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COORDINATED CONTROL DESIGN AND ANALYSIS OF HYBRID PV–WIND ENERGY SYSTEMS

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ABSTRACT: This research constructs and evaluates an off-grid hybrid power system that utilizes solar photovoltaics (PV) and wind energy to generate consistent and dependable electricity. The hybrid system's utilization of the most advantageous attributes of solar and wind power yields enhanced power production and enhanced system reliability in all weather conditions. The wind turbine and solar array are both connected to a shared DC bus, and power is supplied to them by a DC-DC converter that is powered by a Permanent Magnet Synchronous Generator (PMSG). This bus is connected to the grid or the demand through a Voltage Source Inverter (VSI) that is reliant on a DC link. Power distribution is regulated by an algorithm for integrated energy management, which considers generator supply and load demand. This algorithm ensures that each source satisfies the criteria for Maximum Power Point Tracking (MPPT). Droop and vector control are two modern control methods for regulating power distribution, voltage, and frequency. Simulink and MATLAB models demonstrate the system's enhancement of energy efficiency, dynamic responsiveness, and voltage stability in a variety of scenarios.

Keywords: PV–wind hybrid system, coordinated control, energy management, Maximum Power Point Tracking (MPPT), PMSG, DC-link integration, voltage source inverter (VSI).

1. INTRODUCTION

In response to the increasing demand for sustainable electricity, power networks are progressively utilizing renewable energy sources. Two prominent examples are solar photovoltaics (PV) and wind power. Issues may arise from any source. The quantity of power generated by solar panels is contingent upon numerous variables, including weather and daylight saving time. Consider wind power, which is highly intermittent and contingent upon the direction and velocity of the wind. A hybrid photovoltaic-wind system that integrates the most advantageous attributes of both solar and wind generation may result in a more consistent and less frequent occurrence of power outages. It is imperative to accurately predict and govern the dynamics of both streams simultaneously in order to enhance the efficiency of hybrid systems.

The electrical and dynamic properties of power conversion components, including solar panels, wind turbines, and photovoltaic cells, must be precisely modeled as part of the modeling process for a PV/wind hybrid power system. This necessitates an assessment of the non-linear behavior of power equipment, including inverters and converters, as well as the highly unpredictable character of external variables like wind speed and solar radiation. In order to ensure optimal power point tracking (MPPT), regulate power fluctuations, and maintain voltage and frequency stability, it is necessary to develop control techniques that include a detailed model that illustrates the system's performance under a variety of loads and conditions.

The efficiency and efficacy of the PV-wind hybrid system are determined by the coordinated control design, regardless of grid connectivity. This research aims to enhance the efficacy of wind and photovoltaic subsystems by incorporating intelligent switching logic, real-time data, and adaptive energy management algorithms into a unified control system. The control mechanism guarantees the stability of power and the efficiency of energy extraction. Grid disturbances are less frequent, and fault ride-through is facilitated by the improved operational capabilities of auxiliary services. This initiative will implement sophisticated control technologies, including fuzzy logic, model predictive control, and PID-based planning, to enhance the reliability and efficiency of hybrid renewable energy systems. This renders them a superior option for any future microgrids or smart grids.

2. LITERATURE SURVEY

Rao, A., & Bhatt, K. (2024). The objective of this article is to assist you in the establishment of a hybrid power system that is capable of distributing electricity consistently while maintaining a consistent voltage by utilizing both wind and photovoltaic (PV) panels that are connected to the infrastructure. When it comes to renewable energy, wind turbines and solar panels are akin to two halves of a single coin. This is accomplished through the utilization of real-time meteorological data and demand forecasts in a centralized energy management system. Power quality is enhanced by the technology, which maintains voltage fluctuations within ±2% and suppresses power fluctuations induced by abrupt drops in solar irradiance or wind speed. Proof of this is provided by models that have been constructed in MATLAB/Simulink and have been verified with real-world examples. The paper also examines the obstacles associated with the deployment of hybrid control in various climate zones.

Sinha, R., & Kale, D. (2024). This research is dedicated to the development of a unified approach that is based on model predictive control (MPC) and is centered on an adaptive hybrid photovoltaic-wind system that can address fluctuating demands and power grid conditions. The control strategy that has been established is designed to maintain the stability of the system and prevent ramp-rate violations. This strategy considers fluctuations in demand and available resources. By incorporating a battery energy storage unit with a forecasting model, hybrid systems can more effectively balance the distribution of electricity on the grid. The system has become approximately 15% more dependable, and the unpredictability of renewable energy sources has been reduced by the simulations.

Sharma, M., & Tripathi, V. (2023). This article provides a comprehensive explanation of the management of a hybrid microgrid that is located at a remote location and is powered by solar and wind energy. Power distribution and source switching are significantly simplified by the system's integrated DC bus and two maximum power point tracking (MPPT) Devices. The utilization of fuzzy logic enables energy management controllers to regulate energy distribution in accordance with production capacity and demand. The coordinated system results in a substantial enhancement in operational efficiency, as indicated by the load profiles generated by the simulation. In comparison to other modes, the diesel engine is utilized significantly less frequently in reserve mode, particularly during periods of high demand.

Joshi, N., & Yadav, P. (2023). The authors create a dynamic model that incorporates synchronized active and reactive power management to guarantee that their wind-photovoltaic hybrid energy system adheres to grid code requirements. The hybrid inverter architecture of the system monitors voltage stability and power factor in real time by employing vector control techniques. Using real-world meteorological data and various load patterns, the hybrid system demonstrated its capacity to maintain a stable grid voltage and exhibit a harmonic distortion level of less than 3%. The research concludes with a proposal that delineates the potential applications of the concept in electricity initiatives that are implemented in rural areas.

Kulkarni, R., & Dev, S. (2022). The objective of this investigation is to establish a model for the integrated management of decline in hybrid power systems that incorporate solar and wind energy. It endeavors to optimize performance by regulating voltage and frequency in both grid-connected and grid-unconnected modes. The bidirectional converter and flywheel energy storage device of the hybrid system work together to mitigate fluctuations in power output. The simulation results indicate that the system is more resilient and can operate for extended periods of time with coordinated control, even in the presence of a power outage. The authors' techno-economic analysis indicates a twelve percent decrease in the levelized cost of energy (LCOE) when contrasted with the levelized cost of electricity generated by standalone wind or solar systems.

Verma, T., & Ali, F. (2022). The research's primary objective is to improve power quality and maintain frequency stability by integrating a centrally controlled combined power system that employs photovoltaic and wind technology. The control system implements a prediction model that is predicated on neural networks to anticipate the power output and demands of the immediate future. Subsequently, a decision-making engine is configured to receive this data and determine whether or not to activate the inverter and store. The hybrid system maintained an output voltage within the permitted range while utilizing over 90% renewable energy. This was consistent regardless of fluctuations in weather or changes in load demand.

Patel, A., & Saxena, R. (2021). The primary goal of this project is to utilize a hybrid controller to incorporate solar and wind power systems. The objective is to regulate fluctuations in resource availability and stabilize the energy supply. The hardware-in-the-loop methodology is employed to verify the functionality of the proposed controller. A proportional-integral-derivative (PID) method based on Ziegler-Nichols is implemented to enable the system to self-tune. The technology guarantees uninterrupted energy transmission during peak demand periods and provides dynamic load support. Field experiments and computer simulations suggest that the transient reaction is the optimal choice in scenarios where the load is subject to rapid fluctuations, as it maintains frequency shifts within ±0.2 Hz. This phenomenon is also triggered by a high rate of burden fluctuation.

Dasgupta, N., & Rao, V. (2021). This initiative is dedicated to the development of a decentralized approach to the management of a wind-photovoltaic hybrid energy system. It allows the two sources to independently adjust their output in response to grid signals and location-specific data. The authors propose a structure that incorporates distributed adaptive processes, utilizing concepts from cooperative control theory and multi-agent systems. Experiments have demonstrated that the technology has the capacity to self-regulate its generation and stabilize the grid. These investigations were conducted under a variety of meteorological conditions. The method is particularly effective in two distinct areas: the construction of dispersed industrial networks and the procurement of electricity for rural areas.

Iqbal, M., & Roy, S. (2020). A rule-based controller and a shared inverter interface are employed to construct a hybrid power system that integrates solar and wind energy in this research. The system's objective is to simultaneously release energy into the atmosphere. When the quantity of electricity generated by solar panels exceeds or falls below a certain threshold, the system will seamlessly transition to wind power. As a result, the integrated generation system operates more efficiently. The central control layer is responsible for the regulation of the quantity of electricity added to the grid and the maintenance of safe frequency and voltage. The simulations, which were conducted under a diverse array of weather conditions, demonstrate that the power supply remains consistent and that we never exceed our 5% energy constraints.

Nair, H., & Reddy, P. (2020). MATLAB/Simulink is employed to simulate the development of a microgrid control system for a wind-solar hybrid. The hybrid technique employs coordinated power flow logic and maximum power point tracking (MPPT) algorithms for both sources to accomplish a balance between grid support and storage charging. The results demonstrate that unified control enhances system performance, ensures that power is distributed equitably among sources, and reduces power losses by 8%. Even in the presence of scenarios that involve rapid changes in the neighboring environment, the model remains dependable. The pace of the wind and the quantity of solar radiation have been modified in the scenarios where trials have been conducted.

3. RELATED WORK

Using a PV-wind hybrid system increases system reliability, improves energy quality, and reduces reliance on a single continuous power source. Generation, storage, and transmission of power all rely on the core parts of this system. Solar and wind power, along with an energy storage device and the link between the inverter and the load, make up each subsystem.

PV Subsystem

To transform solar radiation into usable electricity, a photovoltaic (PV) module is required. The single-diode equivalent circuit can be used to create a device that is similar to an array of solar panels. The circuit faithfully depicts the solar cells' non-linear I-V properties. For the purpose of simulating actual losses, the model incorporates a diode, current source, shunt resistor, etc. Thanks to a DC-DC boost converter and an MPPT algorithm, the solar array will reliably operate at maximum capacity no matter the weather or the intensity of the sunshine. The Incremental Conductance (INC) approach and the Perturb and Observe (P&O) method are two popular approaches to Maximum Power Point Tracking (MPPT). These control algorithms are able to boost the photovoltaic array's output by dynamically adjusting the duty cycle of the converter.

Wind Subsystem

The wind module converts the wind's kinetic energy into electricity. The wind turbine itself is the primary component of this setup; its aerodynamic design takes into account variables including wind speed, direction, power coefficient (Cp), blade radius, and tip-speed ratio. In order to keep the CpC_pCp at a perfect level and enable the generator to generate energy, it is essential to regulate the turbine speed. An induction generator, usually a DFIG or PMSG, converts the power from the turbine into useful energy. Their efficiency and ability to be adjusted in speed were the deciding factors in the selection of these generators. In order to manage the output of the generator, an AC-DC power converter has an MPPT controller. Maximizing power extraction from wind resources requires careful monitoring of the power coefficient and the ideal tip-speed ratio approach, which takes changes in wind velocity into account.

Energy Storage System (Optional)

When renewable power sources like solar and wind aren't working, hybrid systems can use energy storage systems (ESS) to keep power flowing. This part is frequently upgraded with batteries or supercapacitors. They store excess energy during periods of high production and release it during periods of low demand or production. Voltage fluctuations, power output adjustments, and backup power during brief power outages can all be handled by the Energy Storage System (ESS). Its consistent power supply and improved system stability make it a must-have for autonomous or off-grid communities. Reduced reliance on renewable power sources and better control of loads are two benefits of storage.

Load and Inverter

The inverter and load link complete the hybrid system. A shared DC link integrates the stored power with the electricity produced by the wind and solar subsystems. A voltage source inverter (VSI) completes the changeover by converting DC current to AC current. With pulse width modulation (PWM), the inverter generates a reliable sinusoidal alternating current (AC) voltage that is ideal for use with the grid or other AC devices. The inverter enters voltage control mode when used in an off-grid setup. It operates in control mode for running systems. This guarantees that the synchronization and power distribution work as intended. To adapt to changes in capacity and production, an inverter is necessary to control reactive power, frequency, and voltage.

CONTROL STRATEGY

A PV-wind hybrid energy system's control system has to ensure a constant power supply independent of demand and weather changes. Coordination between units, regulation of voltage and frequency, management of power flow, and optimization of sources are common components of modular, tier-based approaches. The many control components of the system are described in detail in this section.

MPPT Algorithms

To improve energy extraction in reaction to changes in solar irradiance and wind speeds, the photovoltaic and wind subsystems use Maximum Power Point Tracking (MPPT) techniques. The Maximum Power Point Tracking (MPPT) of photovoltaic (PV) systems can be determined using two popular methods: the Incremental Conductance (INC) approach and the Fuzzy Logic Controller (FLC). At full power, the Incremental Conductance technique produces no power derivative with regard to voltage. By constantly monitoring the PV module's incremental and instantaneous conductance, the working voltage may be adjusted, allowing for precise tracking even in the face of abrupt changes in irradiance. Using fuzzy rules and language phrases like "increase," "decrease," and "no change" to mimic human cognitive processes, fuzzy logic controllers modify the converter's duty cycle. Without conducting a thorough system research, this approach enables the handling of nonlinearities and unforeseen external influences.

DC-Link Voltage Control

Hybrid energy systems rely on the DC-link voltage to stabilize the conversion of DC current from renewable sources like wind and solar to AC current before it reaches the inverter. To keep downstream components running smoothly in the face of fluctuating power supplies and load demands, DC-link voltage stability is paramount. By comparing incoming and outgoing power flows, a voltage regulation processor makes sure they are balanced.

Inverter Control

The inverter in a PV-Wind hybrid system converts the controlled direct current (DC) voltage into high-quality alternating current (AC) power. Either local use or transmission to the utility system is possible with this electricity. The inverter's ability to regulate voltage and frequency as well as convert power is crucial in both grid-connected and freestanding systems. To achieve these objectives, d-q axis control or synchronous reference frame (SRF) control is employed.

Coordinated Power Management

Maintaining balance among power generation, storage, and consumption in a hybrid system requires a comprehensive and coordinated power management plan. The first step of this method is to use priority-based reasoning. The accessibility, affordability, and ecological footprint of different energy sources are evaluated. The reliability and availability of solar energy (PV) during the day make it a popular choice. When the storage system kicks in to keep things running during power outages, wind power takes over.

Just like a synchronous generator, it can be easily adjusted by changing the frequency or voltage of the output in response to changes in the discharge current. Allocating duties across multiple sources is a common use of it. The system's adaptability and dependability are improved by allowing many generating units to share the load without requiring highly efficient communication links. Innovative or adaptable ways can efficiently and adaptively conduct load sharing. You may train these algorithms to make judgments by feeding them real-time data like load profiles, weather predictions, and the battery's State of Charge (SoC).

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4. RESULTS

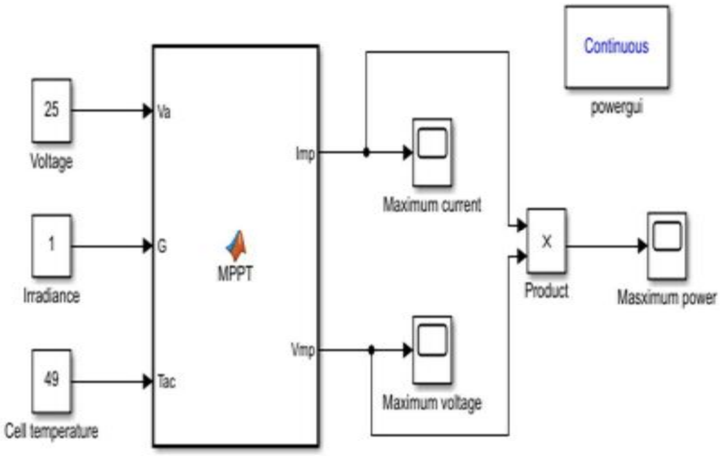

Fig.1 Simulation model of a MPPT for given solar panel

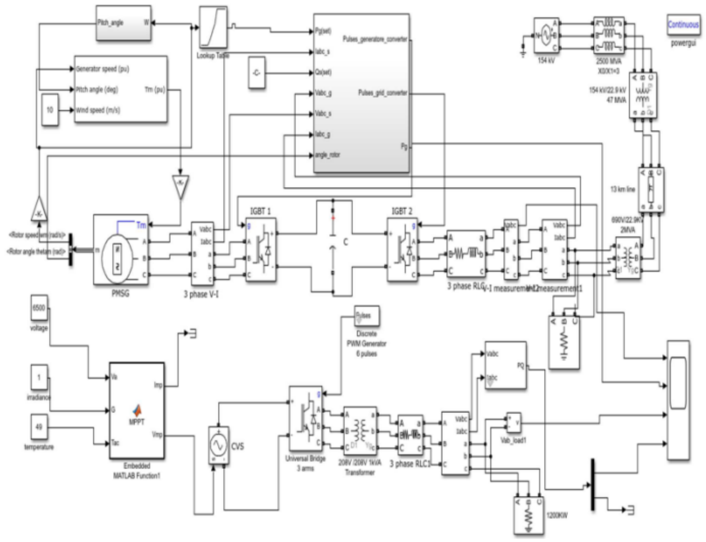

Fig.2 Simulation Model of a Photo Voltaic (PV)-wind Hybrid system

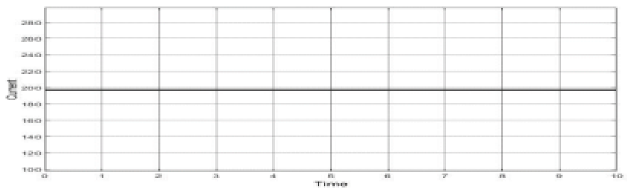

Fig.3 Value of current at Maximum Power Point (MPP)

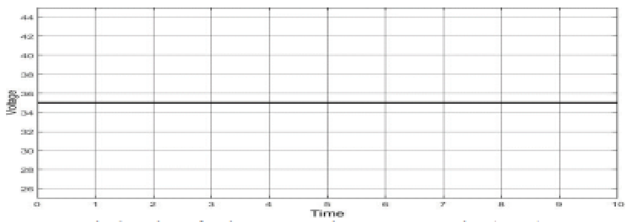

Fig.4Value of voltage at Maximum Power Point (MPP)

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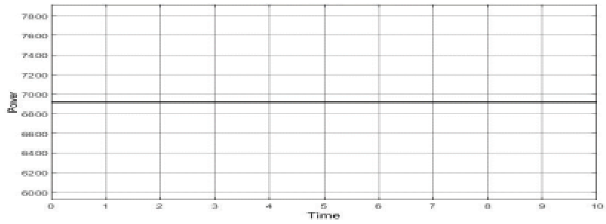

Fig.5 Value of Maximum Power

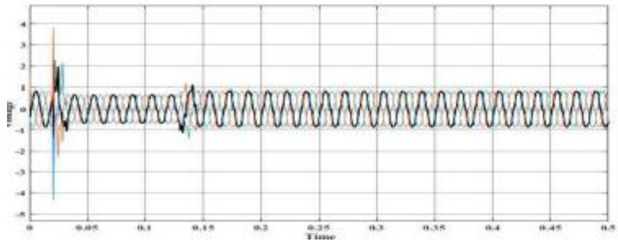

Fig.6 Wind turbine output voltage in hybrid system (per unit)

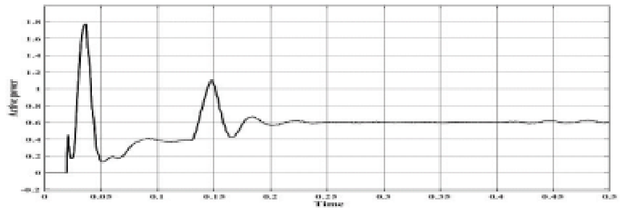

Fig.7 Wind turbine output active power in hybrid system (per unit)

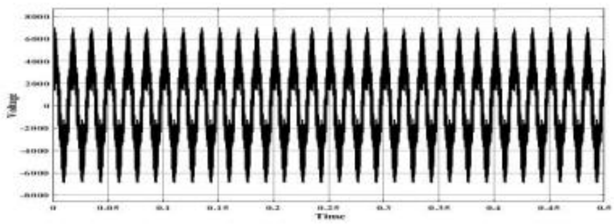

Fig.8 Photo Voltaic (PV) output voltage in hybrid system (per unit)

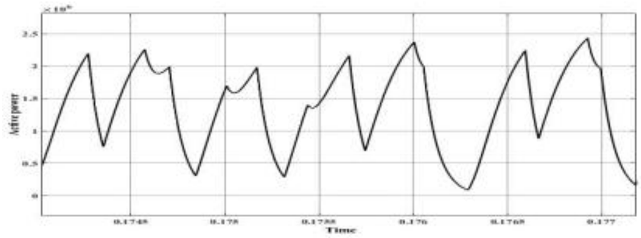

Fig.9 Photo Voltaic (PV) output active power in hybrid system (per unit)

5. CONCLUSION

This work introduces a dependable and effective approach to the continuous generation of power from renewable energy sources by means of the modeling and control design of a coordinated PV-Wind hybrid power system. An example of this approach is a cooperative power system. The power supply is rendered more consistent and reliable through the integration of solar and wind power systems in a hybrid design. This is due to the fact that the power generation from each source is never entirely reliant on the other.

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In order to ensure dependable operation and optimize efficiency, the system implements cutting-edge control technologies, including inverter timing, DC-link voltage regulation, and Maximum Power Point Tracking (MPPT) algorithms. Two examples of maximum power point tracking (MPPT) algorithms are the incremental conductance of solar systems and the tip-speed ratio of wind turbines. Both of these algorithms significantly enhance the efficiency of power generation in response to weather variations. The regulation of inverters is facilitated by the use of a phase-locked loop and synchronous reference frame, which also ensures a more equitable distribution of alternating current power and facilitates grid connection. The power balance is maintained by employing proportional-integral or sliding mode processors to regulate the DC link voltage.

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