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Development Of an Intelligent Optimization Model for Hybrid Solar and Wind Energy Systems

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Abstract- The growing demand for sustainable and efficient energy sources has led to increased interest in hybrid solar-wind energy conversion systems. This research focuses on the comprehensive study of the modelling, control, and optimization aspects of hybrid solar-wind energy converters, with a specific emphasis on the implementation of Control Algorithm for Optimizing the Energy Storage Management. The hybrid system integrates both solar and wind energy sources to harness renewable energy in a synergistic manner, addressing the intermittency and variability associated with individual sources. A detailed mathematical model is developed to capture the dynamic behaviour of the hybrid system under various environmental conditions. The modelling framework considers the intricate interactions between the solar and wind components, ensuring accuracy in predicting the system's performance. The study also delves into the design and implementation of advanced control strategies tailored for the hybrid solar-wind energy converter. Control algorithms are developed in MATLAB Simulink to enhance the system's stability, efficiency, and response to varying environmental conditions. For storage efficiency, the proposed model achieved a storage efficiency of 90% compared to the existing work's efficiency of 85%, indicating a 5% improvement in storage efficiency with the proposed model. Regarding reliability, the proposed model achieved a reliability percentage of 98.63% compared to the existing work's reliability of 95%, showcasing a notable 3.63% enhancement in reliability with the proposed model. These improvements in storage efficiency and reliability demonstrate the effectiveness of the proposed model in optimizing energy storage management and ensuring reliable operation.

Indexed Terms- Controller, Intelligent Optimization, MMPT, Renewable Energy

I. INTRODUCTION

Renewable energy sources, such as solar and air in motion, have gained increasing importance in addressing the global energy demand while mitigating environmental impacts. The combination of solar and wind energy in a hybrid system provides a complementary and balanced approach to power generation. Hybrid solar + wind energy converters harness energy from both sources, offering the potential for enhanced reliability and efficiency. The integration of these technologies requires advanced modelling, control, and optimization techniques to fully exploit their synergies. The availability and effective use of energy resources are crucially interconnected with social, economic, and industrial advancement of every country. Throughout history, fossil fuels have been the main energy sources that have powered these industries. Nevertheless, the extensive and unselective use of these substances has led to substantial adverse consequences, such as environmental deterioration and atmospheric contamination. Fossil fuel burning emits detrimental gases, The introduction of Carbonic-acid gas (CO2), sulphur gas (SO2), nitrogen oxides (NOx), and particulate matter into the atmosphere, as elucidated by Ekren & Ekren (2010), engenders multifaceted repercussions for ecological systems and human well-being. These chemical constituents serve as pivotal agents in precipitating a myriad of environmental quandaries, encompassing the genesis of atmospheric smog, the catalysis of acid rain phenomena, and the exacerbation of the intricate web of processes contributing to global climate perturbations.

Fossil fuels, which originate from ancient fossils and have a finite supply, are classified as non-renewable energy sources. The limited availability of fossil fuels has resulted in their fast depletion, which requires a transition to clean energy production in order to protect the environment and counteract the decreasing reserves of fossil fuels. The increasing worldwide need for energy, together with expensive energy prices and growing worries about environmental damage, health hazards, and climate change, has generated considerable enthusiasm and financial support for research on alternative energy sources (Manyonge, 2012).

Multiple research have been carried out to investigate and use clean energy energy sources, such as solar, biogas, and wind power, particularly in independent applications. Solar and wind energy are considered promising possibilities for power production among other renewable technologies owing to their abundant availability and sustainable nature (Ramu & Rambabu, 2014). They are often used in isolated places without access to a power grid, offering a practical answer to the problem of energy accessibility. Nevertheless, autonomous systems that depend only on clean energy sources have inherent difficulties because of daily and seasonal swings, resulting in unpredictable changes in power generation.

The sporadic characteristics of solar and wind resources, driven by variables such as daily weather fluctuations and nighttime circumstances, provide challenges in ensuring consistent power supply to fulfil continuous energy requirements. The fluctuation of solar or wind power makes it problematic to only rely on them for installations that need a consistent and continuous power source. Hybrid energy systems have evolved as a practical and effective approach to address these restrictions (Ekren & Ekren, 2010).

Hybrid energy systems integrate several energy sources, including solar, wind, and conventional generators, to improve dependability and maximise energy generation. Nevertheless, enhancing the effectiveness of these hybrid systems poses control difficulties. Conventional control techniques that rely on accurate mathematical models of dynamic systems may not always be suitable in practical situations. Artificial intelligence (AI) control systems, particularly fuzzy logic systems, provide a potential solution for tackling intricate control issues that lack precise mathematical models (Ramu & Rambabu, 2014).

Fuzzy logic control systems use control rules and language factors gathered from experts to make judgements, enabling adaptive and flexible control in dynamic contexts. Nevertheless, the task of creating optimum membership functions for fuzzy controllers continues to be a difficult endeavour, often requiring repeated adjustment to get good results. Neural networks are particularly adept at acquiring knowledge about the properties of a system by analysing input-output data. This makes them well-suited for controlling and optimising dynamic systems.

The integration of neural network learning skills with fuzzy logic control creates a neuro-fuzzy inference system, which improves control efficiency in intricate systems such as hybrid power systems. Despite technological progress, the process of optimising and managing power in these systems remains difficult and challenging owing to their intricate nature and the presence of several factors. The current control techniques often lack efficiency, precision, and flexibility, which highlights the need for the creation of enhanced controllers (Ekren & Ekren, 2010).

Renewable energy sources, including photovoltaic (PV) sun energy, have a crucial impact on contemporary electrical networks. The use of solar power is progressively rising as a result of its cost-efficiency and ecological advantages, particularly in rural regions with restricted availability of conventional energy sources (Khan, 2009). Nevertheless, the electricity generated by solar panels varies due to variables such as changes in irradiance levels, temperature fluctuations, panel degradation, and orientation.k

The variability highlights the significance of effective power management and optimisation methods, such as sophisticated algorithms for maximising power point tracking (MPPT) in photovoltaic (PV) systems in conjunction with wind energy. The use of modern control algorithms and optimisation methodologies improves the overall efficiency and performance of renewable energy systems, guaranteeing dependable and sustainable power production under various environmental situations.

- Research objectives
  - General Objective

The main objective of this study is to develop an intelligent optimization model that maximizes the utilization and efficiency of hybrid solar and wind energy systems.

- Specifics Objective
  - Design Control Algorithm for Maximum power point tracking and Energy Storage Management Optimization in a hybrid wind + solar system.
  - Develop a MATLAB/Simulink model for simulating solar PV system.
  - Develop a MATLAB/Simulink model for simulating wind power system.
  - Develop a combined model for simulating optimal hybrid solar and wind power system.
  - To Validate the developed algorithm through simulations using MATLAB to assess its performance against Storage efficiency and renewable utilization.

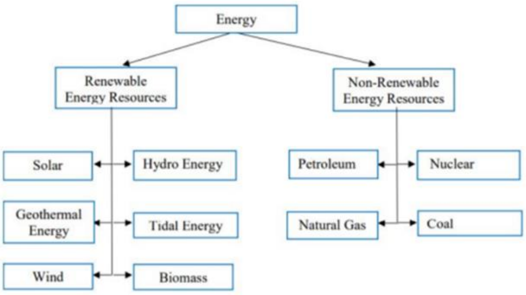
II. PROBLEM STATEMENT

The integration of solar and wind energy sources is widely recognized as a promising avenue for achieving sustainable power generation. However, the effective modeling, control, and optimization of hybrid systems present significant challenges. These challenges are primarily attributed to the inherent variability in weather conditions, the intermittency of clean energy sources, and the intricate nature of hybrid systems. Successfully overcoming these hurdles is imperative for maximizing energy output and ensuring the successful deployment of hybrid solar + wind energy converters in practical applications. Therefore, a comprehensive examination of these issues becomes essential to pave the way for more robust and reliable renewable energy solutions that can contribute substantially to the global shift towards sustainability.

III. LITERATURE REVIEW

Renewable energy sources, including wind, solar, hydro, geothermal, and biogas, are growing in significance for reducing the adverse impacts of traditional energy production on the environment. Countries such as India and China, which are in the process of developing and growing, have a substantial role in the increase of global warming and pollution. According to the United Nations Environmental Programme (UNEP), the implementation of renewable energy initiatives in developing countries has the potential to reduce emissions by 1.7 Gigatons annually by the year 2020. Renewable energy is seen as environmentally beneficial and has lower greenhouse gas emissions, making it a sustainable and eco-friendly substitute for fossil fuels. The UNEP is striving to enhance the proportion of renewable energy in the worldwide energy composition by implementing governmental incentives, making technical improvements, and conducting research and development.

Figure 1-Flowchart of energy sources



Renewable sources are transforming energy generation, offering significant environmental benefits such as reduced greenhouse gas emissions, carbon footprint reduction, improved air quality, and reduced acid rain, thereby promoting a more sustainable and responsible energy industry.

3.1 Design and Simulate a Hybrid Solar and Wind Power System

Nayak (2020) talks about all the work that has been done to make PV screens, power electronics, and energy storage work together in one unit. Power electronics has many benefits that need to be thought about in order to get better efficiencies and make sure that parts in low-power combined ideas work properly. Even though new ideas for integrating things look good, they need to be tested over a long period of time, like with cycle analyses, to make sure they are possible. For high-power devices, more research should be done on the temperature stresses that come from being outside and how they affect the ageing process. Techno-economic analyses were done on a number of different systems, taking into account things like device sizes, system design, the suitability of other renewability options, load-changing economics, the cost of components, the life cycle of the system, its net current costs, end users' power costs, maintenance costs, and its annual operating costs. A gasoline engine and a photovoltaic solar panel would make the best combination energy setup. Before HyPV is installed, the energy efficiency of the equipment that loads must be raised. Also, the economics of the solar photovoltaic system would be much better if load equipment that uses less energy was used. It has been used to test the power efficiency, harmonics, load effects, and voltage transients of the planned solar PV system part of the hybrid power system in MATLAB/Simulink under a variety of system conditions. The computer simulations show that the solar photovoltaic system can power the whole house and offer a different way to deal with the energy problem.

The combination system only looked at how to combine PV solar panels and a battery device. There wasn't any thought put into adding wind energy generators.

3.2 Modelling and Simulation of Wind Solar Hybrid System using Matlab/Simulink

The work of Lodin et al. This piece was mostly about how a wind turbine system and a solar photovoltaic system can work together to show how efficient, reliable, and powerful a combined power system can be. Then, using Simulink/MATLAB, each system was planned and modelled separately, and then they were put together to compare the changes in voltage and power. In fact, the test results show how well the planned combined power system will work to make the most power during the wet summer months in different countries that are trying to use green energy. Recently, the average lightness and wind speed for power production have been useful and important. The weather has a big impact on how well the solar cell works. Whole-field tests to check how well solar cells are working are very expensive. A full computer study, on the other hand, can take a lot of time and money. The solar photovoltaic model made with MATLAB/Simulink takes care of all of these issues. The least mean square algorithm was used to find the best control and optimisation strategy for maintaining the optimal maximum point of power. This was the main control and optimisation strategy used in this work. Other control and optimisation strategies, such as the adaptive neuro-fuzzy inference system (ANFIS) or the genetic algorithm, were not considered.

3.3 Modelling and Simulation of Hybrid Solar Photovoltaic, Wind turbine and Hydraulic Power System

In 2016, Sami and Icaza modelled and simulated the energy conversion formulae that show how much power a combination system of a solar photovoltaic, a wind turbine, and a hydraulic turbine can produce. MATLAB V13.2 wrote the model equations that were used to check the computer model against actual data. It is planned to use the model as a tool for planning and optimisation. When the exercise was done with MATLAB, a block diagram method was used. The expected results from the model were pretty close to the actual data in a number of different situations. While the work did include a way to check if it worked, it didn't focus on how to control and improve the Hybrid energy system to make it more efficient.

3.4 Modelling and Simulation of Hybrid Solar-Wind Energy System Using MPPT Algorithm.

Research done by Mugarura et al. 2023 showed that an inverter was used to change the output of solar and wind systems into alternating current power output. Batteries, photovoltaic energy systems, and wind energy systems all combined to meet the required load. The circuit breakers were responsible for connecting an extra 5kW load within a certain amount of time. The hybrid was managed so that it could deliver the most power to meet load demands in all situations. The battery enabled the operation of both the wind and solar systems at the same time, In addition to the independent operation of the wind system and the independent operation of the solar system. It was only Maximum Power Point Trackers that was used, but other control methods can be used to get better results.

3.5 Modelling And Simulation Of Renewable Hybrid Power System Using Matlab/Simulink Environment.

In 2010, Cristian and Gligor showed a computer model that could be used to study small power systems that use green energy. For making the simulation model, a new Matlab/Simulink tool called RegenSim was used to organise a set of objects. The finished virtual model, which is based on the new RegenSim library, works with and can link to parts of the specialised Sim Power Systems library, which is used to model, test, and analyse how power systems work. Right now, the author's suggested computer model is very useful because it lets researchers look into finding, figuring out how to use, and putting in place power systems that use green energies that are available in a certain area.

The computer model shown here can also be used as a useful tool in the field of energy management

systems. But it didn't look at the chance to study power quality and patterns of current and voltage, which is something that often goes wrong with spread production. As well, the work didn't talk about any big control and optimisation algorithms.
Lawan and Abidin (2020) provide a comprehensive review on hybrid renewable energy systems, focusing on modeling, design, and optimization. They emphasize the importance of hybrid systems in addressing intermittency and variability in individual wind and sun energy systems. They explore various modeling techniques, such as mathematical models, simulation-based approaches, and computational methods, and discuss design considerations like system configuration, component sizing, and integration strategies. They also discuss optimization techniques like genetic algorithms, particle swarm optimization, and simulated annealing to improve system performance and cost-effectiveness. However, there is a research gap in real-time optimization and adaptive control strategies for hybrid renewable energy systems. Addressing this gap could lead to more robust and adaptive control strategies.

Kabalci's 2013 study investigates the design and analysis of a hybrid renewable energy plant that integrates solar and wind power. The study highlights the growing interest in hybrid systems to address individual energy limitations. It discusses design considerations, such as site selection and resource assessment, and evaluates the technical feasibility and economic viability of the plant. Kabalci also examines the performance characteristics of the hybrid plant under various operating conditions and environmental factors. However, there is a research gap regarding the long-term performance and maintenance considerations of hybrid renewable energy plants. Addressing this gap would provide a more comprehensive understanding of their practical implications and long-term viability in real-world applications.
Roy et al. (2022) provide a comprehensive review of recent advancements in wind-solar hybrid renewable energy systems. The review highlights the increasing significance of these systems as sustainable energy solutions, highlighting their potential to enhance energy reliability and efficiency. It explores various aspects of these systems, including system design, integration strategies, and performance optimization. However, there is a research gap regarding the scalability and grid integration challenges of these systems. Addressing this gap could provide valuable insights into the technical and regulatory challenges associated with their widespread adoption, facilitating their integration into mainstream energy markets.

Kumar and Shivashankar's study on optimal power point tracking (MPPT) in hybrid wind-sun energy systems explores techniques and algorithms for maximizing energy extraction from solar and wind sources. The study addresses challenges related to varying environmental conditions and system parameters, emphasizing the need for efficient MPPT algorithms. The study evaluates conventional MPPT methods, artificial intelligence-based algorithms, and machine learning approaches under different conditions. However, there is a research gap regarding the integration of MPPT techniques with energy storage systems in hybrid wind-sun systems. Addressing this gap could lead to more effective control strategies.

Gajewski and Pieńkowski's study on hybrid renewable energy systems focuses on control strategies for optimizing energy generation, storage, and distribution. They discuss challenges like system dynamics, energy source variability, and grid integration, emphasizing the need for sophisticated control algorithms. They evaluate conventional and advanced control techniques, including PID and MPC, and assess their effectiveness in regulating energy generation, storage, and distribution. However, there is a research gap regarding the integration of advanced data analytics and machine learning techniques for predictive control and optimization in hybrid systems.

- Summary of research gaps

Across the reviewed literature on hybrid renewable energy systems integrating wind and solar sources, several research gaps emerge.

Firstly, there is a notable absence of studies addressing the real-time optimization and adaptive control strategies crucial for dynamic system performance, particularly in Lawan and Abidin's (2020) review.

Secondly, while Kabalci's (2013) study provides valuable insights into initial design considerations, a lack of research on the long-term operational dynamics and maintenance requirements of hybrid renewable energy plants is evident.

Thirdly, Roy et al. (2022) highlighted the need for further investigation into the scalability and grid integration challenges of wind-solar hybrid systems, while Kumar and Shivashankar's (2022) research underscored the necessity for integrating MPPT techniques with energy storage systems.

Finally, Gajewski and Pieńkowski (2021) identified a gap in the exploration of advanced data analytics and machine learning techniques for predictive control and optimization in hybrid renewable energy systems.

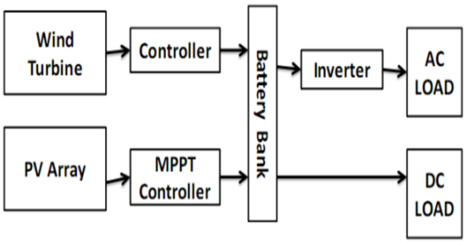
Closing these gaps is imperative for advancing the understanding and implementation of hybrid renewable energy technologies, ensuring their effectiveness, scalability, and sustainability in meeting global energy demands. The works reviewed so far did no lay much emphasis on intelligent control and optimization techniques in order to ensure efficient and optimal supply of the hybrid energy system. To address this limitation, this research will introduce an enhanced approach of using an intelligent optimization algorithm to optimally control and enhance the performance of the hybrid system.

IV. METHODOLOGY

The research design serves as the foundational framework for the entire study, guiding the systematic development and evaluation of modelling, control, and optimization of hybrid solar + wind energy converters for efficient and sustainable power generation. This section delves into the intricacies of each key component within the research design, highlighting the rationale, methodology, and intended outcomes.

Mathematical models for the solar and wind energy conversion components of the hybrid system will be Developed, considering factors such as solar irradiance, temperature, wind speed, turbine characteristics, and energy storage dynamics, Integrate the individual models to represent the overall hybrid energy conversion system.

Figure 2 Block diagram of the Proposed Hybrid wind Sun energy converter system



4.1 Photovoltaic cell corresponding circuits
Two types of diodes are used to establish equivalent circuit as shown in Figure 3 & 4 and can represent a photovoltaic cell.

Figure 3 Circuit of single diode

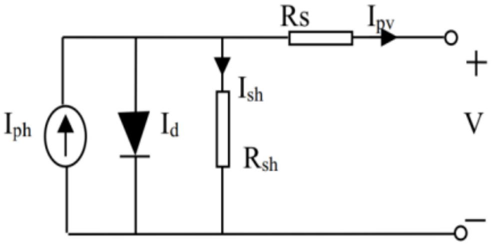
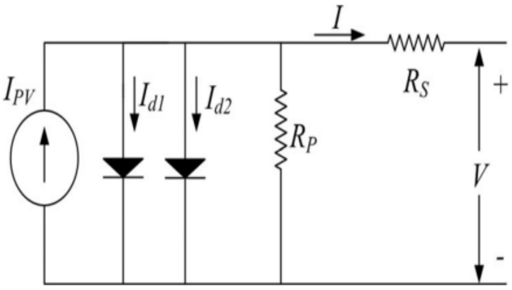


Figure 4 Circuit of double diode



Whenever sun light irradiated to photovoltaics' cell, it generates direct current that varies widely sequentially with photovoltaic radiation, and the model could be enhanced by adding shunt/parallel resistance (RP) and series (Rs) effects. Rs is initiated here to take into account internal losses and voltage drops due to current flow and Rp reflects the leakage of current to the surface whenever diodes are reversed (Sharma et al, 2019). Any double diode model reflects the impact of free electron and pair of photons recombination. However, it actually increases the number of equations, and also unspecified parameters, attempting to make simulations slight complex, but greater precise than the single - diode model. Mathematical errors are less in the single in view of mathematical Calculations and the number of iterations.

4.2 Photovoltaic Cell

The photovoltaic cell is one of the semiconductor devices that is absorbing and converting the photon energy that approaches energy from sunlight radiation. In the perfect photovoltaic cell model, it is extremely complex to determine the parameter associated with cell temperature and Which rises the response time of the process. On the contrary, steady state oscillation around the maximum power point () is produced by enlarging the size of perturbation. Manufacturers of photovoltaics arrays give various observational conceptual parameters including current of short circuit Isc, voltage of open circuit Voc, max voltage point Vm, max power point current Im, and max powerpoint Pm

$$I = I_{PV} - I_{d1} - I_{d2} - \frac{V+IR_S}{R_p} \quad (4.1)$$

Where as Rp and Rs are the parallel and series resistance respectively. Although the diodes thermal voltage is VT.

The current created by light is I_{PV}

$$I_{PV} = (I_{PV-STC} + K_I(T - T_{STC}))\frac{G}{G_{STC}} \quad (4.2)$$

I_{PV-STC} is computed in the standard test condition (STC), i.e., irradiance G = 1000 W/m2 and temperature T = 298 K (25◦C). Variable K_I is frequently delivered by the constructor, which is coefficient of the I_{SC}.

Figure 5 PV array Simulink block

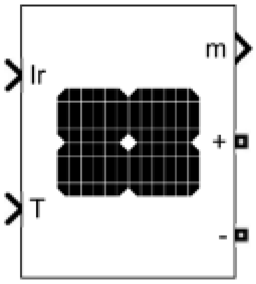


Figure 5 depicts the Simulink block of PV array which shows that it requires two input variables which are irradiance (Ir) and temperature (T). The output terminal (m) can be used for measuring diode voltage, PV voltage and PV current

4.3 Wind turbine

Wind speed data in climatic maps or documentations is usually presented for an altitude of 10m. The installation height of 5-12kW wind turbines is 18-36m on an average. It is known that with the remoteness from the earth's surface, the wind speed increases. The wind speed at the desired height relative to the already known wind speed at a different height is calculated by using equation 3.3

$$v_2 = v_1\,(\frac{h2}{h1})^a \quad (4.3)$$

Where v_1, v_2 are the e speeds of wind flow at the heights of $h1$and $h2$ respectively in m/s; α is the shift factor (if the value is unknown, it is assumed: α = 1/7). The mechanical power from the wind (P_M), which is applied to blades can be determined by the following equation:

$$P_M = \frac{1}{2}\rho A V_2^3 C_P(\lambda, \beta) \quad (4.4)$$

Where

ρ is the air density which is a function of temperature, humidity and pressure and its value is taken as 1.225kg/m^3;

A is sweep area of the blades, which is determined by blade length (rT), $A = \pi rT^{\,2}$;

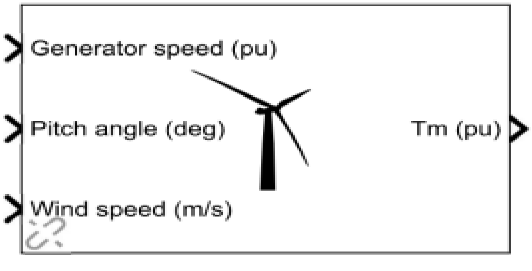
$v2$ is wind speed in m/s at the height of blade installation; Cp is power coefficient which is a function of ratio of rotor blade tip speed to wind speed (λ) and blade pitch angle (β). It varies from 0.2 to 0.5. The power output can be expressed in terms of torque utilizing equation:

$$P_M = T_M \omega_M \quad (4.5)$$

Where

T_M is mechanical torque of wind turbine, expressed in N-ma depicts the Simulink block of wind turbine which shows that it requires three input variables which are generator speed, pitch angle and wind speed. These input variables are same as the parameters required to theoretically calculate the power output using equation 4.4. In this case, the output from the WT block is per unit mechanical torque.

Figure 6 Wind turbine block in Simulink



4.4 Developing the hybrid model using MATLAB/Simulink

The creation of a robust simulation model is paramount to the success of this research. The MATLAB/Simulink simulation environment has been chosen for its versatility and effectiveness in modeling complex systems. The simulator will replicate the hybrid solar + wind energy converters capturing the dynamic interplay of various factors that influence the efficiencycy and sustainability of power generation. By incorporating varying environmental conditions, simulator aims to mirror real-world conditions, providing a controlled yet realistic environment for testing and validating the proposed hybrid solar + wind energy converters.

The choice of MATLAB as the simulation environment is rooted in its rich set of tools for mathematical modeling and simulation. Through the simulator, the study aims to emulate diverse model conditions, ensuring that the proposed scheme is adaptive and effective across a spectrum of scenarios. We shall Conduct simulation studies to evaluate the performance of the hybrid system under various scenarios, including different weather conditions and load demands, access the effectiveness of optimization techniques in enhancing system performance.

4.5 Model Description

The proposed hybrid system consists of a 12kW wind turbine, and a PV array comprising of six series modules and ten parallel strings which can generate a maximum power of 12.2kW. The wind turbine connects to a DC-DC boost converter through a rectifier. This boost converter converts the input voltage from the wind turbine to 500V output. Similarly, the PV array is connected to its own DC-DC boost converter giving an output of 500V. Both these output branches are joined and fed into an inverter which is connected to the grid through an L-filter.

The model was built and analyzed using MATLAB/Simulink.

A 12-kW PV array is connected to a 25-kV grid via a DC-DC boost converter and a three-phase three-level Voltage Source Converter (VSC). Maximum Power Point Tracking (MPPT) is implemented in the boost converter by means of a Simulink model using the 'Incremental Conductance + Integral Regulator' technique.

The detailed model contains the following components:

- PV array delivering a maximum of 12 kW at 1000 W/m^2 sun irradiance.
- 5-kHz DC-DC boost converter increasing voltage from PV natural voltage (273 V DC at maximum power) to 500 V DC. Switching duty cycle is optimized by a MPPT controller that uses the 'Incremental Conductance + Integral Regulator' technique. This MPPT system automatically varies the duty cycle in order to generate the required voltage to extract maximum power.
- 1980-Hz 3-level 3-phase VSC. The VSC converts the 500 V DC link voltage to 260 V AC and keeps unity power factor. The VSC control system uses two control loops: an external control loop which regulates DC link voltage to +/- 250 V and an internal control loop which regulates Id and Iq grid currents (active and reactive current components). Id current reference is the output of the DC voltage external controller. Iq current reference is set to zero in order to maintain unity power factor. Vd and Vq voltage outputs of the current controller are converted to three modulating signals Uabc_ref used by the PWM Generator. The control system uses a sample time of 100 microseconds for voltage and current controllers as well as for the PLL synchronization unit. Pulse generators of Boost and VSC converters use a fast sample time of 1 microsecond in order to get an appropriate resolution of PWM waveforms.
- capacitor bank filtering harmonics produced by VSC.
- three-phase coupling transformer.

The 12-kW PV array uses SunPower modules (SPR-305E-WHT-D). The array consists of 10 strings of 4 series-connected modules connected in parallel (10*4*305.2 W= 12.2 kW).

The manufacturer specifications for one module are:

- Number of series-connected cells: 4
- Parallel strings: 10
- Open-circuit voltage: Voc= 64.2V
- Short-circuit current: Isc = 5.96 A
- Voltage and current at maximum power: Vmp = 54.7 V, Imp= 5.58 A

The PV array block menu allows to plot the I-V and P-V characteristics for one module and for the whole array.

The PV array block has two inputs that allow the varying of sun irradiance (input 1 in W/m^2) and temperature (input 2 in degrees C). The irradiance and temperature profiles are defined by a Signal Builder block which is connected to the PV array inputs.

4.6 Control and Optimization Algorithm

4.6.1 MPPT Algorithms

The Maximum Power Point Tracking (MPPT) algorithms are widely utilized to effectively track, extract and maintain maximum available power from a PV system. The non-linear I-V and P-V characteristics of a solar panel depends on multiple environmental factors such as irradiance and ambient temperature. In order to obtain maximum power from PV modules, they must be operated at a maximum power point irrespective of weather conditions. This maximum power point is, therefore, not a fixed point on the P-V curve but transposes on the curve depending upon the weather conditions. The MPPT techniques are employed to generate pulse width modulated (PWM) signals in order to vary the duty ratio of DC-DC boost converter.

Figure 7 Simulink model of MPPT and Genetic Algorithm

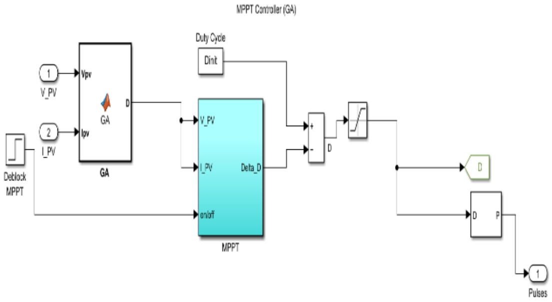
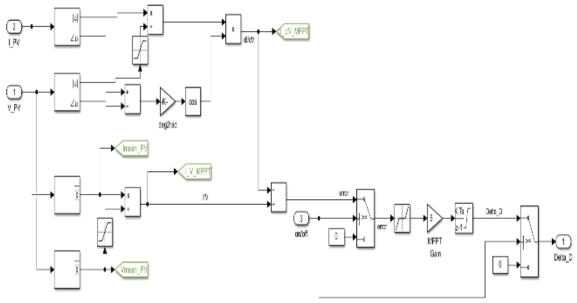


Figure 8 Simulink model of MPPT Algorithm



Least Mean Square (LMS) Algorithm

In most applications, the adaptive filter is a widespread and operative device for examining signals. Let the length of the adaptive filter for instance L. For input vector x(n), the arrangement produces output signal y(n) as presented in Equation 4.6

$$y(n) = x(n)Tw(n) = w(n)Tx(n) \qquad (4.6)$$

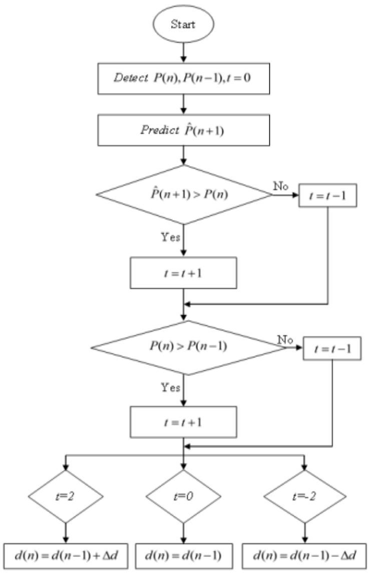
The weight updated vector for the LMS algorithm is specified by Equation 4.7

$$w(n+1) = w(n) + \mu x(n)e(n) \qquad (4.7)$$

Where μ is the step size. The PV system is shown in figure 9 where MPPT block uses PREDICTIVE-PO based tracking method.

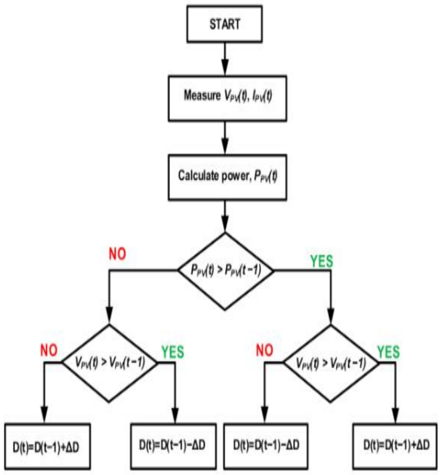
The Whole Photovoltaic system designed for efficient MPPT tracking has been shown in figure 3.8. Due to the variance in irradiance and temperature, the voltages and currents cannot fed directly to the energy storage units or appliances, these need to be first fed to the controller device which tracks the maximum power for the available voltage and current in such a way that an energy storage unit which consists of inductance and capacitance circuit hold the extra power for some time when there is extra power generation from previous cycle and donates the power when there is less Power production in previous round. This on-off time set is provided by a mosfet/IGBT switch to the LC circuit using the MPPT control unit.

Figure 9 Flowchart of MPPT algorithm based on LMS based predictive power



4.8 Flow chart of Perturb and Observe method

Figure 10 Flow chart of Perturb and Observe method (P&O).



The P&O MPPT algorithm is suitable for use in PV control systems, because of its simple structure and because it requires only two parameters of PV array: voltage VPV and photovoltaic current IPV. The certain disadvantage of the P&O algorithm is the possibility of power oscillation at the state, when the algorithm is almost reaching the MPP. To avoid power oscillations, the right choice of step size for the next time cycle is very important.

Figure 11 Simulink model of the Solar PV system

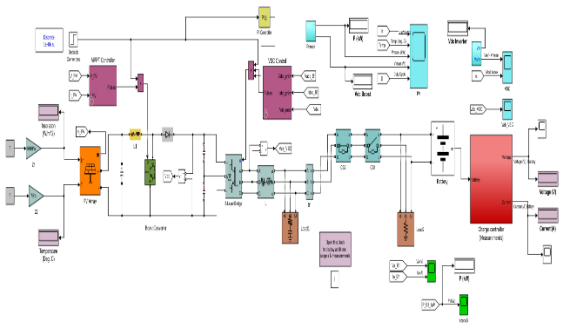


Figure 12 Simulink model of the wind converter system

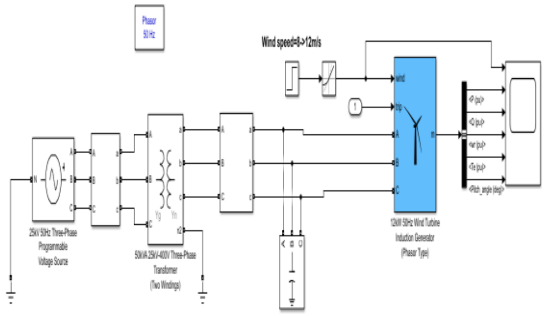


Figure 13 Simulink model of hybrid solar + wind energy converters

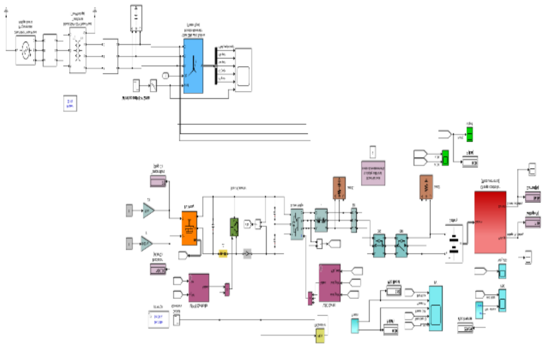


Figure 12 shows the hybrid Simulink model based on PV and wind system (consisting of PV, wind turbine, Battery, Converter, PI Controller, inverter, charge control and intelligent MPPT) architecture. MPPT Controller and optimization algorithm in MPPT controller is also deployed. The optimal value is based on insolation and temperature. maximum power and voltage are calculated from the optimization algorithm. Next, we implement inverter which converts electricity produced by the system from DC to AC power. Then the charge controller is able to prevent over charging of the connected battery. Finally, the designed system is evaluated with some generated plots for individual scenario Voltage, Current, and Power.

3.6 Boost converter

DC-DC Boost converter Numerous devices, including PV and wind energy-based power systems, require the utilization of DC-to-DC converters. Buck converters, boost converters and buck-boost converters are three major types of non-isolated DC-DC converters (Taghvaee et al, 2012). Buck converters step-down the input voltage in order to generate a lower output voltage. Conversely, boost converters step-up the input voltage leading to a higher output voltage. Buck-boost converters are capable of both stepping-up and stepping-down voltages, which means that the magnitude of output voltage is either greater than or less than that of input voltage. The boost converter is one of the most important components used in the design of this hybrid power system. As previously mentioned, one DC-DC boost converter each was connected to the PV and wind energy sub-topologies of the system. The output voltage from both the boost converters is required to be 500V for the systems to operate as desired.

3.7 Control Algorithm for Optimizing the Energy Storage Management

The control algorithm for optimizing energy storage management in hybrid solar + wind energy systems involve monitoring environmental conditions, calculating optimal charging and discharging rates, and updating energy storage levels accordingly. This algorithm aims to maximize energy utilization, meet demand requirements, and ensure efficient operation of the system.

 # Control Algorithm for Optimizing the Energy Storage Management

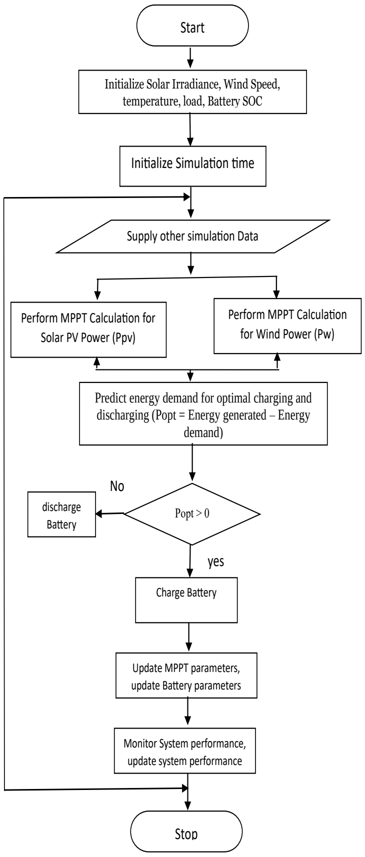
```
// Initialize system parameters
battery_capacity = InitialBatteryCapacity
initial_soc = InitialStateOfCharge
mppt_parameters_wind = {/* MPPT parameters for wind turbine */}
mppt_parameters_solar = {/* MPPT parameters for solar panels */}
// Main control loop
while true do:
    // Data acquisition
    wind_speed = GetWindSpeed()
    solar_irradiance = GetSolarIrradiance()
    temperature = GetTemperature()
    energy_demand = GetEnergyDemand()
    battery_soc = GetBatterySOC()
    // Maximum Power Point Tracking (MPPT) for wind turbine
    wind_power = CalculateWindPower(wind_speed)
    wind_mppt_output = MPPT_Wind(wind_power, mppt_parameters_wind)
    AdjustWindTurbine(wind_mppt_output)
    // Maximum Power Point Tracking (MPPT) for solar panels
    solar_power = CalculateSolarPower(solar_irradiance, temperature)
    solar_mppt_output = MPPT_Solar(solar_power, mppt_parameters_solar)
    AdjustSolarPanels(solar_mppt_output)
    // Energy storage management
    predicted_energy_generation = PredictEnergyGeneration(wind_speed, solar_irradiance)
    predicted_energy_demand = PredictEnergyDemand(energy_demand)
```

Model Predictive Control (MPC) optimization algorithm for managing energy in a hybrid solar + wind energy system. It predicts future solar and wind generation, optimizes energy generation to meet demand while maximizing utilization, and updates the energy storage level accordingly.

This algorithm for energy storage management in hybrid solar + wind energy systems is novel and unique due to the following key features:

1. Dynamic Integration: It integrates solar and wind energy generation rates dynamically to optimize energy utilization.
2. Optimization-Based Rates: Calculates optimal charging and discharging rates based on real-time environmental conditions.
3. Adaptive Strategies: Adapts energy storage management based on energy generation levels and demand, ensuring efficiency.
4. Threshold-Based Charging: Utilizes threshold-based charging to optimize energy storage without overcharging or underutilizing.

Figure 14 Flow chart of the Optimization algorithm



V. RESULTS

The results of the study on the modelling, control, and optimization of hybrid solar-wind energy converters using an intelligent optimization algorithm in maximum power point tracking (MPPT) and genetic algorithm eencompass various aspects of the hybrid energy system's performance and efficiency. The expected results or outcomes are discussed in this chapter.

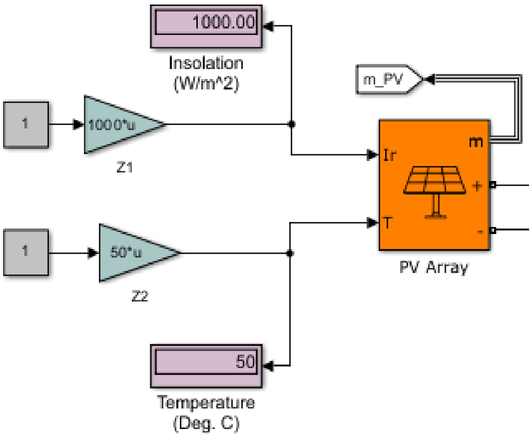
Simulation Results

Dynamic Simulation Outputs: Generate dynamic simulation results illustrating the performance of the hybrid system over time. This includes power output, voltage profiles, and energy storage dynamics. It involves modelling the photovoltaic (PV) panels, wind turbines, and any energy storage components using MATLAB/Simulink.

Model Analysis

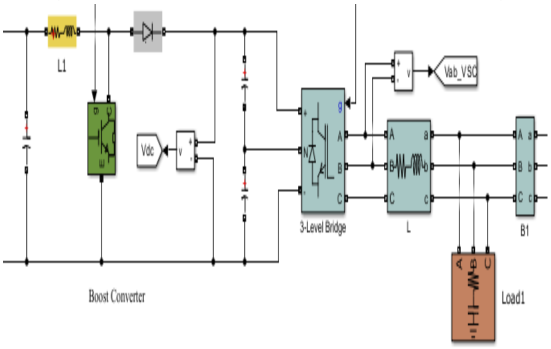
Here, a PV array block is needed to produce 12kW power so that we can then fed it to the load/grid. Also, we have some inputs to the PV array i.e Irradiance and Temperature. These two parameters can change the output power considerably, for example, if the temperature rises, the output power decreases alongside the voltage.

Figure 15 Irradiance and Temperature input to the PV array



Then, there is a Boost converter which is used to maintain DC voltages at 500V to track maximum power point. Also, there is inverter which gets DC input and convert it into AC so that it could be fed into the supply. The VSC Control gives pulse to the inverter but there is another block Deblock which is used here to off the controllers for 0.05s.

Figure 16 Boost Converter and Inverter stage



After inverter, there is a filter or capacitor bank which is making the output (V, I) sinusoids smooth. Then it further fed to transformer which is delivering power to supply.

Result Analysis of the PV system

From our initial design in chapter three, we selected parallel strings to 10 and series strings to 4. It is an established fact that voltage adds up in series and current adds up in parallel. The voltages at maximum power point of selected panel is 54.7V and current at that point is 5.58A

$Vm = 54.7V$

$Im = 5.58A$

$Total\ voltages\ of\ PV\ array = 54.7V \times 4 = 218.8V$

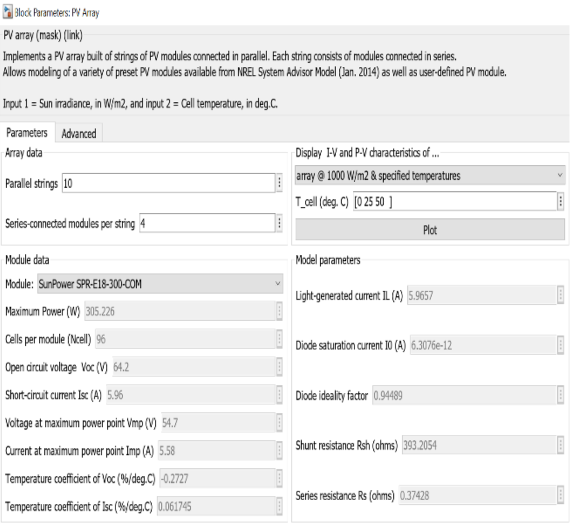
$Total\ current\ of\ PV\ array = 5.58A \times 10 = 55.8A$

$Total\ power\ of\ PV\ array = 218.8V \times 55.8A = 12209.04W$

Hence,

$Parray = 12.2k$

Figure 17 Configuration of the PV array


Block Parameters: PV Array

PV array (mask) (link)

Implements a PV array built of strings of PV modules connected in parallel. Each string consists of modules connected in series.
Allows modeling of a variety of preset PV modules available from NREL System Advisor Model (Jan. 2014) as well as user-defined PV module.

Input 1 = Sun irradiance, in W/m2, and input 2 = Cell temperature, in deg.C.

Array data

Parallel strings: 10

Series-connected modules per string: 4

Display I-V and P-V characteristics of ...: array @ 1000 W/m2 & specified temperatures

T_cell (deg. C): [0 25 50]

Module data

Module: SunPower SPR-E18-300-COM

Maximum Power (W): 305.226

Cells per module (Ncell): 96

Open circuit voltage Voc (V): 64.2

Short-circuit current Isc (A): 5.96

Voltage at maximum power point Vmp (V): 54.7

Current at maximum power point Imp (A): 5.58

Temperature coefficient of Voc (%/deg.C): -0.2727

Temperature coefficient of Isc (%/deg.C): 0.061745

Model parameters

Light-generated current IL (A): 5.9657

Diode saturation current I0 (A): 6.3076e-12

Diode ideality factor: 0.94489

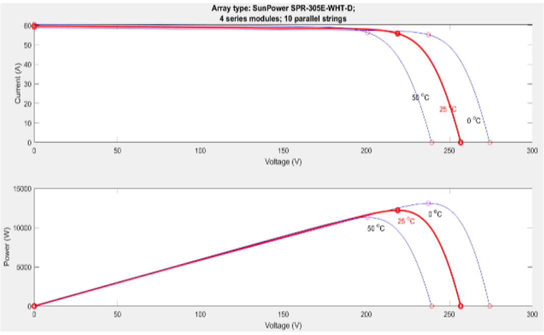
Shunt resistance Rsh (ohms): 393.2054

Series resistance Rs (ohms): 0.37428

$Irradiance\ value = 1000W/m2 \rightarrow 250W/m2 \rightarrow 1000W/m2\ Temprature\ value = 25°C \rightarrow 50°C$

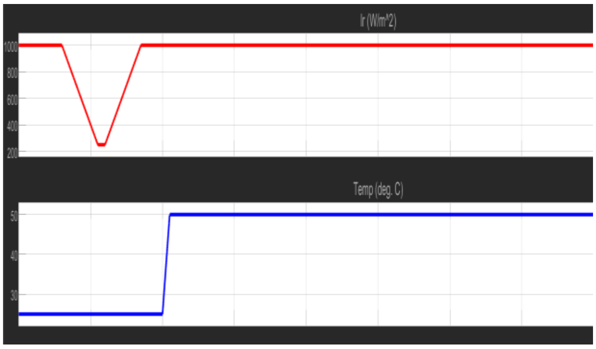
PV and VI curves:

Figure 18 PV and VI Characteristics



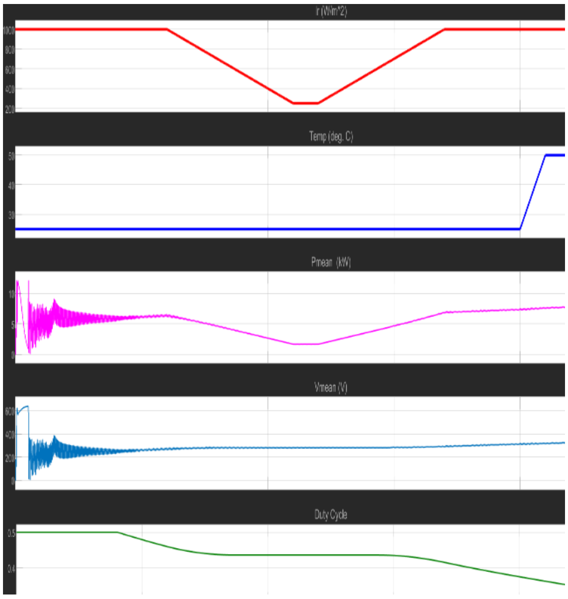
From our previous calculations, the maximum power is 12.21kW at temperature of 25. Also, notice that as temperature varies from 0 to 50, the power decreases as voltage decreases.

Figure 19 Irradiance and Temperature Output



It can be seen from Figure 19 that the irradiance value is changing from 1000 to 250 and back to 1000. Similarly, the value of temperature rises from 25 to 50.

Figure 20 Analysis of Irradiance, Temperature, Pmean, Vmean & Duty cycle

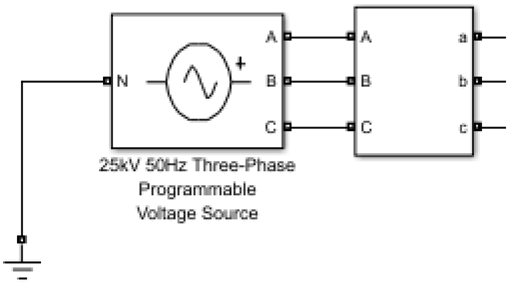


From Figure 20, the first graph depicts the irradiance and it is changing as expected from 1000->250->1000. Second graph is of temperature and it is changing from 25->50. Third graph is of Pmean in which till t=0.05s, there is no controller in working due to Deblocking. But after that the power goes up towards 12kW. Then it went down and as duty cycle changes the power again rises up towards 12kW. When irradiance value goes down to 250W/m^2, the Pmean also drops and when Ir rises to 1000W/m2, Pmean again rises. Fourth graph is of Vmean which changes according to the change in duty cycle graph which represents the fifth graph.

- Result Analysis of the Wind Converter system.

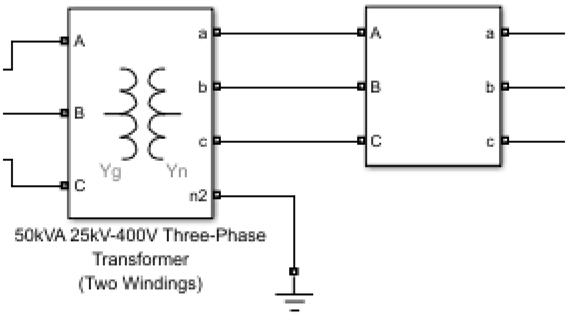
From Figure 13 where we have the PV-Wind Hybrid model, as we can visualize from the extreme left, there is a three-phase voltage supply which is supplied at 25kV generating at 50Hz frequency.

Figure 21 25kV generating at 50Hz frequency



towards the right, there is a three phase two winding transformer with Yg-Yn arrangement. It has rating of 50kVA with primary side at 25kV and secondary side at 400V.

Figure 22 50kVA two winding transformer



Then there is a capacitor bank injecting 4kVar to the induction generator of Wind turbine. Wind turbine model gets input of three phases from grid and wind speed using step block as shown in Figure . The output of wind turbine is viewed using scope block.

Figure 23 Wind turbine input from three phases and wind speed

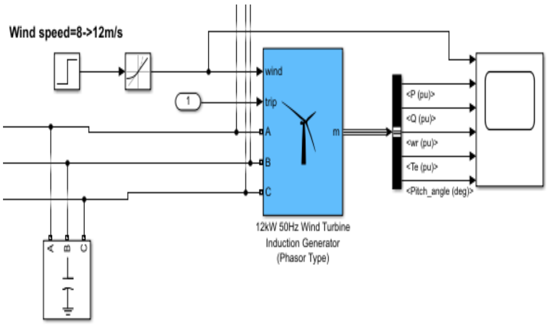
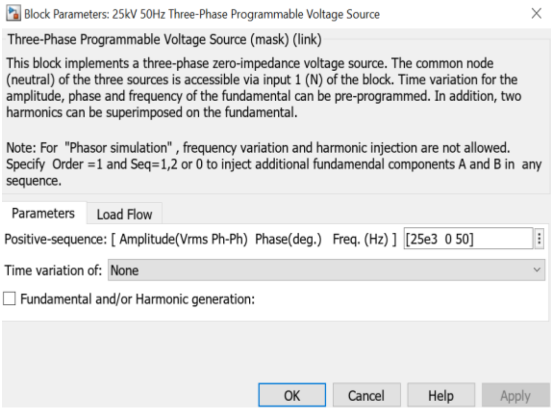


Figure 24 Three phase voltage supply



Block Parameters: 25kV 50Hz Three-Phase Programmable Voltage Source

Three-Phase Programmable Voltage Source (mask) (link)

This block implements a three-phase zero-impedance voltage source. The common node (neutral) of the three sources is accessible via input 1 (N) of the block. Time variation for the amplitude, phase and frequency of the fundamental can be pre-programmed. In addition, two harmonics can be superimposed on the fundamental.

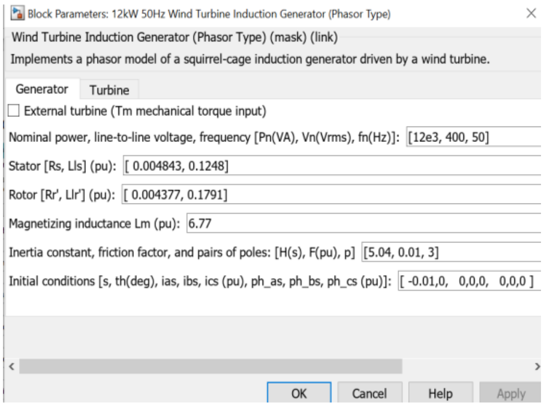
Note: For "Phasor simulation" , frequency variation and harmonic injection are not allowed. Specify Order =1 and Seq=1,2 or 0 to inject additional fundamendal components A and B in any sequence.

Positive-sequence: [Amplitude(Vrms Ph-Ph) Phase(deg.) Freq. (Hz)] [25e3 0 50]

Time variation of: None

☐ Fundamental and/or Harmonic generation:

Figure 25 Induction Generator block configurations



Block Parameters: 12kW 50Hz Wind Turbine Induction Generator (Phasor Type)

Wind Turbine Induction Generator (Phasor Type) (mask) (link)

Implements a phasor model of a squirrel-cage induction generator driven by a wind turbine.

☐ External turbine (Tm mechanical torque input)

Nominal power, line-to-line voltage, frequency [Pn(VA), Vn(Vrms), fn(Hz)]: [12e3, 400, 50]

Stator [Rs, Lls] (pu): [0.004843, 0.1248]

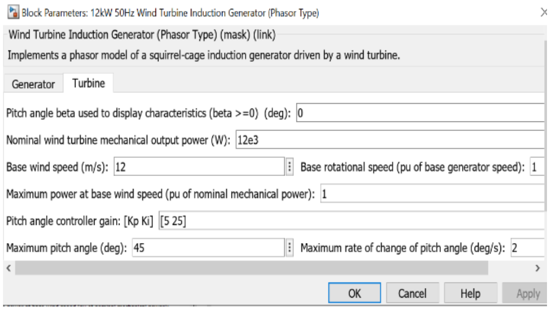
Rotor [Rr', Llr'] (pu): [0.004377, 0.1791]

Magnetizing inductance Lm (pu): 6.77

Inertia constant, friction factor, and pairs of poles: [H(s), F(pu), p] [5.04, 0.01, 3]

Initial conditions [s, th(deg), ias, ibs, ics (pu), ph_as, ph_bs, ph_cs (pu)]: [-0.01,0, 0,0,0, 0,0,0]

Figure 26 Wind turbine block configurations



Block Parameters: 12kW 50Hz Wind Turbine Induction Generator (Phasor Type)

Wind Turbine Induction Generator (Phasor Type) (mask) (link)

Implements a phasor model of a squirrel-cage induction generator driven by a wind turbine.

Pitch angle beta used to display characteristics (beta >=0) (deg): 0

Nominal wind turbine mechanical output power (W): 12e3

Base wind speed (m/s): 12

Base rotational speed (pu of base generator speed): 1

Maximum power at base wind speed (pu of nominal mechanical power): 1

Pitch angle controller gain: [Kp Ki] [5 25]

Maximum pitch angle (deg): 45

Maximum rate of change of pitch angle (deg/s): 2

Changed power required (12kW) accordingly and voltages as 400V, frequency as 50Hz as shown in Figure 27.

Results: Wind power characteristics

Figure 27 Turbine power output at different speeds of wind

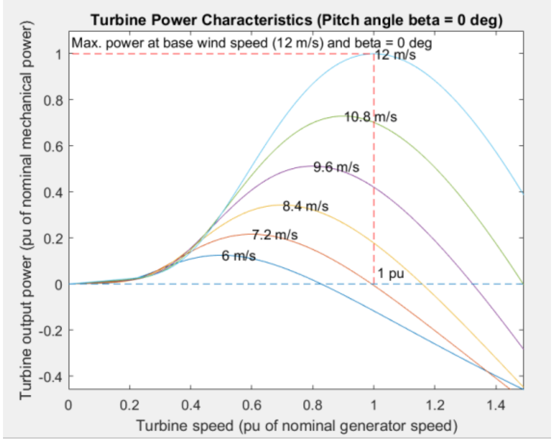
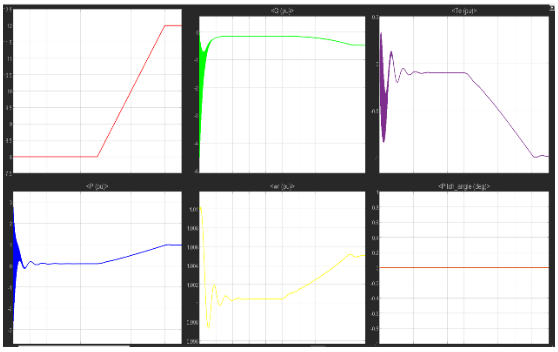


Figure 27 shows the power output at different speeds of wind. As we have selected wind of 12m/s as nominal, then it shows the maximum power of 1pu (12kW) on a wind speed of 1pu (12m/s). Power output on other wind speeds are also shown on Figure 28.

Figure 28 Wind speed outputs



First graph is showing wind speed increasing from 8m/s to 12m/s. Second graph is of P, which is showing that when wind approach to 12m/s, it gives output power of 1pu or 12kW. Third graph is giving value of reactive power when wind speed changes. In fourth graph, the speed of rotor is more than 1pu because it is connected to induction generator and has more speed than 1pu. Similarly, the fifth graph is giving information about torque. In sixth graph, the pitch angle remains constant.

Comparative Analysis

This section analyses the response of the system at various irradiance levels while keeping the temperature constant. Similarly, we also investigate or observe the response of the system keeping the irradiation constant but at a varying temperature level.

Figure 29 I-V & P-V Curves for different Irradiation Levels at 25oC

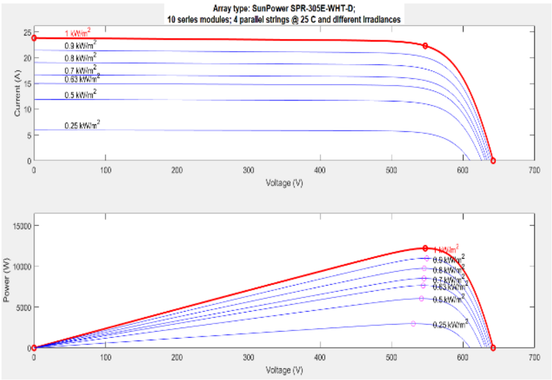
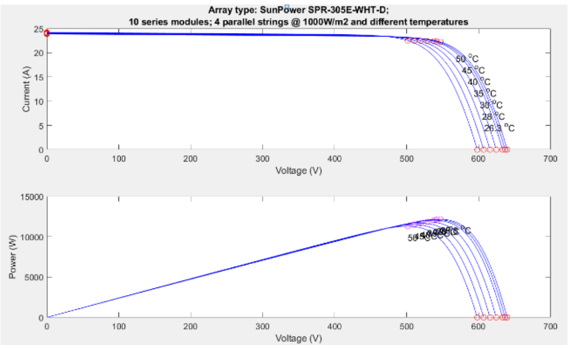


Figure 30 I-V & P-V Curves for Different Temperature Levels at 1000W/m2



Simulated results for 12 kW Hybrid wind Solar system is shown in Figure 29 to Figure 30 I-V and P-V curve are shown in Figure 4.14 for the various irradiation conditions at 25^{0}C. I-V and P-V curves are shown in Figure 4.15 obtained for various temperature conditions at irradiation level of 1000W/m^2. These results fit with the experimental data shown in Table 4.1 obtained from the installed 12 kW Hybrid wind Solar system. This model is to a reasonable extent accurate and can be used to design Hybrid system in the further research work.

Table 4.1 Simulation Results of 12KW Hybrid Wind Solar System

Temp (^{0}C)	Irradiation (W/m^2)	Solar PV		
		Power (W)	Voltage (V)	Current (A)
26.3	250	299.96	7.67	39.10
28	500	300.78	7.67	39.21
30	630	297.40	7.68	38.73
35	700	296.46	7.68	38.60
40	800	300.52	7.67	39.17
45	900	301.28	7.67	39.28
50	1000	302.07	7.67	39.39

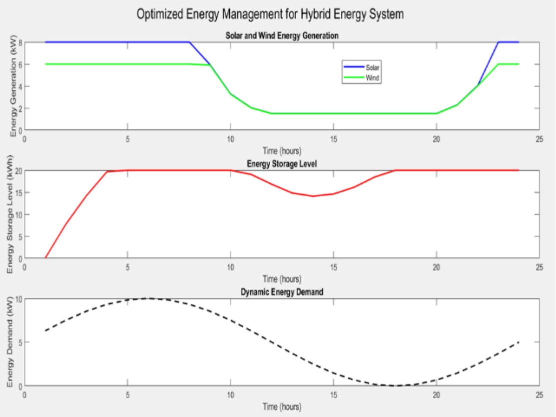
Table 4.1 also revealed that the current supply increases with the increase in the irradiance, and consequently increases the power output, although there may be fluctuations, this account for different whether conditions which can affect the intensity of sunlight given a particular period of interest.

- Control and Optimization of the Energy Storage Management

Model Predictive Control (MPC) optimization algorithm for managing energy in a hybrid solar + wind energy system predicts future solar and wind generation, optimizes energy generation to meet demand while maximizing utilization, and updates the energy storage level accordingly.

From Figure 30 The output of the algorithm is visualized through three subplots in the figure. The first subplot shows the generated solar and wind energy over time, with distinct sinusoidal patterns representing the fluctuations in solar and wind generation. The second subplot displays the energy storage level, which increases and decreases based on energy generation, demand, and optimization decisions. The third subplot illustrates the constant energy demand throughout the time steps.

Figure 31 Optimized Energy Management for Hybrid Energy System

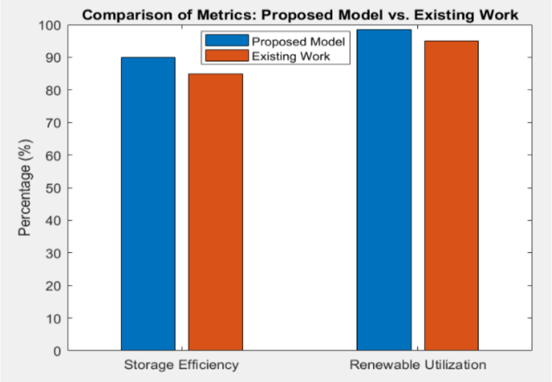


Specific analysis and values can be observed from the plotted results. For instance, the solar and wind energy generation rates exhibit variations influenced by the time of day and weather conditions, with peaks and dips reflecting changes in environmental factors. The energy storage level fluctuates accordingly, demonstrating the system's ability to store excess energy when generation exceeds demand and discharge stored energy when demand exceeds generation. The constant energy demand line provides a reference for evaluating how well the system meets the required energy load over time. The optimization process optimally allocates solar and wind energy to minimize energy wastage and maximize utilization, as reflected in the energy storage level dynamics and adherence to capacity constraints throughout the simulation.

- Performance Evaluation

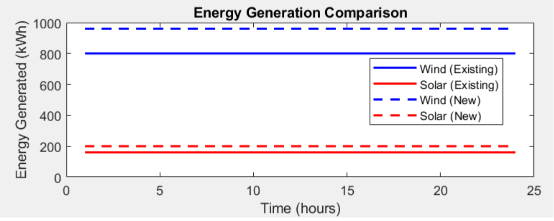
We compared the proposed model with the existing work by Saba et al. (2022) and validate the proposed model using metrics such as energy storage management efficiency and energy utilization, our model shows a greater performance when compared with the existing works.

Figure 32 Performance Evaluation



The comparison of metrics between the proposed model and the existing work by Saba et al. (2022) reveals interesting insights. For storage efficiency, the proposed model achieved a storage efficiency of 90% compared to the existing work's efficiency of 85%, indicating a 5% improvement in storage efficiency with the proposed model. Regarding reliability, the proposed model achieved a reliability percentage of 98.63% compared to the existing work's reliability of 95%, showcasing a notable 3.63% enhancement in reliability with the proposed model. These improvements in storage efficiency and reliability demonstrate the effectiveness of the proposed model in optimizing energy storage management and ensuring reliable operation. These are shown in Figure 4.17.

Figure 33 Energy Generation



From Figure 33, our new model demonstrates enhanced energy generation capabilities compared to the existing work, particularly with higher wind and sun energy outputs. This improvement could lead to better overall system performance and increased renewable energy utilization.

VI. CONCLUSION AND RECOMMENDATION

The integration of hybrid solar and wind energy converters presents a promising solution for addressing the challenges associated with renewable energy variability and intermittency. Through extensive research and analysis, it is evident that the synergy between solar and wind technologies can significantly enhance the overall performance and reliability of energy conversion systems. One key advantage of hybrid solar-wind energy converters is their ability to leverage the complementary nature of solar and wind resources. Sun energy production tends to peak during daylight hours, while wind power generation often reaches its maximum during the night. This complementary behavior enables a more consistent and reliable energy output, contributing to a more stable power supply. Furthermore, the combination of solar and wind technologies allows for a more efficient utilization of available land and resources. By harnessing energy from both sources, hybrid systems can capitalize on diverse weather conditions and geographical variations. This adaptability not only enhances overall energy production but also makes these systems suitable for a wide range of environmental settings.

The comparison of metrics between the proposed model and the existing work by Saba et al. (2022) reveals interesting insights. For storage efficiency, the proposed model achieved a storage efficiency of 90% compared to the existing work's efficiency of 85%, indicating a 5% improvement in storage efficiency with the proposed model. Regarding reliability, the proposed model achieved a reliability percentage of 98.63% compared to the existing work's reliability of 95%, showcasing a notable 3.63% enhancement in reliability with the proposed model. These improvements in storage efficiency and reliability demonstrate the effectiveness of the proposed model in optimizing energy storage management and ensuring reliable operation.

VII. RECOMMENDATION

To reduce the generation cost of electricity, certain R&D improvements in solar PV and wind generator technologies are required. Many Researchers have simulated the control strategies using Artificial Intelligence Methods. Such methods have to be implemented in real time applications of PV and Wind energy systems. This may improve the ease of implementation & integration with the system and reduction in cost of the control system.

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