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Robust Power Management for Smart Microgrid Based on an Intelligent Controller

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***Abstract*—A microgrid (MG) is an autonomous electrical system that can operate independently or link to the grid. It is usual practice to use a single grid organization to improve energy access and ensure a consistent supply of electricity. Microgrids (MGs) can be unstable if islanded given that they lack the predominant grid's high friction and are subject to large voltage and frequency swings. Standards, directions, and accessibility and interoperability criteria all address the dependability of a microgrid, the use of distributed local resources, and cybersecurity. This work presents a revolutionary intelligent controller, Adaptive. This study proposes a novel intelligent controller, the Adaptive Network-based Fuzzier Inference System - Drooping Controller (ANFISDC), with a drooping coefficient modification, to provide optimal power sharing while minimizing power overloading/curtailment. To provide the essential stability and lucrative power sharing for the islanded the microgrid, the dropping coefficient is changed to account for the power fluctuations of RES (renewable energy source) components as well as the relationship between electricity production and demand. Furthermore, secondary control is used to restore the frequency/voltage drop caused by the droop control. Simulations with load fluctuations in MATLAB/Simulink show that the proposed strategy improves the stability and economic viability of microgrids powered by energy from renewable sources based on droop. The outcomes of the simulation demonstrate how well the suggested ANFISDC approach works to keep the microgrid operating steadily and profitably.**

Keywords*—Adaptive Network-based Fuzzier Inference System - Drooping Controller (ANFISDC).

I. INTRODUCTION

Energy production, transmission, and distribution networks are the three main classifications into which conventional electrical power systems fall. The transmission networks link the production plants to the electricity distribution systems, which provide power for all customers within a certain area. Energy pools are formed by connecting various power systems for a variety of causes, mostly economical as well as technological [1][2]. Electricity is generated and distributed through regional and neighborhood networks that operate independently but are interconnected to form an electrical grid. The increasing global population, digitalization, and growth in manufacturing are the primary factors that contribute to the rising demand for electricity. The rising demand for power, combined with the usage of traditional renewable energy sources, has resulted in a large increase in greenhouse gas (GHG) emissions worldwide. Fig. 1 depicts the estimated energy consumption across several industries worldwide, which is expected to exceed 30 TWh by 2040 [3]. By 2040, residential and business sectors will consume the most electricity. Additionally, transportation demand will have more than doubled, yet it will still account for only 2% of overall energy usage. Meeting the increasing demand for energy necessitates the installation of additional power generation resources. However, the existing method, which relies on centralized conventional generating sources (CGSs) located far from demand centers, is unsustainable. These CGSs primarily rely on burning gas, coal, or diesel fuel to generate electricity, which contributes significantly to carbon dioxide emissions and global warming. Therefore, the expansion of CGS installations will only lead to increased carbon emissions [4].

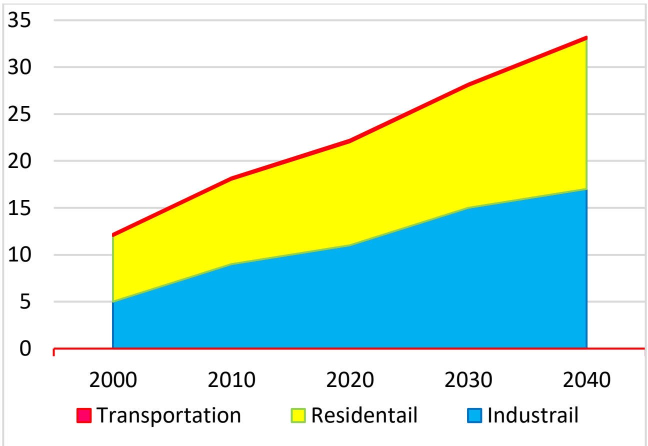

Fig. 1. Sector-wise global electricity demand

Fig. 2 presents a renewable energy strategy that demonstrates how to raise the percentage of renewable energy used in total energy consumption by 66% by 2050 as well. If the present pace continues, the percentage of renewable energy will only rise by about 0.25% every year, or 25% of all energy consumed by 2050. Nonetheless, the International Renewable Energy Agency (IRENA) has unveiled a robust roadmap for renewable energy (REmap) that aims to increase the percentage of renewable energy by 1.5% year by 2050, when renewable energy will account for

60% of the total energy used [7]. Electrical systems are changing into more intricate, multi-level systems these days due to new technology being developed as well as changes in business practices and regulatory frameworks. As a result, the whole thing often resembles a collection of interconnected computer components, software, as well as electronic communication grids. As per the definition provided by the European Technical Platform Smart Grids, the smart grid (SG) is a power system that has the ability to dynamically combine the behaviors of every user it serves, including generators, customers, and individuals who do both, to effectively provide environmentally friendly, economical, and secure energy [8].

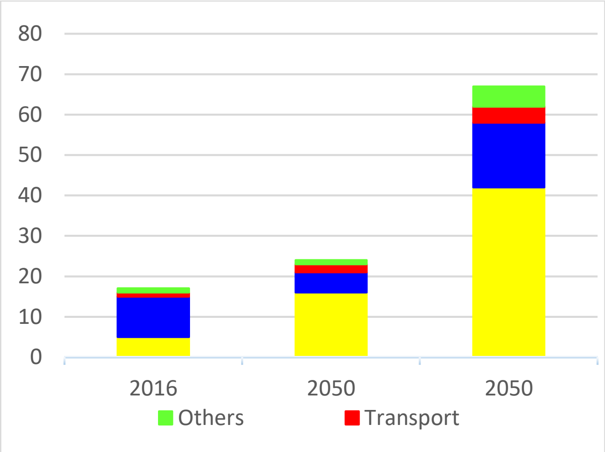

Fig. 2. Strategy for increasing the percentage of energy from renewable sources by 2050

The best approach to handle this issue is to apply government regulations and invest in university research on the creation and deployment of renewable energy sources (RESs) such as solar, wind, biomass, and other comparable technologies. To produce the best findings, this study should have at least 20 years of experience [5]. Over the last decade, RESs have demonstrated significant promise for mainstream implementation. Their objectives include fulfilling rising energy demands, ensuring long-term viability, minimizing carbon emissions, and supporting global conservation efforts. It is becoming more and more economical to generate energy from alternative RESs. In some areas, solar and wind power facilities at the utility scale can be more affordable than conventional generation methods. Therefore, it is important to gradually increase the proportion of energy derived from renewable sources in the total energy consumption [6].

Consequently, Fig. 3 shows the global increase in carbon dioxide emissions. Between the years 2000 and 2015, there was an over 40% rise in global emissions. Since the year 2010, emissions in the United States as well as the EU have begun to decline. Pollution is going to continue to rise up to its maximum in 2015, at which time emissions will begin to decline shortly before 2040.

The main objective of this paper is to enhance the robust control performance of the smart microgrid system by ensuring that voltage regulation is continuous with the presence of a three-phase fault, thereby improving the overall resilience and reliability of the system. This problem is formulated as an optimization problem that minimizes the effect of perturbation on the load voltage, taking into consideration various factors such as system configuration, control loops, and controller tuning as seen in Fig. 4.

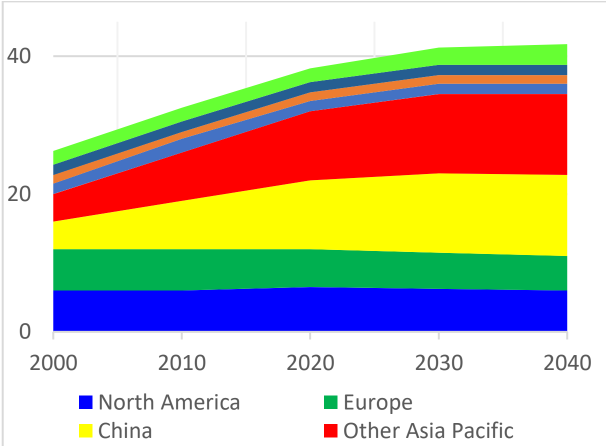

Fig. 3. Global carbon emissions trend

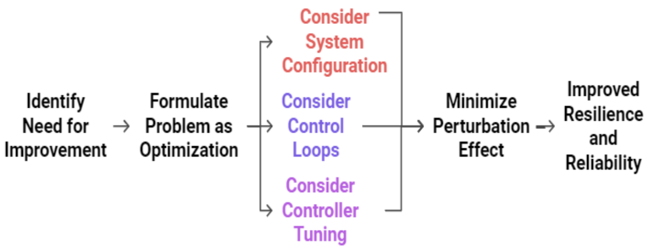

Fig. 4. Main Objective flow of works

II. Problem Statement

Considering the discussions above, the conventional electric power system has several problems:

1) Environment difficulties: Man-made emissions of carbon are caused by conventional power production technologies. Therefore, several approaches are needed to solve this greenhouse gas issue. In addition, the electrical grid is extremely vulnerable to collapse due to natural disasters including hurricanes, earthquakes, as well as storms. Hurricanes Sandy as well as Katrina both caused blackouts that revealed the weaknesses in conventional electric power systems.

- Due to declining investment and outdated infrastructure, it is increasingly difficult to build upgrades that can match the rising demand for electricity, leading to traffic and unstable power supplies.

- The integration of modern technologies into existing infrastructure is a challenge, particularly with regard to advancements in materials, electrical engineering, and communication technology. An overview of the infrastructure and environmental issues that traditional power plants confront is shown in Fig. 5. The grid's susceptibility to natural disasters, the need to address man-made carbon emissions, the challenges posed by aging infrastructure and low investment, and the challenges of incorporating cutting-edge materials, electrical engineering solutions, and communication technologies into current power networks are all included in this.

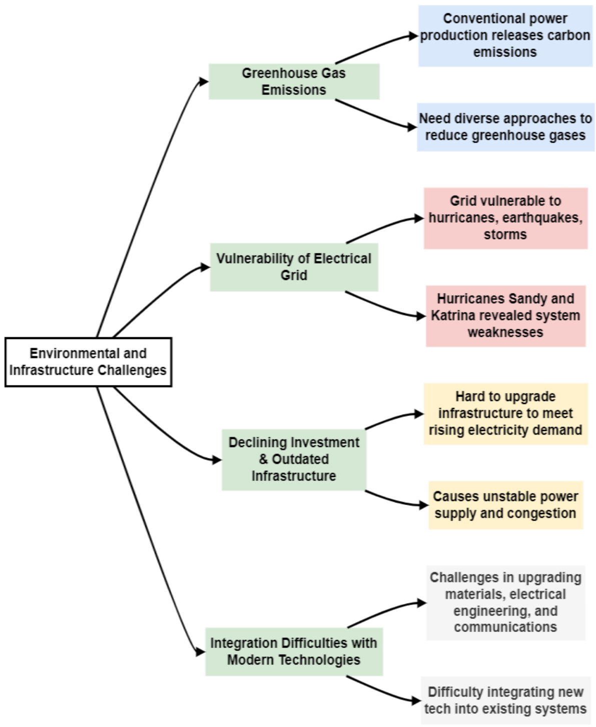

Fig. 5. Major infrastructure and environmental issues impacting traditional power systems

III. RELATED WORK

The research from the past and present about the best designs for microgrids globally is investigated in the following paragraphs. Among these endeavors are the works that the writers of [9]. The goal of this research is to determine if sources of renewable energy may lessen the negative effects of greenhouse gas pollution on the socio-economic growth of the biggest customer base in the globe. The results corroborate the notion that carbon dioxide emissions are naturally detrimental to human well-being and progress in the economy, and they indicate that there are actually adverse overall effects of the link between CO2 emissions as well as renewable energy on modern socio-economic growth [10]. To fulfil the worldwide goals for environmentally friendly power generation, effort must be made on the establishment and installation of clean energy generating throughout a sizable percentage of each state.

An additional ANFIS technology serves as a power management system for a grid-connected hybrid power plant that integrates batteries, hydrogen, and energy from renewable sources. In [11], a fuzzy-sliding-mode regulation technique and the adaptive neuro-fuzzy inference system (ANFISDC) for microgrid networks are outlined. In reference [12], a fuzzy logic controller-based voltage-frequency (V/F) management strategy is suggested for managing a microgrid supply connected to the grid inverters. One of Jang's greatest neuro-fuzzy technologies from 1993 was ANFIS [13], which, using just the information at hand, uses neural learning principles to find and adjust the fuzzy inference method's variables and architecture.

A research that assessed the practicality of creating a small electrical grid on the King Abdullah campus of Azad Jammu and Kashmir University in Pakistan is cited as [14]. Solar electricity was integrated into the architecture through the use of a hybrid microgrid. The study's findings show that the recommended combination microgrid structure, which uses solar power as a renewable power source, can meet load demand while achieving the lowest energy cost, and that it is a highly dependable and effective technology. Furthermore, the authors of [15] contemplated developing a hybrid electrical system with a diesel-powered generator, grid, and other sections for Eskisehir Osmangazi University. Likewise, research [16] used HOMER software to carry out a feasibility analysis for the construction of a hybrid power plant for Assiut University, concentrating primarily on PV system size and taking into account centralized and dispersed load needs. This strategy was chosen to ensure dependability and effective operation while lowering the total system costs. It has been found that using the centrally managed load demand arrangement for the microgrid architecture improves the efficiency of the system. Furthermore, Abdelmalek Essaâdi University in Morocco was given a solar, grid, and battery microgrid [17]. The research team came to the conclusion that the suggested system design may meet the electrical load requirements with a COE as low as 0.187 USD/kWh, with solar PV being the major source of power.

In [18], a techno-economic study of a microgrid on the Madinah University campus was suggested. To choose the option with the least negative impact on the natural world as well as the economy, the scientists examined three distinct combinations of PV combined with wind energy. The results of the study showed that the photovoltaic (PV) system may offer a reduced COE of about 0.051 USD/kWh, with a payback period of 18.6 years, as well as might be regarded as a perfect microgrid construction configuration for present load demands and architectural restrictions. The contributors of [19] also thought about how to create the best possible microgrid in an urban university campus. The demand for load adjustment of grid-connected and isolated microgrid designs was examined by taking into account sources of energy such as solar power, wind, as well as batteries. In the end, the scientists came to the conclusion the connection to the grid architecture is better appropriate for the present-day load circumstances as well as can cut the COE in half as compared with the islanded design. Nevertheless, adding additional capabilities to the concept might make applying the suggested strategy more difficult [20].

The investigators performed a techno-economic study of a microgrid for a university campus that depends on PV and biomass electricity [35] in a study like this. To attain independence, Hybrid energy storage devices were also linked to this microgrid. According to the suggested approach, a combination of wind, biomass, and photovoltaic energy can fulfill the required load demands. Additionally, by incorporating hybrid battery packs, the system's self-sufficiency can be increased by up to 99%. They additionally came to the conclusion that the ideal system arrangement could produce extra energy to offset the university's thermal load. However, the planning process did not consider additional evaluations, including environmental and sensitivity tests.

Researchers in [36] conducted a feasibility analysis and designed a microgrid for KIIT University's Campus. They took into account wind as well as solar power sources as other sources of energy when creating the campus's microgrid construction. After conducting a study of sensitivity to evaluate the system's dependability, it emerged that the least economical and dependable arrangement for the microgrid was one that used solar and wind power. An ideal microgrid architecture was developed by researchers [37] in Saudi Arabia to implement renewable energy in the Yanbu region of the Kingdom. Using the Giza Pyramids Construction (GPC) optimization method and taking into account the COE and NPC as the primary socioeconomic criteria, the best possible design for the system was assessed. They concluded that a mixed microgrid powered by biomass and solar was the most effective and cheapest [38]. Table I shows the different types of renewable energy sources used in MG applications. When selecting technologies for communication, it is important to consider MG applications to provide reliable and affordable communication among MG components.

TABLE I. MG: ENVIRONMENTALLY FRIENDLY SYSTEMS FOR ENERGY

Ref	PV	Wind	Fuel cell	Biomass	Hydro	heat and power
[21]	✓	✓				
[22]	✓				✓	
[23]	✓	✓				✓
[24]	✓		✓			
[25]	✓		✓			
[26]		✓	✓			
[27]	✓	✓	✓			
[28]	✓	✓				✓
[29]	✓			✓	✓	
[30]	✓	✓		✓		
[31]	✓	✓	✓			✓
[32]	✓	✓	✓			
[33]	✓	✓				✓
[34]		✓		✓		

IV. METHODOLOGY

Microgrids are defined as "low-voltage and/or medium-voltage grids outfitted with supplementary facilities collecting and managing their own supply and demand-side resources, potentially also in the event of islanding, virtually independently." Fig. 6 depicts an MG device that includes power conversion devices (PCs), electricity consumers (loads), and distributed energy resources (DERs) such RESs, CGSs, and ESSs [39]. When in grid-connected mode, the MG system trades excess energy with the main grid for monetary compensation. The system is controlled by both local controllers (LCs) and a centralized controller. Efficient management and coordination of DERs in MG increases system efficiency and promotes equitable growth [40].

When connected to the grid, the Microgrid (MG) adds or withdraws electricity to match its capacity and load needs, while complying with market regulations and optimizing efficiency and cost. Similarly, it has the ability to disconnect from the main grid in the event of a failure while still providing electricity to linked important loads. The MG is outfitted with SCADA technology to provide dependable and cost-effective operation. The control system must efficiently manage all distributed energy resources (DERs) to ensure the microgrid's stable, dependable, and cost-effective functioning.

The intangible flow of a robust power management methodology for microgrids is simplified in Fig. 7, which begins with resilience control and disturbance identification, moves on to robust adaptive techniques, integrates AI and advanced technologies, and ends with evaluation, comparison, and continuous improvement.

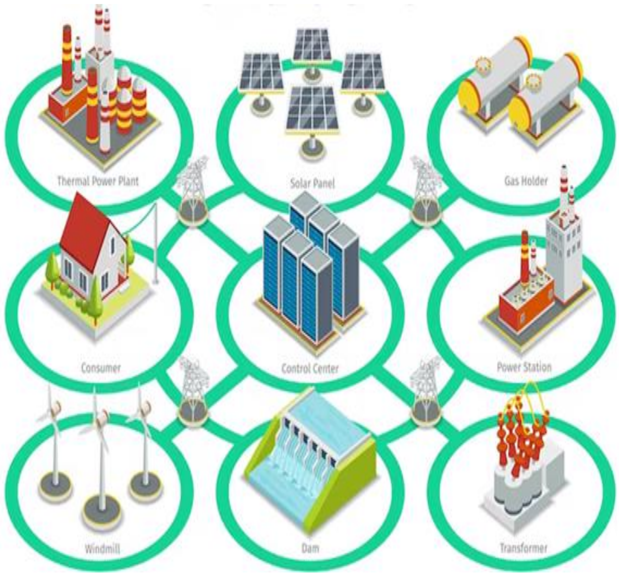

Fig. 6. MG general scheme

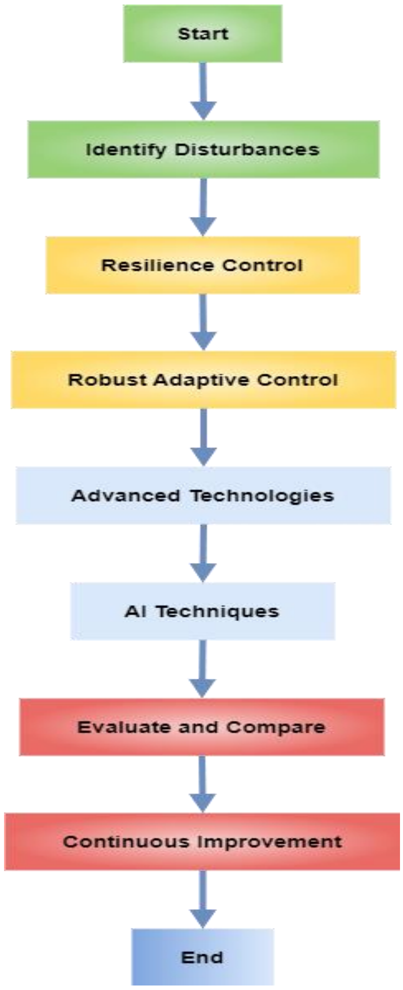

Fig. 7. A simplified flowchart of a robust power management methodology for microgrids

V. Proposed System Design

The system suggested in Fig. 6 combines solar and wind power with other renewable sources. While the solar system charges the battery, the conversion device operates in buck mode. When the battery is not receiving power, it operates in boosting mode to supply the entire network. Through a conversion device, a battery either injects or takes actual electricity. Typically, the battery packs are connected to the PV system via a parallel. Solar energy systems typically use lead-acid or lithium batteries for storage.

A. Intelligent Controller

Fig. 7 and Fig. 8 show two new suggested control strategies that are intended to provide an accurate response in the hybrid microgrid network throughout regular operation. Fig. 7 and Fig. 8 display two novel control strategies aimed at providing accurate responses in a hybrid microgrid system during regular operation. The purpose of this paper is to find the factor that has a significant impact on the voltage level of the DC connection. By identifying this factor, it will be possible to reduce the workload of the controller in regulating the DC-link voltage. This, in turn, will allow for the use of a lower controller gain while still maintaining system stability.

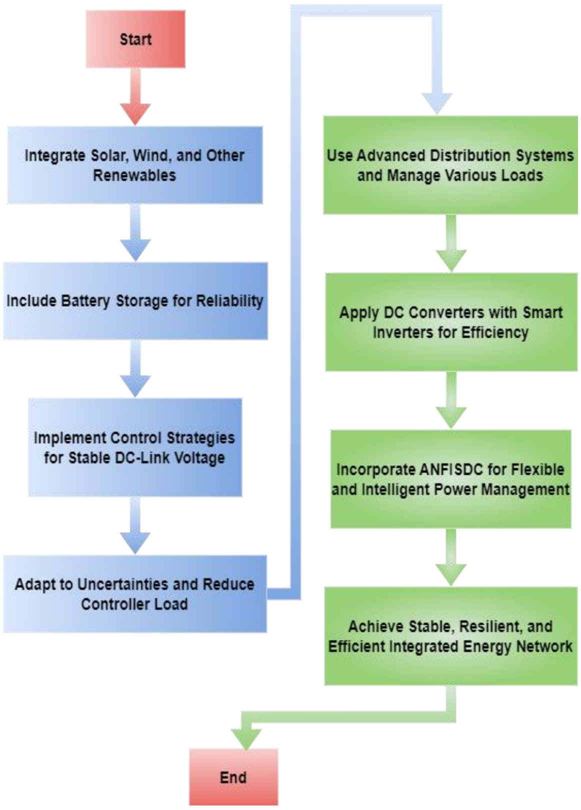

Fig. 8. Improves overall system efficiency and resilience, lessens controller strain, and adjusts to operational uncertainty

B. Energy Distribution System (EDS)

Quick and unforeseen variations in the distribution system's electrical usage can lead to oscillations in frequency as well as voltage, which can cause instability in the system. These days, advancements in technology, changes in business models, and evolving legislation have transformed the distribution system into a complex and interconnected network at various levels. This creates a network of interconnected hardware, software, and communication methods, often referred to as smarter grids [41][42]. EDS' high DER penetration improves network security and dependability, despite DERs' stochastic nature and impact on distribution network operations. When combined with undesired occurrences, these DERs could adversely affect grid efficiency; thus, EDS has to be able to adapt to these modifications in an efficient manner. This is known as short-term system resilience.

C. Renewable Power Sources

The increasing amount of distributed electricity produced from renewable energy sources (RESs) is posing an exciting opportunity for the electrical power systems industry. One of the primary disadvantages of electricity generation from various sources is its intermittent nature. To address this issue, networks are connected to battery storage and the electrical grid. This allows for greater usage of the fluctuating power supply from renewable energy sources [43]. These storage areas are necessary for a house or other dwelling to function properly. The differences between production and result power can be compensated for using either short- or long-term energy storage. Renewable Energy Sources (RES) use solar radiation in two ways: directly through solar cells, concentrators, and collectors, and indirectly through the power of wind turbines, marine power, and other sources. Renewable energy sources (RES) on Earth's surface are technological devices that gather energy that is available within a given range, transform it, and provide it to people for use.

D. Wind Power Sources

Utilizing the principles of aerodynamics, WT transforms wind power into mechanical strength that is then fed into the generator in order to produce electrical energy. Generators, gearboxes, power transformers, power electronics conversion devices, as well as rotors make up the majority of contemporary WTs. The two primary forms of WTs are vertical-axis and horizontal-axis WTs.On the other hand, a lot of horizontal direction WTs have been produced and put into place. The cubic power of wind speed determines how much electricity a wind turbine can generate. To get the most electricity possible out of WTs, MPPT techniques are applied.

The wind farm located in the San Gorgonio Pass in California has a capacity of 615 MW. In 2018, China had a wind energy capacity of 211.6 GW, making it the leading wind energy producer in the Asian and Pacific region. The country has established itself as one of the leading producers of wind energy globally. Its target is to achieve 250GW of wind capacity installed by 2020, which is in line with the federal government's objective of generating 15% of power from renewable sources by the same year. In addition, China aims to have 1,000GW of wind energy by 2050 and 400GW by 2030. By 2020, the Gansu Wind Farm Project reach to maximum power output of 20GW.

E. Load Configuration

Both household and business loads are included in the loads. Industrial loads, which means air conditioners, are displayed on asynchronous devices to illustrate how industrial inductive demands affect Microgrids. The resort island's daily non-seasonal consumption profile informs the construction of individual loads. The simulation of residential loads is based on the real variation in the particular load profile for the designated resort island.

F. DC Converters with Smart Inverters

Microgrids can be classified into three types based on the electricity and voltage they use: AC, DC, and hybrid. One advantage of the AC microgrid is its ability to consume main grid electricity. In an AC microgrid, the AC bus acts as the base. It connects to all power generation sources, such as wind turbines, via AC/AC power converters, regardless of voltage or frequency. Meanwhile, sources with DC output, such as solar panels, are connected to the AC bus via a DC/AC converter. In terms of system efficiency and size, the DC microgrid surpasses the AC microgrid. This benefit also applies to operational costs and investment. The DC system requires fewer power converters, resulting in smaller sizes and better performance. However, the DC transmission protection mechanism is not as advanced as that of the AC structure. To develop future electrical systems, it is essential to investigate various elements such as the system structure, stabilization methods, control schemes, and security systems. A hybrid microgrid, which has both AC and DC buses, has the capacity to power both AC and DC loads.

VI. SIMULATION RESULTS AND ANALYSIS

The proposal system design is building by using Matlab/Simulink, which corresponds to the system configuration and parameters displayed in Fig. 9. Primary recovery, voltage, and frequency are provided by secondary control. The final step in droop control is fuzzy base the droop parameter adjustment. Two different droop control strategies are used in the first simulation to accomplish responsible and balanced power sharing through frequency regulation. To make the simulation more manageable, RES is represented as a change in DC power; specific statistics are displayed in Table II. In the second simulated scenario, a traditional power unit and a renewable energy source (RES) unit photovoltaic or wind energy are paralleled to produce a variable load.

Information on wind power generation is based on accurate data from Wind Farm HaoGuanying and other sources. The photovoltaic power plant in China's Liaoning Province is the source of the energy. Except for the rated electrical capacity, Table II controller parameters and architecture are identical in simulation Case 2. For the purpose of showcasing the effectiveness of the recommended control strategy, a simulated test was performed on a microgrid consisting of battery and photovoltaic modules using Matlab/Simulink. The variables used in the simulation are listed in Table II.

A wind energy system consists of a multipole synchronous generator and an electronically controlled turbine for wind power. The rectifier helps convert the three-phase voltage output into DC voltage. In order to keep the rectified DC voltage steady even when it fluctuates, the rectifier output is connected to a DC-DC buck-boost converter. Even though the converted DC voltage varies, the rectifier's final voltage doesn't change since the voltage it produces is linked to a DC-DC buck-boost converter. Using MPPT technology, the maximum power of the converter was successfully calculated by calculating the ratio of efficiency to turbine speed, The detailed simulation of wind energy system is presented with Fig. 10 and Fig. 11.

SAPF injects the correcting voltage concurrently with the voltage supply using a series injection transformer. The DC-link voltage generating process utilizing solar power (PV) and wind energy (WE) systems is depicted. The quantity of energy present in the DC-link has a significant impact on the compensation of the SAPF inverter, which uses a VSI composed of semiconductors and DC-link capacitors. This makes it possible to set the capacitor linked to the DC voltage reference value. The detail simulation is presented in Fig. 10, The ratio of power between the load being operated and the source may alter as a result of changes in the load scenario.

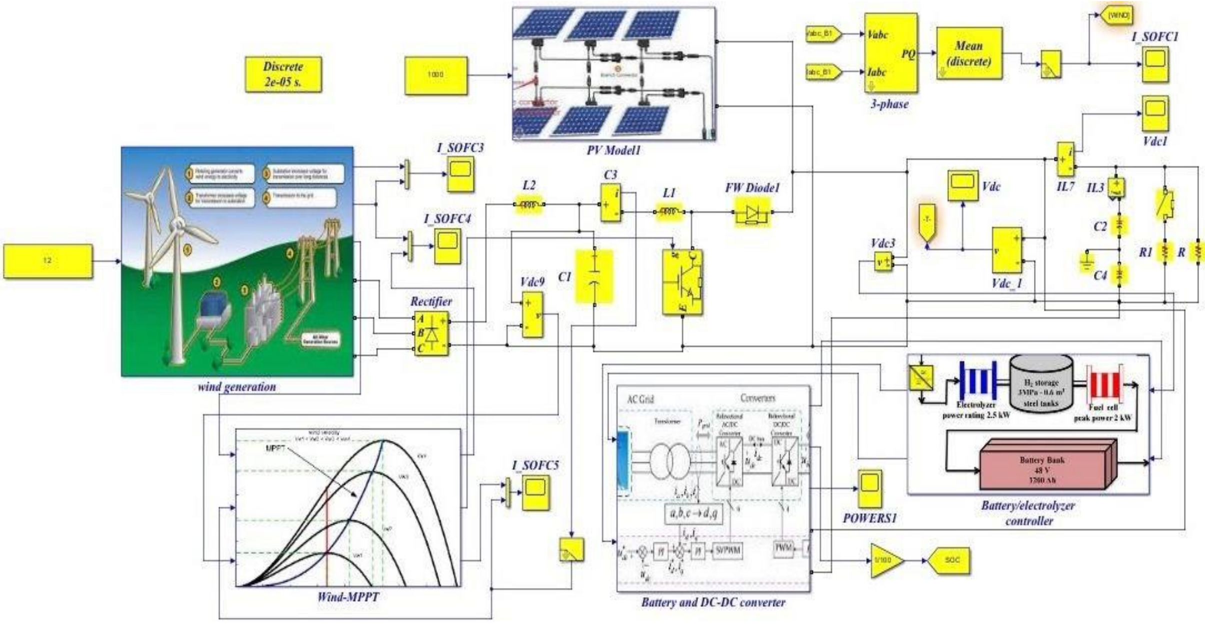

Fig. 9. Simulation diagram of proposal design of microgrid system

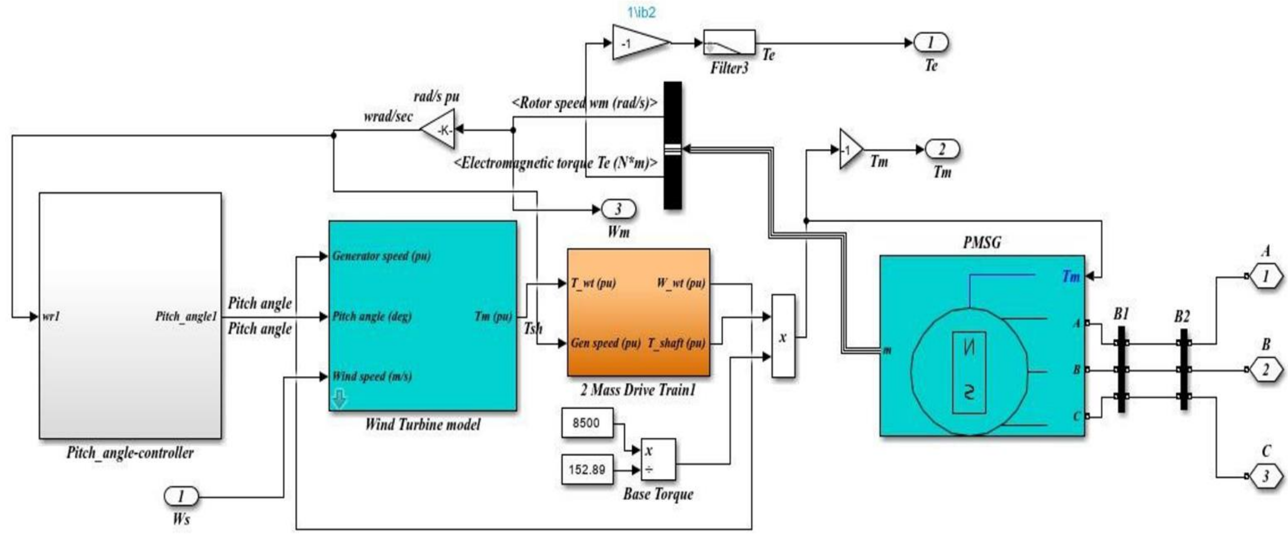

Fig. 10. Simulation diagram of wind energy system

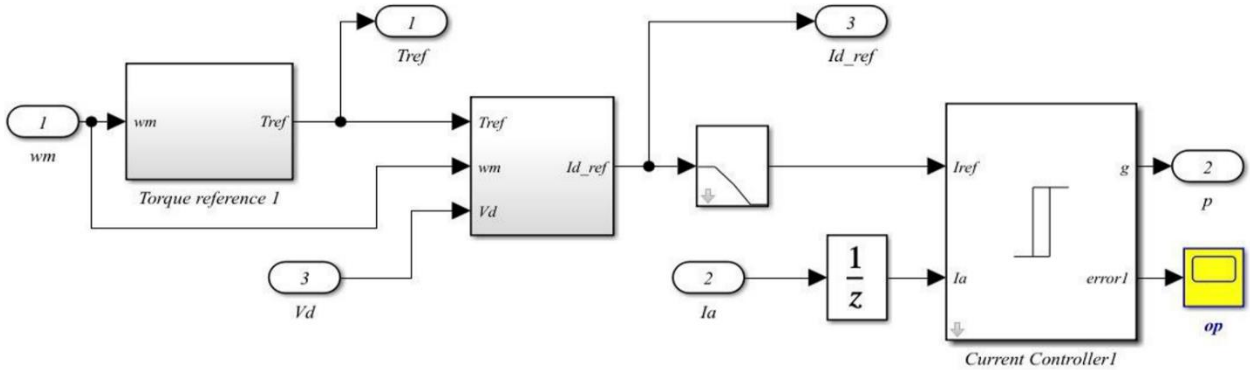

Fig. 11. The Simulation Diagram of MPPT with Current Controller

TABLE II. THE MICROGRID PARAMETERS OF PROPOSAL SYSTEM. DESIGN

Microgrid Parameters		**Primary Control Parameters**	
RES1	20 kW	mp1	2.18e-5
RES2	20 kW	mp2	2.18e-5
ZLinel	0.2 + j0.0006 Ω	pil, Kpr1	1, 100
ZLine2	0.175+j0.00095 Ω	Kpi2, Kpr2	50, 500
L, C	1.8 mH, 50 μF	Rvi, Lvi	0.12, 1.8e-3 mH
Rated Frequency	60 Hz	**Secondary Control Parameters**	
Rated voltage	208 V	KPf, KiF	0.5e-3, 0.1
		KPE, KIE	0.1e-3, 0.11

The input and output information set is utilized for training ANFIS once the ANFIS-based droop regulation model has been implemented. The droop controller is made up of input data, such as active and reactive electrical power, and output information such as frequency and voltage intensity independently. Two ANFIS circuits are separately implemented to manage the frequency and voltage outputs in order to ensure smooth operations. Furthermore, ANFIS can only function with multiple-input-single-output (MISO) signals. The system creates and stores an input-output dataset, from which related ANFIS models are created and trained. The fault tolerance thresholds are assessed following ANFIS's ongoing training and the minimal training RMSE result indicates that The ANFIS algorithm has been taught successfully. The output of wind part of microgrid at low power presents in Fig. 12.

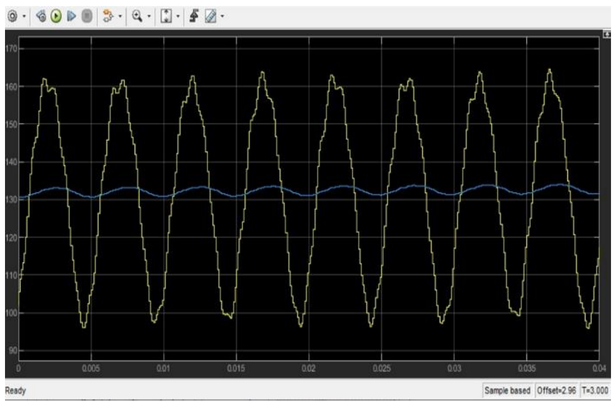

Fig. 12. Zoom in for the output of wind part of microgrid

A distribution transformer is responsible for connecting a home to the electrical grid. The home energy management system is designed to feed any excess electricity generated by the solar or wind system into the electrical network. Additionally, if the production of power from the solar or wind system is not enough, the system can provide electricity to the home energy management system. A DC-to-AC inverter, which transfers power between the energy control system of the house and the power grid, operates in one direction. The solar power plant is allowed to operate at its standard test conditions, which include a working radiation of 1000 w/m2 and a temperature of 25C. The output of MPPT unit presents in Fig. 13.

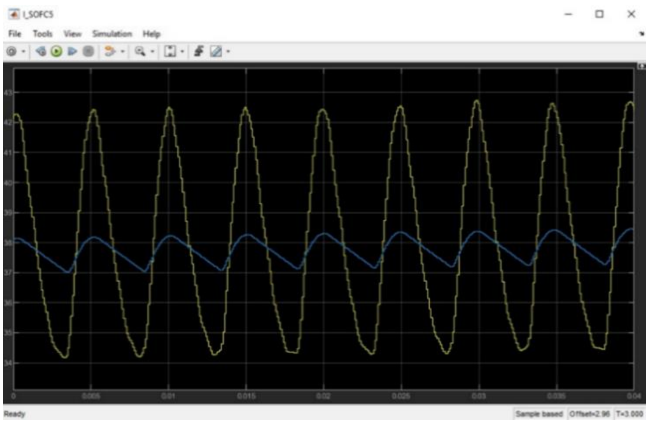

Fig. 13. The MPPT unit output with zoom in to explain the stability in output

With an unbalanced load, the ultimate output voltages (see Fig. 13) are regarded as balanced. It is implemented for different system voltages and load situations. In this scenario, tests are conducted on the single-phase load linked between two phases to see if the load voltage is imbalanced. Using the voltage that was measured prior to compensation, the controller establishes the reference compensating voltage for the hybrid capacitor. Phase angle jumps and voltage imbalances must be appropriately identified in order to calculate the current and voltage that is injected through the SAPF. This is to make up for phase angle and voltage imbalances.

For varying system voltages and load situations, unbalanced voltage is applied in conjunction with unbalanced load. The system performance is assessed under asymmetrical voltages and unbalanced loads. Third Test Case. It is assumed that the load with system voltages is identical. Not in this test situation balanced. In order to verify this state, the system It is necessary to generate the voltage using fifth and seventh-order harmonics. On a single-phase load, the load is supposed to be operated as unbalanced. Precise voltage measurements are transmitted to the controller because of the imbalance in voltage between the power supply and the load. Te p-q, which is based on ANFIS, determines the necessary voltage. It is delivered to the repetition controller to generate the required gating signal in order to obtain compensation. For varying system voltages and load situations, unbalanced voltage is applied in conjunction with unbalanced load. The system performance is assessed under asymmetrical voltages and unbalanced loads.

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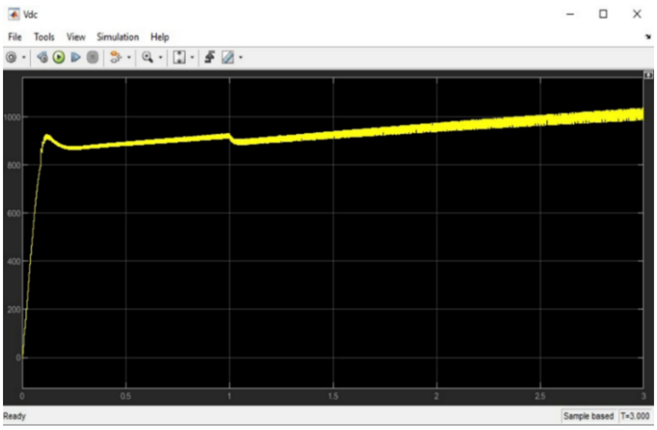

Fig. 14. The overall testing for proposed system design based on different testing cases

In conclusion, thorough assessment of the hybrid microgrid's dynamic response to changing load scenarios and droop-based control techniques is shown in Fig. 15. This figure demonstrates how the system can adjust to real-time variations in generation and demand while maintaining steady operation, achieving balanced power sharing, and guaranteeing strong frequency regulation.

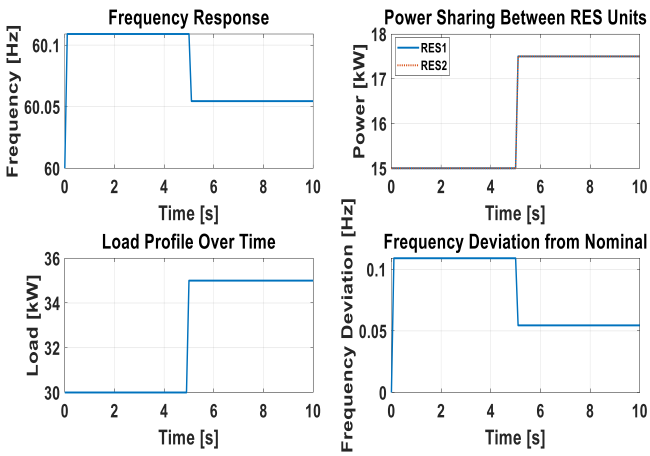

Fig. 15. Comprehensive evaluation of the hybrid microgrid's dynamic response under varying load conditions and droop-based control strategies

Fig. 16 provides a comprehensive view of the MPPT-controlled PV output, showcasing both the transient and steady-state phases of operation. The top subplot presents the full simulation timeline, starting from initial ramp-up as the MPPT algorithm identifies and converges toward the maximum power point. During this period, the power output gradually increases until it stabilizes, reflecting the algorithm's effectiveness in tracking the optimum operating condition. The bottom subplot zooms in on the 3–5 second interval, where the system has already reached a steady-state. Within this closer view, the output power exhibits only minor oscillations around its nominal setpoint, demonstrating that the MPPT strategy has successfully settled. The resulting steady, reliable power level confirms the controller's capability to maintain efficient and stable performance after the initial transient phase.

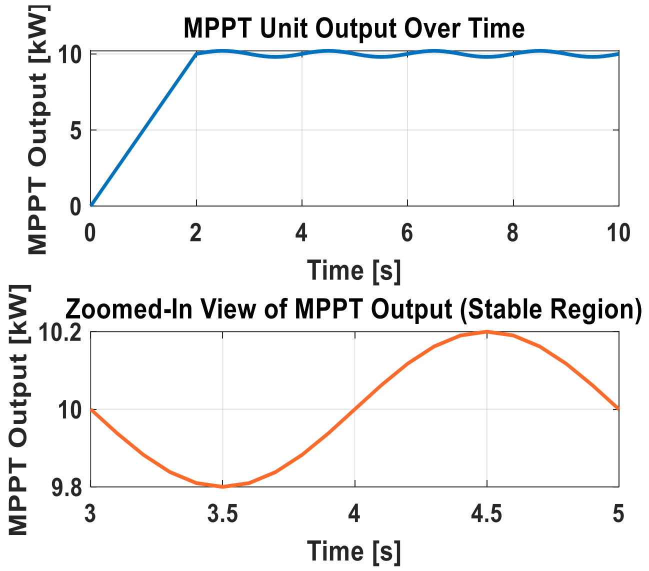

Fig. 16. Comprehensive view of the MPPT-controlled PV output

VII. CONCLUSIONS

MG systems should incorporate several features, including power quality, cybersecurity, supplementary services, transition mode capabilities, protective systems, and energy management, because of their connectivity to the main grid and continuous digitization. Fortunately, norms and guidelines for specific MG tasks are in place or being developed, they are not currently available for all important MG functions. Furthermore, clarification is required for functionality-level benchmarking, and system-level MG benchmarking remains to be established. The literature does not agree on performance measures or standards-derived requirements. To improve things, we discussed and highlighted the following topics: Testing takes into account the key aspects of MG, relevant standards, and current system-level MG designs. Specific cybersecurity requirements and evaluation standards impacted local resource use and dependability inside MG. Potential breakthroughs in functional and system-level MG testing, as well as existing restrictions.

This study can be used as a guide to begin benchmarking both at the system and functionality levels of MG. We anticipate that this article will support the demand for improved and stronger standardization within the MG network level, together with globally specified MG structures for testing that enable benchmarking.

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