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Design and Performance Analysis of Grid-Connected Hybrid Renewable Systems

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***Abstract*—Renewable energy development aims to meet the world's energy needs while replacing fossil fuels and moving to more renewable energy sources (RES). However, several different RES are tied together, taking into account the local load, and connected to add more energy to the current grid. Sadly, it requires a considerable amount of land. Yet the effects of climate change and the expanding global population both put food security in danger and the contest for scarce land resources has increased. In this regard, it has been claimed that agro-photovoltaic systems, which combine photovoltaics with plant growth, present a chance for the synergistic integration of renewable energy and food production. In this study, a methodology is shown where a grid-connected APV system is combined with other sustainable generation such as wind turbines (WT) and biomass generators. The Perturbation and Observation (P&O) based MPPT controller is implemented to harness the maximum power from APV. An energy management system is employed to use the stored energy in the battery and store the renewable energy generated by APV. To simulate the performance and effectiveness of grid-connected-RES-energy storage, a thorough study has been conducted. WT and BM connected to the existing power grid can generate an avg. of 3508 kW/day. and the APV system can produce avg of 50 kWh/day. The simulation results demonstrated that the suggested strategy works since the controller may use the most power feasible in both steady-state and diverse weather conditions.**

***Keywords*—Agro-photovoltaic, Solar, Wind, Biomass, Battery, Micro-grid, Performance Analysis.**

I. Introduction

Renewable energy has garnered international attention due to its potential environmental and human survival benefits. In this context, photovoltaic (PV) devices are believed to capture sunlight energy even more efficiently than plants [1]. All nations experience electricity losses, but they are more prevalent in developing nations such as Bangladesh, Sri Lanka, and Pakistan. The average electricity loss in developing nations is 17%, while the average electricity loss in developed nations is 6%, according to the World Bank [1]. Agro-photovoltaic (APV) with grid connections is one of the most effective methods for combating this issue. Agro-Photovoltaic refers to the concurrent use of land for agriculture and solar photovoltaic energy generation. Combining solar panels and produce on the same land maximizes land use and yields multiple benefits.

Multiple investigations have demonstrated that APV improves land productivity. Consequently, it has great potential as a resource-efficient, co-productive RES in areas with dense populations or limited land areas, such as mountainous regions and islands [2]. However, its greatest potential is anticipated in semi-arid and desiccated regions, where several combinatorial side effects may be expected [3]. In this region, crop agriculture is frequently negatively impacted by intense sunlight and associated water losses. It has been demonstrated that water use efficiency increases beneath PV panels, and equivalent results have been demonstrated for APV installations [4]–[6]

Numerous studies and research efforts have focused on agro-photovoltaic (APV) systems that are grid-connected. APV systems can increase the economic value of cultivation, contribute to the decentralized, off-grid electrification of developing nations, and improve land-use efficiency [7]–[10]. APV systems have been demonstrated to be an effective means of connecting local agriculture and photovoltaics, and investments in APV systems can result in substantial economic and environmental benefits [11]. APV systems are a land-use concept that combines the production of solar energy with agricultural activities conducted beneath photovoltaic modules. APV can contribute to sustainable agriculture and resolve local environmental and socioeconomic issues [8]. The operation of APV systems can be affected by solar radiation, crop growth, and the effect of solar panels on crops. For APV systems to be successful, proper crop selection and cultivation methods, seed and vegetation designs, and management approaches are crucial [8]. The impact of APV systems on the efficacy of PV modules is a crucial aspect of APV design and operation. Ongoing research and modeling efforts are concentrated on optimizing APV systems and comprehending their impact on agriculture, solar module performance, and system operation [9]. A global analysis of the energy yield of APV systems in agricultural greenhouses was the focus of the study. The results indicated that APV systems have the potential to substantially improve greenhouse farming's energy efficiency [12]. Literature shows this kind of system, which combines solar energy and agriculture, has several advantages that make it an attractive option for farmers and energy providers. APV systems can help reduce greenhouse gas emissions from the agricultural sector. By using solar energy in agricultural areas, farms can easily meet their energy needs with the electricity generated, which encourages photovoltaic self-consumption. Previously no such study was conducted on combining the APV, WT, BM, battery, and grid in a system and checking the system's stability and effectivity. In this study, we tried to fill this research gap by designing a system considering APV, WT, and BM connected with the grid and running the performance analysis on the model.

II. Systems Modeling

The performance and stability of the system are tested in the MATLAB Simulink software environment. In this section, the methodology used to design and implement the grid-connected RES connected with the battery, and biomass is shown in Fig. 1. The whole system is built on MATLAB using respective parts.

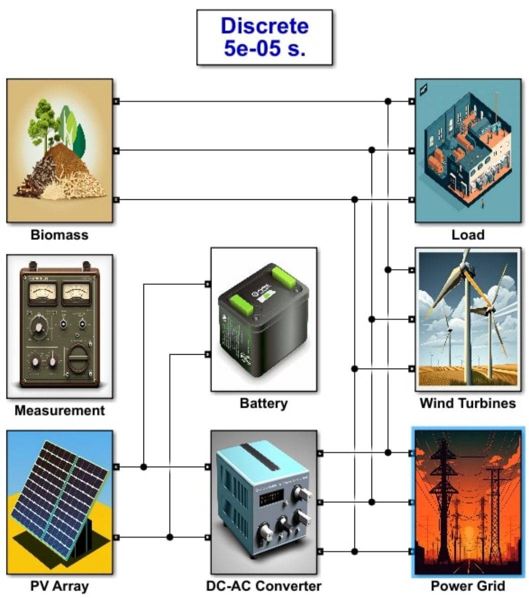

Fig. 1: Simulink model.

A. APV model

APV is to raise the solar panels to 2m above the ground and increase the spacing between them to avoid excessive shading of the crops. But as for modeling, it is not important to consider, as only the solar-generated current can be measured and analyzed. A small-scale PV array is designed by using **SunPower 230E-WHT-D** module consisting of 11 parallel strings and 21 series connected modules per string 21 made the desired 53 kWp capacity APV model shown in Fig 2.

The Perturbation and Observation (P&O) MPPT technique is applied in the above PV model to harness the maximum amount of energy from the APV model. The algorithmic flowchart for P&O logic is shown in Fig 3. By adjusting

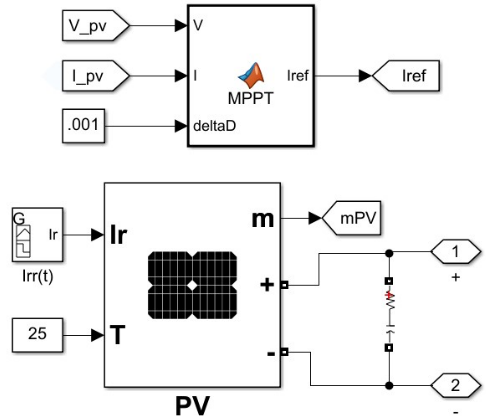

Fig. 2: APV model.

the duty cycle, the voltage is either decreased or increased depending on the power to meet the maximum power.

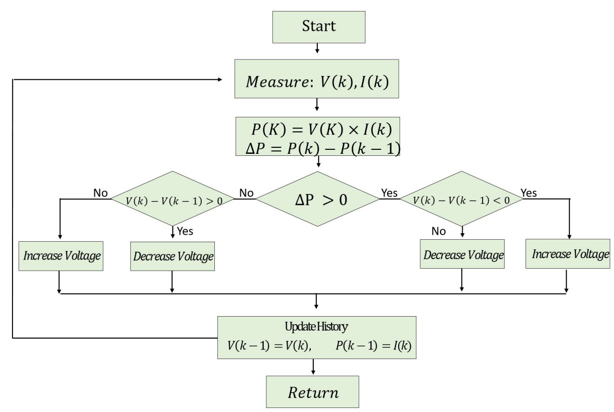

Fig. 3: Flowchart of P&O MPPT.

B. 3-ϕ Inverter model

A phase-locked-loop (PLL) method is used to transform the DC into 3-ϕ AC. In order to synchronize the input DC voltage with the 3-ϕ AC signal, several PLL blocks [13], are used as shown in Fig 4. The duty signal generated by the P&O is used as a pulse to the IGBT inverter bridge.

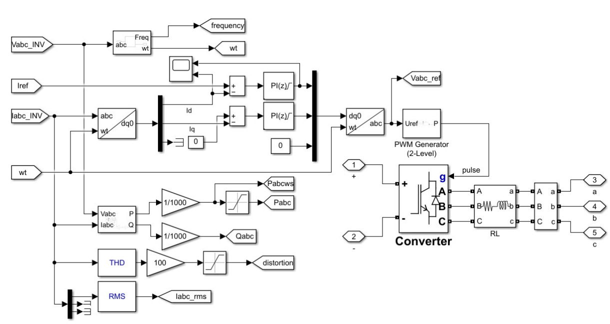

Fig. 4: Inverter model.

All the necessary parameter regarding the inverter is given in Table I.

TABLE I: Inverter Parameter

Name	Values
AC Frequency	60 Hz
AC rating (APV)	60 kWp
APV rating	53 kWp
V_{rms} (line-to-line)	380V
V_{grid} (phase-to-neutral)	310V
V_{grid} (line-to-line)	540V

C. Battery Model

A bi-directional charging module is considered while building the energy storage unit used in the model as shown in Fig 5. The nominal voltage of 45V and the current capacity of 100ah are considered while selecting the battery energy storage capacity [14].

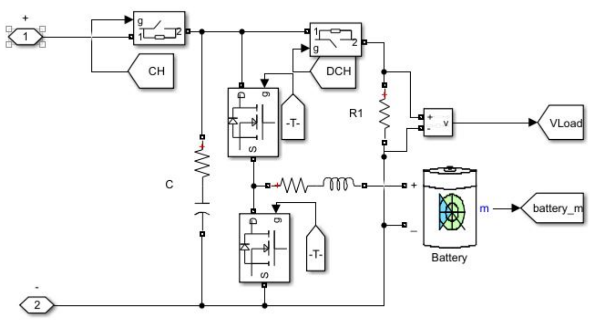

Fig. 5: Battery model.

The charge controller of the battery shown in Fig 6 is based on the two checking criteria. transform the DC energy to AC energy, if the APV generation is available and the battery is under the maximum threshold then it is allowed to charge the battery. otherwise, at the time of no APV generation, the battery tends to discharge the energy to the inverter which will deliver the stored energy to the grid.

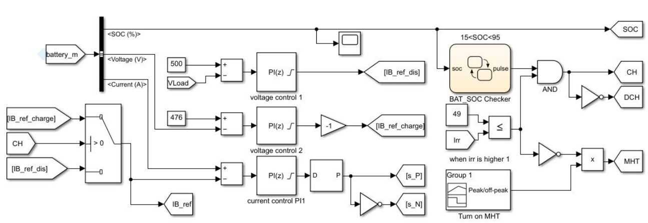

Fig. 6: Battery Charge Controller.

D. Biomass model (BM)

Biomass generator converts biomass into electrical energy. A single-phase AC source of 2.5MW is taken then an AC-AC PLL inverter is attached to convert the single-phase current into a three-phase current [15]. as is shown in Fig 7.

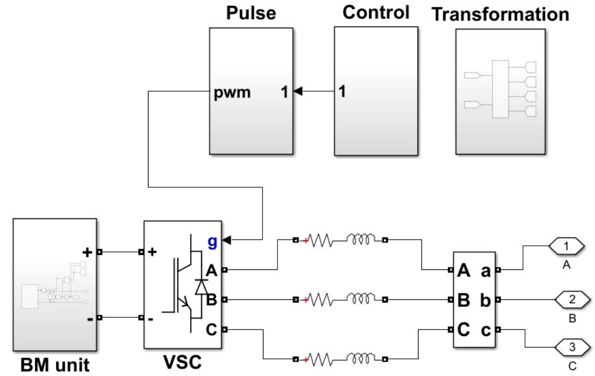

Fig. 7: Biomass model.

To replicate the BM generator, another AC source is taken which can be turned on/off manually. BM usually generates a single-phase current. So another VSC is used to convert the single-phase AC into 3-ϕ AC for grid synchronization.

E. Wind Turbine model

A peak generation capacity of 1.5MW is considered for the designing of the WT model as shown in Fig 8. AC voltage generated from WT is around 575 V. A step-down Y-Y transformer is used to adjust the voltage to the grid level.

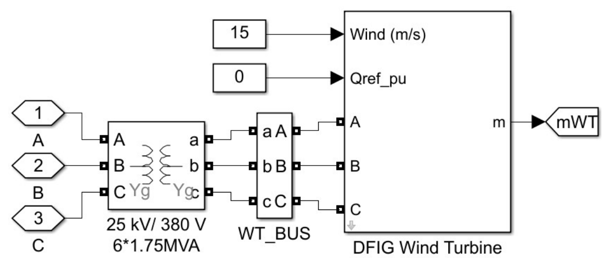

Fig. 8: Wind Turbine model.

III. Analysis Conditions

The proposed model is developed and the simulation is tested on MATLAB R2021a simulink environment considering the parameters:

- Accelerator mode is used for 3.00 seconds for simulation run-time.
- X-Y Axes in certain graphs were restricted smaller scale for better visibility.
- 24 Hours is presented on a scale of 1 second. *i.e.* - From 0.0s to 0.04s represents 1 hour solar insolation data.

The hourly meteorological data are needed for the system to simulate the performance analysis, collected using a public database of NREL Tool. The input meteorological is selected Location: Chittagong and Date 1 July 2022 for solar insolation and temperature data are shown in Fig. 9. Constant load demand 3MW Active power consumption is considered while considering the load model.

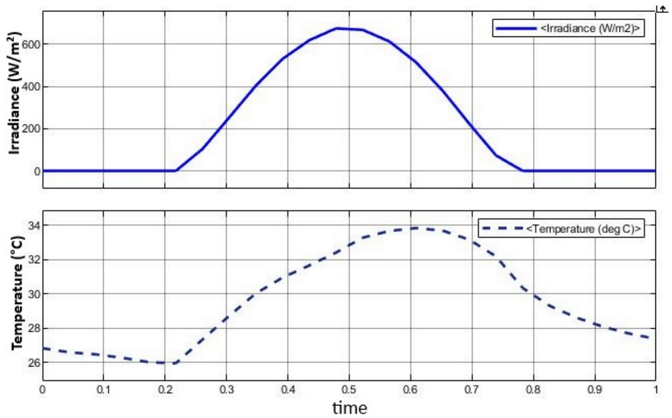

Fig. 9: PV Input Resources

IV. Results and Simulations

Hourly APV generation is shown in Fig 10. The current induced from the PV panel is only observed when the solar insolation is radiated on the surface of the panel representing the daily solar radiation time of a day.

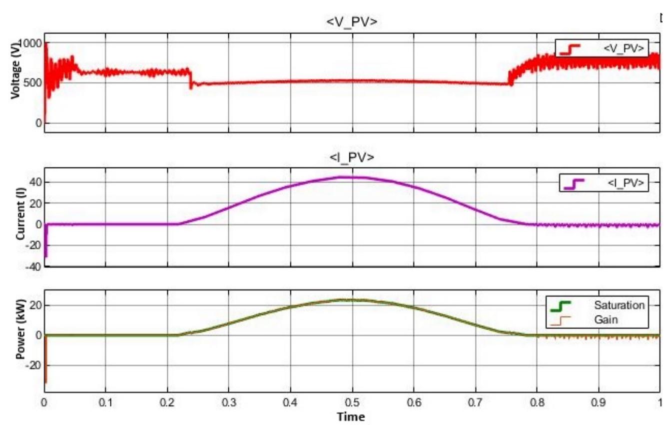

Fig. 10: APV generation

The battery's SOC and voltage levels are shown in Fig 11.

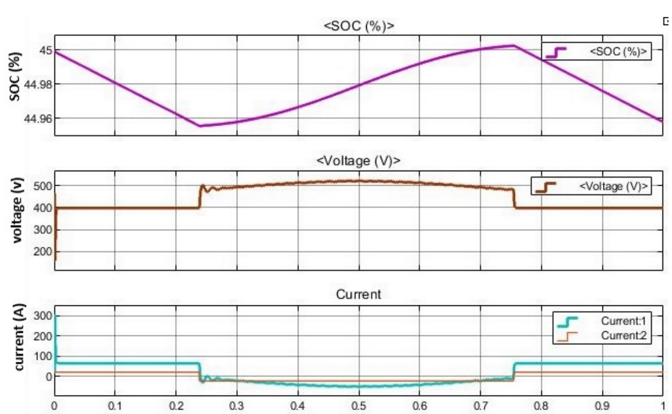

Fig. 11: Battery SOC, Voltage

During the nighttime, when renewable generation is unavailable, the EMS of the battery is set to be discharged and during the daytime, the EMS sets the battery model to be charged with available renewable generation.

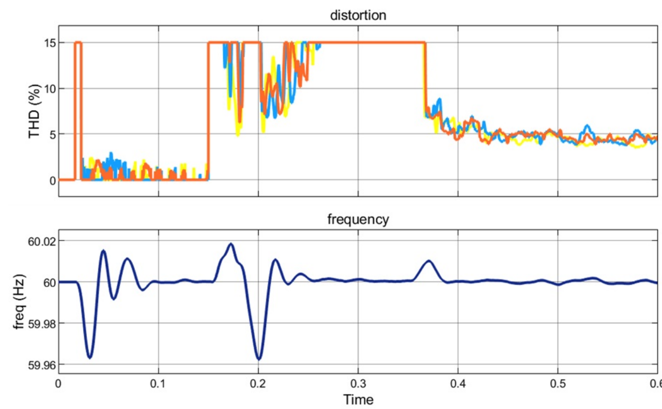

Fig. 12: Inverter Performance Curve.

The inverter performance is shown in Fig 12, The active and reactive component is shown in the first sub-figure, and the second figure shows the frequency shape throughout the simulation. At the beginning of the simulation run, there are some distortions in the frequency curve, meaning the inverter is trying to match the phase angle by shifting the frequency and subsequently matching the angular length. But afterward, the frequency is observed stable.

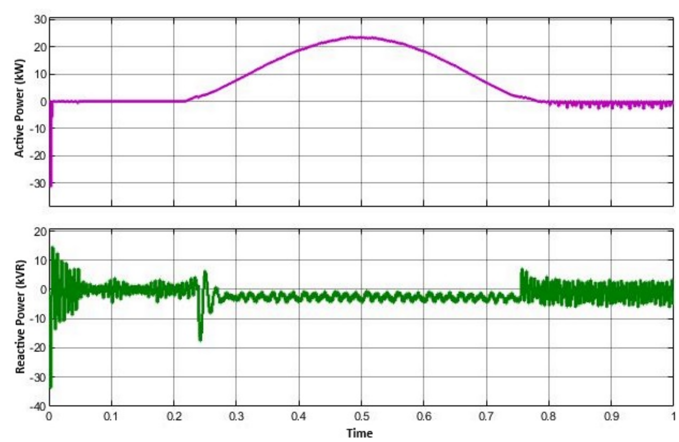

Fig. 13: Inverter Power

The Biomass (BM) generates the single-phase AC current, VSC AC-AC three-phase converter is used to transform the single-phase AC to three-phase AC. The RMS current and the active power generated from the Biomass generator are shown in Fig 14. The three-phase current is generated from the BM generator when it is set to start. Initially, there is some high current flow due to the inductive characteristics and as the simulation progress, the distortion is alleviated comprehensively.

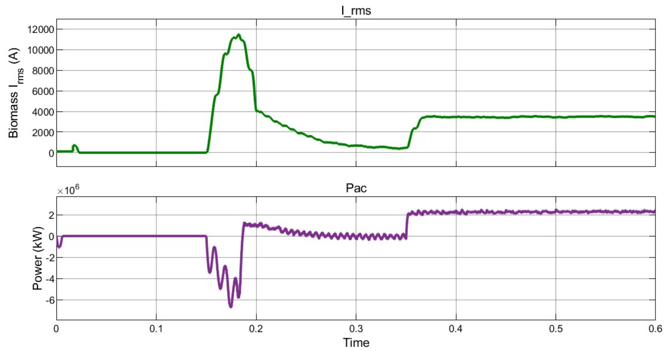

Fig. 14: Biomass I_{rms} and Power.

The performance analysis of the WT is shown in Fig 15. The frequency curve shows the frequency is stable throughout the wind generation. The total harmonic distortion (THD) is shown if any disturbance is observed throughout the simulation.

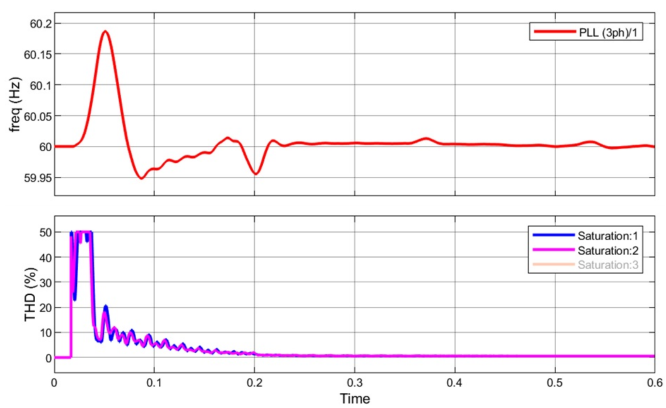

Fig. 15: WT Performance Response.

The frequency curve and THD of performance analysis of the existing power grid are shown in Fig 16.

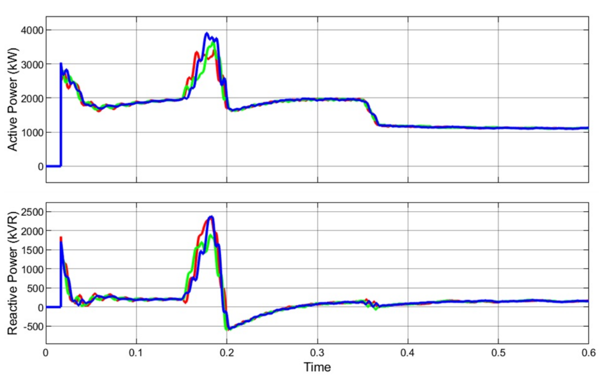

Fig. 16: GRID Active and Reactive Curve

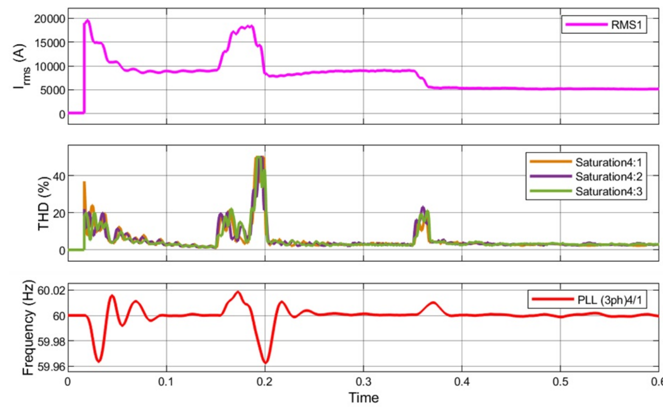

Fig. 17: Grid Performance Curve

The performance analysis of the existing load is shown in Fig 18. The total residential load is taken at around 30 kW and the industrial load is taken at 80 kW. The Per unit active and reactive power response throughout the simulation is shown in Fig 18. Active and reactive power analysis is a key aspect of power systems engineering and refers to the calculation and analysis of the active and reactive power flows in an electrical network. Active power is the real power that is used to perform work, such as running motors and lighting. Reactive power is the power that is used to create and maintain the electromagnetic fields in the network but does not perform any useful work. The frequency curve shows the frequency is stable through the simulation process. The THD is shown in the below figure. Where any disturbance is captured throughout the process. It is seen at first due to high way.

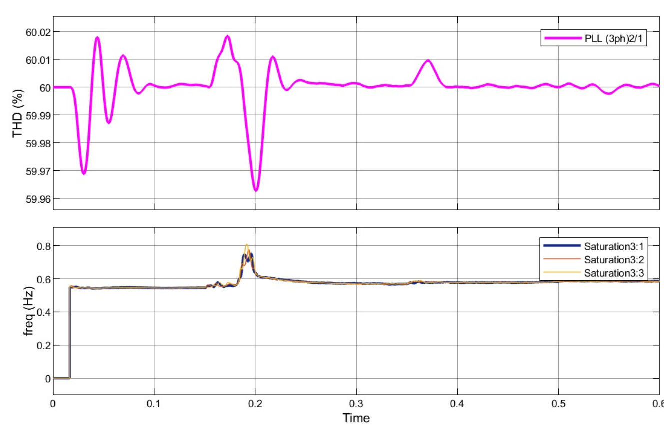

Fig. 18: Load active and reactive

A. Data Table

Peak generation and load consumption data are shown in Table II. The APV system is designed with a PV module capacity of 53 kWp, resulting in an average renewable energy output of 50 kW based on the Simulink PV output power curve. Similarly, for the WT system, a 1500 kWp DFIG WT Module is used to generate an average renewable energy output of 1084 kW based on measurements obtained from the wind power display block in Simulink.

TABLE II: Simulation Output

Items	Installed Capacity	Avg. Renewable Generation	Load demand	Avg. Load Consumption
APV	53 kWp	50 kW	3000 kW	2957 kWh
WT	1500 kWp	1084 kW		
BM	2500 kWp	2424 kW		
Energy Supplied to the grid		601 kW		

Finally, in the BM system, an installed capacity of 2500 kWp is determined from the BM curve, resulting in an average renewable energy output of 2424 kW based on measurements obtained from the BM power display block in Simulink. The garments and agro-farming operations require an installed load of 3000 kW, but the average load consumption is slightly lower at 2957 kWh. We also have the ability to supply excess power back to the grid at a rate of 601 kW.

V. Conclusions

In this study, we examined a system comprised of an APV system, WTs, battery banks, and a biomass generator that is connected to a grid model and load demand. Each part is developed separately and then interfaced together to replicate a real-life system. The AC phase synchronization works simultaneously for the Wind turbine, Biomass model, and PV inverter. THD is observed higher when the current flow is higher. In the BM system, an installed capacity of 2500 kWp is determined from the BM curve, resulting in an average renewable energy output of 2424 kW based on measurements obtained from the BM power display block in Simulink. The garments and agro-farming operations require an installed load of 3000 kW, but the average load consumption is slightly lower at 2957 kWh. We also have the ability to supply excess power back to the grid at a rate of 601 kW. THD is measured over a period of time to check the performance stability of a RES. The performance of the grid-connected renewable system is found stable overall and in the calculation.

Future studies should focus on finding the economic viability of the system so that this type of model can be installed all over the country. As renewable energy is quickly expanding, we will be able to achieve fully green energy within a couple of years.

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