# Performance Investigation of a Microgrid System with Bidirectional DC-DC Converter Control for Renewable Energy Integration

Capstone Report

Bakdaulet Aldashov

Nazarbayev University
Department of Electrical and Computer Engineering
School of Engineering and Digital Sciences

This project report was created on TexStudio editing platform using LaTeX. All the figures were drawn using draw.io online software tool.

**Electrical and Computer Engineering**
Nazarbayev University
http://www.nu.edu.kz

**Title:**
Performance Investigation of a Microgrid System with Bidirectional DC-DC Converter Control for Renewable Energy Integration

**Theme:**
Capstone Project Report

**Project Period:**
Fall 2024

**Project Group:**
Lab's Name

**Participant(s):**
Bakdaulet Aldashov

**Supervisor(s):**
Prashant Jamwal

**Copies:** 1

**Page Numbers:** 24

**Date of Completion:**
April 25, 2025

**Abstract:**

The focus of this project is on the performance of a microgrid system incorporating renewable energy sources (photovoltaic (PV) and wind turbines), battery storage, and a bidirectional DC-DC converter. The objective is to assess the efficiency and stability of energy flow management and continuous power supply to the load from the point of view of varying conditions. Finally, MATLAB/Simulink simulations were performed on both steady state and dynamic (fluctuating PV generation, wind speed and load demand) conditions. Results show that energy storage must be controlled optimally to minimize AC grid dependence and maintain state of charge (SOC) of battery within reasonable levels. The microgrid system was analyzed and key performance metrics such as voltage regulation, current distribution, power flow optimization, and integrating renewable energy sources were effectively optimized. Balance between the battery and the DC bus is primarily carried out by the bidirectional DC-DC converter. The balance of study concludes that microgrid systems, operating with efficient energy management, are able to deliver a sustainable and resilient power answer for modern energy needs. Usage of the battery management system will be future work, investigating hardware implementation and optimization.

# Contents

# Preface

Nazarbayev University, April 25, 2025

Bakdaulet Aldashov
<bakdaulet.aldashov@nu.edu.kz>

# Chapter 1

# Introduction

The tendency toward renewable energy in modern world is not just a trend, rather, it is a promising determined move toward cutting carbon emissions and gaining sustainability. By 2050, ICE (internal combustion engine) vehicle carbon emissions are expected to significantly decrease, mostly as a result of the increase of numbers of electric cars. The size of this revolutionary change is demonstrated by statistics from the International Energy Agency (IEA) that suggest EV numbers may reach 30 million units by 2030 [1]. The increasing demand for clean energy solutions around the world has led to a shift towards new paradigms in energy generation, storage and distribution technologies. This shift relies heavily on the variability of clean energy which is produced by renewable energy sources. The intermittency of these sources is a major challenge in its adoption. Microgrids are smart ways to address this issue at the community level, allowing for energy production and storage while having the ability to operate in island mode or synchronized operation with the main grid [2][3].

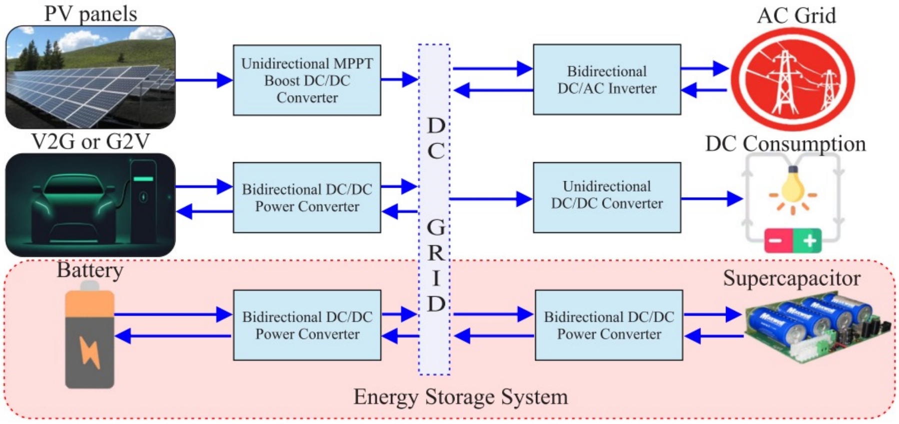

**Figure 1.1:** Simplified DC microgrid scheme [4].

While this transition brings with it a host of challenges that the electricity sector faces in its efforts to comprehensively reconfigure its generation and distribution structures, the growing demand for electricity to power electric vehicles requires a fundamental redesign of the energy infrastructure if such growth is to be managed sustainably [5][6][7]. Traditional energy systems based on intensive use of fossil fuels are becoming obsolete in the face of growing demand. Thus, development towards renewable resources, as[4][8][9] point out, must be complemented by the development of new energy storage technologies - solar and wind. From **Figure 1.1** it is pretty clear that at the core of the efficient operation of the microgrid are considered to be converters that serve as a main power transfer component between different sources [10][11]. The function of each of the remaining four converters in the modular control scheme will be necessary to support voltage regulation and optimize power flow to ensure the reliable operation of the microgrid under dynamic operating conditions. Based on the study of L. Al-Ghussein and his colleagues, the expansion of DC microgeneration technologies are one of the perspective direction in this field [12]. Since the clean energy sources including photovoltaic panels and wind power generators can be easily and effectively integrated to DC microgeneration technologies, also it can be applied to energy storage elements and electric vehicles. As it can be seen from **Figure 1.1**, the EV charging stations use DC-DC converter techologies to transfer power, being one of the essential components in the EV industry [18]. So based on their improved efficiency, dependability, and smooth integration with renewable energy sources, DC microgrids present an effective path towards decentralized and sustainable energy systems.

One of the primary characteristics that microgrid systems offer is the fact they are able to function autonomously or as part of the primary grid, thereby providing better energy security, notably in regions where grid electricity access could be challenging. The application of renewable energy sources in combination with storage systems ensures power generation in rural areas and keeping the energy stored for further uses.

The primary aim of this project is to investigate and observe the behaviour of microgrid systems connected with photovoltaic and wind energy sources along with Battery Energy Storage System (BESS) by connecting the whole system via Bidirectional DC-DC converter based components. The converters serve as extremely crucial tools in regulating the energy transfer between the sources and storage to make the operation of the entire system effective and also to maintain stability of the grid. The investigation is done on the behavior of the system under various operating conditions and its transient response under changes in irradiance, wind speed and load.

This project report provides simulation-based data used for modeling and observing the model in MATLAB/Simulink, on steady state and dynamic state modes.

The simulation also includes investigation of the created system’s behaviour under different weather scenarios, such as sunny days with no wind, windy days with no sun, the weather with no sun and wind, and grid-connected operation.

## 1.1 Ethical and Professional Responsibilities

- **Ethical Responsibility:**
  The development and implementation of this project involve several ethical considerations, particularly regarding safety, environmental integrity, and intellectual property rights. Working with high-voltage components, such as solar panels, DC generators, and bidirectional DC-DC converters, requires strict adherence to safety protocols. Compliance with IEEE and IEC standards, such as IEC/IEEE 80005-1, ensures the safety of personnel and equipment. Project members are trained in electrical safety, follow best laboratory practices, and utilize personal protective equipment (PPE). Emergency shutdown systems are included to mitigate risks during experimental operations.

  Environmental concerns also play a crucial role in the project. While the project promotes renewable energy integration, the experimental use of a gasoline-powered DC generator generates carbon emissions. Efforts are made to minimize its usage, favoring simulations and renewable sources like solar panels. Proper disposal and recycling protocols are followed for batteries and other hazardous components containing materials such as lithium and nickel.

  Academic integrity is another key ethical focus. The project strictly avoids plagiarism, ensuring proper citation of all external research and data. This transparency honors intellectual property rights and facilitates ethical future research. By addressing these ethical aspects comprehensively, the project prioritizes safety and environmental responsibility while upholding academic and professional standards.

- **Informed Judgments:**
  Ensuring well-informed decisions throughout the project involves a careful balance of technical precision and societal considerations. Technical decisions are grounded in rigorous research and data analysis. For example, the choice of bidirectional DC-DC converters, their topological designs, and the operational algorithms are informed by a detailed study of efficiency, reliability, and compatibility with renewable energy sources. Performance metrics such as energy conversion efficiency, stability, and cost-effectiveness are critically evaluated to guide decision-making.

  On a societal level, the project considers the broader implications of its outcomes. Microgrid technology has the potential to transform energy accessibility in underserved communities, providing reliable and sustainable solutions. Consultation with experts in renewable energy and power systems ensures that the project aligns with global energy goals and societal needs. Transparency in documenting methodologies and results enables stakeholders, including academic researchers and industry professionals, to assess the project's reliability and applicability. Regular feedback from mentors and peers helps refine approaches and address potential oversights.

This dual emphasis on technical rigor and societal impact underscores the project's commitment to making informed and responsible judgments, ensuring its relevance and contribution to both the academic and practical domains.

- **Global Context:**
  This project addresses a globally significant challenge: integrating renewable energy into modern power systems. Microgrid technology, supported by bidirectional DC-DC converters, offers scalable and sustainable solutions for regions with diverse energy needs. In developed countries, these technologies enhance energy efficiency, support the transition to renewables, and reduce dependence on fossil fuels. Conversely, in developing regions, they provide opportunities for electrification in off-grid or rural areas, bypassing the need for extensive infrastructure investments.

  The global applicability of this project highlights the need to navigate varying regulatory and technological landscapes. Stringent environmental standards in some countries may accelerate the adoption of such solutions, while regions with limited access to advanced technologies may face barriers to implementation. By designing adaptable and cost-effective solutions, the project addresses these disparities and supports equitable energy transitions.

  Furthermore, the project aligns with international sustainability goals, one of which can be considered the initiative "Sustainable Development Goal (SDG) 7" proposed by the UN, which promotes the generation of affordable and clean energy. This alignment demonstrates its potential to contribute meaningfully to global efforts in combating climate change and promoting energy access, making it relevant across diverse socioeconomic and geographic contexts.

- **Economic Impact:**
  The economic impact of this project is multifaceted, encompassing both short-term and long-term considerations. In the short term, the project reduces energy infrastructure costs by promoting bidirectional DC-DC converters, which enable efficient energy management in microgrids. By optimizing renewable energy integration, the project minimizes dependency on fossil-fuel-based systems, offering cost-effective alternatives for energy storage and distribution.

  In the long term, the widespread adoption of this technology could significantly lower energy production costs, particularly in rural and off-grid communities. Reduced reliance on centralized grids and fossil fuels will decrease operational costs for industries and households. However, this transition may pose economic challenges, such as the displacement of workers in traditional energy sectors. Addressing these challenges requires retraining programs and support systems to facilitate the transition to renewable energy jobs, ensuring equitable economic benefits.

Overall, the project contributes to a more sustainable economic framework by reducing costs, fostering innovation, and supporting the transition to a green economy. Its potential for widespread adoption underlines its significance in shaping a cost-effective and environmentally responsible energy landscape.

- **Environmental Impact:**
  This project strongly aligns with environmental sustainability by facilitating the adoption of renewable energy systems and reducing carbon emissions. By integrating bidirectional DC-DC converters into microgrids, the project promotes efficient energy storage and management, minimizing reliance on fossil-fuel-based generators. Simulations prioritize renewable energy scenarios, reducing the experimental dependence on gasoline-powered generators and their associated carbon emissions.

  The project also addresses environmental concerns associated with energy storage components, such as batteries. Proper disposal and recycling protocols are established for hazardous materials like lithium and nickel, ensuring that environmental harm is minimized. Additionally, energy-efficient design principles are incorporated, reducing overall resource consumption during experimental and operational phases.

  In the long term, the improved efficiency of clean energy systems contributes to lower energy consumption and reduced waste. By supporting cleaner energy systems, the project aligns with global efforts to mitigate climate change and promote environmental sustainability.

- **Societal Impact:**
  The societal implications of this project are substantial, particularly in terms of energy accessibility and equity. Microgrid systems, supported by bidirectional DC-DC converters, provide reliable and affordable energy solutions to underserved communities, including rural and off-grid regions. This reduces energy inequality and promotes social development by enabling access to essential services powered by electricity.

  It supports the transition to cleaner energy sources, contributing to the decrease of traditional energy sources that have higher footprint and increased negative impact to the environment. For industries such as healthcare, telecommunications, and education, reliable microgrid systems ensure uninterrupted energy supply, enhancing societal resilience.

However, the project also recognizes potential societal challenges, such as job displacement in traditional energy sectors. To address these issues, the project advocates for training programs and policies that support workers transitioning to renewable energy roles. By promoting sustainability, equity, and resilience, the project has the potential to deliver widespread societal benefits, bridging the gap between technological innovation and social well-being.

# Chapter 2

# Background

DC microgrids are one of the most important aspects of modern energy system innovation, they are flexible in configuration, allowing the integration of various energy components. The central elements of the work are the bidirectional DC/DC converters, which form a very important element in the energy transfer mechanisms. Bidirectional converters ensure the smooth exchange of energy between sources with different characteristics, different types of loads and storage devices, thereby ensuring the highest possible level of operation within the constraints of the microgrid. In this article, we will consider non-isolated bidirectional converters, the most common topological structure of which is the bidirectional converter based buck/boost DC-to-DC converter. Non-isolated converters are simple and flexible to implement, offering a relatively simple gateway for microgrid integration. However, as also discussed in [13], these converters have difficulty with respect to impedance related to voltage and current control from a general microgrid perspective. The challenges are overcome for the realization of DC microgrid technologies.

This project demonstrates the characteristics of DC microgrids and points out the key role of the non-isolated bidirectional converters, underlining with specific emphasis the bidirectional boost/buck converter. It also shows the process how the aforementioned converters share the energy both ways. The following description not only highlighted the advantages of bidirectional conversion but also acted as a catalyst for our research work. While referring to the works done by [14] [15], numbers of studies were conducted in order to investigate the intricacies of bidirectional converters and possible impacts that they could have on microgrid designs. These studies focus on the characteristics and zero current switching (ZCS) turn-on function ways to reduce losses and improve efficiency in bidirectional converters where optimization of energy storage system performance is pursued. Several studies have shown the converters' stability factors in terms of its interleaved feature thus preventing losses by spreading switch intervals [16][13][17]. In addition, the authors also developed the enable function for zero current switching operation, which is used for minimizing power loss during the inverting process, thus improving the efficiency.

Empirical analysis and theoretical modeling have shown that such design strategies are considered effective. The results can be seen in the improvement of the bidirectional conversion efficiency of storage systems, especially for A2BCT via circuits. The group of researchers aimed to develop a systematic approach to minimize losses by making the best use of resources to improve the entire system's total effectiveness, and therefore the system's overall behaviour [17] obtained results during the project can be used for the energy storage applications and designing the bidirectional converters. As mentioned earlier, solving the design problems and optimizing the operational parameters will lead to more efficient, feasible and sustainable energy storage options.

According to the research work of scientists from NKUST[18], isolated version of this type of converters' development has become significantly relevant. Such a device can be utilized for either boost(step up) voltage operation or buck (step down) operation in microgrids, taking into account the flexibility in energy management. It was clear how the proposed converter enhances adaptability and reliability in systems with microgrids through this. The design of the converter implements the latest engineering to optimize the dynamics of energy flow in microgrids. The proposed design provides flexibility in implementation, as well as operation under conditions that vary greatly, which allows the obtained characteristics to be repeated under some conditions and under others. The isolation feature of the converter further enhances system stability by dampening voltage fluctuations to maintain constant power supply. This device provides resiliency and sustainability in microgrid solutions since energy exchange is controlled within the device itself. Such developments point out the role of bidirectional converters in enhancing the effectiveness and viability of the contemporary microgrid technologies. The academics looked at several converter architectures and determined in the following work their efficiency profiles and suitability in the dynamic context of modern EV ecosystems [18]. Focusing on bidirectional converters in EVs, this investigation examines the interplay between control strategies and bidirectional converters in such systems as outlined by Martinez-Vera and Banuelos-Sanchez [19]. Their study highlights the important role of improved control methods which helps to gain higher performance of the converters, creating a foundation for dynamic control algorithms suitable for electric vehicles operation. The following pattern similar to the previous work was also explored and discussed by the other researchers [6], in which they also investigated the performance of such converters in EV applications, by testing two different types of converters such as CBB which is Cascaded Boost/Buck and CHB, Combined Half Bridge. Their aim was to investigate which one is the best and more efficient option for electric vehicles applications.

Coming back to the study [19], Martinez-Vera and Banuelos-Sanchez observe the control paradigms: a discussion of how different strategies affect the efficiency, stability and responsiveness associated with bidirectional converters in the context of electric vehicles. They also establish, through both practical tests and theoretical models, the effectiveness of different algorithms for controlling the power flow, voltage levels and current dynamics control in the EV environment. Furthermore, another value of their study is that it has provided insights into the developments in the EV environment and the associated new challenges for bidirectional converters. At the end of the day the study of converter applications inspired by Martinez-Vera and Banuelos-Sanchez, critically examines real-world scenarios and trends of EV entry into play to develop an understanding of the adaptability of control strategies to the changed demands of electric mobility.

# Chapter 3

# Methodology

## 3.1 System Overview

Based on **Figure 3.1**, it can be observed that the design comprises several main elements including the solar PV panel, wind turbine generator, battery system (BESS), the control panel and loads for different dynamic conditions. Also, the whole system is connected to the AC grid via AC-DC inverter, therefore the grid supplies energy to the load in case the renewable sources' power is insufficient.

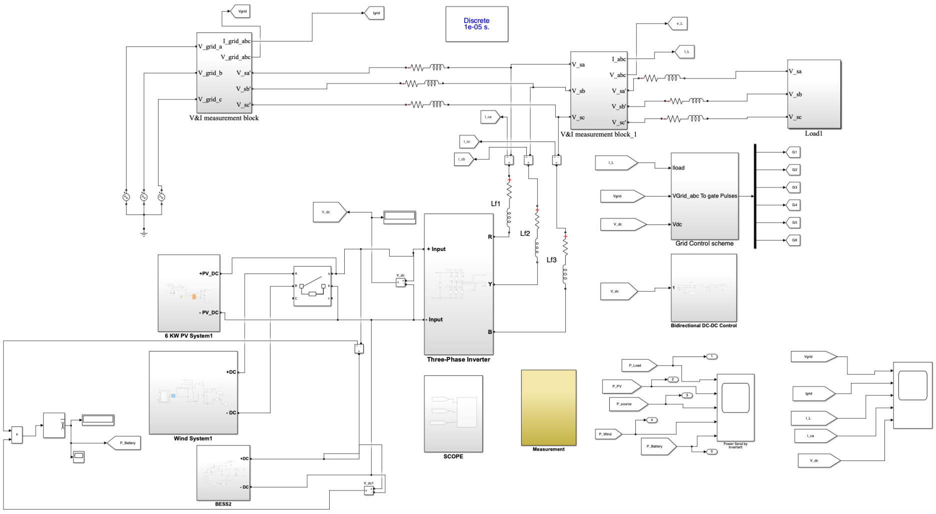

**Figure 3.1:** The microgrid system designed in MATLAB/Simulink.

## 3.2 Photovoltaic (PV) System

The PV (Photovoltaic) panels are able to generate the electrical power from the solar energy, so the PV power is directly drawn from solar factors. Temperature and irradiance are the prime factors in electrical measurements of solar energy. The last one plays the most key role in the amount of solar energy. Maximum Power Point Tracking (MPPT) system is included in the microgrid to make sure it operates at its let peak power points so as the system can thereby generate as much power as it can from the solar panel. In this system, the Perturb and Observe (P&O) technique is used to monitor the ideal maximum power point by varying the duty cycle of the converter. The power from the generated power is computed as follows:

$$P_{PV} = V_{PV} \cdot I_{PV}$$

Where: $P_{PV}$ - power generated by the PV system (W), $V_{PV}$ - voltage, and $I_{PV}$ - the current from the PV array.

The current from the PV array is modeled based on the I-V characteristics which can be observed in Appendix A, considering the effect of irradiance and temperature, as described by the equation from [20]:

$$I_{PV} = I_{SC} \left( \frac{G}{G_{ref}} \right) \left[ 1 - \exp \left( \frac{V_{PV} - V_{OC}}{N \cdot V_T} \right) \right]$$

Where: $I_{SC}$ - the short-circuit current, $V_{OC}$ - the open-circuit voltage, $N$ - the diode ideality factor, $V_T$ - the thermal voltage.

## 3.3 Wind System

**Figure 3.1** shows that the wind energy system converts mechanical power of the wind into electrical power. Permanent Magnet Synchronous Generator (PMSG) is connected to wind turbine and produces power as per wind speed. The output produced from the wind system is mainly a function of the wind speed and the efficiency of the turbine.

According to the following equation, the power generation from the wind turbine is determined:

$$P_{Wind} = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot C_p$$

Where: $P_{Wind}$ - power generated by the wind turbine (W), $\rho$ - the air density, $A$ - the swept area of the turbine blades, $v$ - the wind speed (m/s), $C_p$ - the power coefficient of the turbine.

In this model the perfonnance of the turbine is dynamically adjusted by means of the control of the PMSG generator according to the real time wind conditions and to maximize the extraction of energy.

## 3.4 Battery Energy Storage System (BESS)

The Battery Energy Storage System (BESS) receives energy which is in excess from the PV and wind systems and stores it so that it is available for use when the renewable sources can not provide the load demand. Battery State Of Charge (SOC) is one of the things that have to do with energy distribution and besides not overcharging the battery and not overdischarging the battery.

By the following equation, the State of Charge can be updated:

$$SOC(t) = SOC(t-1) + \frac{1}{C_{bat}} \cdot (P_{bat} \cdot \Delta t)$$

Where: $SOC(t)$ is the state of charge at time $t$, $C_{bat}$ is the battery capacity (Ah), $P_{bat}$ is the power supplied or drawn from the battery (W), $\Delta t$ is the time step (s).

When the renewable generation is insufficient, the battery supplies the power to the system, assuring that the load demand is always outused.

## 3.5 AC Grid Control

Low renewable generation is applied as a means of employing the AC grid as reserve power. A three phase inverter synchronizes a DC bus and the AC grid for synchronization of the grid. To achieve synchronization, it synchronizes the phase as well as the frequency of the grid with the output of the inverter. The system can be fed with the power from the load or can import excess energy when the amount generated by the system in excess of load demand.

The grid management system enables peaceful coexistence, so that energy flows the best way from the microgrid to utility grid.

## 3.6 Power Management and Control Strategy

Adaptive dynamic power management strategy (ADPM) is used by the power management system to exploit available renewable resources, enable battery storage to be effectively handled, and achieve grid stability. They are the key components of the system which are:

- Maximum Power Point Tracking (MPPT): Ensures optimal power extraction from the PV system.
- Wind turbine power generation is adjusted according to the real time conditions.
- SOC management of the battery's charging and discharging as required by the system.

- Grid Interaction: When the renewable generation cannot support the load, the grid is used to support the system.

At lower SOC, the battery will get the grid power first to feed the load. Instead, too much renewable energy is generated, and is stored in the battery, helping the system be more energy efficient and less reliant on the grid.

## 3.7 Simulation Cases and Dynamic Behavior

Assessment of performance and flexibility of the system led to its simulation under different conditions using MATLAB/Simulink. The scenarios simulated include:

- Windy Day, No Sun - Wind power generation with no solar input.
- Sunny Day, No Wind - PV power generation with no wind.
- The system is also supplied by the AC grid for power (No Wind, No Sun).
- Wind, Sunny Day - PV and wind systems produce power, which is stored in the battery if the current energy is above the energy being used.
- Dynamic Solar Radiation - Dynamic solar radiation tries cloud cover or time of day effects.
- Load Demand – The load demand is increased or decreased dynamically.

The system was studied for its dynamic behavior, the change in behavior of the system as conditions such as fluctuating irradiance, wind speed, and load change. Here the results will show the way energy of MPPT, wind turbine controller and battery supply flows energy to minimize distribution of energy, so that load is always fed with energy and the super fluous energy is bruted either in the battery or connected with the grid.

## 3.8 Simulation Setup

Both simulations were conducted using MATLAB/Simulink R2023b using a fixed step solver (`ode45`). Each case was simulated for 30 seconds and was observed in real time through the Scope blocks to the DC bus voltage, battery SOC, and power outputs. Data was also logged from the workspace to analyse the performance metrics like efficiency load support after simulation.

# Chapter 4

# Results and Discussion

The performance of the microgrid system was investigated under different energy supply conditions and four different cases were simulated to study the system's dynamic response. These cases addressed the combined interaction between photovoltaic (PV) panels, wind turbines, battery storage, and the AC grid, and the system's capacity to deliver reliable power to the load in several configurations. These simulations results show the impact of integrated control system on the renewable energy sources and the power distribution.

## 4.1 Case 1: No Wind and No PV

In Case 1 **Figure 4.1**, if there are no wind or PV generation available, the entire 11 kW load is supplied by the AC grid at first. The results of simulation showed that the grid is capable of delivering up 11 kW to meet the load. The PV begins supplying 6 kW, at 0.2 s, at its maximum capabilities under maximum irradiance (1000 W/m$^2$) now, and the battery begins charging as its state of charge (SOC) is less than 25%. When the wind turbine's contribution decreases, it operates at 0.3 s at 2.5 kW. And it charges the battery with compensating for the fluctuations, providing a stable electrical power.

Eventually, the system reaches a steady state that supplies the load demand of 11 kW and has the PV providing 6 kW, wind supplying 2.5 kW, and the AC grid supplying the remaining 2.5 kW. The system stabilizes and the battery does not go dead.

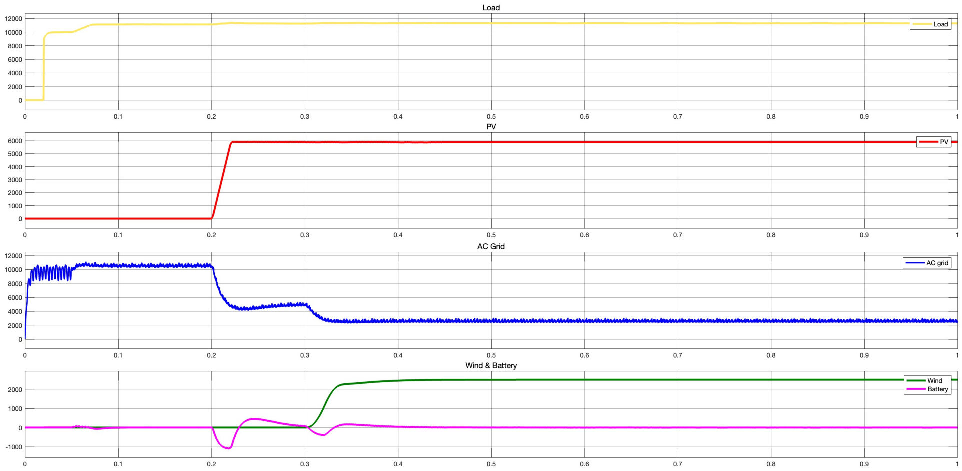

**Figure 4.1:** Simulation results for Case 1: Steady-State Condition with No PV or Wind Power.

## 4.2 Case 2: Dynamic PV Generation

The PV system's output is dynamic for this case. Based on **Figure 4.2**, the entire 11 kW load is supplied initially from the AC grid. The wind turbine begins to supply 2.5 kW at 0.3 s. At the time of 0.4 s, the PV system supplies 6 kW, and only 2.5 kW from the grid. It is because the surplus energy starts charging the battery. The battery pays back by discharging when needed, and charging when surplus is generated from PV power that fluctuates.

The grid soon adjusts to supply the remaining power after the PV system is deactivated at 0.8 s. In the steady state with the grid supplying 8.5 kW and the wind turbine supplying 2.5 kW, the system operates.

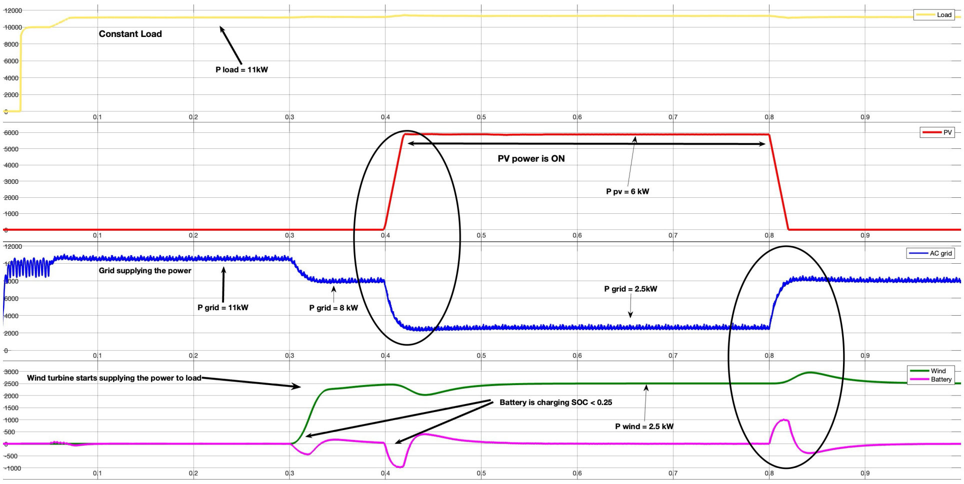

**Figure 4.2:** Simulation results for Case 2: Dynamic PV Generation.

## 4.3 Case 3: Dynamic Load and PV

In this case, in Figure **4.3**, the load is dynamic, from 5 kW and up to 11 kW. However, initially, the grid supplies the whole 11 kW load. When started at 0.2 s, the PV system generates 4.1 kW and the grid output decreases to 6.6 kW. The wind turbine reduces the grid contribution to 2.5 kW beginning at 0.3 s, with 2.5 kW supplied by the turbine at 0.3 s. 0.3 kW assist is being provided by the battery in stabilizing the system.

The PV system output is at 0.6 s of 4.1 kW, and the rest of 4.4 kW grid power is added so that the wind still performs 2.5 kW. With steady state conditions, the system stabilizes around 0.6 s to satisfy the grid with the PV and the wind.

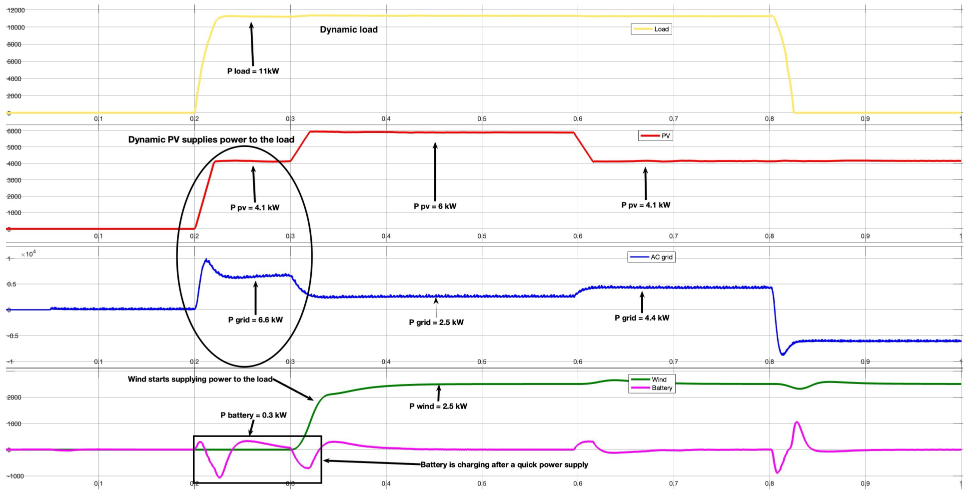

**Figure 4.3:** Simulation results for Case 3: Dynamic Load and PV.

## 4.4 Case 4: Grid, PV, and Wind Power with Constant Load

As it can be observed from **Figure 4.4**, the load is 5 kW constant. In the beginning, 5 kW is supplied by the AC grid. About 2 minutes later—after 0.3 s—the wind turbine begins supplying 2 kW to this grid and the grid's contribution drops to 3 kW. The PV system is replaced at 0.4 s by inputs of 3 kW starting from the grid. The PV system is turned off at 0.8 s, and it remains off until 0.

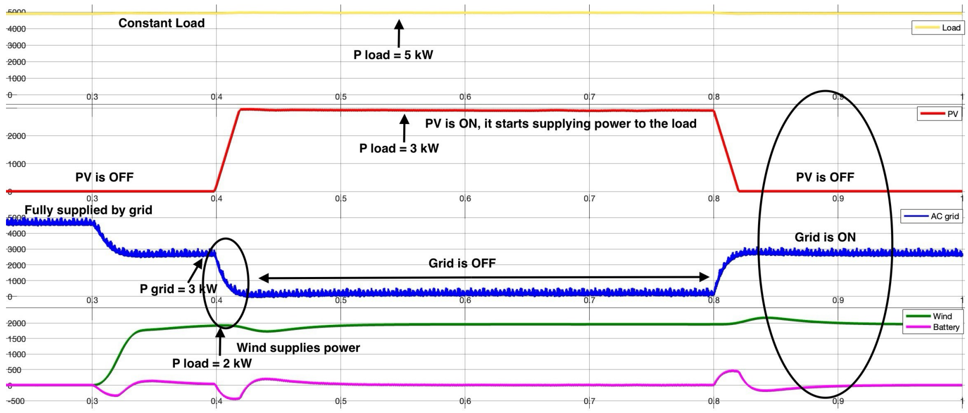

**Figure 4.4:** Simulation results for Case 4: Grid, PV, and Wind Power with Constant Load.

After the PV is off, the grid takes its turn, continuing to offer 3 kW and the wind turbine 2 kW, which stabilizes the system to the steady state.

## 4.5 Key Observations and Analysis

1. Integration of Dynamic Power Sources (e.g. PV and wind power) enables the microgrid to decrease dependence on the AC grid and increase resilience to periods of high generation as the microgrid can operate as a stand-alone system with the addition of these generation sources. Often battery storage is used to provide this load stability as it causes it to charge up when excess energy is available and discharge where the supply is unstable or the load is higher.

2. Control System and Energy Flow: Control system handles the power flow between renewable sources and the AC grid with high efficiency, and it can function stably both when renewables change dynamically. Its state of charge (SOC) is tightly monitored and controlled such that the battery is charged when extra energy is present and discharged to retain the system balance.

3. Voltage and Current Dynamics: During transitions between the different energy sources, voltage values (328 V peak amplitude) remained unchanged for AC grid voltage values. The fluctuation of current was also based on the grid power, PV power, wind power, and the battery availability. Active contribution of the renewable systems in minimizing the current from the grid verified the efficient distribution of energy.

4. AC Grid Functioned as Backup Power Source: During periods when PV and wind power were not enough for load, the AC grid acted as a backup power source. The system was able to provide a reliable energy to the load with minimal grid dependency using this flexible interaction.

5. Battery SOC Control and Battery Management: The battery was balanced as it needed to be neither overcharged, nor overdischarged. It is necessary to guarantee the durability of the battery and of the whole system.

# Chapter 5

# Conclusion

In the research, a combination of renewable energy sources, Photovoltaic (PV) panels and wind turbine, with battery storage provides reliable power supply to a steady load with a microgrid system. Different operational scenarios comprising renewable power generation variations and load changes and power source shifts were used to evaluate the system. The power management capabilities of the system(s) were evaluated in MATLAB/Simulink simulations from many sources to ensure stability.

Using the simulation results, the system is tested with the efficiency in check on the handling of the energy flow. By coupling such PV power and wind energy to batteries they could provide power supply that adapted on the fly to meet demand continuously. The smart control setup should have worked well to allow the microgrid to handle shifts between sources and the AC grid to reduce grid dependence during times of peak renewable generation.

During periods of excess power generation, the battery storage system was crucial for stabilizing the power supply and charging; during those times when renewable energy sources were not sufficient to meet the demand, the battery storage system discharged. It provided a constant output to the load at any time of fluctuating energy availability.

In the overall system behavior, the necessity of a well coordinated energy management strategy was observed to be coupled with usage of renewable energy sources, battery storage and grid together smoothly meeting the load demand. Based on this study, microgrids equipped with the right control systems and energy management strategies can be the sustainable, resilient, and reliable solution for providing the energy demands of the modern infrastructure.

# Bibliography

[1] Doros Nicolaides, David Cebon, and John Miles. “Prospects for electrification of road freight”. In: *IEEE Systems Journal* 12.2 (2017), pp. 1838–1849.

[2] Monzer Al Sakka et al. “DC/DC converters for electric vehicles”. In: *Electric Vehicles-Modelling and Simulations* 100.466 (2011).

[3] Jeremy Jie Ming Kwok et al. “Microgrid scheduling for reliable, cost-effective, and environmentally friendly energy management”. In: *Industrial & Engineering Chemistry Research* 52.1 (2013), pp. 142–151.

[4] Fabiano Gonzales Nimitti and António Manuel Santos Spencer Andrade. “Bidirectional converter based on boost/buck DC-DC converter for microgrids energy storage systems interface”. In: *International Journal of Circuit Theory and Applications* 50.12 (2022), pp. 4376–4394.

[5] João Pedro Carvalho Silveira et al. “Evaluation of bidirectional dc-dc converter topologies for voltage regulation in hybrid microgrids with photovoltaic and battery technologies”. In: *2018 13th IEEE International Conference on Industry Applications (INDUSCON)*. IEEE. 2018, pp. 215–221.

[6] Mehnaz Akhter Khan et al. “Performance analysis of bidirectional DC–DC converters for electric vehicles”. In: *IEEE transactions on industry applications* 51.4 (2015), pp. 3442–3452.

[7] Dakshina M Bellur and Marian K Kazimierczuk. “DC-DC converters for electric vehicle applications”. In: *2007 Electrical Insulation Conference and Electrical Manufacturing Expo*. IEEE. 2007, pp. 286–293.

[8] R Rajasekaran and P Usha Rani. “Bidirectional DC-DC converter for microgrid in energy management system”. In: *International Journal of Electronics* 108.2 (2021), pp. 322–343.

[9] Purushothaman Serukkur Kulasekaran and Sattianadan Dasarathan. “Design and analysis of interleaved high-gain bi-directional DC–DC converter for microgrid application integrated with photovoltaic systems”. In: *Energies* 16.13 (2023), p. 5135.

[10] Loiy Al-Ghussain et al. "Sizing renewable energy systems with energy storage systems in microgrids for maximum cost-efficient utilization of renewable energy resources". In: *Sustainable Cities and Society* 55 (2020), p. 102059.

[11] Nguyen Anh Dung et al. "Analysis and implementation of a high voltage gain 1 MHz bidirectional DC–DC converter". In: *IEEE Transactions on Industrial electronics* 67.2 (2019), pp. 1415–1424.

[12] Greg Stahl, Miguel Rodriguez, and Dragan Maksimovic. "A high-efficiency bidirectional buck-boost DC-DC converter". In: *2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*. IEEE. 2012, pp. 1362–1367.

[13] Adel El-Shahat and Sharaf Sumaiya. "DC-microgrid system design, control, and analysis". In: *Electronics* 8.2 (2019), p. 124.

[14] Pramod Kumar Aylapogu et al. "Modeling and implementation of a new ZCS interleaved bidirectional buck–boost DC–DC converter for energy storage systems". In: *Electrical Engineering* 99 (2017), pp. 1283–1293.

[15] Jiulong Wang et al. "Review of bidirectional DC–DC converter topologies for hybrid energy storage system of new energy vehicles". In: *Green Energy and Intelligent Transportation* 1.2 (2022), p. 100010.

[16] KR Bharath, Harsha Choutapalli, and P Kanakasabapathy. "Control of bidirectional DC-DC converter in renewable based DC microgrid with improved voltage stability". In: *International Journal of Renewable Energy Research (IJRER)* 8.2 (2018), pp. 871–877.

[17] Rajvikram Madurai Elavarasan et al. "Investigations on performance enhancement measures of the bidirectional converter in PV–wind interconnected microgrid system". In: *Energies* 12.14 (2019), p. 2672.

[18] Yu-En Wu and Yao-Ting Ke. "A novel bidirectional isolated DC-DC converter with high voltage gain and wide input voltage". In: *IEEE Transactions on Power Electronics* 36.7 (2020), pp. 7973–7985.

[19] Erik Martinez-Vera and Pedro Banuelos-Sanchez. "Review of Bidirectional DC-DC Converters and Trends in Control Techniques for Applications in Electric Vehicles". In: *IEEE Latin America Transactions* 22.2 (2024), pp. 144–155.

[20] Vijayakumar Gali et al. "Experimental investigation of adaptive multi-generalized integrator-based controller for electronically interfaced hybrid microgrid system". In: *Renewable and Sustainable Energy Reviews* 207 (2025), p. 114965.

# Appendix A

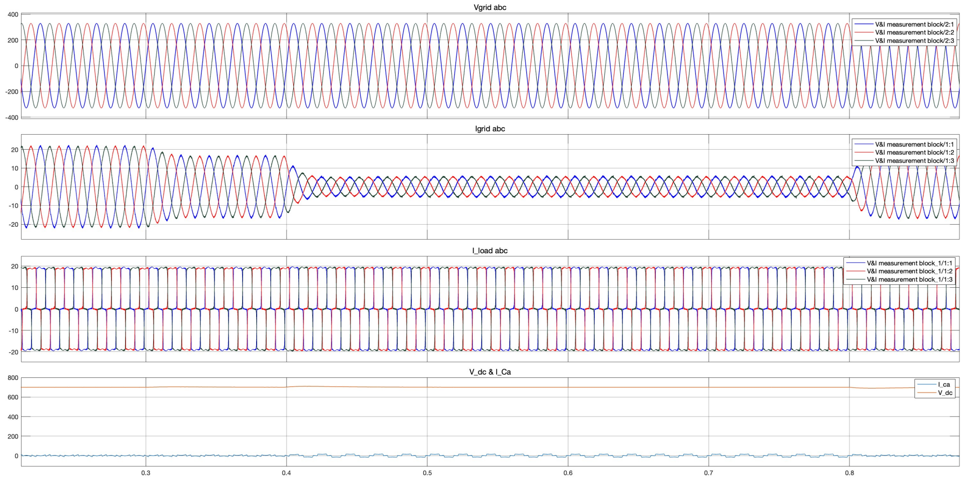

**Figure A.1:** Voltage and Current measurements for the Grid in case 2.

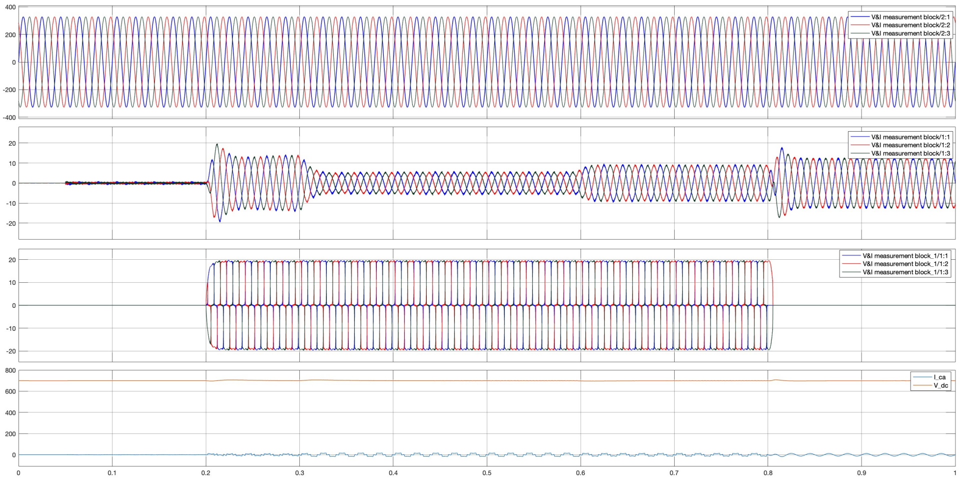

**Figure A.2:** Voltage and Current measurements for the Grid in case 3.

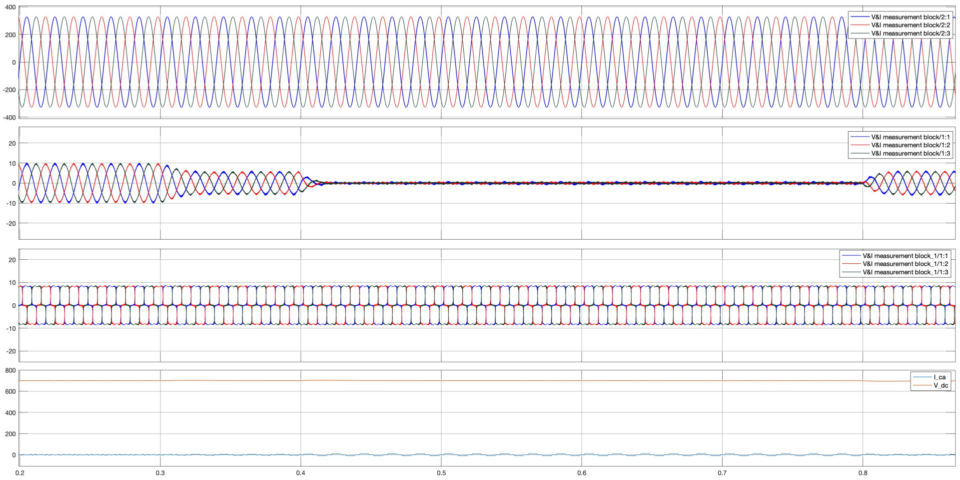

**Figure A.3:** Voltage and Current measurements for the Grid in case 4.