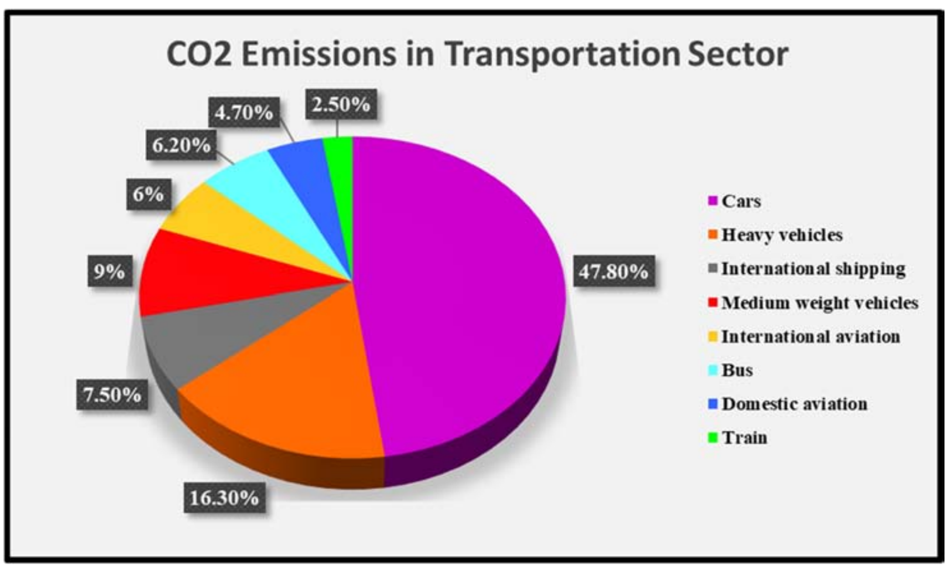

Fig. (1). Estimated CO_2 emissions in the transport sector.

To drive the EV, a mechanical support is required; therefore, the motor operation is employed [4]. The energy attained from the PV is low, and it is unable to satisfy the requirements of the EV motor. To boost the output of PV, a DC-DC converter is required. There are various types of converters to increase the voltage, like Buck, Buck-Boost, Single-Ended Primary Inductor Converter (SEPIC), Flyback, and Boost.

The buck converter regulates the output voltage by rapidly switching the transistors, diodes, and other energy storage elements. Regardless, the increased current levels at the motor diode lead to the higher thermal stress on the converter components [5]. For maintaining stable DC lead voltage, which is necessary for the various vehicles, the DC buck-boost converter is a crucial source for voltage regulation. However, there is a lack of galvanic isolation from the input to the output and regulation, and it induces amplified voltage ripple at the output. This makes it relatively less suitable for high-powered EV systems [6]. The SEPIC converter modifies the output voltage like a voltage adjuster. The modifications in the voltage output are done with respect to the duty cycle. Even though the SEPIC converter highly relies on the duty cycle during unfavorable operational conditions, the conduction loss increased due to that loss, which is not appropriate for EV optimization [7]. The flyback converter generates output by adjusting the duty cycle of the flyback switches. Nevertheless, with a high voltage spike in the switches, energy gets discharged. Nevertheless, with discharge, the elevated dissipations are unavoidable [8]. Theoretically, boost converters attain infinite voltage gain while neglecting the parasitic parameters with an extreme duty cycle. Even so, in practical scenarios, due to the high duty cycles, the demand for the output voltage is not sufficient, and also leads the switches to remain for a longer time [9]. These limitations are overcome by using the proposed double-quadratic boost converter, which generates efficient energy to run the EV.

The control performance is essential to attain a stable output without oscillations, and thus, the PI controller is equipped to null the error, and its parameters are tuned by using an optimization algorithm to further enhance the stable performance. It becomes complex while providing optimal tuning parameters, as it requires multiple iterations [10]. The Genetic-Algorithm Based Proportional Integral Controller (GA-PI) is an approach of natural selection in which each population of chromosomes provides an optimal solution with respect to the fitness value. It optimally tunes the PI controller using this GAPI metaheuristic optimization algorithm. The GA approach is not suitable for real-time control applications, as it is computationally intensive and introduces delay during response time [11]. The drawbacks are rectified by using the CSO algorithm, which provides an efficient, precise, and solid solution for optimization problems.

LITERATURE SURVEY

S. G. Srivani *et al.* (2024) [12] have proposed a flux-additive DC-DC converter integrated with an IC engine, fuel cell, and battery that ensures efficient power management for advanced hybrid EVs (HEVs). This converter offers high power density and provides higher efficiency, allowing for compact designs that

CHAPTER 8

High-Gain Cubic Boost Converter and Raccoon Optimized PI Controller for HRES-Powered Grids

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Abstract: Traditional centralized power stations face challenges such as high greenhouse gas emissions, reliance on non-renewable resources, and inefficiencies in meeting peak power demand. Additionally, Renewable Energy Sources (RESs) like solar and wind complicate efforts to maintain a consistent power supply and grid stability. This study proposes a Hybrid Renewable Energy System (HRES) that integrates a Photovoltaic (PV) system with a Doubly Fed Induction Generator (DFIG) based Wind Energy Conversion System (WECS) to address these challenges. The PV system incorporates a High Gain Cubic Boost Converter (HG-CBC), regulated by a Raccoon Optimized Algorithm (ROA) based Proportional Integral (PI) controller, to enhance voltage levels. The DFIG based WECS stabilizes power flow through a Pulse Width Modulation (PWM) rectifier and a PI-controlled PWM generator. Moreover, a 3-phase Voltage Source Inverter (3Φ VSI) converts DC power into AC for grid integration. Experimental verification using MATLAB/Simulink demonstrates a high efficiency of 98%, showcasing the model's ability to significantly boost system reliability and suitability for HRES-powered grids.

Keywords: DFIG, High gain cubic boost converter, HRES, PV system, Raccoon optimized algorithm, VSI, WECS.

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INTRODUCTION

Renewable Energy Sources (RESs) are connected to the electrical grid to meet the growing demand for energy worldwide and reduce the pollution that fossil fuels cause in the environment [1]. Among the various RESs, including PV systems, Wind Turbines (WTs), fuel cells, and biomass, PV and wind energy emerged as the most widely adopted due to their numerous advantages [2]. PV systems, in particular, are highly favoured for their environmentally friendly nature, offering a clean and sustainable alternative to conventional power generation methods [3]. This widespread adoption is further driven by economic development and industrial energy demands.

The inconsistency of RES poses difficulties for single operation, despite several advantages. WECS are affected by variations in wind speed, while PV systems are influenced by changes in solar radiation and temperature. These limitations are effectively addressed through hybrid solar-wind generation systems, which combine the strengths of both energy sources to enhance reliability and consistency [4]. Solar systems are less efficient at night or during cloudy weather, whereas wind speeds fluctuate with time and season. Particularly, low wind speeds often coincide with sunny days, allowing solar systems to operate at peak efficiency. This complementary relationship ensures a balanced and dependable power generation system [5].

There are different types of converters to step up the voltage such as, the DC-DC Boost Converter, being one of the most commonly used converters in PV systems due to its ability to step up the low output voltage of solar panels to a higher level suitable for grid integration. In a study [6], a conventional boost converter used for PV applications achieves voltage regulation by adjusting the duty cycle of the switch. However, traditional boost converters are often limited by their voltage gain, therefore, they are insufficient for high-voltage applications, especially when the PV array operates at lower voltage levels. Similarly, Zeta Converters are used [7] to provide better voltage regulation and efficiency while reducing the overall stress on the converter components. The Zeta converter's unique ability to provide both step-up and step-down voltage regulation makes it particularly suitable for applications in hybrid systems. Another well-known topology is the Buck-Boost Converter. In a study [8], a buck-boost converter is used in the HRES system to stabilize the power delivered to the grid. This converter offers flexibility in voltage regulation, but its efficiency is lower compared to other converters. To address this issue, HG-CBC offers improved voltage boosting capability with reduced losses and enhanced efficiency.

The control performance is essential for achieving a stable output without oscillations, for which a PI controller is utilized. Recent control strategies include Proportional-Integral-Derivative (PID) Controller, Sliding Mode Controller (SMC), and Fuzzy Logic Controller (FLC). PID is well-suited for simple, well-modelled systems requiring stable performance, but it struggles with nonlinearities and tuning complexities [9]. SMC improves the systems with high uncertainties and non-linear behavior, offering robustness, but SMC is sensitive to changes in system parameters [10]. Further, FLC provides a flexible and intuitive approach to managing complex systems, especially when precise models are hard to define. However, FLC demand more computational resources and careful design of rule-based systems to avoid performance issues [11].

LITERATURE SURVEY

Fig. (**1**) presents a review of classical optimization approaches, summarizing the strengths, weaknesses, highlighting the effectiveness, and challenges of methods in solving optimization problems.

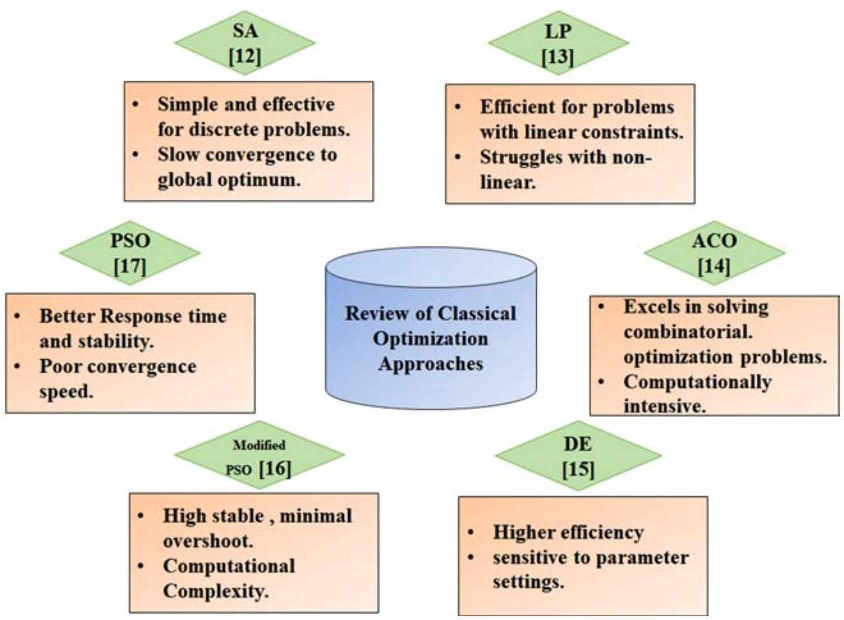

Fig. (1). Classical optimization approaches.

The key contributions of the proposed work are as follows:

- To develop HRES designed to address challenges such as greenhouse gas emissions and grid stability.

CHAPTER 9

Energy Storage and Advanced Control Systems with TRIFLEX DC-DC Converter for Renewable Energy Grids

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Abstract: The integration of Renewable Energy Sources (RES) into the power grid presents challenges related to their inherent variability and intermittency. To address these issues, this paper introduces an efficient energy storage and control system designed for seamless integration of RES into the grid. The Photovoltaic (PV) system utilizes a Triflex DC-DC boost converter, which effectively boosts the voltage output. The system's performance is further optimized through an Improved Kangaroo-optimized Proportional Integral (PI) controller, which enhances the stability and efficiency of the energy conversion process by minimizing voltage deviation. In parallel, the wind energy system, based on a Doubly Fed Induction Generator (DFIG), is managed by a PWM rectifier and a PI-controlled PWM generator ensuring stable power flow integration with the grid. The MATLAB simulation tool is employed to model the proposed hybrid system, with detailed simulations conducted to optimize the control strategies and evaluate the system's performance. The results demonstrated that the proposed converter improves the overall system performance, achieving an energy conversion efficiency of 97%. This study highlights the potential of advanced control approaches and hybrid systems in enhancing the integration of renewable energy into modern grids, while addressing challenges such as variability, efficiency, and grid stability.

Keywords: Doubly-Fed Induction Generator, HRES, Improved Kangaroo-optimized PI controller, Photovoltaic, Triflex DC-DC boost converter.

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INTRODUCTION

Background and Challenges

The rapid advancement of RES, including solar and wind energy, is anticipated to be vital in attaining carbon neutrality and boosting the global economy [1]. A PV system transforms sunlight into Direct Current (DC) voltage, which generates low energy in the event of climatic changing conditions [2]. Wind energy is another commonly utilized RES, but it brings considerable operational challenges due to its unpredictable and fluctuating nature, particularly in remote and vulnerable transmission networks [3]. To tackle these challenges, Hybrid Renewable Energy Sources (HRES), such as Wind-Solar, are employed which gives an adequate supply to the grid system. Also, effective DC-DC converters are crucial for efficiently stepping up the low voltage of PV into high voltage, enabling better utilization of RES [4, 5].

In a study [6], a conventional DC-DC boost converter is presented as efficient for increasing low solar output voltages to the desired levels, providing a simple solution for low-power uses. However, this converter involves lower gain of voltage, increased ripple of current and voltage, along with considerable switching and conduction losses. Further, the Interleaved Boost converter enhances dynamic performance, reduces input current and output voltage ripple, and boosts efficiency in PV systems [7]. Nonetheless, the voltage gain of the interleaved boost converter fails to increase as anticipated with the duty cycle, which restricts its performance under specific conditions [8]. In a review [9], a high-gain boost converter is introduced, which provides a substantial voltage gain at lower duty ratios, making it effective for elevating low-input DC voltage to higher DC voltages. However, the converter increased electromagnetic interference due to the high-frequency switching operation [10]. Therefore, this paper introduces a Triflex boost converter that improves upon the limitations of previously discussed converters. However, effective control strategies are crucial for the successful deployment of these systems. Additionally, controllers are essential in managing power flow, ensuring stability, and optimizing the performance of the charging system. The PI controller is known for its simplicity and efficiency in regulating system dynamics, and its ability to maintain steady-state accuracy and stability. However, PI controllers have drawbacks regarding tuning and performance optimization, which affect their overall efficiency [11].

Several optimization methods have been explored, including Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Grey Wolf Optimizer (GWO). The PSO-PI optimized controller improves efficiency and dependability by minimizing manual tuning, facilitating a smoother combination of power into the power grid. Nevertheless, the PSO-PI optimization approach demands considerable computational power and time for initial adjustments [12]. The GA-PI optimized controller enhances the response speed and reduces the impact of external disturbances, improving the steadiness and performance of grid-connected PV systems. Nonetheless, this optimized controller is highly sensitive to changes in system parameters, necessitating frequent re-tuning to sustain optimal performance as conditions fluctuate [13]. The GWO-PI optimized controller strengthens the stability and reliability of the PV grid system by minimizing oscillations and ensuring stable operation under diverse grid conditions [14]. Nonetheless, the GWO algorithm exhibits slower convergence in some instances, making it less efficient than other optimization methods for real-time applications [15]. Henceforth, the proposed work introduces a novel, improved kangaroo-optimized PI controller to overcome these challenges.

This work aims to establish an optimized hybrid renewable energy system that effectively delivers energy in an efficient, stable, and reliable manner, using both solar and wind energy resources. This work focuses on improved energy conversion, control, and storage that address the shortcomings of conventional systems. The overall system performance has improved while still increasing the amount of energy delivered to the grid cleanly and sustainably to meet growing energy demands.

LITERATURE REVIEW

Mantu Kumar Ram *et al.,* (2023) [16] developed a DC-DC boost converter to improve output voltage. This converter has the ability to manage set-point and load disturbance responses independently, which produces higher output voltage control without the need for specific circuit parameters and load information. However, the complexity of developing the converter lies in its complexity, particularly when adapting it to other hardware setups and scaling it for diverse applications. Rasha Kassem *et al.,* (2024) [17] present a soft-switching Multiphase Interleaved Boost Converter (MIBC) that improves efficiency for PV power system applications. This method's capacity to handle power from various RES maximizes the consumption of energy and improves overall system efficiency. However, this converter increased design complexity by requiring sophisticated control systems and algorithms for effectively handling several power sources. Chandu Valuva *et al.,* (2023) [18] introduced a PI controller optimized with the Marine Predator Algorithm (MPA) that efficiently reduces transmission losses. The MPA-based PI controller effectively minimizes active power losses while improving voltage stability in wind-solar systems. However, this approach has the complexity of the optimization process, leading to increased system resource usage and time requirements for large-scale systems.

CHAPTER 10

IoT-Driven Monitoring and Control in PV-Based Smart Grids Using SEPIC-Boost Converter with Improved Elephant Optimized PI Controller

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Abstract: Smart grids are regarded as an advanced solution for energy distribution due to their ability to optimize power flow and integrate renewable sources. Additionally, it achieves greater efficiency and sustainability when paired with Photovoltaic (PV) systems. However, the limited output from PV not always meets the full energy demands of the grid. Henceforth, this paper presents a PV-based smart grid, utilizing a SEPIC-Boost converter integrated with an improved Elephant Optimized PI controller. The proposed converter is designed to boost the voltage from the PV system while improving the efficiency and stability of the smart grid. The Elephant Optimized Proportional Integral (PI) controller tunes the control parameters, minimizing system deviations and improving power regulation. Internet of Things (IoT) based monitoring allows real-time data from PV and converter collection and remote management, ensuring better system performance, fault detection, and energy optimization. The outcomes of the proposed work are evaluated and simulated using MATLAB software, which shows the proposed converter achieving a higher efficiency of 93% and a voltage gain of 1:8.

Keywords: Elephant optimized PI controller, Internet of Things, PV, Smart Grid, SEPIC-Boost converter.

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INTRODUCTION

Many years ago, fossil fuels were widely used as the primary source of energy due to their availability and high energy density. However, fossil fuels do not provide a sustainable energy solution due to the finite nature of these resources and the environmental issues associated with their use, such as greenhouse gas emissions and pollution [1]. Because of these limitations, Renewable Energy Sources (RES) are utilized as sustainable alternatives, which are environmentally friendly and abundant by offering a cleaner and more sustainable energy solution [2]. There are various types of RES, including solar energy, wind energy, Fuel Cells (FC), and geothermal energy [3, 4]. Among these, PV is considered one of the most promising and efficient RES. Compared to other RES, it offers significant advantages such as ease of installation, scalability, low operational costs, and the ability to harness energy directly from sunlight, making it an ideal choice for sustainable energy production [5, 6].

Due to fluctuations in environmental conditions, the PV output voltage is increased using converters to ensure an adequate energy supply to the grid. Many researchers have established conventional converters such as Boost, Cuk, Boost-Cuk, and SEPIC for grid supply, which are depicted in Table **1**.

Table 1. Comparison of conventional converters.

Converters	Advantages	Limitations
Boost [7, 8]	• Increases the input voltage by using low-voltage sources. • The implementation is simple and easy.	• However, the voltage gain is limited; a high duty cycle leads to inefficiency and instability.
	• It achieves a greater efficiency level by minimizing losses.	• Nevertheless, high frequency switching generates the noise and Electromagnetic Interference (EMI), which requires filtering methods.
Cuk [9 - 11]	• It offers a continuous current by reducing the ripples and improving the compatibility.	• Nonetheless, the output voltage has ripples and noises, which leads to the requirement of enhanced filtering.
	• It offers both step-up and step-down voltage leading tothe flexible system for various applications.	• However, it is more complex than other simple converters.
	• It ensures the input and output currents are continuous and reduces the stress on the load.	• Nevertheless, during the power transfer, the system experiences high current and voltage stress.
Boost-Cuk [12]	• It achieves higher efficiency with a proper and simple design.	• However, there is a limited power supply that faces the issue during the current flow.

Converters	Advantages	Limitations
SEPIC [13, 14]	• The input current is continuous and reduces ripples, making it suitable for sensitive applications.	• However, the circuit is more complex. • Nevertheless, the additional components lead to higher power losses.

To address these challenges, the SEPIC-Boost converter is integrated to improve the overall efficiency with lower ripple current and has a smaller size and smaller switching loss. Additionally, PI controllers are essential in RES systems for maintaining stability and enhancing system response in real-time applications. For these, many traditional optimization techniques, such as Particle Swarm Optimization (PSO) [15] and Ant Colony Optimization (ACO) [16], are used to tune the parameters of the PI controller. The PSO method offers efficient and easy-to-implement solutions for continuous optimization problems; however, it suffers from low performance with improper tuning parameters. ACO enhances the effectiveness of solving the global optimization problems in the continuous domain. Nonetheless, it struggles to solve the discrete optimization problems, which leads to improper performance. To overcome these limitations, the Elephant optimized PI controller is utilized in the proposed system, achieving stabilized performance and accuracy with a low distortion value. Overall, this system serves as a preventive measure to ensure stable voltage and current levels caused by the PV system. For this purpose, IoT is employed to monitor the voltage and current output from the PV system.

The proposed approach is employed to overcome the limitations of conventional converters and controllers. The contributions of the proposed system are described below.

- Integrating the SEPIC-Boost converter aims to achieve higher efficiency, higher output voltage, and lower ripple current.
- Implementing an Elephant optimized PI controller for improving the stability and performance by tuning the PI controller parameters with enhanced efficiency in the grid integration process.
- IoT integration enables real-time PV system monitoring and control, allowing remote tracking of voltage, current, and power output, which improves transparency, operational efficiency, and rapid fault detection.

PROPOSED METHODOLOGY

For a sustainable power supply to the grid, IoT-based PV systems are utilized. Moreover, this paper proposes the integration of a SEPIC-Boost converter with an Elephant Optimized PI controller for efficient power management of a three-phase grid, as demonstrated in Fig. (**1**).

CHAPTER 11

AI Solutions for Smart Grid Cyber Threats: Artificial Fish Swarm Routing and Neural Network Security Models

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Abstract: Smart Grids (SG) have become a groundbreaking technology in the energy sector, enabling efficient power management. They combine various energy sources and rely on an extensive control and communication network through the Internet of Things (IoT), promoting a more reliable, intelligent, and carbon-free energy system. The digital technologies also expose SGs to various cybersecurity threats and attacks. Henceforth, this work proposed an Artificial Intelligence (AI) solution to address cyber threats in SG, utilizing an energy management system based on a routing algorithm. An SG system incorporating wind, Photovoltaic (PV), and a battery-based energy management system has been adopted. The Artificial Fish Swarm Optimization Algorithm (AFSOA) and the Artificial Neural Network (ANN) model are proposed for sending sensed data securely to the end-user *via* the shortest path. The performance of the microgrid has been tested and validated across various operational modes, including direct wind energy supply, energy feedback to the grid, battery-powered supply, power supply from the external grid, and load-limiting modes. The results demonstrate significant improvements in terms of network throughput, end-to-end delay, packet delivery ratio, energy consumption, and reduced encryption and decryption times, enhancing both performance and security. The system aims to provide real-time monitoring and analysis to end users, with effective control. This proposed work addresses the challenges of energy efficiency, security, and sustainability in modern energy systems.

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Keywords: Artificial neural network, Artificial fish swarm optimization algorithm, Battery, Photovoltaic, Internet of things, Smart grid, Wind.

INTRODUCTION

SG is a developing technology that provides smart tracking, interconnectivity of diverse modalities of generation, communication in both directions, and improved utilization of resources while reducing the need for new power plants [1]. This enables two-way electricity flow among utility suppliers by integrating an advanced structure involving computer technology, energy systems, and telecoms with existing power facilities. Additionally, it enables real-time tracking of grid data, integration of hybrid renewable energy sources, and enhances grid network flexibility [2, 3]. To increase grid efficacy, adaptability, and reliability, the SG employs an intricate combination of IoT-based smart devices, including sensors and actuators, secure gateways, potent servers, and WAN networks. SGs have equipped themselves with advanced metering infrastructure, optimizing energy use and demand management [4, 5].

The capacity of SG technology to integrate unstable energy sources into the electrical grid makes it beneficial in areas with substantial possibilities for renewable energy output, like solar and wind power [6]. Hybrid systems greatly reduce energy interruption, improve grid stability, and are less costly because of a common infrastructure [7]. This system is powered by wind energy, and it has connections to the grid *via* the PV and batteries. The wind, PV, and battery storage system's power outputs are monitored and paired to a standard DC bus using regulated DC-DC converters [8]. The bidirectional power flow aims to regulate the electrical energy flow across various sources to meet load consumption criteria *via* collecting control signals from the Energy Management System (EMS) [9]. In this regard, wireless sensor networks perform an important role in data sensing, collection, and transmission. Wireless multi-hop routing in various SG environments is still an essentially unexplored area [10]. To resolve this issue, various routing protocols have been developed to exchange data on transmission line attributes, routing data, and other relevant details through sharing platforms. The system is made up of several energy routers with different efficiencies, connection resistors, and alternative paths for connecting to each other [11]. In these routing algorithms, effective communication occurs when both the link and node are in the correct state. Initially, the source and target routers are chosen, and the various routes connecting them are identified through the algorithm [12]. After determining the optimal route, energy dispatch is formulated using nonlinear programming techniques. The Depth-First Search (DFS), Dijkstra's algorithm, and the Open Shortest Path First (OSPF) Protocol are various algorithms that identify all the connections between energy exchange pairs. These algorithms are easily used in a large network and are independent of network size. Despite these advantages, it provides some limitations such as more complex implementations and less security [13, 14].

Integrating IoT with the SG creates a vast cyber-physical network that permits remote monitoring and control of interconnected devices. The intelligent electricity system in the SG is faced with various types of unauthorized malicious access, that is, cyber-attacks [15, 16]. It is a complex substructure where system faults resulting from a cyberattack cause significant damage to the entire network in a short period. Thus, early identification and prevention of cyberattacks are essential for ensuring prompt responses and minimizing potential harm [17]. The data-driven approach to detection makes use of Machine Learning (ML) and numerical analysis from historical data in search of patterns or anomalies that indicate cyber-attacks [18]. Techniques like Support Vector Machine (SVM), Random Forest (RF), and Deep Neural Networks (DNN) utilize their learning capabilities to differentiate between normal and malicious data. These models successfully identify cyber threats and flaws because they are often trained in either supervised or unsupervised environments. However, these approaches encounter notable challenges, including poor generalization, limited scalability, high computational requirements, and reduced adaptability [19]. To address the problem of finding the shortest network for secure data sharing with the end-user, the Artificial Fish Swarm Routing and Neural Network is proposed in this work.

The aim of this study is to create and test a secure and intelligent energy management system using AI methodologies to establish communication reliability and optimal routing within SG platforms. The study also addresses cybersecurity concerns in energy systems, while also enhancing energy dispatch efficiency and system efficiency.

The objectives are:

- To sense energy from a PV-wind-battery grid, with the aid of IoT IoT-based SG system.
- To implement the AFSOA for determining the shortest and most efficient routing paths.
- To utilize an ANN-based security approach to safeguard the system against cyber threats.

PROPOSED METHOD DESCRIPTION

The proposed approach creates a grid network of sensors that allows multiple routes from the source to the destination, ensuring an increased packet delivery

CHAPTER 12

Optimizing Static GEP for a Sustainable Energy Future: Methods and Case Studies

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Abstract: Generation Expansion Planning (GEP) plays a pivotal role in ensuring sustainable and cost-effective electricity generation to meet future energy demands. GEP involves selecting and integrating appropriate power generation technologies while considering economic, technical, and environmental constraints. This chapter provides a comprehensive overview of static GEP, focusing on its application to a hypothetical 3-bus test system. This study provides a comprehensive evaluation of renewable energy systems by assessing their economic feasibility, environmental impacts, and grid stability challenges. It focuses on solar, wind, and hydro energy technologies, employing advanced methodologies such as sensitivity analysis, payback period calculations, and return on investment (ROI) evaluations to determine financial performance. Emphasis is placed on renewable integration benefits, including emission reductions, socio-economic growth, and land-use optimization. Key challenges such as storage requirements, grid failures, and peak load management are analyzed using simulations and predictive models. Policy incentives and grid upgrades are investigated to enhance financial feasibility and system resilience. Scenarios for grid stability under varying renewable penetration rates (30%, 50%, 70%) are modeled, highlighting the importance of hybrid storage systems, dynamic energy dispatch, and smart grid technologies. Findings underscore the potential of renewable systems to deliver economic returns while reducing environmental impacts, provided strategic planning, policy support, and technological advancements are implemented. Recommendations focus on storage expansion, flexible energy dispatch, and integrated socio-economic planning to enable a transition toward a sustainable energy future.

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Keywords: Battery storage systems, Cost optimization, Generation expansion planning (GEP), Multilateral transactions, Renewable energy integration.

INTRODUCTION

Generation Expansion Planning (GEP) is a critical process in power system planning that focuses on determining the optimal mix, location, and timing of generation resources to meet future electricity demand. It aims to minimize costs while ensuring reliability, environmental sustainability, and compliance with regulatory constraints. With the increasing penetration of Renewable Energy Sources (RES), the complexity of GEP has significantly increased, necessitating the use of advanced optimization techniques and computational models. The global energy sector is undergoing a transformative shift, driven by the urgent need for sustainability, decarbonization, and energy security.

As climate change accelerates and fossil fuel resources become increasingly scarce, renewable energy sources such as solar, wind, and hydroelectric power have emerged as viable alternatives to traditional energy systems. These renewable technologies not only reduce greenhouse gas emissions but also contribute to socio-economic growth, job creation, and energy independence. However, integrating renewables into existing power grids poses unique challenges related to intermittency, storage, scalability, and grid stability. Static GEP provides a framework for optimizing energy resource allocation, infrastructure development, and operational performance to meet future energy demands. It evaluates cost-effectiveness, environmental impacts, and technological feasibility, enabling policymakers and engineers to design sustainable energy systems. This study explores methods for enhancing static GEP by analyzing renewable integration scenarios, economic metrics, and storage solutions. This literature survey explores recent advancements in GEP methodologies, highlighting studies that address various constraints, including renewable integration, transmission limits, emission controls, and storage systems. The surveyed papers present innovative algorithms and frameworks for solving large-scale, non-linear optimization problems, ensuring economic efficiency and operational reliability. The focus is on technical aspects such as metaheuristic optimization, multi-agent systems, and advanced machine learning techniques. The survey also covers frameworks that incorporate flexibility, demand response, and smart grid technologies to adapt to the evolving energy landscape. By reviewing these methodologies, this work provides insights into current trends, challenges, and future directions for GEP research and applications. The challenges of integrating RES into power systems with high penetration levels have been discussed. Their study highlighted the importance of operational flexibility to handle the variability and intermittency of RES [1]. The authors emphasized the need for grid stability and proposed an optimization model that incorporates economic constraints. Additionally, the paper discussed advanced forecasting techniques to predict energy demand and generation, ensuring effective planning. The study also suggested methods to incorporate emerging technologies such as smart grids and storage systems. An integrated expansion planning model that simultaneously considers generation, transmission, and storage has been introduced [2]. The study prioritized the use of Battery Energy Storage Systems (BESS) to mitigate intermittency challenges posed by RES. It proposed a Flexible Ramp Spinning Reserve (FRSR) mechanism to address short-term variations and maintain reliability. The paper employed hierarchical clustering to manage uncertainties in load and RES output, ensuring optimal results. The model also adhered to low-carbon policies, highlighting its sustainability focus.

A coordinated planning framework for transmission and distribution systems integrated with smart grid technologies has been developed [3]. The paper emphasized the role of demand response programs and electric vehicles in improving grid flexibility. It proposed a stochastic multistage programming approach to handle uncertainties and employed the Benders Dual Decomposition method for optimization. The model was validated using IEEE test systems, demonstrating its practical applicability. Furthermore, the study highlighted the economic benefits of integrating distributed generation and storage technologies [4]. The 2022 IEEE Xplore paper proposed a two-layer GEP model focusing on flexibility balance. The first layer addressed long-term capacity planning, while the second layer optimized short-term ramping capabilities. This dual-layer approach ensured the integration of RES without compromising system stability. It utilized advanced optimization techniques to balance capacity and ramping requirements, enabling reliable operations. The study also highlighted the importance of incorporating grid flexibility to manage RES variability effectively.

An investment dynamic in GEP using a multi-agent system has been explored [5]. It modeled the interactions between market participants, simulating investment decisions under competitive market conditions. The study considered strategic behaviors and reactions among stakeholders, providing insights into market-driven expansion planning. It also analyzed the impact of regulatory policies and market structures on GEP outcomes. The framework supported scenario analysis to assess the robustness of planning decisions. The impact of inertia and reactive power constraints in GEP has been investigated [6]. The paper highlighted how neglecting these constraints could lead to cost inefficiencies and operational infeasibilities. It proposed the Low-Carbon Expansion Generation Optimization (LEGO) model to address these challenges. The study incorporated reactive power support and inertia constraints to improve system stability. Additionally, it

SUBJECT INDEX

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