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Development and Simulation of a Hybrid System Combining Solar Photovoltaic (PV) Arrays and Wind Turbines Using Integrated Energy System Modeling

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ABSTRACT
This paper aims to create a simulation for a renewable energy system that integrates solar and wind power to meet the energy demands of a local grid efficiently. The process begins with determining the optimal sizing and layout of the solar and wind components, taking into account factors such as available space, solar irradiance, wind speed, and local weather conditions. Selecting the appropriate components, including solar panels, wind turbines, inverters, and batteries, is crucial for the system's success. Key considerations in this selection include efficiency, reliability, and compatibility. To manage the operation of the renewable energy system, an Integrated Energy System Modeling (IESM) is developed. This model is designed to optimize energy distribution among solar panels, wind turbines, batteries, and the nanogrid, ensuring maximum use of renewable energy while meeting energy demands. Simulation software is used to model and assess the system's performance under various scenarios, aiding in analysis, validation, and optimization. Additionally, optimization algorithms are employed to determine the most effective system configuration, control strategies, and dispatch algorithms. This thorough approach ensures the development of an efficient renewable energy system tailored to the specific needs of the local grid.

***Keywords**: photovoltaic systems, energy cost analysis, carbon emissions, hybrid renewable energy systems, power management strategies, optimal sizing, wind energy, wind turbines*

I. INTRODUCTION

The increasing global demand for clean and sustainable energy has heightened interest in renewable energy systems. Solar and wind energy are prominent due to their abundance and widespread availability. By carefully determining the appropriate size and configuration of solar and wind components, and considering factors like available space, climate conditions, and resource availability, an efficient and effective system can be developed.

Using specialized software to simulate the performance of a solar-wind renewable system allows for detailed analysis under various scenarios. Optimizing and simulating such a system connected to a nanogrid offers a reliable and sustainable solution for localized power generation. Leveraging abundant solar and wind resources, optimizing system configurations, and integrating with a nanogrid helps reduce carbon emissions, promote energy independence, and advance a greener future.

Nanogrids are particularly well-suited for residential communities, commercial buildings, or remote areas with limited access to the main grid. They provide flexibility, control, and sustainability on a smaller scale, enabling consumers to actively participate in the energy transition and enhance energy resilience at the community level..

II. INTEGRATED ENERGY SYSTEM MODELING (IESM)

Integrated Energy System Modeling (IESM) involves the comprehensive simulation and optimization of energy systems that integrate multiple renewable energy sources, such as photovoltaic (PV) arrays and wind turbines, along with other energy generation, storage, and consumption components.

In the context of PV arrays and wind turbines, IESM entails modeling the entire energy system, including:

PV Array Simulation: Modeling the behavior of PV arrays involves considering factors such as solar irradiance, temperature, shading, and electrical characteristics of the PV panels. This simulation helps predict the electricity output of the PV array under various conditions.

Wind Turbine Simulation: Wind turbine modeling includes factors such as wind speed, turbulence, air density, and the mechanical and electrical characteristics of the turbines. This simulation predicts the electricity output of the wind turbines based on environmental conditions.

Energy Storage Simulation: Incorporating energy storage components like batteries allows for the storage of excess energy generated by the PV array and wind turbines for later use when renewable energy generation is low. Energy storage simulation involves modeling battery charging and discharging processes, efficiency losses, and state-of-charge dynamics.

Grid Integration Simulation: Modeling the connection of the PV array and wind turbines to the electrical grid involves simulating power converters, inverters, grid interactions, and control strategies to ensure stable and efficient integration with the grid.

Energy Management System (EMS): Developing an EMS involves implementing algorithms and control strategies to optimize the operation of the entire energy system. The EMS coordinates the generation, storage, and consumption of energy from the PV array, wind turbines, and other sources to maximize efficiency, minimize costs, and ensure reliable power supply.

By integrating various elements within a unified simulation framework, the Integrated Energy System Model (IESM) facilitates comprehensive analysis, optimization, and design of PV array and wind turbine setups. This framework empowers engineers and researchers to assess diverse system configurations, control strategies, and operational scenarios, aiming to enhance the performance, reliability, and economic feasibility of renewable energy systems.

Photovoltaic cells are electrically interconnected in series and/or parallel configurations to generate elevated voltages, currents, and power outputs. PV modules, comprising these interconnected cell circuits encased in a protective laminate, serve as the foundational components of PV systems. Photovoltaic panels, comprised of one or more PV modules arranged as a pre-wired unit, are easily installable in the field. A photovoltaic array represents the entirety of the power generation unit, encompassing any number of PV modules and panels.

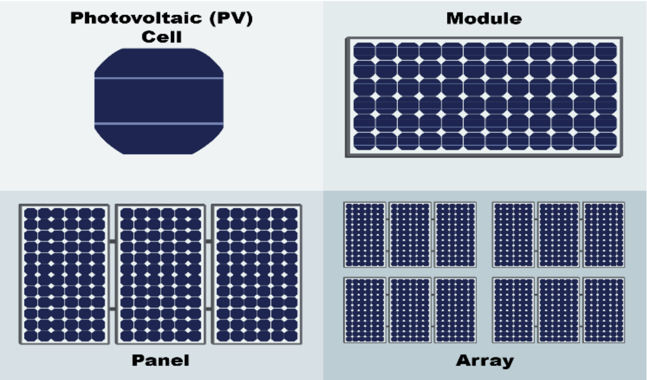


Figure 1: Diagram of Photovoltaic Cells, Modules, Panels, and Arrays.

The performance of photovoltaic (PV) modules and arrays is typically evaluated based on their maximum direct current (DC) power output (measured in watts) under Standard Test Conditions (STC). STC are defined by a module operating temperature of 25°C (77°F), incident solar irradiance of 1000 W/m², and an Air Mass 1.5 spectral distribution.

Test Conditions and Solar Panels

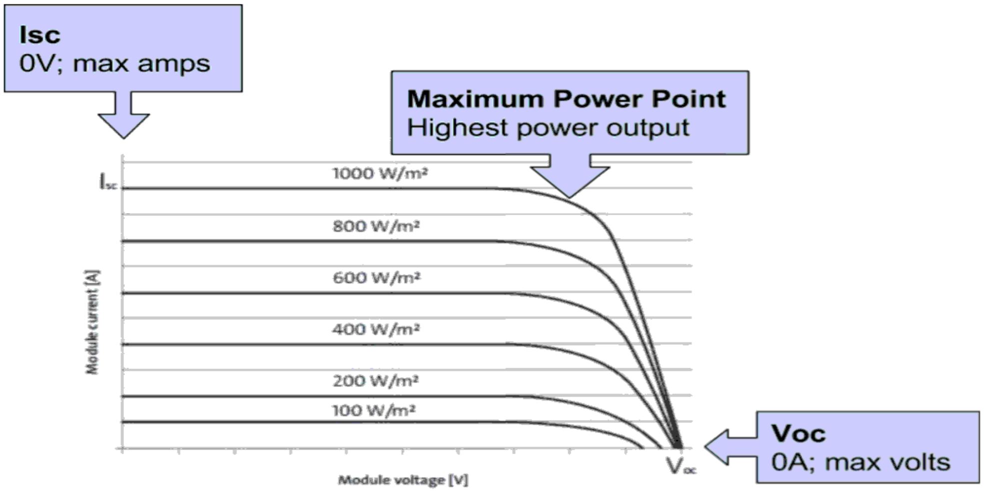
Standard Test Conditions (STC)

STC refers to a standardized set of criteria used to test solar panels. These conditions include a cell temperature of 25°C (77°F), light intensity of 1000 W/m² (equivalent to the sun's intensity at noon), and an atmospheric density of 1.5 (representing the sun's angle perpendicular to the panel at 500 feet above sea level).

Normal Operating Cell Temperature (NOCT)

NOCT provides a more realistic assessment of a solar panel's performance under typical operating conditions. Instead of 1000 W/m², it uses 800 W/m², reflecting a mostly sunny day with scattered clouds. It assumes an air temperature of 20°C (68°F), and includes a wind speed of 2.24 MPH cooling the back of a ground-mounted panel. These ratings are generally lower than STC but more representative of actual performance.

Rated Output Specifications and Solar Panels



Rated output for solar panels at different light intensities (W/m2). The “knee” of the curves is where the most power is produced, and the voltage & current is optimized.

Open Circuit Voltage (V_{oc})

Open circuit voltage is the voltage output of a solar panel with no load attached. This can be measured with a voltmeter across the panel's positive and negative leads, reflecting the maximum voltage the panel can produce under STC.

Short Circuit Current (*Isc)*

Short circuit current is the current produced when the panel's positive and negative leads are directly connected, without a load. Measured with an ammeter, Isc represents the highest current output under STC.

Maximum Power Point (P_{max})

P_{max} denotes the optimal power output of a solar panel, found at the "knee" of the current-voltage (I-V) curve. This is the point where the product of voltage and current (Volts x Amps) is maximized. Maximum Power Point Tracking (MPPT) charge controllers or inverters aim to maintain operation at this point to maximize efficiency. The power rating of a solar panel is typically its Pmax, calculated

$$P_{max} = V_{mpp} \times I_{mpp}$$

Maximum Power Point Voltage (V_{mpp})

V_{mpp} is the voltage at which the power output is at its peak. This is the target voltage for MPPT equipment under STC.

Maximum Power Point Current (I_{mpp})

I_{mpp} is the current at which the power output is maximized, and it is the target amperage for MPPT equipment under STC.

Table I: Solar Panel Nominal Voltage Cheat Sheet:

Nominal Voltage	12V	20V	24V
Number of Cells	36	60	72
Open Circuit Voltage (Voc)	22V	38V	46V
Max Power Volts (Vmp)	18V	31V	36V

Table II: Specifications of PV Panels

PV Panel specification		**Boost DC/DC converter specification**	
PV model	1STH-215-P	L1	4 mH
Short circuit current (Isc)	7.84 A	C1	100 µF
Open circuit voltage (Voc)	36.3 V	C2	100 µF
Maximum Voltage (Vmpp)	29 V	Ro	20 Ω
Maximum current (Impp)	7.35 A		
Maximum power (Pmpp)	213.15 W		
Number of cells in series (Ns)	60		
Temperature coefficient of Isc	-0.36099%/°C		
Temperature coefficient Voc	0.102%/°C		
Diode ideality factor (A)	0.98117		
Series resistance (Rs)	0.39383Ω		
Shunt resistance (Rsh)	313.3991Ω		

III. MODELLING OF PV ARRAY

The components of the identified system are simulated using the MATLAB/Simulink software tool, as previously described.

3.1 PV Module

A generalized PV model is constructed using MATLAB/Simulink to demonstrate and validate the nonlinear I-V and P-V output characteristics of PV modules. The behavior of photovoltaic (PV) cells can be represented by an equivalent circuit incorporating a photocurrent source, a single diode junction, and additional components such as an IGBT-based buck-boost converter, an inverter circuit, and a filter circuit to enhance the voltage obtained from the boost converter. Additionally, a light load connected in parallel with the circuit can be included. The Simulink model of the PV module is depicted in Figure 1.

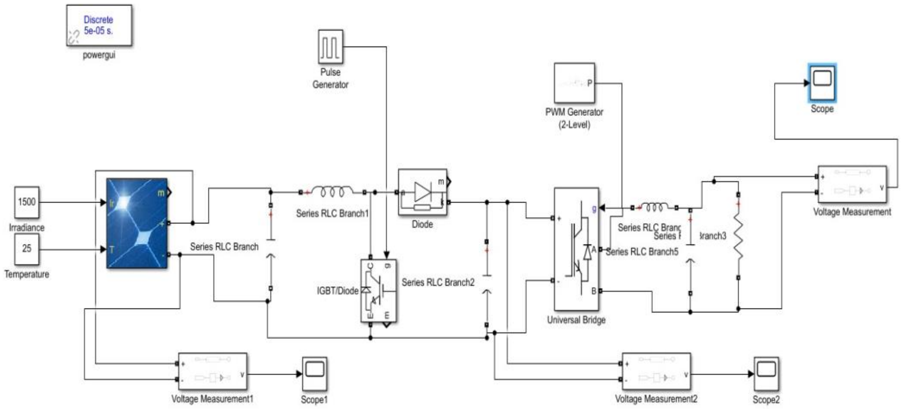


Figure 3.1: Simulink Model of PV Array Using MATLAB

The output power of a PV array can be modeled using the equation:
$P_{\text{out}}=A\times G\times\eta$
Where:

- P_{out} is the output power of the PV array (in Watts).
- A is the surface area of the PV array (in m^2).
- is the solar irradiance (in W/m^2).
- is the efficiency of the PV array.

This equation assumes ideal conditions and doesn't account for factors like temperature and shading.

3.2 WT Module

The wind turbine consists of essential components including a rotor, a generator, three blades, and a drive train. To manage high wind speeds, the generator output power is regulated by adjusting the pitch angle. Power transmission to the grid is facilitated through a power electronic interface. The wind turbine harnesses kinetic energy from the wind passing through its blades, generating power accordingly. Below, the Simulink model illustrating the equations governing a wind turbine is presented in Figure 2.

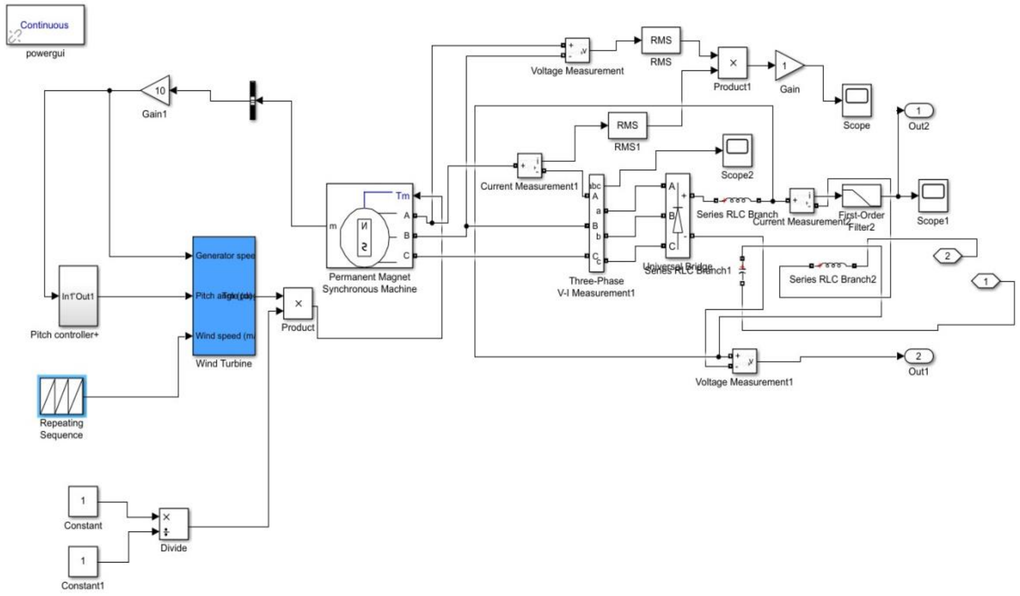


Figure 3.2: MATLAB/ SIMULINK Model of Wind Turbine Block

The output power of a wind turbine can be modeled using the equation:

$P_{\text{out}}=0.5\times\rho\times A\times v3\times C_p$

Where:

- Pout is the output power of the wind turbine (in Watts).
- ρ is the air density (in kg/m^3).
- A is the swept area of the turbine blades (in m^2).
- v is the wind speed (in m/s).
- C_p is the power coefficient, representing the efficiency of the wind turbine.

This equation also assumes ideal conditions and doesn't consider factors like turbine efficiency and wind speed variations

3.3 Energy Storage Modules

Electricity demand varies depending on the time of day and season. Traditional power grids lack the ability to store excess electricity, leading to mismatches between supply and demand. With the increasing adoption of microgrids, combining various local generation sources optimizes energy usage. Some generation methods have slower response times, while others offer limited operational flexibility. Additionally, certain generation methods can quickly adjust output based on real-time load demands. Given these factors, energy storage becomes crucial for managing such systems effectively. Effective energy storage solutions should provide the required power to the system while storing excess energy efficiently, consuming minimal electricity. This study focuses on two types of short-term storage: storage batteries and supercapacitors.

IV. EXPERIMENTAL RESULTS

The simulation result of photovoltaic array and wind turbine modelled in MATLAB / SIMULINK is shown below.

The following is the scenario when just the PV organization is turned happening then the winds & lithium components are turned off altogether. The sun radiation ranges from 250 to 1000 w/m^2 but will be in the intermediate to high category.

The demand frequency is adjusted to 50 Hz. Despite the fact that the wind velocity is zero (off) and the irradiance & temperatures are varied, the load demand remains unchanged seen in Fig 12. The PV module's real rated current is roughly 440 A, with a 230 V voltage. The solar array's power output is 100 KW. Following calculation, fuzzy MPPT power is produced is about 104 KW. As a result, the productivity is somewhere everywhere 100 %. Because when renewable power transistor is powered on, most other components are turned off. Wind speeds is 12 m/s. The load demand remains constant with various wind direction. The planned renewable power infrastructure will have an effectiveness of 85 % and 100 %, as demonstrated in figure 15 and figure 16. This productivity only applies to electricity supply well after PMSG. It does not apply to wind turbines since their performance is determined by mechanical motion and many other considerations.

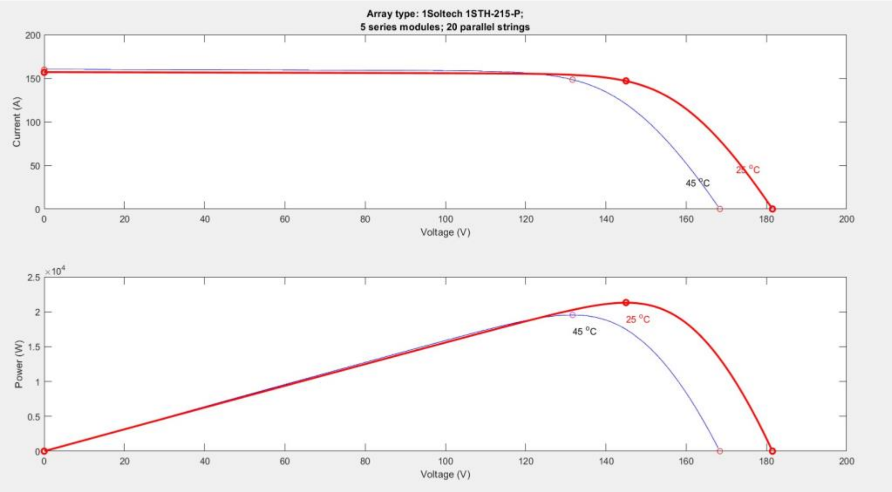


Figure 4: Simulation outcomes for I-V and P-V curves of PV array

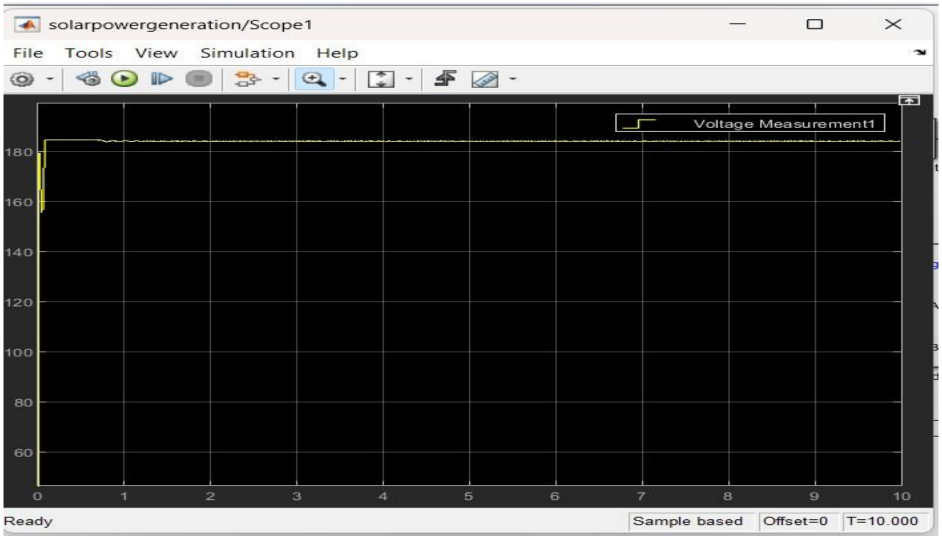


Figure 5: Voltage measurements derived from the solar PV array

To preserve added energy & send electricity to the application, a battery management technology with a bidirectional DC-DC converter was employed. In the battery bank, an FLC was used to manage the charge and discharge processes. Additional FLC was also employed to regulate and alter the illumination and air velocity. Simulation software was used to develop and analyze the full mixed powertrain throughout fixed climate situations and operating modes.

It may be inferred that using a combination system by combining a Solar and wind generator equipment with an energy storage system is so much more economic and dependable than using a single PV or renewable energy system. Implementing additional mixed powertrain with a different power management model might be an interesting future subject. MPP may also be monitored employing various highly efficient techniques.

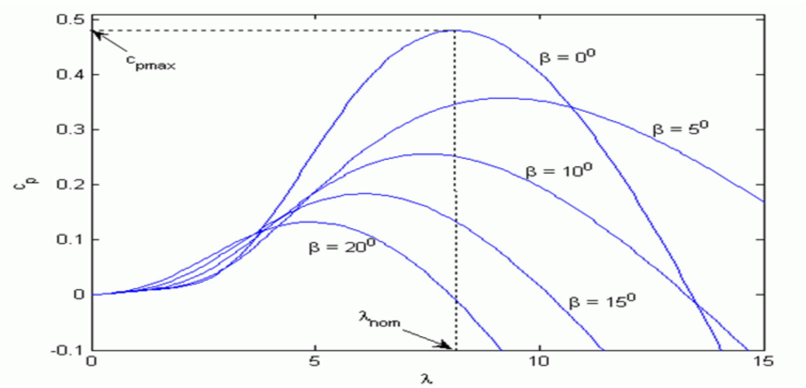


Figure 6: Simulation outcomes for WT Power Curve

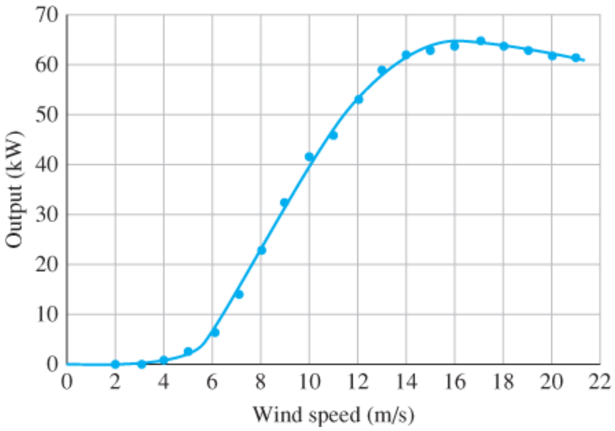


Figure 7: Simulation outcomes for Wind Turbine Power Curve

V. CONCLUSION

In conclusion, the design and simulation of a solar photovoltaic (PV) array and wind turbine hybrid model using Integrated Energy System Modeling (IESM) presents a significant step forward in optimizing renewable energy systems. By integrating these components into a single simulation framework, IESM enables a holistic analysis, optimization, and design process that considers various system configurations, control strategies, and operational scenarios. Through the application of IESM, engineers and researchers can evaluate the performance, reliability, and economic viability of renewable energy systems more comprehensively. This approach allows for a deeper understanding of how solar PV arrays and wind turbines interact within the larger energy system, including factors such as energy conversion efficiency, grid integration, and energy storage. Moreover, the use of IESM facilitates the identification of optimal design parameters and operating conditions to maximize the utilization of renewable energy resources while minimizing costs and environmental impacts. By simulating different scenarios and conducting sensitivity analyses, stakeholders can make informed decisions about technology deployment, policy interventions, and investment strategies.

Overall, the design and simulation of solar PV array and wind turbine hybrid models using IESM represents a valuable tool for advancing the transition to a more sustainable and resilient energy future. By harnessing the power of integrated modeling and simulation, we can accelerate the adoption of renewable energy technologies and mitigate the challenges associated with climate change and energy security. Simulating a solar-wind renewable system connected to a load is a multifaceted endeavor that requires thorough analysis of various factors. Through the application of sophisticated methods like simulation software, optimization algorithms, and energy management systems, it becomes feasible to create robust and efficient power generation systems. These systems are adept at harnessing solar and wind energy to effectively fulfill the energy needs of localized grids.

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