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Design and Analysis of a Standalone Hybrid Microgrid for Agricultural Irrigation Using Solar and Diesel Energy Sources

Bhagyashri Meshram[1], Prof. Gaurav Karlekar[2], Prof. V. M. Pimpalkar[3]
[1]*PG Scholar, Department of Electrical Power Systems, Ballarpur Institute of Technology, Ballarpur, Maharashtra, India.*
[2,3]*Assistant Professor, Department of Electrical Power Systems, Ballarpur Institute of Technology, Ballarpur, Maharashtra, India.*

Abstract: Agricultural irrigation requires a reliable and continuous energy supply, particularly in rural and remote regions where grid availability is limited or inconsistent. Traditional irrigation systems largely depend on diesel generators, which lead to high fuel costs, operational expenses, and environmental pollution. To address these challenges, this study proposes a stand-alone hybrid microgrid system integrating solar photovoltaic (PV) panels, diesel generators, and battery energy storage for agricultural irrigation applications. In the proposed system, solar PV acts as the primary energy source, converting solar energy into electrical power for irrigation pumps. A Maximum Power Point Tracking (MPPT) technique is employed to maximize solar energy extraction under varying environmental conditions. Battery storage is incorporated to store excess solar energy and provide backup power during night-time or low solar irradiance. The diesel generator functions as a secondary source to ensure uninterrupted operation when renewable energy is insufficient. The system is modeled and analyzed using MATLAB/Simulink to evaluate performance under varying load and weather conditions. Results indicate that the hybrid microgrid significantly reduces diesel fuel consumption, operational costs, and greenhouse gas emissions while maintaining reliable irrigation power supply, making it a sustainable solution for rural agricultural energy systems.
Keywords: Maximum point of power tracking (MPPT), solar, grid interaction, diesel generators, voltage source converters, and irrigation work etc.

I. INTRODUCTION

The global agricultural sector consumes more energy than any other industry because irrigation systems require electricity to operate. The majority of irrigation power requirements in developing and rural areas depend on diesel generators because these locations experience unreliable electricity grid access. Diesel generators enable operations to run smoothly while providing dependable power sources but their widespread usage drives up fuel expenses while generating more greenhouse gases and harming the environment [1]. Agricultural operations need cleaner energy solutions because rising fuel costs and climate change concerns create urgent demand for sustainable energy options.

Solar photovoltaic (PV) systems have become popular because they provide renewable energy which is becoming more affordable and has positive impacts on the environment. Most agricultural regions receive sufficient solar energy which matches their irrigation needs during the day [2]. PV systems convert sunlight into electrical power which helps decrease the need for fossil fuel resources. The natural patterns of solar energy production which develop because of daily sun cycles and weather changes and seasonal variations make it impossible to generate constant power for irrigation needs from solar energy when it functions as the only energy source [3].

The hybrid energy systems which use solar PV together with diesel generators and battery energy storage systems provide an effective solution to these problems. Hybrid microgrids combine the advantages of renewable and conventional energy sources, which creates reliable systems that make maximum use of renewable energy resources [4]. The solar photovoltaic system functions as the main power source in these systems, while diesel generators provide emergency power during periods of low solar energy or when demand reaches its highest point. The system uses battery storage to improve its performance by controlling power variations and storing excess solar energy, which it uses to deliver power during periods of nighttime and cloudy conditions [5].

Microgrids function as local energy systems which can operate either as part of a grid or independently without it. The rural agricultural areas which lack access to electrical grids function as ideal environments for establishing stand-alone microgrids which provide dedicated power supply [6].

Research shows that PV-diesel-battery hybrid microgrids reduce both diesel fuel usage and operational expenses while decreasing carbon emissions when compared to systems which use only diesel power [7].The advancement of power electronics together with control algorithms and energy management systems has resulted in improvements to system stability which boost efficiency and enable systems to scale up their operations.

Energy management systems (EMS) provide essential support for hybrid microgrid systems to achieve their maximum operational efficiency. Intelligent EMS systems prioritize renewable energy resources while they manage battery operations and diesel generator scheduling to achieve the lowest fuel usage and equipment maintenance needs [8]. The Maximum Power Point Tracking (MPPT) technique enables PV panels to achieve their highest energy output under different environmental conditions which results in better overall system efficiency [9]. The evaluation of techno-economic feasibility and optimal system sizing requires simulation platforms and optimization tools which use both HOMER and MATLAB-based models for their assessment [10].

The hybrid microgrid research field has produced multiple studies but the research area still needs to overcome several existing obstacles. The research needs to solve the problems which include accurate load forecasting for irrigation systems and understanding long-term battery degradation and managing control system complexity and developing site-specific design requirements [11]. Most studies investigate either generic rural electrification systems or island systems while they fail to examine the specific agricultural load patterns and operational restrictions which farmers need to operate their businesses [12]. The agricultural sector requires hybrid microgrids which need to solve these existing gaps.

II. EXISTING SYSTEM

In most agricultural regions, irrigation systems primarily rely on grid electricity or diesel generators to operate water pumps. However, in many rural and remote areas, grid supply is often unreliable due to frequent power outages, voltage fluctuations, and limited infrastructure.

As a result, farmers commonly depend on diesel generators as an alternative power source for irrigation. Although diesel generators provide reliable power, they involve high fuel costs, regular maintenance, and significant environmental pollution due to greenhouse gas emissions. Additionally, diesel-based systems are inefficient for long-term agricultural operations and increase the overall cost of farming. Some areas have begun using standalone solar irrigation systems, but these systems face limitations because solar power is only available during daylight hours and is affected by weather conditions. Consequently, existing systems struggle to provide continuous, cost-effective, and sustainable power for irrigation needs.

III. PROPOSED SYSTEM

The proposed system is a hybrid microgrid designed to provide reliable and sustainable power for agricultural irrigation. It integrates a solar photovoltaic (PV) system, a diesel generator, and a battery energy storage system to ensure continuous electricity supply. The PV system acts as the primary energy source, generating clean power during daylight hours. An MPPT (Maximum Power Point Tracking) controller is used to maximize the efficiency of the PV panels by operating them at their optimal voltage and current conditions. The battery storage system stores excess solar energy and supplies power during low solar generation periods. The diesel generator functions as a backup source when renewable energy and battery storage are insufficient. An advanced energy management system controls power distribution, reduces diesel consumption, and ensures stable and efficient operation for irrigation loads.

IV. PROJECT DESCRIPTION

The static synchronous compensation system operates as a regulated voltage source inverter (VSI) which supplies electrical power to the grid. The system maintains supply current in accordance with designated phase-angle values which it achieves by balancing supply current with actual voltage supply. The inverter delivers reactive current which creates electrical energy that can be used to counteract both the inductive generator and non-linear load generated reactive current and harmonic emissions. The process improves electricity quality through power factor enhancement.

The electrical converter generates its current command through a process which involves subtracting the synchronized grid voltage from the electrical system. The grid connection methods at the point common coupling (PCC) base power quality improvements have been reversed. The grid-connected system displays an example of its functioning operation.

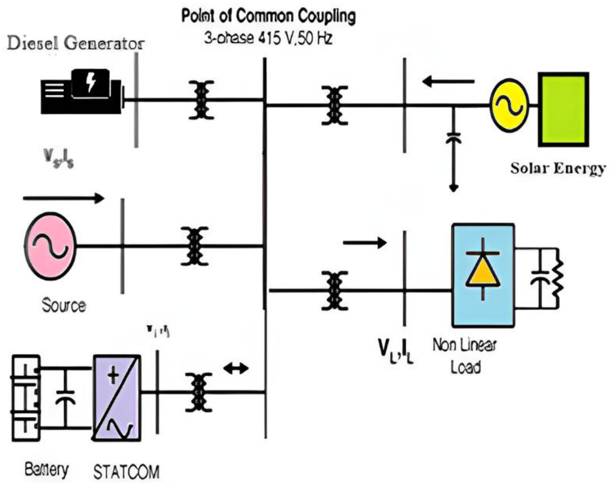

Figure 1.Grid Connected Solar and DG generator System

The project implements DG generator together with PV solar panels for irrigation systems which support agricultural activities. The solar panels generate electrical power which the charging controller distributes to users. The charging control system supplies power to operate the solar tracking system. The solar tracking device enables accurate sun-based solar panel alignment. The leftover energy serves two purposes which include powering devices and charging batteries. The system depends on battery backup for power supply during nighttime. The DC electrical supply system transmits power through DC distribution cables which connect to DCDB (DC Distribution Box) for further distribution. The boost converter enables us to extend our transmission range for longer distances. The microgrid network can be disabled through a single button which activates fault protection measures. The microgrid network repeats its operation to extend its coverage area.

The proposed hybrid microgrid system for agricultural irrigation uses solar photovoltaic (PV) panels and battery energy storage and diesel generator to produce continuous power supply. Solar PV panels act as the primary energy source which converts sunlight into electricity during daytime. The system uses a charge controller with Maximum Power Point Tracking (MPPT) to manage DC power distribution which optimizes power extraction from solar energy sources under different weather conditions. The regulated energy supply system directly powers irrigation pumps while also charging the battery storage system.

The battery provides backup power during night-time and periods of low solar availability which enables continuous irrigation operation. The diesel generator starts automatically to provide necessary power when solar and battery power together fall short of meeting load requirements thus maintaining system reliability. An intelligent microgrid control unit continuously monitors load demand and battery state of charge and solar generation to manage power flow efficiently among the sources. This control strategy prioritizes renewable energy usage, minimizes diesel runtime, reduces fuel consumption, and enhances overall system efficiency and sustainability.

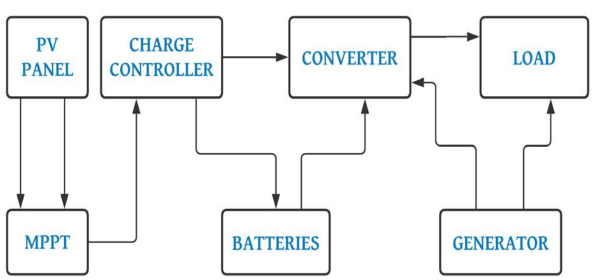

Figure 2: Representation of Hybrid Solar PV- Diesel System

The researchers created a hybrid microgrid system for agricultural irrigation projects which they could model and test through MATLAB/Simulink. The MATLAB environment allows users to create precise mathematical representations of system components which include solar photovoltaic (PV) arrays, diesel generators, battery energy storage systems, DC–DC converters, inverters, and irrigation pump loads. The simulation framework enables accurate evaluation of system performance under varying solar irradiance, temperature, load demand, and operating conditions specific to agricultural irrigation.

The research team used MATLAB to implement control strategies which included Maximum Power Point Tracking (MPPT) for PV systems and intelligent energy management algorithms to achieve optimal power generation and efficient energy source usage. The battery model supports analysis of state of charge (SOC) charging–discharging behavior and backup operation during nighttime or low solar conditions. The diesel generator model is incorporated to supply power during peak irrigation demand or insufficient renewable availability.

MATLAB/Simulink permits users to evaluate various operating scenarios which test both off-grid and grid-connected irrigation systems. The developed schematic model shows how all subsystems work together to create a complete view of hybrid microgrid systems used in agricultural irrigation.

V. TOPOLOGY OF THE HYBRID SYSTEM

To specify these parts and describe their roles, the general topology must be established before concentrating on any one of the system's components. Figure 1 shows the layout of the system under study. There is representation of the many power directions. The entire paper makes use of the sign system shown in Figure 3. The PV generator, the energy storage capacity of the batteries, the user demands Report Word plus dump demand, the internal combustion engine, and the electronic converters who transform power are the fundamental components of the combined system. Details on the parameters and calculations for the batteries' health and state of charge are given in the sections that follow. The sign convention implies that the rules of physics account for the structure's imbalance of power:

$$P_{DIESEL}(t) = P_{LOAD}(t) + P_{DUMP\ LOAD}(t) - P_{PV}(t) - P_{BAT}(t) \qquad (1)$$

When using PDIESEL, battery energy storage and pv solar power plants provide PPV and PBAT, respectively, of the electrical power. PLOAD and PDUMP LOAD, respectively, are the power consumption percentages for the primary load plus the dump load.

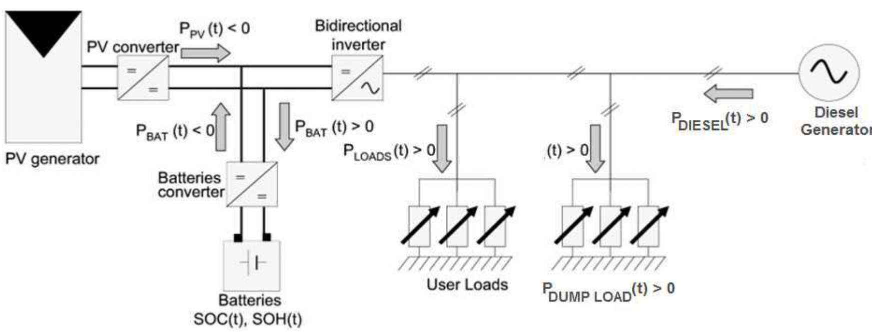

Figure 3: Sign language and power hierarchy in the system for investigation [3]

This approach's main goal is to generate electricity in any way, from any source (AC or DC, frequency-independent), and use converters to convert it into the proper voltage needed to power loads or storage systems. To enhance the amount of renewable energy collected, many other sources (hydro, wind, etc.) might be added to the same concept; however, this would complicate the system and make research into it more difficult. The system's independence will be guaranteed by the battery bank. It is equipped with a special DC/DC converter that controls how much the battery charges and drains. The bidirectional converter may have the ability to control other system components in order to employ the optimal battery management technique.

VI. MICROGIRD MODELING FOR HYBRID SYSTEM

A. PV system

The approach taken to model the PV array in this study is as simple as looking at relevant factors and figuring out how they could affect the amount of electricity generated, then using mathematical equations to determine the voltage and current produced at the chosen temperature and irradiance to the power that is produced at the usual temperature circumstances (STC). The factors that determine STC are an incidence of 48.2 documents, an outer temperature of 25 degrees Celsius, and an air mass of 1.5. The PV panels always operate at the maximum voltage point of the I = f (V) curves if the charge controller has an MPPT system installed. Thus, the PV generator's output current is as follows [6]:

$$I_{pv}(t) = I_{mp} \cdot \frac{G(t)}{G_{STC}} \cdot \left[1 + \frac{\mu_{I,OC}}{100}\left(T_c\ (t) - 25\right)\right] \qquad (2)$$

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where Imp, which is found in the PV panel's datasheet, is the operational current when the power is at its highest. Additionally, the panel's MPPT controller's output voltage is:

$$V_{pv}(t) = V_{mp} \cdot \left[1 + \frac{\mu_{V,OC}}{100}\left(T_c\,(t) - 25\right)\right] \quad (3)$$

The temperature factor of VOC [%/ºC] is represented as µV, OV. As a result, the PV system incorporating MPPT's final output power is:

$$P_{pv}(t) = V_{pv}(t).I_{pv}(t) \quad (4)$$

B. Diesel generator

In order to determine the optimum course of action for lowering the hybrid system's operating costs, we are investigating effective power flow regulation in conjunction with leadership in this project. Considering the diesel engine's complete automation, which generates the necessary output power while preserving constant frequency and voltage levels, we may not be very concerned with the system's internal workings or structure. The most important aspects that must be considered are the quantity of fuel utilised by the electricity-producing generator and how it relates to the demand load. The diesel fuel use of a 15 KVA single-phase generating set is depicted in Figure 2 [7], per the manufacturer's datasheet. The proportion of nominal capability on the electrical plant and the hourly fuel consumption are nearly linearly correlated. Using this graph as a model, one may compute the engine's running fuel consumption using linear interpolation techniques.

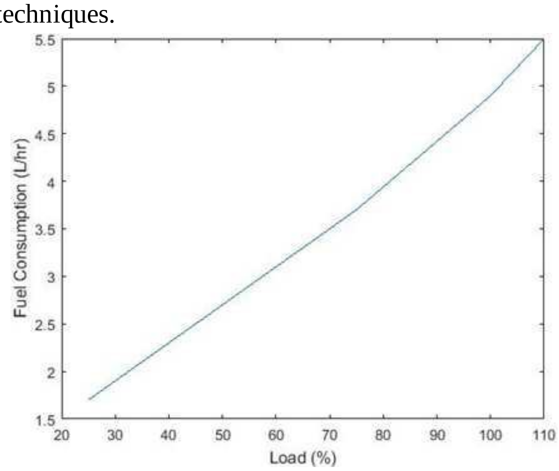

Figure 4. Fuel consumption of diesel generators

C. Battery

1) Battery Modelling

The model selected for this investigation considers the battery's level of charge. The fundamental model of a circuit having an ideal voltage with fixed impedance for a battery is enhanced by this dynamic model with an additional source of power that depends on the state of charge (SOC) and constant internal resistance (Figure 3).

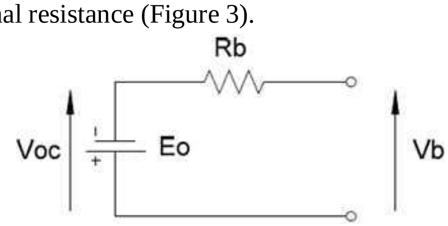

Figure 5: Basic Circuit Diagram [8]

Equation () represents the expected linear relationship between the open circuit current and the state of an ion charge (Voc) [8]:

$$V_{OC} = U_{max}.SOC + U_{min}.(1 - SOC) \quad (5)$$

These figures, which come from the datasheet provided by the battery manufacturer, Demonstrate that the open channel value with a full battery is Umax, and the open circuit cost with an empty battery is Umin. The charging temperatures at the batteries's terminals can regulate how much current is used to charge the battery. This current can be computed utilising the equation provided above [9]:

$$I_{ch} = \frac{V_S - V_{OC}}{R} e^{-a.SOC} \qquad (6)$$

The equation can be changed by computing the coefficient a by replacing the voltage & state of charge with the experimental values. To finish our battery model, we need to add a state of full model to it. There are two possible consequences when the charge state is altered: charging and discharging [10].

- ***While the device is charging:***

$$SOC(t + \Delta t) = SOC(t) + \frac{\eta_{bat} \cdot I_{ch} \cdot \Delta t}{C_b} \qquad (7)$$

There will definitely be losses because not all the the power that is put into a battery could be stored. The battery's charge efficiency is indicated by ηbat, or round-trip efficiency. This factor has ranges between 0.7 and 0.85 during the charge phase and equals 1 during the discharging phase. Cb is the battery's overall capacity and the duration of the charge [10].

 While discharging:

$$SOC(t + \Delta t) = SOC(t) - \frac{I_{disch} \cdot \Delta t}{C_b} \qquad (8)$$

2) Cycling and Capacity Degradation

Because the estimations of the projects' energy costs are highly unpredictable due to the ambiguity around the estimated lifetime of the batteries, modelling the batteries' lifetime is a critical component of simulation of hybrid power systems. Potential renewable energy sources investors confront a great deal of uncertainty because the life cycle cost of the batteries is one of the primary power system costs. The depth of charge-dis cycles, power, cell voltage, the effectiveness of the charge control system (e.g., voltage along with to the state of the position restricts as well as regulation), the duration of a dead battery nation, the time since the last full charge, the temperatures, and so forth are just a few of the many variables influencing the lifespan of a battery.

A number of academic studies that concentrate on the optimisation and simulation of environmentally friendly standalone systems, such as batteries, have been released. Nonetheless, the battery lifetime has traditionally been calculated using the number of comparable full cycles and set values determined by the results of several studies. In ideal circumstances, the cycle counting approach might be used to estimate it (CCM).

The CCM makes the assumption that when the Ah-throughput reaches the nominal battery capacity, the cycle is complete. To estimate the lifespan, To find the number of complete cycles, add the amount of charge (Ah flow) that a battery has cycles using the calculation below (ZN) [8]:

$$Z_N(t + \Delta t) = Z_N(t) + \frac{I_{disch} \cdot \Delta t}{C_N} \qquad (9)$$

where Idisch represents the discharge current's absolute value. The battery has a nominal maximum capacity of CN. The battery is nearing the end of its life when its capacity drops to 80% of the advertised capacity. This degradation-related capacity loss is computed by applying the Schiffer equation [8]:

$$C_{deg}(t) = 0.8\, C_N . \exp\left[-5.\left(1 - \frac{Z_N(t)}{1.6.Z_{IEC}}\right)\right] \qquad (10)$$

whereby ZIEC is the product's anticipated total number of cycles as per IEC regulations. Therefore, the difference between the battery's initial legal capacity and the amount of capacity lost due to degradation is used to compute the battery's residual capacity:

$$C_{rem}(t) = C_N - C_{deg}(t) \qquad (11)$$

VII. POWER MANAGEMENT SYSTEM

A database is required to explain, model, and validate the leadership plan. Because of this, we were able to retrieve the data on sun irradiation, ambient temperature, and the diesel engine's electrical load. In order to size the hybrid energy source and develop a strategy that works with it, these data will be used.

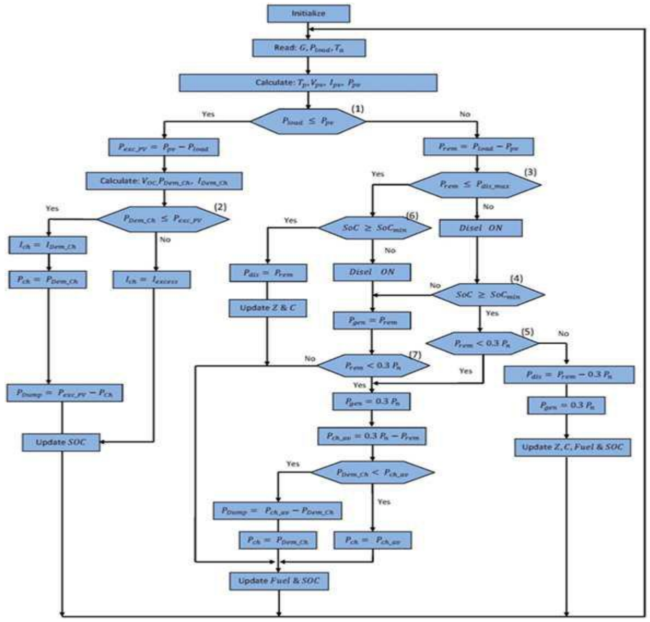

Figure 6: Power management strategy in hybrid system

It elaborated the management and control strategy for the PV-Diesel-Battery combination by starting with the examined models of the system's components, considering the previously stated constraints and goals, and using the actual study data as a guide. The technique is depicted as an infinite loop in Figure 4's flow chart, which reads inputs form an external source and outputs the results throughout each interval. The inputs, which include the ambient temperature Ta, the requested power by the load Pload, and the solar irradiation G, must be read once the system parameters have been initialised. This information is gathered from the case studies profile surface, which offers a sample each ten minutes. The temperature of the panel, as well as the voltage and current that is output of the PV system, are determined using the mathematical model of the PV system. Included also are converter losses. By using this data, power may be evenly distributed across all of the sources (diesel, PV), loads (main while dump loads), and battery power storage, extending battery life and minimising the hybrid system's overall cost per kilowatt.

VIII. DESIGN AND SIMULATION

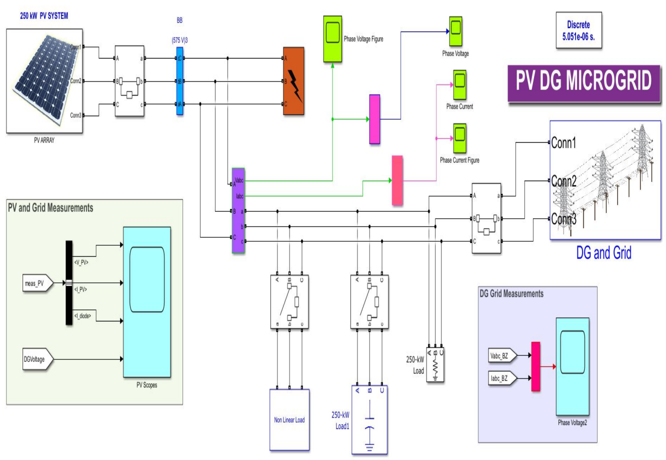

Figure 7. Design of a Stand-Alone Hybrid Microgrid System using Diesel generator and PV

Designing a stand-alone hybrid microgrid system involves integrating a diesel generator and photovoltaic (PV) panels to ensure reliable, sustainable power. The PV panels serve as the primary energy source, harnessing solar power to supply electricity. A battery storage system stores excess solar energy for use during low solar periods. The diesel generator acts as a backup, providing power during extended cloudy periods or high demand.

A microgrid controller manages the energy flow, optimizing the use of PV and diesel generator to ensure continuous power supply, reduce fuel consumption, and lower emissions. This hybrid system enhances energy reliability and sustainability.

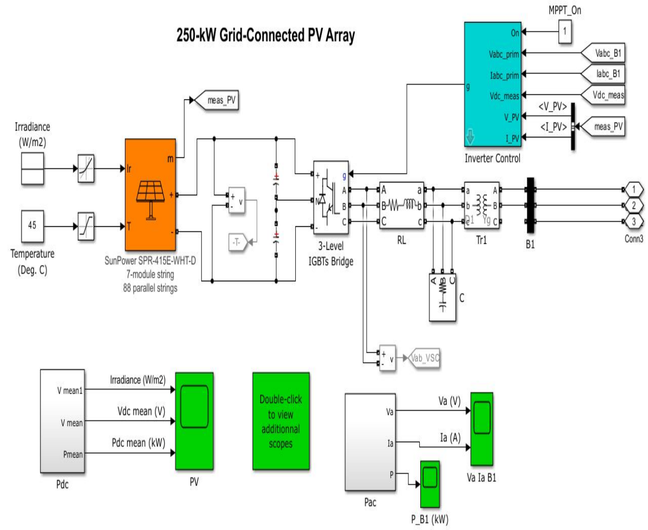

Figure 8. PV Array Design

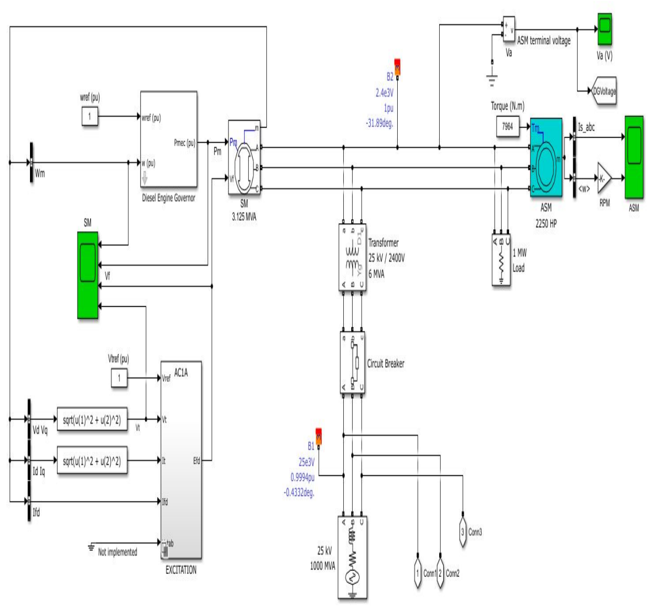

Figure 9. DG and Grid system design

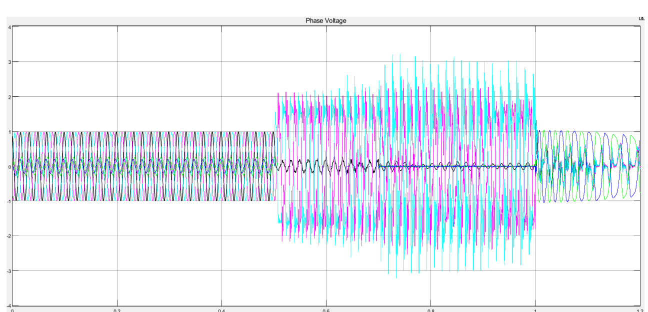

Figure 10. DG and grid measurement at linear load in the grid

At a linear load in the grid, measuring the performance of a Diesel Generator (DG) and grid involves monitoring key parameters to ensure efficient and stable operation. Critical measurements include voltage, current, power factor, and frequency. The voltage and current measurements help in assessing the load distribution and power quality. The power factor indicates the efficiency of power usage, while frequency stability ensures synchronous operation between the DG and the grid. These measurements are essential for optimizing the DG's performance, ensuring seamless integration with the grid, and maintaining overall system reliability and efficiency.

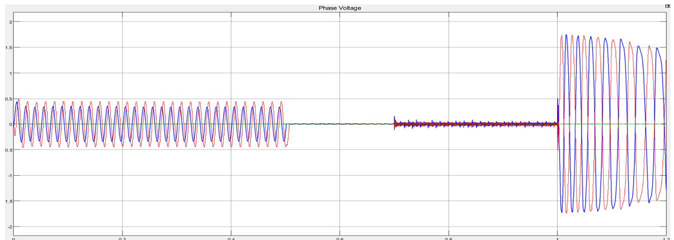

Figure 11. Phase current after fault simulation in the system connected with PV

After a fault simulation in a system connected with photovoltaic (PV) panels, the phase current measurements provide critical data on the system's response. Typically, a fault causes a sudden increase or imbalance in phase currents. Protection devices such as circuit breakers and fuses should activate to isolate the fault. The PV system's inverter may also respond by shutting down or reducing output to protect the system. Monitoring these phase currents helps in diagnosing the fault type and location, ensuring the protection mechanisms function correctly, and guiding corrective actions to restore normal operation while safeguarding the equipment and maintaining system stability.

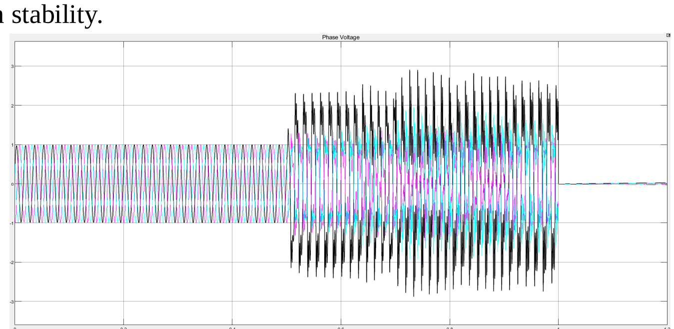

Figure 12. Phase voltage after fault simulation in the system connected with PV

After a fault simulation in a system connected with photovoltaic (PV) panels, phase voltage measurements are crucial for assessing the impact and response. Typically, a fault causes a sudden drop or imbalance in phase voltages. Protective devices like circuit breakers and relays should activate to isolate the faulted section and prevent further damage. The PV system’s inverter might disconnect or adjust its output to protect against overvoltage or undervoltage conditions. Monitoring these phase voltages helps identify the fault type and location, ensure protection devices operate correctly, and guide necessary actions to restore normal voltage levels and maintain system reliability and safety.

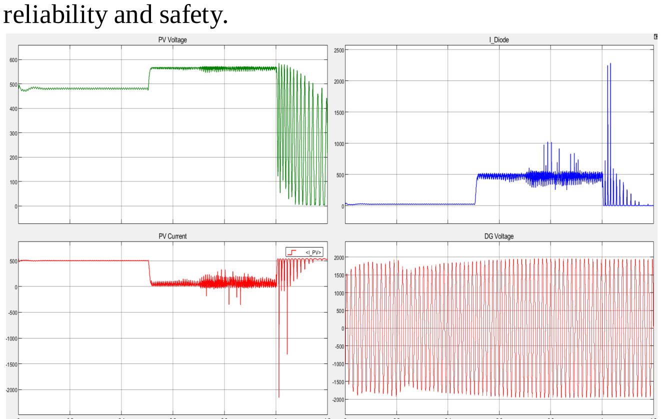

Figure 13. PV and Devices voltage from 1-3 and DG and Grid Voltage at the last scope

In a hybrid microgrid system, monitoring the voltage at various points ensures optimal performance and reliability. Voltage measurements at PV panels (Devices 1-3) show the output from each panel, typically around their nominal voltage (e.g., 300-400V DC). These voltages help assess the panels' efficiency and identify potential issues.

The Diesel Generator (DG) and grid voltage are measured at the final scope, usually after the inverter and before load distribution, ensuring consistent 230/400V AC for the system. These measurements help verify that the DG and grid maintain stable voltage levels, ensuring seamless power delivery and system stability.

System design, modelling and simulations are essential to optimize, control and enhance system operations. This chapter presents the simulation, results and discussion for the photovoltaic-diesel hybrid mini-grid with energy storage applied for rural electrification. The results consist of the designed mini-grid model's grid voltage and current to compare them with the expected voltage and current levels. Simulations were also run with different types of loads to analyze static and dynamic characteristics of the loads. The model has been used to determine optimal position for PV array and diesel generator. Developed power management algorithm has been simulated to observe characteristics. Simulation results of the designed model's battery charging and discharging characteristics were obtained. The characteristics and impacts of faults in the mini-grid model were also studied and investigated.

IX. CONCLUSION

With the use of solar energy and DG generators, agriculture irrigation can readily satisfy their energy needs. For these buildings, using battery backup becomes vital when the required power output surpasses the daily consumption. Emerging as a massive source of readily usable energy, The development of alternative energy sources, such as wind, hydropower, and wave energy, is significantly aided by solar power. A significant portion of the earth's surface receives enough sun radiation, even in the face of significant latitude variations, to enable low-grade heating of buildings and water.

This work created an improved power strategy to govern a combination of renewable energy sources that includes a diesel generator. We have made the decision to use an off-grid hybrid PV, diesel, and battery renewable energy system to put our management strategy into practice. Every single part of the system, including the battery store system, PV solar array, and diesel generator, was covered in detail. The constituent elements have been used to create mathematical models. The MPPT controller has output power, voltage, and current to the PV system model. The batteries are linked to a model that determines the charge shift condition when charging or discharging, determines the number of battery life periods utilised, and takes into consideration the battery's capacity evolution following gradual degradation. The amount of charging current utilised is estimated by the model. The diesel generator idea has concentrated on calculating the amount of diesel fuel consumed during engine operation. Prior to the development of the battery management approach,

We have determined the requirements and rules that the approach must adhere. An instance has been chosen and its hybrid plant has been sized in order to replicate the management approach on an actual base electrical power in a hybrid solar energy system. This extends the battery's life and guards against damage by enabling charging and discharging the battery when necessary and in a manner that takes capacity loss into account. We concentrated on optimising the plan by adjusting a few factors. We used the system's cost to operate per day as a useful indication in our comparison optimisation to evaluate the management method. The lowest permitted value for the state of charge was the first parameter to be optimised. Our system operates under both constant and variable settings; the lowest operating cost was at separate parameters, such the quantity of diesel generators and batteries in the system, can be researched and discussed in separate studies.

In conclusion, putting into practice a successful battery management strategy can enhance the efficiency and dependability of an environmentally friendly hybrid system, reduce operating costs by extending battery life, and reduce investment costs by reducing the number of batteries required to attain the same degree of efficiency and dependability.

REFERENCES

[1] Q. Hassan, S. Jaszczur, and M. Abdulateef, "A review of hybrid renewable energy systems: Solar and wind-powered solutions—Challenges, opportunities and policy implications," *Results in Engineering*, vol. 18, pp. 100–118, 2023.

[2] M. Uddin, A. A. B. Abu-Siada, and M. F. Romlie, "Microgrids: A review, outstanding issues and future trends," *Energy Strategy Reviews*, vol. 47, pp. 101042, 2023.

[3] J. Lata-García, J. Reyes-Lopez, and J. Jurado, "Optimization and evaluation of a stand-alone hybrid system (solar, biomass, diesel generator, and battery) for rural electrification," *Sustainability*, vol. 16, no. 20, pp. 9012, 2024.

[4] D. Yamegueu, A. Azoumah, and X. Py, "Improving the performance of PV/diesel microgrids through energy management strategies: Rural African case studies," *Energy, Sustainability and Society*, vol. 14, no. 1, pp. 1–15, 2024.

[5] W. Wang, Y. Liu, and H. Zhang, "Techno-economic assessment of PV–diesel–battery hybrid energy systems for agricultural applications," *Energy Reports*, vol. 11, pp. 120–134, 2025.

[6] R. G. Mohamed, M. A. Tolba, and A. M. Azmy, “A modified energy management strategy for PV–diesel hybrid microgrid systems using predictive optimization,” *Scientific Reports*, vol. 15, no. 1, pp. 87716, 2025.

[7] J. C. León Gómez, “Review of hybrid renewable energy systems: Architectures, battery systems and optimization techniques,” *Clean Energy Research*, vol. 4, no. 2, pp. 84–101, 2023.

[8] S. Jamal, M. S. Alam, and A. Hussain, “Rule-based energy management system optimized using genetic algorithms for hybrid renewable energy systems,” *Scientific Reports*, vol. 14, pp. 54333, 2024.

[9] A. S. Aziz, A. Eladl, and M. T. Elsheikh, “Techno-economic evaluation of off-grid PV/diesel/battery hybrid energy systems using foresight dispatch,” *Sustainable Energy Technologies and Assessments*, vol. 52, pp. 102164, 2022.

[10] M. A. Omar, “Opportunities for corporate investment in PV, battery, and diesel hybrid microgrid systems,” *Energy Policy*, vol. 182, pp. 113844, 2024.

[11] M. Bilal, S. M. Muyeen, and M. J. Hossain, “Hybrid optimization algorithm for sustainable design and sizing of standalone microgrids,” *Results in Engineering*, vol. 20, pp. 102007, 2025.

[12] T. Michael, J. Okello, and P. Ssemakula, “Design and optimization of PV–battery–diesel hybrid systems for island electrification: A systematic review,” *KIU Journal of Engineering and Technology*, vol. 6, no. 1, pp. 45–62, 2025.

[13] Dr. Jayeshkumar Pitroda, Lalakiya Biraj, Naghera Dhiraj, Narodiya Jay, Patel Harsh, “A Critical Literature Review on Benefits Due to Passive Solar Energy System in Educational Building”, International Journal of Constructive Research in Civil Engineering (IJCRCE), Volume 2, Issue 5, 2016.

[14] Deepak Purohit, Goverdhan Singh, Udit Mamodiya, “A Review Paper on Solar Energy System”, International Journal of Engineering Research and General Science, Volume 5, Issue 5, September-October 2017.

[15] Qianwen Xu, Jianfang Xiao, Peng Wang, Xuewei Pan, Changyun Wen, Sakshi Gupta, Neha Sharma, “A Decentralized Control Strategy for Autonomous Transient Power Sharing and State-of-Charge Recovery in Hybrid Energy Storage Systems”, IEEE Transactions on Sustainable Energy, Vol. 8, No. 4, October 2017.

[16] Yanzhi Wang, Xue Lin, Massoud Pedram, “Integrating Residential Photovoltaic (PV) Power Generation and Energy Storage Systems into the Smart Grid”, IEEE Transactions on Sustainable Energy, Vol. 7, No. 1, January 2016.

[17] Sanjeevikumar, P.; Grandi, G.; Blaabjerg, F.; Wheeler, P.; Hammami, M.; Siano, P., “Control Strategies for High Output Voltage DC-DC Boost Power Converter”, International Journal of Computational Intelligence Systems (IJCIS), 2018.

[18] Hemanshu, R.; Hossain, M.J.; Mahmud, M.A.; Gadh, R., “Control for Microgrids with Inverter Connected Renewable Energy Resources”, IEEE PES General Meeting, 2019.

[19] WESSOF, E., “Global Installed PV Capacity Leaps to 303 Gigawatts”, Green Tech Media, April 2017.

[20] TSAGAS, I., “Spain Approves ‘Sun Tax’, Discriminates Against Solar PV”, Renewable Energy World, October 2018.

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