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Design and implementation of Hybrid Renewable energy (PV/Wind/Diesel/Battery) Microgrids for rural areas

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ABSTRACT

This study examines the variation in sensitivity of a microgrid system comprised of photovoltaics, wind turbines, diesel engines, and batteries. The primary objective is to increase our knowledge of renewable energy resources (RERs) and their technical and economic factors in the context of the conceptual design of a microgrid system. The investigation employs Typhoon HIL software for simulation and testing, concentrating on hybrid PV/Wind/Diesel/Battery systems and devising a perturb & observe (P&O) maximum power point tracking (MPPT) strategy. Additionally, the study investigates the Optimal Power Controlling MPPT technique and the development and implementation of hybrid renewable energy resources (HRES).

The Typhoon HIL system is utilised in the power, automotive, and aerospace industries, among others, to simulate and test control systems in real-time. This study presents a control strategy for a microgrid system that combines renewable energy sources such as solar and wind power with reserve power options such as diesel generators and batteries. The coordinated control technique is implemented by employing a centralized control method, effectively managing the flow of electricity from diverse distributed energy resources (DER) and ensuring the microgrid's stability. The findings indicated that the coordinated control method and dynamic models could be utilised to design and optimize microgrid systems. Future research can concentrate on refining the accuracy of the models and verifying the proposed coordinated control method in microgrid systems that operate in the real world.

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تصميم وتنفيذ شبكات الطاقة الهجينة المتجددة
(الكهروضوئية/طاقة الرياح/الديزل/البطاريات) للمناطق الريفية

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ملخص: تهدف هذه الدراسة إلى استطلاع التباين في حساسية نظام الشبكة الصغيرة المكون من الخلايا الكهروضوئية، وأجهزة توليد الرياح، والمحركات الديزلية، والبطاريات. الهدف الرئيسي هو زيادة معرفتنا بمصادر الطاقة المتجددة وعواملها التقنية والاقتصادية في سياق التصميم المفهومي لنظام الشبكة الصغيرة. تعتمد هذه الدراسة على استخدام برنامج(Typhoon HIL) للمحاكاة والاختبار، مع التركيز على نظم الخلايا الكهروضوئية/الرياح/الديزل/البطاريات الهجينة، ووضع استراتيجية تعقب نقطة أقصى قدرة باستخدام طريقة الاضطراب والمراقبة (O&P). بالإضافة إلى ذلك، تبحث هذه الدراسة في تقنية التحكم المثلى في تعقب نقطة أقصى القدرة وفي تطوير وتنفيذ مصادر الطاقة المتجددة الهجينة (HRES). يُستخدم نظام (Typhoon HIL) في صناعات الطاقة والسيارات والفضاء، وغيرها، لمحاكاة واختبار أنظمة التحكم في الوقت الحقيقي. تقدم هذه الدراسة استراتيجية تحكم لنظام الشبكة الصغيرة يجمع بين مصادر الطاقة المتجددة مثل الطاقة الشمسية وطاقة الرياح مع خيارات الطاقة الاحتياطية مثل مولدات الديزل والبطاريات. يتم تنفيذ تقنية التحكم المنسق باستخدام طريقة التحكم المركزي، لإدارة تدفق الكهرباء من مصادر الطاقة الموزعة المتنوعة وضمان استقرار الشبكة الصغيرة. أشارت النتائج إلى إمكانية استخدام تقنية التحكم المنسق والنماذج الديناميكية في تصميم وتحسين أنظمة الشبكات الصغيرة. يمكن أن تركز الأبحاث المستقبلية على تحسين دقة النماذج والتحقق من طريقة التحكم المنسقة المقترحة في أنظمة الشبكات الصغيرة التي تعمل في العالم الحقيقي.

1. INTRODUCTION

Approximately 13% of the global population lacks access to electricity due to economic constraints, high population density, and geographical remoteness. This assertion is significant in sub-Saharan Africa and South Asia [1]. Diesel and kerosene are fossil fuel varieties employed for fulfilling energy requirements; nonetheless, their utilization is accompanied by certain disadvantages, rendering them less desirable alternatives. The increasing global need for energy has driven the development of conventional power plants. Nevertheless, these power plants are associated with environmental and health hazards due to their dependence on fossil fuels, which also contribute to the accumulation of greenhouse gases [2].

Microgrids (MGs) play a critical role in the electrical network by helping to manage the challenges posed by rapid energy demand growth. As a result, the design of MGs has become a primary focus for academics and engineers. Ensuring that MGs are designed effectively is essential to meeting energy demands and maintaining the electrical grid's stability [3]. The daily increase in energy consumption can be attributed to the growing human population, which drives energy demand. As urbanization and industrialization continue to spread, energy becomes an essential factor in improving the lives of both urban and rural residents. However, the depletion of fossil fuel reserves and the rising cost of these resources have necessitated the adoption of renewable energy sources, also known as alternative energy sources [1], [4]. Solar and wind energy are among the most frequently utilised sources, and their increased demand has led to the development of hybrid systems that incorporate two or more generation units and an energy storage system or fossil fuel generator for backup during peak demand hours. Such hybrid systems offer a reliable and sustainable solution to meet energy demands in both urban and rural areas [4]–[6].

To combat climate change and mitigate its associated risks, adopting renewable energy sources plays a pivotal role in attaining a state where greenhouse gas emissions are effectively balanced at zero. Because of its cleanliness, abundance, and reliability, solar energy has rapidly emerged as the preeminent choice for power generation, surpassing all other alternatives [7]. Despite abundant renewable energy sources on certain islands, rural communities experience significant electricity shortages. In recent years, there have been notable advancements in power electronics, which have facilitated using renewable energy sources (RES) to deliver cost-effective electricity for various applications [4], [6], [8], [9]. The relatively high specific cost of generated units from RES is a significant barrier to the broad adoption of these sources. Including a diverse range of renewable resources in the energy mix and implementing energy storage devices is important owing to the inherent intermittency of nearly all renewable sources [10]. The depletion of conventional energy sources has led to an increasing need for renewable alternatives such as wind and solar power. The objective of a hybrid energy system is to enhance overall system efficiency and provide a balanced energy supply by integrating diverse sources of renewable energy [11], [12]. The investigation of microgrid power systems, which integrate photovoltaic and wind energy in hybrid arrangements alongside diesel generators, is being conducted to assess their potential utility and economic viability as an energy source. These systems have various Maximum Power Point Tracking (MPPT) techniques, such as Perturb & Observe (P&O) [13]–[16].

The P&O methodology is widely employed as the predominant type of MPPT in photovoltaic (PV) systems. Despite being subjected to steady-state illumination, these approaches possess inherent limitations, including the production of oscillations around the MPPT [14]. In terms of both efficiency and accuracy, the Incremental Conductance (INC) technique outperforms the P&O method. However, it is worth noting that the regulating circuit of the INC approach is comparatively more intricate. The buck converter is a specific type of DC-DC converter topology. The direct application of the MPPT controller to the converter duty cycle enables the efficient algorithmic modulation of the operational voltage of the solar array [17], [18]. MPPT algorithms are primarily designed to tackle the challenge of continuously looking for the optimal power output. Integrating many panels into a larger system through a single MPPT controller demonstrates effective functionality. This approach optimizes array efficiency and minimizes the overall system cost by enabling the converter circuit to extract the highest power achievable from a cell [16], [19].

To mitigate the occurrence of equipment failure and the subsequent rise in installation costs, implementing an MPPT controller might be employed as a short-term solution. The MPPT controller is an attractive option since incorporating more solar panels necessitates an upfront expenditure of 30-50% of the overall system cost, even when equipped with an appropriate charge controller. Implementing an MPPT, a power electronic device, represents a highly viable approach to enhance the overall efficiency of a solar panel system. Various solutions, such as wind, PV, battery, and diesel systems, can optimize power generation and reduce costs [6], [20].

The concept of microgrids was initially introduced in a scholarly investigation by [21], which proposed its use to effectively address customers' energy requirements by integrating multiple energy sources. The rising popularity of small-scale energy production devices is anticipated to enhance global power capacity and facilitate the integration of renewable energy sources into the existing system. Microgrids offer a viable solution for addressing the challenges of integrating renewable energy sources by establishing a localized electric grid incorporating distributed energy generating and energy storage devices [22]. Various countries are currently engaged in the research and development of microgrids that rely on renewable energy sources. These nations have implemented programs to facilitate the establishment of local energy communities to cater to the energy needs of these regions. To address the need for enhancing the civil dimension of energy at a local level, Poland has implemented an energy cooperative to bridge this gap. Aligned with the energy development policy of the EU [23], the primary objective of this collaborative initiative is to enhance the efficacy of utilizing renewable energy sources in rural regions while addressing the issue of electrification.

Hence, the principal aim of the microgrid is to provide electricity in a reliable and economically efficient manner. The distribution and administration of electricity within the microgrid is facilitated by an advanced energy management system (AEMS). Various optimization procedures have been employed in recent academic studies to enhance the efficiency of microgrids [24]. These studies have investigated energy sustainability, demand response techniques, control systems, and energy management systems [25]. Multi-energy microgrids (MGs) are equipped with an EMS that effectively reduces operational costs and enhances energy utilization efficiency [26]. Generating units, which include naturally aspirated engines and wind turbines, are classified as non-renewable energy sources. On the other hand, RES encompass biomass, PV systems, wind turbines and fuel cells, all of which fall under the category of distributed generation [27].

This paper highlights significant contributions to designing an AC microgrid suitable for rural areas, particularly the control strategy that the system utilizes. However, this study contributes to the existing body of knowledge by investigating the sensitivity variation of a microgrid system incorporating photovoltaics, wind turbines, diesel engines, and batteries. The primary objective of this study is to enhance our comprehension of Renewable Energy Resources (RERs) and their pertinent technical and economic factors in the context of the conceptual development of a microgrid system. Additionally, the study team intends to perform a sensitivity analysis on the microgrid system based on the P&O MPPT algorithm. Typhoon Hardware-in-the-Loop (HIL) will be employed for simulation and testing inside the inquiry. Within the realm of mini-grids, the primary emphasis of this study is on HRESs, which are periodically supplemented by diesel generators as a contingency measure. This study examines the literature on HRESs, specifically emphasizing the valuable insights gained through implementing mini-grids in places characterized by underdevelopment. This paper presents a fresh contribution consisting of comprehensive recommendations to optimize the power generation derived from solar systems, wind turbines, diesel generators, and battery storage technologies. Hence, this research study's contributions encompass examining multiple MPPT techniques for a hybrid PV/Wind/Diesel/Battery system and developing an O&P MPPT approach. This study also examines the Optimal Power Controlling MPPT technique and the development and implementation of HRES.

Given that numerous developing countries are in the early stages of implementing HRES, this research is relevant to address their specific requirements. A comprehensive understanding of the key aspects that contribute to the success or failure of such systems is of utmost importance. The study confirms that the system can deliver considerable power to consumers. The remaining sections of this article are organized as follows: Section 2 covers the details of the research site and available data. Section 3 presents the modelling techniques used, while Section 4 provides information on the distributed control system and its architecture. In Section 5, the study's findings are discussed, analyzed, and interpreted, and Section 6 offers a summary.

2. BACKGROUND

The traditional power grid depends on large synchronous generators for unidirectional electricity generation. The massive deployment of renewable energy sources presents challenges, as evidenced by grid-based energy storage devices [28]. Power electronic-based distributed generator system components face common obstacles such as energy storage, voltage regulation, and state of charge management; as the number of decentralized sources, such as solar PV and wind integration, the control issues become more complicated. Various techniques have been developed to address these challenges, including decentralized, centralized, distributed, hierarchical, and consensus-based solutions [29].

The evaluation and classification of the advancement of the hybrid storage system over the past two decades, from its conception to the latest research discoveries in the field, have been conducted [30]. In the context of isolated microgrids characterized by variable electrical profiles, utilizing a hybrid energy storage system (ESS) comprising both lead-acid batteries and supercapacitors presents a compelling approach to address the issue of swift battery discharge. In [31], a novel control method, a new battery deterioration model, and an economic viability analysis are presented. In addition, microgrid management and control using PV panels, batteries, supercapacitors, and DC loads in the presence of variable solar radiation are proposed in [32].

The mitigation of power quality issues, specifically voltage variations resulting from integrating renewable energy sources into the grid, can be achieved using an innovative electric power device known as an electric spring (ES), as outlined in the study referenced in [33]. The concept of over-speed-while-storing control, as described in reference [34], is a novel approach to coordinated control in permanent magnet synchronous generator (PMSG)-based wind turbine generators (WTGs). This control strategy involves adjusting the rotor speed to mitigate the machine-side converter's input power (MSC) during minor voltage sags. In the event of a significant decrease in voltage, the coordinated control system decelerates the rotor to maximize energy preservation from the input of the MSC. Surplus power is stored within a supercapacitor energy system (SCES) to mitigate peak demand. Using alternating current (AC) or direct current (DC) can provide power to a microgrid. To establish a connection with AC microgrid lines, energy sources that produce DC electricity, such as solar panels and fuel cells, will necessitate the process of DC-AC conversion. AC-DC-AC inverters are essential for achieving higher synchronization with the grid when harnessing power from AC-generating sources such as wind, hydro, and geothermal.

Model predictive control (MPC), initially called Receding Horizon Control (RHC), was developed throughout the 1960s and 1970s to implement control applications within the chemical industry. The approach above to regulating was soon adopted within scientific and academic circles, garnering significant acceptance. As a result, numerous scholarly literature [35] have extensively characterized and contrasted different types of predictive controllers. Predictive controllers have gained significant popularity due to MPC's ease of understanding and effectiveness in constraint-based systems. Predictive controllers achieve the transmission of the appropriate control signal to the converter and ensure the desired behavior of the system by minimizing the cost function. To minimize the cost function, MPC transmits control signals to the converter at regular intervals, as stated in reference [36].

MPC significantly impacts the efficacy and reliability of microgrids. Hence, further investigation was conducted on supplementary control approaches in conjunction with MPC-based control structures [37].

The transition from brown energy technologies (BETs) to green energy technologies (GETs) is imperative because around 12.3% of the global population lacks access to electricity. Approximately 79.9% and 2.2% of global power production are derived from nuclear and fossil fuel sources. In contrast, modern renewable and traditional biomass sources provide approximately 11% and 6.9% of the energy mix, respectively [2], [9]. The substantial expenses associated with operating traditional power plants, the resultant environmental degradation, and the inherent instability in fossil fuel costs collectively lead to significant environmental and economic challenges. The ability to promote rural electrification through renewable energy resources (RERs) has been facilitated by cost reductions, potentially resulting from advancements in crucial technologies [4], [19].

The difficulty faced by rural areas in connecting to the utility grid is primarily attributed to several factors, including the distances from existing transmission and distribution (T&D)

infrastructures, the presence of steep topography, low population density, and low load demand. These factors collectively contribute to both the economies of scale and technological obstacles that hinder the integration of rural areas into the utility grid [38], [39]. Consequently, individuals worldwide are increasingly migrating from rural areas to urban centers, resulting in a decline in general living conditions and a deceleration in urbanization. This paper proposes and develops a microgrid system incorporating photovoltaic, wind, diesel, and battery technologies based on analyzing the techno-economic advantages of RERs. Implementing a microgrid system that effectively utilizes various resources can lead to several benefits, including a dependable power supply, reduced emissions, and decreased fuel expenses [7], [40]. This research study establishes a standard by which the financial and ecological performance of various microgrid systems can be assessed.

3. LITERATURE REVIEW

As exemplified in the study conducted by the authors [41], a novel DC microgrid technology has been proposed, enabling electricity provision to remote locations not connected to the main power grid. The design of this system was specifically tailored to cater to the needs of remote and rural locations, hence incorporating modularity, portability, and adaptability as its key features. The combination of DC-interfaced points can be achieved without synchronization, a capability not present in AC-interfaced points. Nevertheless, a hybrid energy system was developed and optimized to meet the load demand at the most cost-effective level by including wind turbines, PV panels, biomass, and pump-hydro-storage technologies. We used hourly wind, radiation, and temperature data to compare the existing and hybrid PV/WT/biomass/battery-storage systems, evaluating their respective cost, environmental impact, and efficiency [42]. In [43], [44], the ideal capacity of a hybrid PV/Wind/PHS power system for an urban community was determined using an optimization process. The planned system comprises a 28 MWh PHS, a 5 MW wind farm, and a 1 MWp solar PV array. The system meets 85% of the energy needs of the load with renewable energy, mostly wind and solar, with the PHS covering the remaining 15%. Considering the inconsistencies of wind turbines, photovoltaics, and the load, an optimal scheduling method for microgrids with battery energy storage systems is proposed to address the stochastic unit commitment issue [45]. This approach aimed to reduce the microgrid's total operation cost, focusing on operation scheduling and reducing BESS life deterioration. [46] conducted a study to determine the required power and BESS capacity for maximum shaving performance. Suppose the grid operator implements this study's peak power management techniques. In that case, it may enable them to offer grid flexibility services, including frequency and voltage regulation and demand response capabilities. These features could enable business owners to implement peak shaving strategies and generate additional revenue through BESS applications.

Using renewable energy sources to power autonomous microgrids is increasingly emerging as a feasible alternative for places not connected to the main power grid, such as islands. The construction of a microgrid necessitates considering various elements, encompassing technology advancements, economic feasibility, and environmental impacts, per pertinent local regulations and legislation. A recent case study supports considering site-specific characteristics and power system conditions when constructing effective microgrids [24], [47]. To optimize the microgrid's performance, it is vital to have the necessary electrical and control infrastructure and devices in place. Most distributed generating sources establish a connection with the electrical grid through electronic power converters. Ensuring these converters effectively uphold economic performance [17], [47].

As previously stated, microgrids are decentralized networks of generation, transmission, and distribution infrastructure that can operate in conjunction with the conventional grid or independently in "island mode" or "off-grid" scenarios. Traditional energy systems are now integrating renewable sources such as solar photovoltaics, wind electricity, and hydropower, which are experiencing a growing prevalence [48]. The presence of interactions among units is a crucial aspect of distributed control approaches, alongside the distribution of control tasks to units, which must consider the operation across several time scales. The increasing demand for distributed solutions can be attributed to the heightened emphasis on security and dependability [49]. In this context, the control hierarchy technique plays a pivotal role as a fundamental component of this progress.

A distributed control system (DCS), a decentralized control system, is a computerized control system employed to manage a process within a plant, typically consisting of numerous control loops where autonomous controllers are dispersed throughout the system. The system is process-oriented and uses closed-loop control, with the initial control level being responsible for ensuring the tracking of voltage and frequency set points, as well as power-sharing and output control, due to its fast response time [50]. Moreover, subsequent changes to the system controller modes are based on this control level, which depends on locally measured signals.

Various optimization methodologies have been extensively discussed in the existing literature to achieve the most effective arrangement of hybrid renewable energy systems. This study focuses on hybrid renewable energy microgrids. Such a project has successfully reduced energy costs for a hybrid PV/wind/diesel/battery storage system by employing particle swarm optimization. This technique was utilized to ascertain the optimal system size and operational approach over the project's lifespan [6], [9], [11], [17], [40].

Grid-connected photovoltaic inverters primarily use MPPT techniques to optimize the power output from their PV modules [51]. P&O algorithms have gained popularity because of their versatility in accommodating PV arrays of varying sizes and their generally effective performance across a wide range of scenarios [20], [52]. The optimization of solar panel systems entails the utilization of the buck-boost converter as an impedance matching device, alongside implementing the P&O and constant duty cycle methods. According to certain research, using MPPT control approaches, such as P&O, has demonstrated the potential to enhance solar energy conversion efficiency in PV systems. These techniques can achieve efficiency levels as high as 98% under average insolation conditions [53], [54].

The proposed approach involves utilizing INC as the basis for MPPT techniques. This method aims to establish the operating point of the maximum power point (MPP) by making adaptive voltage step alterations based on the slope of the hybrid curve [15], [18]. These techniques facilitate the prompt adjustment of PV systems to dynamic environmental circumstances, augmenting the capacity to harness solar energy. Implementing the INC technique requires minimal work and does not necessitate a comprehensive understanding of the I-V characteristics of each particular PV panel. This solution's exorbitant cost and intricate nature challenge its implementation [16], [55].

The modulation of power from PV arrays can be achieved with a high degree of ease and precision by utilizing the P&O MTTP Algorithm. The MPP is adjusted to coincide with the operating point of the PV array. The response time of the algorithm is affected by atmospheric changes, resulting in a decrease in its efficiency. However, efforts have been made to improve the system's performance by reducing oscillations in steady-state conditions [13], [56]. [17] indicates that the utilization of the biological swarm implementing the P&O MPPT algorithm has the potential to enhance MPPT performance by 12.19 per cent during transient states, owing to its heightened efficiency. The ANN-based MPPT 2-stage method allows for maximum power point tracking to be performed without considering time increments. The proposed method can estimate several factors, including light intensity, temperature, and battery junction temperature, which impact battery power. Moreover, it performs faster than traditional Incremental Conductance and P&O controllers [20], [54].

Fuzzy logic controllers, specifically those used for MPPT, utilize the principles of fuzzy set theory to establish a correspondence between the input and output domains. DC-DC converters have been employed to measure the maximum power in PV systems across various environmental conditions [20], [57]. The IPSO-based MPPT controller approach enhances the efficacy of solar systems by accurately forecasting the I-V and P-V characteristics curves in scenarios with partial shadowing. DC-DC converters, distributed MPPT, low power consumption MPPT for battery charging, and variable intermittent current charging are various approaches utilized in grid-connected systems to enhance the efficiency and performance of PV systems through effective and dependable charging management [40], [57].

4. METHODOLOGY

This section describes the methodology employed in this study, which involved utilizing the Typhoon HIL software for simulation and testing purposes. The presence of power electronics and diverse time constants exacerbates the complexity of microgrid modelling. Simulation tools that utilize HIL technology, such as Typhoon HIL, provide a dependable setting for designing and testing intricate embedded systems [57]. The instruments have been designed to handle very small-time intervals effectively, enabling real-time modelling of inverter performance across a wide range of frequencies. Mitigated risks associated with microgrid installation can be achieved by establishing a connection between the virtual network and operational control hardware and carefully adjusting its operation [39].

TYPHOON HIL is hardware-in-the-loop testing software that allows testing control systems in real time. It is used in various industries, including power, automotive, and aerospace. The proposed energy storage system was designed with an algorithm that continuously monitors and controlling load sharing among various sources. To achieve this, a distributed control system was implemented using the API Typhoon HIL due to its robustness and efficiency. This approach facilitated load sharing among the energy sources in the system, thereby improving its overall performance.

The HIL implementation of HRES utilized a Typhoon HIL. The mechanical components of the system were implemented using Typhoon HIL. To establish the several devices' functionality and oversee the testing board's monitoring, a personal computer (PC) was employed as the host platform. Typhoon HIL's primary focus revolves around the examination and authentication of power electronics through the provision of products and resources. In this investigation, the utilization of the Typhoon HIL system was implemented. The Typhoon HIL system connects to the host's personal computer (PC) using a USB port. The Typhoon HIL Schematic Editor and the HIL SCADA are the main tools utilized in the Typhoon HIL system [58]. These tools can be accessible via the Typhoon HIL Control Centre. Python can be utilized to create automated tests, employing tools such as the Typhoon Test Integrated Development Environment (IDE) and Script editor to verify the models' precision. The Typhoon HIL Schematic Editor facilitates the compilation and loading of the model into the HIL SCADA testing environment. The 'Model Settings' interface in HIL SCADA allows for the real-time adjustment of configurable and editable model features, such as controller gains, for external and internal hardware inputs [15], [59].

The settings of model and the data processed and evaluated were designed using Typhoon HILL Schematic Editor. The control panel was developed, assembled, and constructed using HILL SCADA. This allow the user to designate the specific machine on which the model will be constructed.

Given their relatively low efficiency, HRES must optimize using power derived from intermittent sources. Boost converters and other MPPT techniques are employed to enhance power generation efficiency. Electrical power conversion devices are commonly included in these systems to provide current or voltage conversion, control, and filtering for driving a diverse range of loads. The P&O method is a widely utilized MPPT methodology that employs minor perturbations within the system to enhance the power output of a solar cell, which exhibits variability. If the perturbation increases power, it will persist in the same direction. Once a state of equilibrium is attained, the algorithm optimizes the output to its highest potential. In the following figure (1), the methodology is presented.

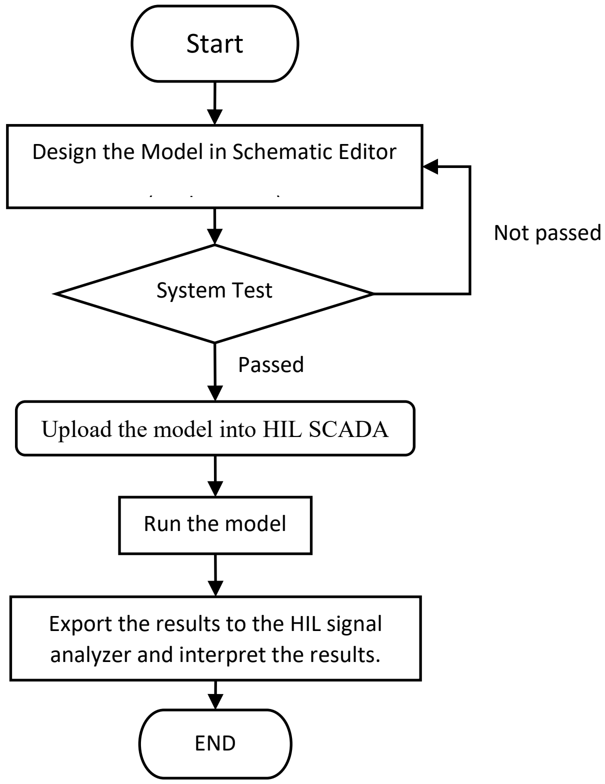

Figure 1. Methodology

The P&O methodologies posit that the operational voltage of the HRES experiences only marginal increments, but a control modification disrupts the power, leading to a transition to the MPP. The P&O formula is utilized to calculate the estimated current and voltage output of an HRES. It also records the power and voltage readings of the solar-powered PV module at regular intervals. The calculation of the RES power involves the retrospective assessment of the current and voltage values.

The popularity of the standard P&O algorithm stems from its ease of implementation in practical applications. The operational point is subject to continual observation and perturbation until it converges to the MPP. If there is a positive change in power, even a minor adjustment in voltage will result in a corresponding modification to the solar panel's power output. Suppose the delta power exhibits a negative value.

In that case, it indicates a significant deviation from the MPP, necessitating the implementation of measures to mitigate the impact of the disturbance before its propagation towards the MPP. To mitigate the issue of prolonged response time and the occurrence of steady-state oscillations, numerous scholars have put forth modifications to the P&O method. The MPP is maintained, while additional local maxima are identified about changes in irradiance within consistent meteorological circumstances.

In this section, we present the model description and the materials used. This system is designed in TYPHOON HIL software, and the mathematical model is thoroughly elucidated. A P&O MPPT flowchart is depicted in Figure 2.

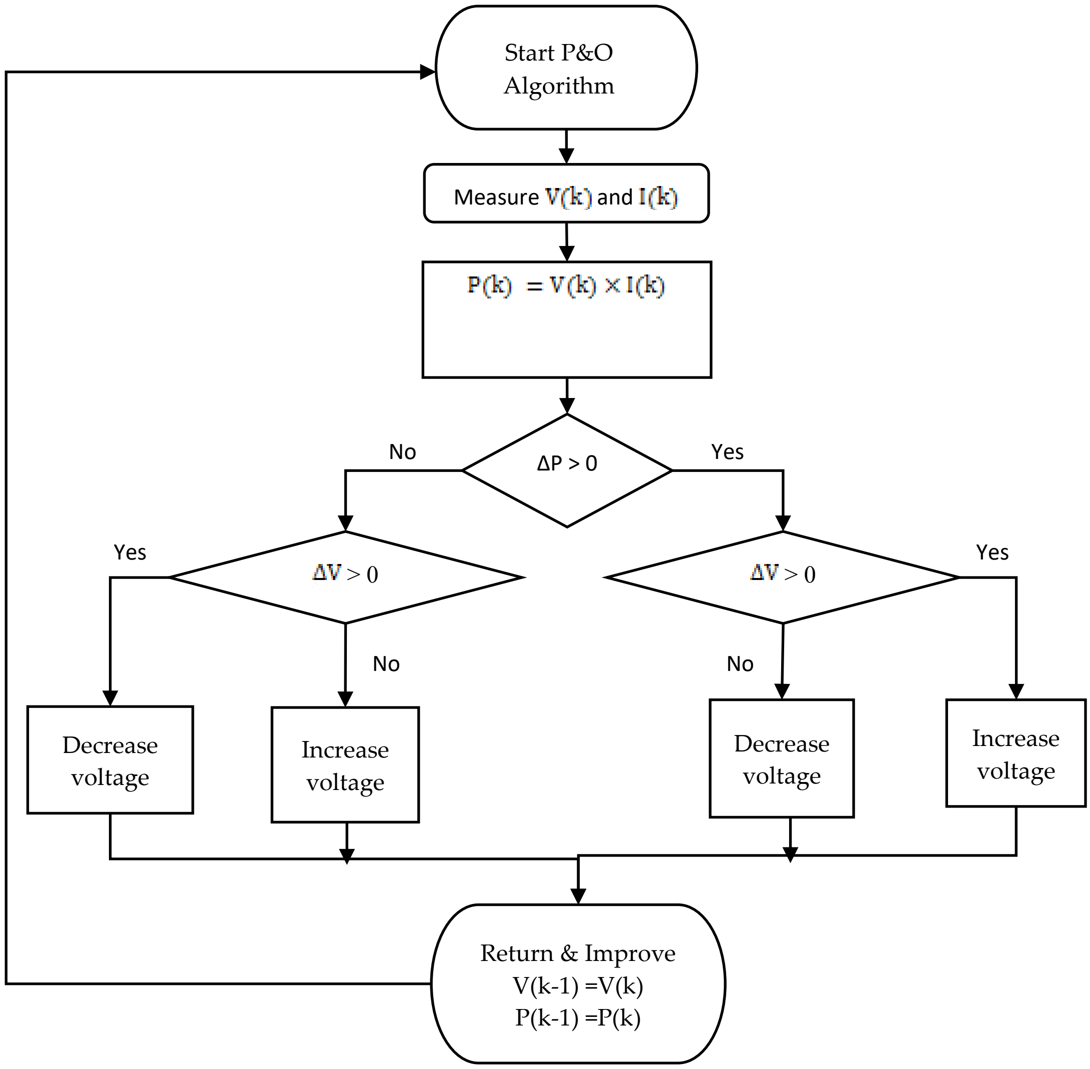

Figure 2. A P&O MPPT flowchart

MPPT, an acronym for "maximum power point tracking," is an optimization method that enables precise and consistent adjustments to the electrical operating point of PV modules, thereby maximizing their energy output [60]. An MPPT system also offers greater flexibility in connecting the PV panel with the load than direct connection techniques. The MPPT tracker ensures that the PV panel operates at its MPP while the converter satisfies the operational requirements of the load. However, in the absence of energy storage, the load must accommodate the variable power supply and utilize the entire output of the solar panel expeditiously [61].

Despite only a modest amount of energy required to produce electricity, the cell's composition absorbs or reflects much sunlight. The optimal operating temperature and light intensity for each photovoltaic cell is the MPP, which represents the output characteristics of a PV cell at a given solar irradiance level and cell temperature [62]. Therefore, the following mathematical equation is utilized to calculate the output power [63]:

$$P = \left[P_{stc} + \mu_p (T_{cell} - T_{stc}) \right] \frac{G}{G_{stc}} \qquad \text{........(1)}$$

where G_{stc} and T_{stc} denote to Standard Test Condition which are 1000 W/m^2 and 25°C respectively, $G(W/m^2)$ is the solar irradiation , $\mu_p = -0.8954 W/°C$, $T_{cell}(K)$ is the actual cell temperature.

To calculate the number of BlueSolar Monocrystalline SPM043602400 panels required to achieve a nominal power of 250 kW, the desired nominal power is divided by the nominal power of a single panel. In this case, the nominal power of one panel is 360 watts.

Number of panels = Desired nominal power / Nominal power per panel ....*(2)*

Number of panels = 250,000 watts / 360 watts ....*(3)*

Number of panels ≈ 695 ....*(4)*

To determine the number of panels required to achieve a specific voltage, the following formula can be used:

Number of panels = Desired voltage / Panel voltage ....*(5)*

In this case, the desired voltage is 480 V, and the panel voltage is 38.4 V. Consequently, the number of panels needed is calculated as

Number of panels = 480 V / 38.4 V ≈ 13 ....*(6)*

Table 1. Parameters of the PV System.

Name	Value	Unit
PV module parameters		
Type of PV module	BlueSolar Monocrystalline	
Nominal power	360	W
Max-Power voltage (VMPP)	38.4	V
Max-Power current (IMPP)	9.38	A
Open Circuit Voltage (Voc)	47.4	V
Short Circuit Current (ISC)	10.24	A
Dimensions (LxWxH)	1956x992x40	mm
Net Weight	23	kg
Temperature Range(µsc)	-40 to +85	°C
PV plant parameters		
Number of cells in series	72	
Nominal voltage	480	V
Nominal power	250	kVA
Nominal frequency	50.0	Hz
Inverter switching frequency	1	kHz
Nominal DC Voltage	1	kV
PV Plant area	1348	m^2
Efficiency	25	%
Execution rate	200	μs

Based on the given specifications, the Max-Power Voltage (VMPP) of each BlueSolar Monocrystalline PV panel from Series 4 is 38.4 V. To achieve a nominal voltage of 480 V; we need to connect multiple panels in series [64]. Table 1 presents the PV power plant parameters used in this study.

The wind energy conversion system utilizes either a fixed-speed or variable-speed generator to convert the mechanical energy generated by the turbine into electrical power that can be effectively utilized. Variable-speed wind energy conversion systems have become more popular than fixed-speed systems due to their ability to optimize turbine performance and capture maximum wind energy, irrespective of wind speed and direction [65]. This has resulted in decreased compressive damage and aerodynamic noise that can be attributed to inadequate energy generation and subpar power quality.

$$T_{t,opt} = \frac{\lambda_{opt}.V_{\omega}}{r} \qquad \text{...........(7)}$$

$$P_{\omega,\max} = \frac{1}{2}\rho.\pi r^2.C_{p,\max}.\left(\frac{\omega_{t,opt}.r}{\lambda_{opt}}\right)^3 \text{........(8)}$$

$P_{\omega,\max}$ (W) is the wind turbine's maximum mechanical output power, ρ (kg/m^3) is the air density, $r\,(m)$ the wind turbine blade radius, $C_{p,\max}$ the maximum wind turbine power coefficient, $\omega_{t,opt}$ (rad/s) is the wind turbine rotor speed, and λ_{opt} that is the optimal tip-speed ratio; the wind speed value represented by V_{ω} (m/s). Table (2) presents the wind turbine parameters.

Table 2. Wind Plant

Name	Value	Unit
	Wind turbine parameters	
Wind Turbine Model	Enercon E-44/500	
Rated Power Output	500	kVA
Rotor Diameter	44	meters
Swept Area	1,518	m^2
Cut-in Wind Speed	2.5	m/s
Rated Wind Speed	13	m/s
Cut-out Wind Speed	25	m/s
	Wind system parameters	
Nominal voltage	480	V
Nominal power	500	kVA
Nominal frequency	50	Hz
Inverter switching frequency	10	kHz
Nominal DC Voltage	1	kV
Effective disk area	448	m^2
Wind turbine efficiency	75	%
Air density	1.225	Kg/m^3

Electrochemical cells, such as rechargeable batteries, are commonly used to store electrical energy. These secondary cells are rechargeable batteries because they undergo reversible electrochemical processes. A diverse range of rechargeable batteries exists, encompassing small-scale button cells and large-scale megawatt-hour banks integrated into the electrical grid.

Rechargeable batteries can be made using chemical components such as lead-acid, nickel-cadmium, nickel metal, lithium-ion, and lithium-ion polymer. Compared to conventional disposable batteries, rechargeable batteries offer both cost-effectiveness and reduced environmental hazards. Rechargeable batteries possess the capacity to be utilized again after the process of recharging, although conventional batteries are designed for single use and necessitate disposal after that. Rechargeable batteries play a significant role in enhancing grid stability through their ability to satisfy peak power demand. Emerging power technologies, such as solar power, can accumulate energy during daylight hours and utilize rechargeable batteries to discharge it at nighttime [66]. The battery parameters of the energy storage system can be expressed as:

During charging mode:

$$E_{CH}(t) = \left(\frac{P_{WT}(t) - P_{load}(t)}{\eta_{conv}} + P_{PV}(t) \right) \times \Delta t \times \eta_{CH} \qquad ....(9)$$

$$SOC(t) = soc(t-1)(1-\sigma) - E_{CH}(t) \qquad ....(10)$$

During discharging mode:

$$E_{CH}(t) = \left(\frac{P_{load}(t) - P_{WT}(t)}{\eta_{conv}} + P_{PV}(t) \right) \times \Delta t \times \eta_{DIS} \qquad ....(11)$$

$$SOC(t) = soc(t-1)(1-\sigma) - E_{DIS}(t) \qquad ....(12)$$

The $SOC(t)$, $soc(t-1)$, $E_{CH}(t), E_{DIS}(t)$, $P_{load}(t)$, η_{DIS} representing the state of charge of the existing battery system at the time, represented as t, (t-1) is the self-charge rate, discharging energy, charging energy added to the demand for the needed energy at the time (t), also the converter efficiency, this includes the efficiency of charging and discharging of the battery storage system.

Table (3) shows the parameters of used energy storage systems (ESSs) where Lithium-Ion is used in this study.

Table 3. Battery parameters

Name	Value	Unit
Battery type	Lithium-Ion	Ah
Nominal voltage	1000.0	V
Capacity	1e6/1000.0	Ah
Initial SOC	80.0	%
Full charge voltage	116.0	%
Nominal discharge current	20	%
Internal resistance	0.025	
Capacity at nominal voltage	93.5	%
Capacity at exponential zone	85.0	%
The voltage at the exponential zone	103	%

Traditionally, generators have served as backup systems for conventional energy generation. However, with the growth of industrial, commercial, and residential development, the demand for electrical energy consumption has increased significantly, surpassing the capacity of conventional energy sources to meet it. The adoption of alternative energy sources, such as solar and wind power, has been hindered by issues of reliability and intermittence, which are influenced by seasonal and weather changes [67]. The generation of power is facilitated through the utilization of a diesel engine in conjunction with a generator. Additional components contributing to this process include a chassis, controls, emergency circuit breakers, heat sources, and an automatic start system. In contrast to small-scale turbines, diesel generators exhibit extended operational periods, higher initial investment requirements, and more intricacy in maintenance procedures. Furthermore, it can be observed that the output of a diesel generator exhibits a direct proportionality to the quantity of diesel fuel it consumes. The connection between diesel generators' output power and fuel content is linear [68]:

$$FC_{design}(t) = \alpha_{DSG}.P_{design}(t) + \beta_{DSG}.N_{design} \qquad \text{...............(13)}$$

Table (4) presents the diesel generator parameters.

Table 4. Diesel generator parameters

Name	Value	Unit
Nominal Power	2.2	MVA
Phase Nominal Voltage	480	V
Nominal electrical frequency	50	Hz
Shunt snubber load percentage of nominal power	5	%
Execution rate	200	μs

5. RESULTS AND DISCUSSION

Under typical circumstances, MPPT algorithms are utilized to optimize the performance of renewable energy sources such as solar panels and wind turbines. Moreover, PV inverters can easily adjust the maximum threshold, allowing for regulating the output power of PV systems without necessitating additional control mechanisms or communication protocols. To maintain equilibrium in power distribution and ensure the system's robustness in the face of unforeseen circumstances, such as reduced demand or unavailability of ESS owing to maintenance activities, the PV and Wind Turbine systems are controlled to operate in a low-efficiency mode. This is achieved by deactivating specific PV arrays and WTs.

Diesel generators can operate in two distinct modes: droop control mode, which involves the management and maintenance of voltage and frequency, and active power/reactive power (P/Q) control mode, where power parameters are determined based on values specified by a centralized controller. The ESS provides user accessibility to the P/Q and droop parameters, employing constant voltage/constant frequency (CVCF) control.

During diesel-on conditions, the operation of diesel generators is regulated by droop control, while the ESS operates under P/Q control to ensure the system's voltage and frequency maintenance. If renewable energy generation surpasses the load demand, diesel generators function at their minimal loading condition, conventionally set at 25% of their rated power. Online generators provide the electrical power for the grid synchronized with the system. The ESS is replenished anytime there is an excess of electricity generated by renewable energy sources that exceed the immediate need.

The microgrid's voltage and frequency are generated, and the ESS minimizes any variations in instantaneous power. The ESS is regulated by the Constant Voltage Constant Frequency (CVCF) as the reference source, particularly when the diesel power is deactivated. The effectiveness of the coordinated control system is contingent upon the capacity to deactivate diesel generators during daylight hours when the power generated by ESSs and renewable sources is sufficient to meet the entirety of the energy demand. By eliminating diesel, there is potential to optimize the utilization of renewable energy sources, thereby reducing our carbon emissions.

Table 5. Scenarios with load and high wind speed

Scenario	Condition
1	With load and high wind speed
2	With Load and Low solar Radiation
3	With Load and high Solar Radiation
4	With Load and low Wind Speed

Scenario 1 focuses on a specific circumstance involving electricity generation and consumption where the incident solar energy on the panels is adjusted at 1000 watts per square meter (W/m2). Solar irradiance represents the quantity of solar energy that reaches the solar panels. In this case, the wind speed is strong, measuring 24 meters per second (m/s). Wind speed is an important aspect of wind power generation since it directly affects wind turbine efficiency. The temperature outside is 25 degrees Celsius (°C). The effectiveness of solar panels and wind turbines can be affected by temperature. Higher temperatures can cause a minor drop in solar panel efficiency. Solar panels convert solar energy into electricity when exposed to specified solar irradiance and temperature conditions. The following figure (3) shows the system output under this condition.

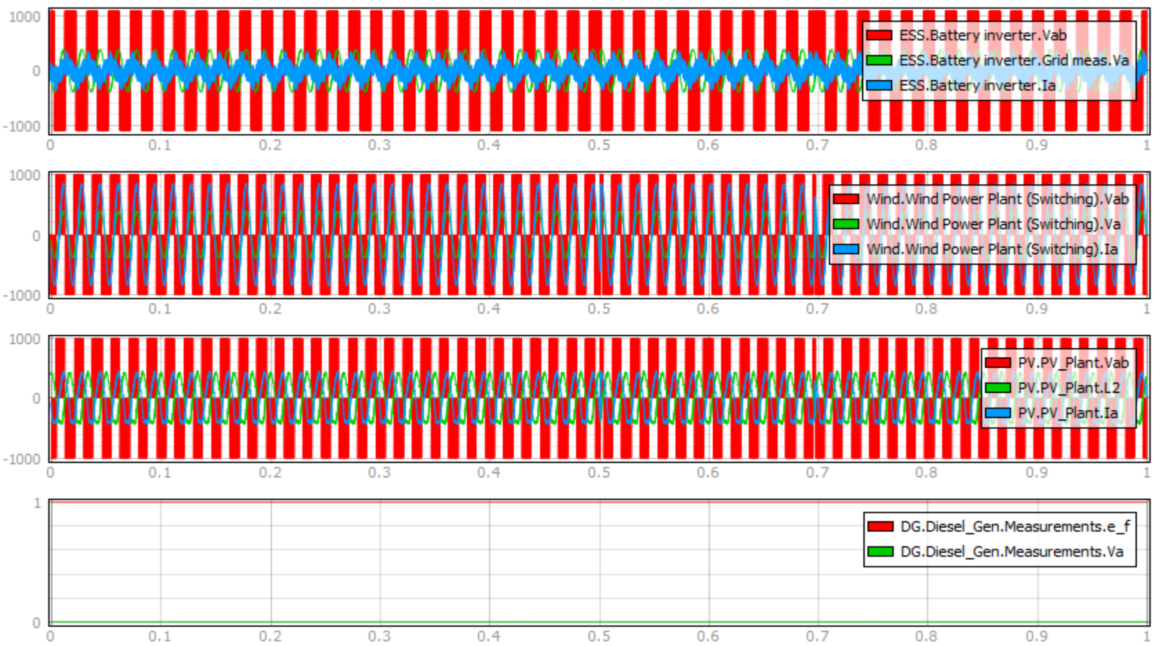

Figure 3. With load and high wind speed.

In this scenario, as shown in figure (4) we have two basic renewable energy sources: sun and wind. However, due to inclement weather or other circumstances, sun irradiance has dropped to 500W/m2, and wind speed has dropped to 20 m/s. As a result, the energy produced by these renewable sources needs to be increased to supply the system's electrical requirements. In this case, the key goal is to guarantee that load demand, which reflects the electricity required to power various gadgets and appliances, is still satisfied despite the decrease in solar and wind energy generation. An energy storage system and a diesel generator are used to accomplish this.

Figure 4. With Load and Low Solar Radiation

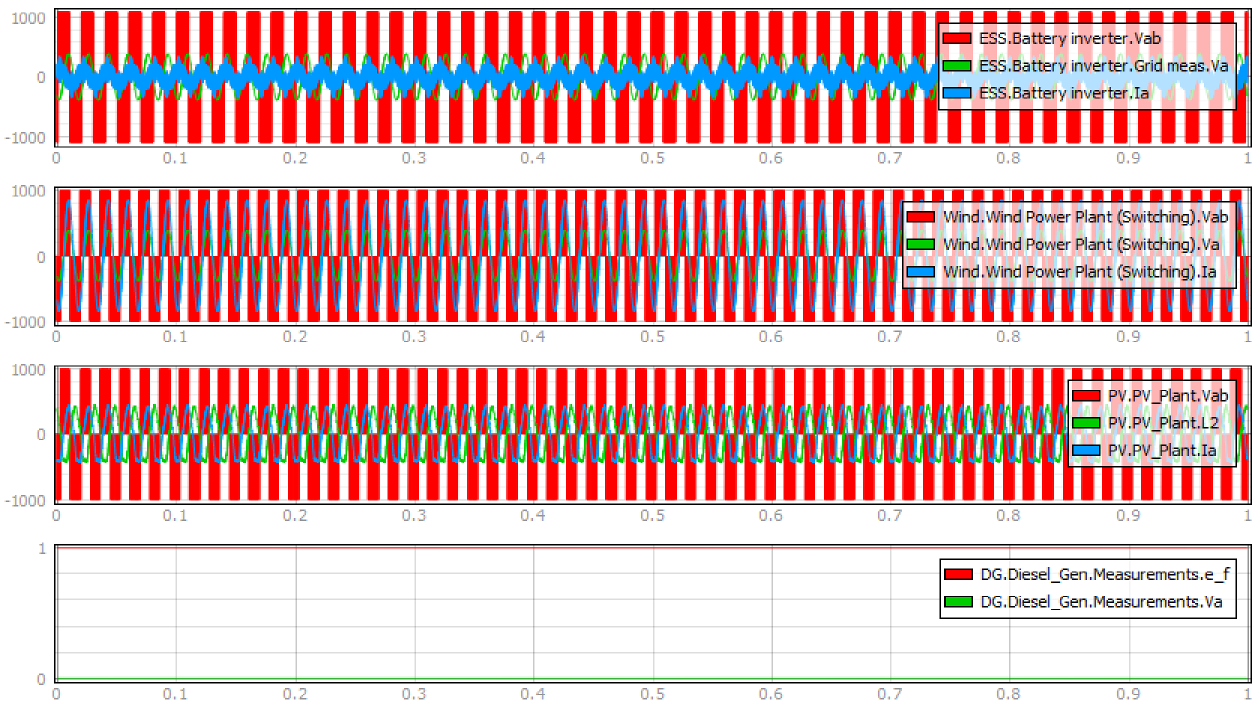

Figure 5. With Load and high Solar Radiation

In the third scenario with Load and high Solar Radiation, in this scenario, the solar irradiation is set to 1500w/m2, where the wind has increased to 25m/s. Solar panels would run at full capacity with the sun irradiation set to 1500W/m2, producing significant power.

This would result in a greater contribution of solar power to the entire energy mix, lowering reliance on other conventional forms of electricity, such as fossil fuels. The following figure (5) presents the system output in this scenario.

In this scenario, with Load and low Wind Speed decreased to 5m/s and the solar irradiance is 500w/m2, the diesel generator is on to supply power to the load. The wind turbine's output power will be much lower at five m/s wind speeds than at higher wind speeds. This decrease in wind energy output may not cover the total load requirement. Solar Power:

A solar irradiance of 500W/m2 shows that the solar panels may still create power at a reduced rate than in periods with greater solar irradiance levels. The production of solar electricity will add to the overall power generated.

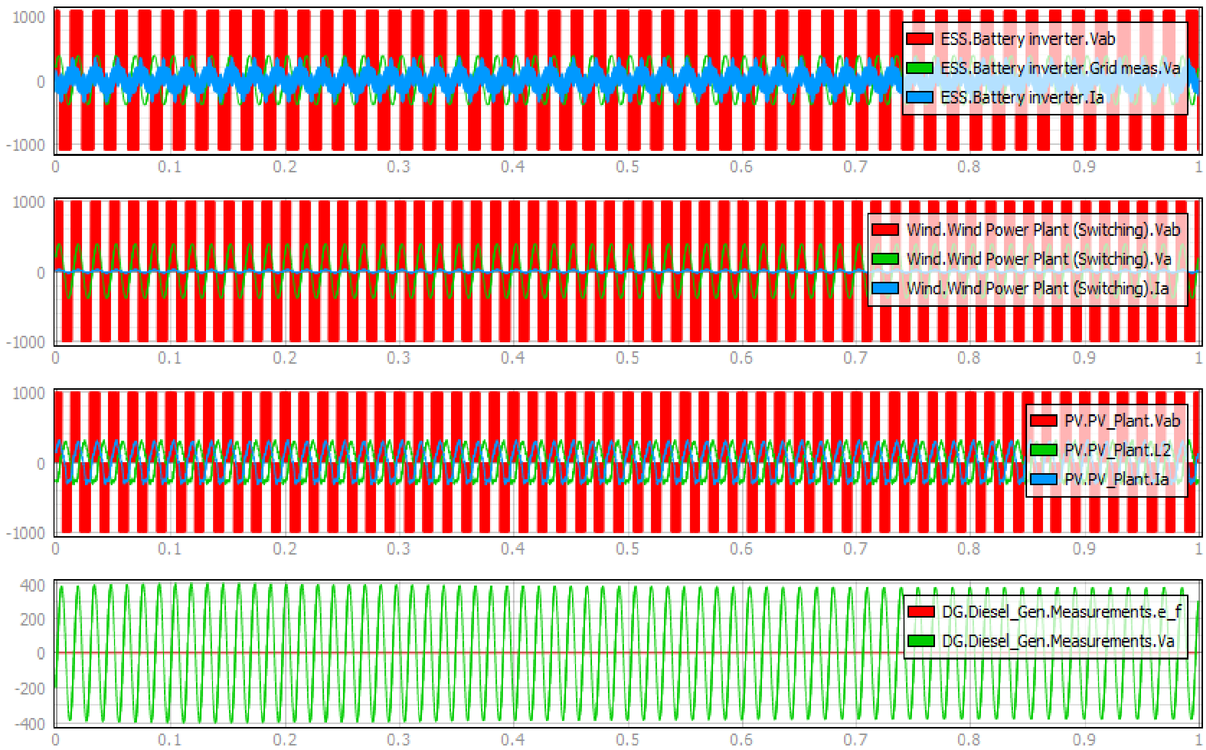

Figure 6. With Load and low Wind Speed

The realistic simulation of the dynamic response of diesel generators necessitates the implementation of appropriate models for the generators themselves and selection of optimal parameters for synchronous machines and their controllers. The literature encompasses mathematical models of synchronous machines, governors, and excitation systems. Power system simulation software often includes a variety of commonly used models as part of its default installation. This study utilizes Power Factory's default models to mimic the dynamic performance of a diesel generator. The dynamic characteristics of synchronous machine models can be obtained by examining the generator datasheets. The Woodward diesel governor is chosen as the governor model due to its current implementation in the system, specifically in managing frequency droop at a rate of 5%. The scenarios have been enumerated and organized in Table 5, while the corresponding findings have been visually shown in Figures 3 to 6.

A wind turbine is exposed to strong wind speeds, which cause its blades to spin and generate power. Where the battery is completely charged, suggesting that a substantial quantity of electricity was stored from earlier charging cycles or when power output surpasses demand, the generator is in standby mode, which means it is not producing energy. It might be a backup power source that can be triggered as necessary. The electricity generated is used to power lighting and power remote cities. This load indicates the power demand in rural regions for lights and other basic electrical demands. This scenario's major goal is to fulfil the energy demands of rural populations, which frequently need access to reliable power systems. Solar and wind power can be ecologically benign and sustainable energy sources in such situations. Describes a unique circumstance in which solar and wind power generation technologies are used under certain environmental conditions. The produced electricity will be used to power lighting and other important services in remote cities. This scenario intends to provide a sustainable solution for supplying electricity to locations underserved by traditional power systems by employing renewable energy sources such as solar and wind power as shown in Figure 3 to 6.

The control characteristics of distributed energy resources (DER) technologies are employed to construct dynamic models about these technologies. These models employ simulations and evaluations to analyses the system's dynamic performance when subjected to coordinated control approaches to determine the optimal microgrid architecture. This enables the identification of suitable operational constraints. This paper presents a dynamic model for a PV system, depicted by a block diagram comprising PV modules, a DC link capacitor, a three-phase pulse-width modulation (PWM) inverter, and an LC filter. The design incorporates the P&O MPPT algorithm. Solar PV systems function as generators of electrical current, whereas PV inverters operate in P/Q mode, commonly called grid-feeding mode.

In the dynamic model of a wind power system, a comprehensive back-to-back converter is incorporated, consisting of an MSC, a DC link capacitor, and a grid-side inverter (GSI). This converter is accompanied by a wind turbine and a permanent magnet synchronous generator (PMSG). In this particular arrangement, the MSC regulates the rotational speed of the Permanent Magnet Synchronous Generator (PMSG) to optimize energy extraction from the wind. In the grid-feeding mode, the GSI and the PV inverter regulate the DC link voltage and reactive output power.

The primary constituents of an ESS encompass batteries, a PWM converter, a DC link capacitor, and an inductor-capacitor (LC) filter. The control mechanism of the ESS converter incorporates both current and voltage control loops. When the ESS converter is operated under CVCF control, it operates in a closed-loop configuration, functioning as an AC voltage source with changeable magnitude and frequency. The current controller is responsible for regulating the output current of the ESS, while the voltage controller is responsible for regulating the terminal voltage of the ESS.

The capacitor is rapidly charged to the appropriate voltage due to the controlled flow of current facilitated by the inductor. In this particular mode of control, the generation of the system's frequency is automated. The output AC voltage of the CVCF ESS serves as a standard for the PV, WT, and diesel generators. The ESS converter is a current P/Q or grid-feeding control source, providing or consuming active and reactive power as required. The terminal voltage of the ESS is synchronized with the terminal voltage of the power system as measured at the Point of Common Coupling (PCC). A phase-locked loop and a synchronous reference frame transform can determine the system's frequency and phase angle.

The generator's architecture comprises four primary components: the synchronous machine, diesel engine, governor, and excitation system. The governor exercises control over the diesel engine's revolutions per minute (RPM), hence maintaining a consistent electrical frequency irrespective of variations in power consumption. The primary purpose of an excitation system is to provide and regulate a direct current to the field winding of a synchronous machine, hence managing the terminal voltage at the machine's output. The generator output voltage in an excitation system is commonly regulated by an automated voltage regulator (AVR) to sustain a consistent value.

The wind turbine continues to contribute to energy generation, despite its output decreasing due to the decrease in wind speed. The energy generated by the wind turbine is coupled with energy from the energy storage system to assist in satisfying load demand. The diesel generator is still operational. However, it is now in standby mode. Standby mode indicates that the generator is not actively producing power since renewable sources and the energy storage system are sufficient to fulfil demand. On the other hand, the diesel generator stays on standby to be used as a backup power source in the event of lengthy periods of low renewable energy output or in crises when energy from renewables and storage is inadequate to satisfy load demand.

Even during low solar irradiation and wind speed periods, the load demand may be satisfied by combining the energy storage system with the wind turbine output. The system's flexibility and the diesel generator's standby availability provide a dependable and sustainable alternative for ensuring continuous power supply while reducing dependency on fossil fuels. This configuration helps reduce greenhouse gas emissions while encouraging a more ecologically responsible approach to power generation and use.

Wind speeds of 25 m/s are ideal for wind turbines. Wind turbines produce power by harnessing the kinetic energy of flowing air. Higher wind speeds provide more kinetic energy, resulting in greater power output from wind turbines. As a result, wind power would contribute significantly to energy generation in this scenario. High sun irradiation combined with strong wind can substantially influence the overall behavior of the power system. The system may suffer an excess of energy generation at periods of peak solar irradiation and strong wind speeds.

This excess energy may be utilized to fulfil higher load needs or saved in energy storage systems such as batteries. The third scenario provides an ideal chance for integrating renewable energy sources into the system. Electricity generation becomes more diverse and sustainable by utilizing solar and wind power. Furthermore, employing renewable energy sources helps to minimize greenhouse gas emissions and supports a cleaner energy system.

However, it is crucial to highlight that controlling such substantial swings in renewable energy output might provide difficulties for grid managers. Because solar and wind power are intermittent, energy storage and grid balancing methods are critical to ensuring a steady and consistent power supply.

The diesel generator is turned on to compensate for the low wind speed and minimal solar electricity output. Diesel generators can produce regular and reliable power regardless of weather conditions, making them valuable when renewable energy is unavailable. Overall, wind power (at a decreased level owing to low wind speed), solar power (at a reduced level due to lower irradiance), and diesel generator power are used in this scenario. The aim is to guarantee that the combined power output can equal or surpass the load's power requirements.

It is worth noting that this circumstance emphasizes the difficulties of integrating renewable energy sources into the electrical system. While renewable energy sources such as wind and solar are ecologically good, their production is weather sensitive and erratic.

Diesel generators provide a reliable backup when renewables cannot fulfil demand, but they have greater running costs and carbon emissions. In an ideal scenario, energy storage devices such as batteries would be employed to store extra renewable energy during favorable conditions and discharge it during periods of low generation to increase overall system stability and sustainability.

6. CONCLUSION

In summary, this study presented an integrated control strategy for a microgrid system, showcasing the incorporation of renewable energy sources such as solar and wind power with backup power options, including diesel generators and batteries. Coordinated control becomes feasible by implementing a centralized control method, which effectively manages the electricity flow from various DERs and ensures the microgrid's stability. The performance of the proposed coordinated control technique was evaluated by simulations of various operating conditions, including no-load operation with the combined use of PV, wind turbine, and generator, low-load operation with limited solar radiation, high-load operation with abundant solar radiation, and low-wind-speed operation under high-load conditions. The successful regulation of power flow, maximization of renewable energy sources, and reduced diesel generator usage by half show that the coordinated management strategy was the most suitable.

The study also presented dynamic models for each DER component, including photovoltaic panels, wind turbines, and diesel generators. These models were used to simulate the microgrid's dynamic performance and evaluate the system's operating limitations. The study's results showed that the coordinated control method and dynamic models presented could be useful for designing and optimizing microgrid systems. Future research can focus on improving the accuracy of the models and testing the proposed coordinated control method in real-world microgrid systems.

Author contribution: Almihat study's conception and design. Almihat did material preparation, data collection, and analysis. The first draft of the manuscript was written by MGM Almihat. MTE Kahn supervision and reviewed the final draft. All authors have read and agreed to the published version of the manuscript.

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