A Grid-Connected ANFIS-MPPT Based Solar PV System and Hybrid Energy Storage

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***Abstract*—The rising popularity of renewable energy sources (RES) has escalated due to limited fossil fuel and environmental concerns. However, due to weather dependency, renewable energy generation is uncertain. In order to ensure maximum renewable generation and store the energy for later use, a methodology was shown in this paper. Maximum power point tracking (MPPT) controllers can significantly improve Solar photo-voltaic (PV) performance. Adaptive Neuro-Fuzzy Inference System (ANFIS) based MPPT controller was implemented for a grid-connected PV system considering different levels of load demand, and weather conditions such as solar insolation and temperature. In a time of no renewable generation and peak energy demand, Energy storage can be a sustainable solution. A hybrid energy storage (HES) system consisting of both battery (BAT) and super-capacitor (SC) performs the best in time of peak load demand, and this was implemented in the system. In the time of no renewable generation, HES is able to provide the deficit energy to the grid. A smart energy management system (EMS) is proposed in this study which can effortlessly manage the energy between generation, energy storage, load demand, and existing grid. The proposed model was tested considering real hourly data. The output response of each component was analyzed to measure the performance and redundancy of the system.**

***Keywords*—ANFIS, Fuzzy logic, MPPT, Renewable Generation, Hybrid Energy Storage, Energy Management System.**

I. Introduction

In recent years, industrialization, population growth, and the demand for individual comfort have led to a significant increase in the world's consumption of electricity, which is mainly produced from fossil fuels. It is anticipated that this energy use and the related CO_2 emissions would persist [1]. Europe and the U.S.A. are the two greatest energy consumers in the world and are responsible for around 36% and 38% CO_2 emission respectively of total annual emissions of the world [2]. Due to limited fossil fuel and environmental concerns, most of the country takes initiative on more renewable generation sectors and less on conventional generation approach. This scenario has compelled and gotten the attention of academics and investors to innovate and integrate renewable energy sources in order to overcome atmospheric issues, the inaccessibility of fossil fuels, and the energy crisis. Among different kind of renewable energy sources such as Biomass, Wind, Hydro-power, and Geothermal, PV system gaining popularity, because of its environment-friendly, produces no noise, are clean, and have lower maintenance [3]. The world's global installed capacity of PV was roughly 5 GW in 2005, rising to almost 940 GW in 2021 [4]. Previously, there were some good works with PV systems to get the best efficiency. Some work was to improve power efficiency by using different types of MPPT tracking techniques such as ANFIS, fuzzy logic, perturbation and observation (P&O), and incremental conductance-based MPPT tracking techniques. Some work was to prove the redundancy of using battery and super-capacitor to improve the overall system response. Here, the overall previous work is focused on one side like using the best MPPT tracking system System response, or Grid integration [5], [6]. Utilizing sustainable resources is the most viable option available when it comes to environmental concerns [3], [7]. Solar photovoltaic systems have been a clean and very cheap way of electrical energy generation. Sooner or later fossil fuels will be depleted and renewable generation in combination with hybrid energy storage can reduce carbon emission by 88% considering lifetime carbon emission assessment of renewable component [8]. However, the effectiveness of renewable generators is still bottlenecking due to low solar PV efficiency. This problem can be solved using the MPPT controller, and ANFIS is proven to be the most efficient method of implementing the MPPT. Another issue with renewable energy is that it is highly insistent and uncertain. So energy storage and a management system are mandatory for seamless energy supply to its demand. The drawbacks regarding traditional energy storage are its high latency in response and life longevity. Hybrid energy storage comprised of batteries and super-capacitors is proven to be the most effective way of designing energy storage. The main objectives for this study's research were the following:

- Modeling a grid-integrated solar photovoltaic system with a hybrid energy storage system.
- Design and implementation of an ANFIS-based PV MPPT system.
- Smart strategy regarding energy management between loads demand renewable and generation.
- Analyzing the performance and the stability of the sys-

tem.

II. Modeling of Systems

The simulation model for the proposed system is shown in Fig. 1, and this is comprised of solar PV as a renewable generation unit that is connected to a DC bus with a HES and DC-AC 3-phase inverter. Another side of the inverter is connected to the grid and dynamic load demands. Distance between the grid, renewable generator, and dynamic load is covered by feeder lines with respective distances to imitate the real-world scenario.

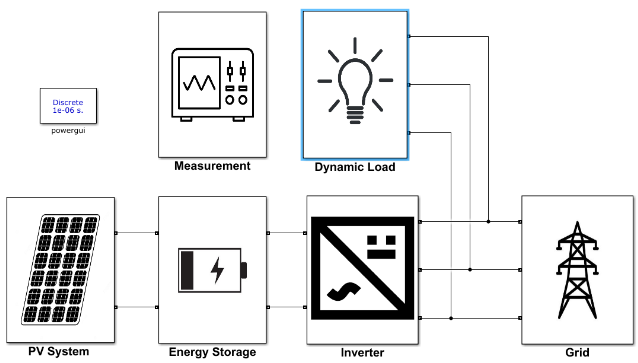

Fig. 1: Proposed Model

Each of the units shown in the above figure was developed separately and discussed in the section.

A. Solar PV Modeling

A Small-scale PV array capacity of 100 kW is employed with **SunPower PL-SUNP-SPR-315E** module from simulink-library comprising 5 series modules and 66 parallel strings modules in the MATLAB Simulink. ANFIS MPPT controller is designed using a similar approach as the DC-DC boost converter, shown in Fig. 2, where the ANFIS logic is used to generate the pulse signal of DC-DC converter [9].

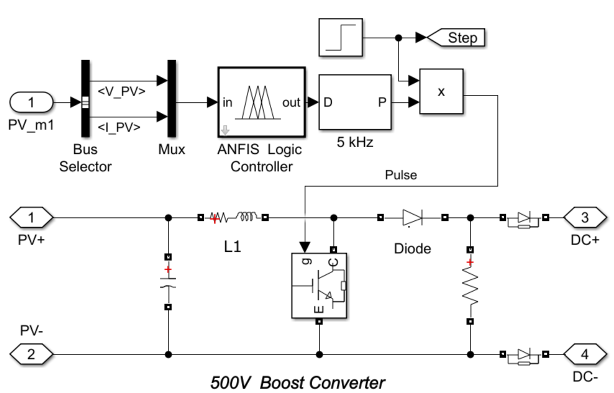

Fig. 2: DC-DC Converter

The training model for the ANFIS controller is an essential part so that it can determine the MPP for a PV array. The data set for the training model was created using the equation (1) where respective solar insolation and temperature MPP can be found.

$$
\begin{aligned}
IMP &= I_{mp} \times \frac{G}{G_{STC}}(1 + \alpha \times (T - T_{STC})) \\
VMP &= V_{mp} + \beta \times (T - T_{STC}) \\
PMP &= VMP \times IMP
\end{aligned}
\tag{1}
$$

Here, V_{mp} and I_{mp} are the maximum voltage point and current point, α and β are the temperature coefficient of short circuit current and open circuit voltage for each module respectively provided by the PV panel manufacturers. Standard test conditions (STC) solar insolation and temperature are 1000 w/m^2 and 25°C. Hourly solar radiation (G) and temperature (T) are randomly generated values between 50-1000 w/m^2 and 10-40 °C to train the ANFIS model the MPP of PV corresponded to different solar insolation and temperature. The prepared data is employed on the Neuro-Fuzzy designer tool of MATLAB to create the ANFIS logic controller file as shown in Fig. 3 using the methodology explained in ANFIS Model [5].

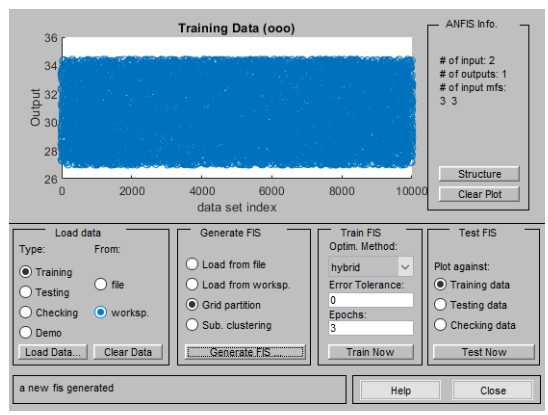

Fig. 3: Neuro-Fuzzy Designer Tool

B. Hybrid Energy Storage (HES)

The HES is formulated using battery and super-capacitor as shown in Fig. 4. The bi-directional charge controller is used to charge and discharge both energy storage [10].

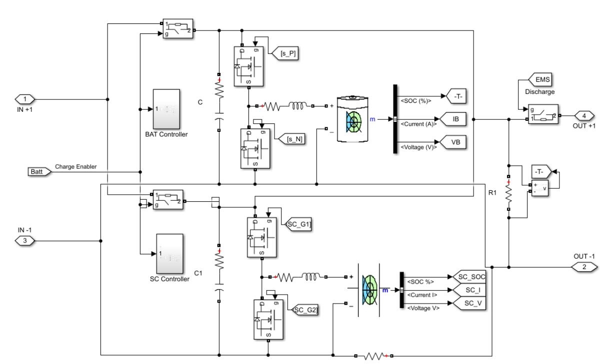

Fig. 4: Hybrid Energy Storage Model

An EMS is proposed to regulate the energy flow of the system shown in Fig. 5. When energy is generated from solar and if the energy consumption is lower than natural, energy will flow to the energy storage. Otherwise, energy will be consumed from batteries and super-capacitors and flow to the grid when renewable generation is not available [11].

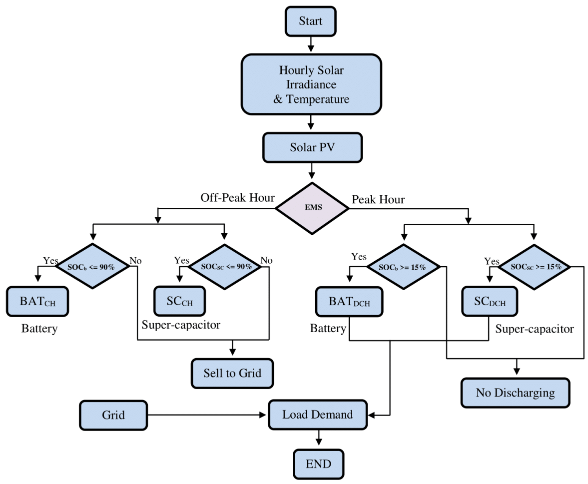

Fig. 5: EMS Flowchart

C. Grid & Inverter Modeling

An inverter model is needed to convert the high-voltage DC to synchronous 3-phase AC which can be coupled with the grid [12]. Voltage Source Converters system is used to build the switching signal for the inverter model as displayed in Fig. 6. The input voltage is 500V DC, the output voltage is

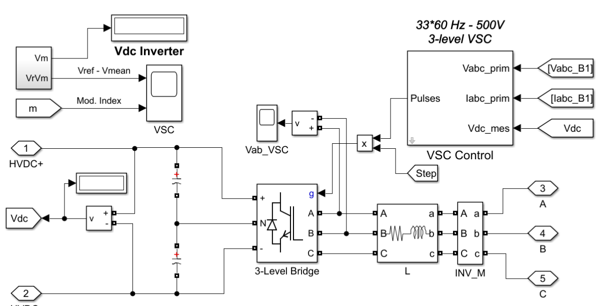

Fig. 6: Inverter Model

33 KV AC, and the switching frequency of the VSC is 60Hz. GRID of 120 KV and 2500 MVA is designed to simulate the grid-integration scenario displayed in Fig. 7.

III. Load Modeling

A circuit diagram of the dynamic load model is shown in Fig. 8. Dynamic load changes the demands every hour so load demand is changing every hour to represent the 24 hours. The transmission line feeder is considered $8km$. Hourly load demand is shown in Fig. 10.

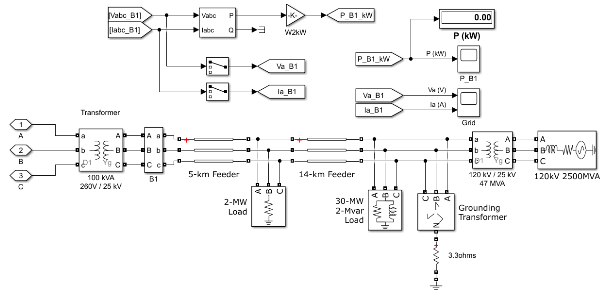

Fig. 7: Grid Model

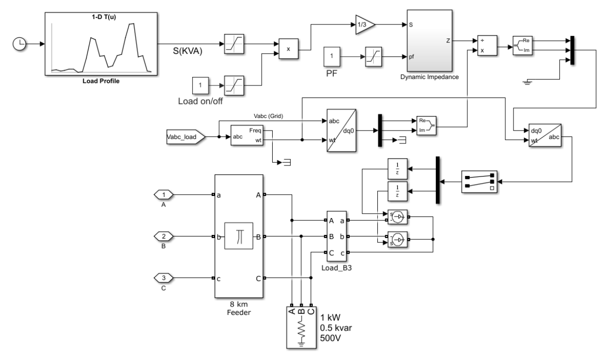

Fig. 8: Dynamic Load Model

IV. Analysis Condition

The renewable resources data sets of Chittagong are selected as a case study to test the performance of the system to develop the simulation model considering the below 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.

A. Renewable resource data

The hourly solar insolation data sets for Chittagong are gathered from the NREL Database [13] that is shown in Fig. 9.

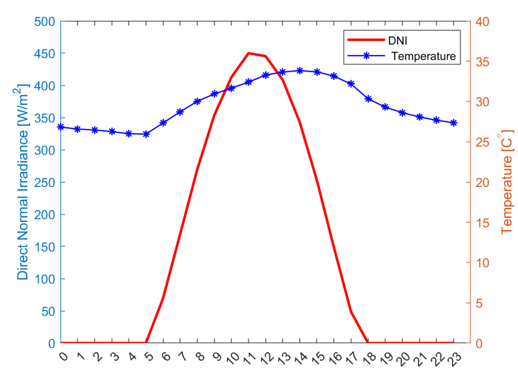

Fig. 9: Solar radiation and temperature

B. Dynamic Load Model

The hourly load consumption data for 24 hours is assumed as shown in Fig. 10 for the dynamic load model.

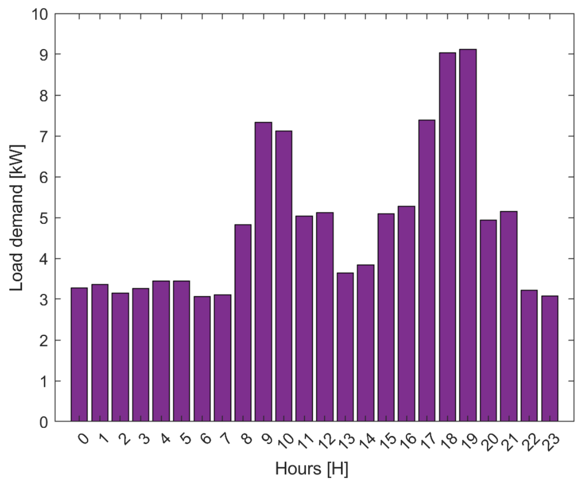

Fig. 10: Dynamic load curve

V. Results & Discussions

ANFIS DC-DC controller is able to harness the maximum power point based on given solar insolation data that is shown in Fig. 11. The voltage and current generated by the PV panels are proportional to the solar radiation the panels are imposed on.

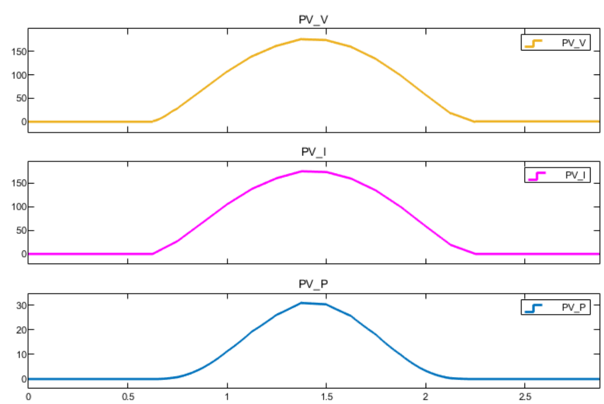

Fig. 11: Solar PV generation

The state of charge (SOC) and the voltage of the HES are shown in Fig. 12. Initially, the SOC of the battery was set to lower than the minimum threshold so that the EMS started changing the battery. Similarly, the super-capacitor SOC was set to lower than the minimum so the energy generated from the PV panel can be stored in the capacitor.

The primary measure used to evaluate the output of a grid-connected inverter's system reliability and a requirement of grid integration standards is the THD of the switching frequency of both 3-phase voltage and current. THD of voltage and current is displayed in Fig. 13, Fig. 14 respectively.

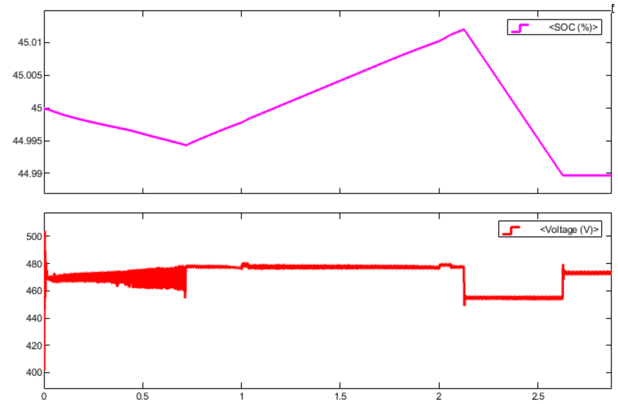

Fig. 12: Battery SOC, Voltage

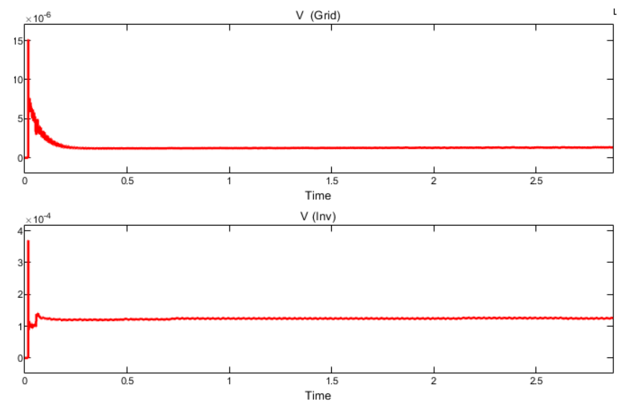

Fig. 13: Total harmonic Distortion of V_{abc}

In both figures, First-order distortion is seen in the voltage and current sequences. This is because of the high current flowing on the inductive load and stayed stable later.

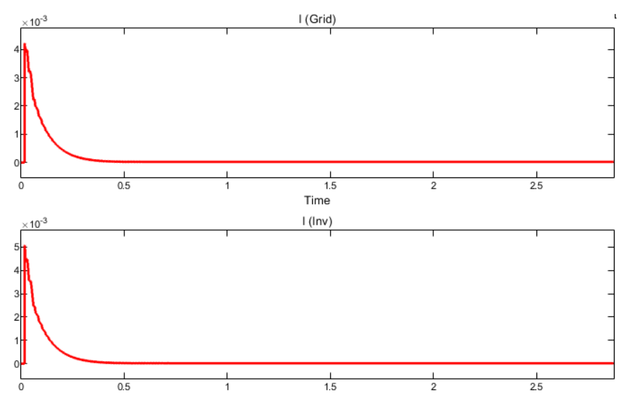

Fig. 14: Total harmonic Distortion of I_{abc}

Voltage and Current response between the grid and inverter are shown in Fig. 15 and Fig. 16 respectively. On the grid side, the voltage and current phase were seen constant over the time of 24 hours in simulation. But there was a high current at the beginning of the inverter current sequence that is displayed in Fig. 16. Over the course of time, this current is balanced out.

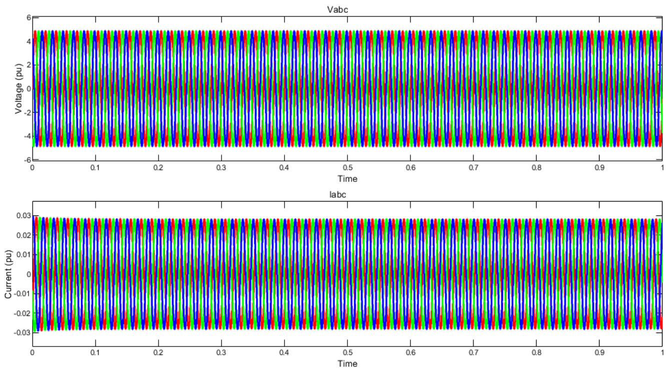

Fig. 15: Grid Voltage-Current PQ

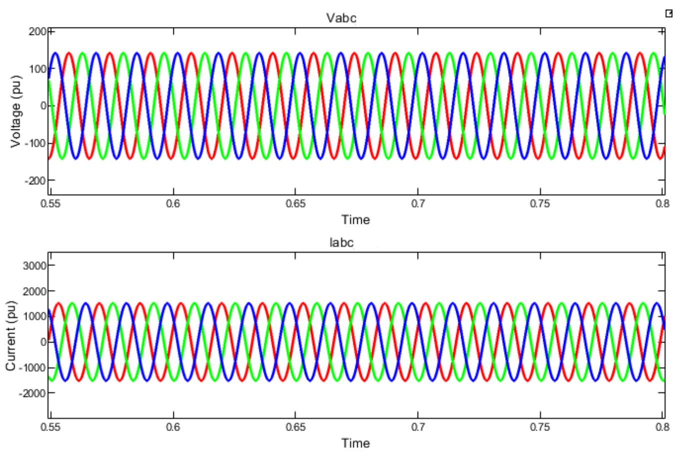

Fig. 16: Grid Voltage-Current PQ

The voltage and current of the three-phase load are shown in Fig. 17. The dynamic load changes over time, and in the peak hour time, the current consumption is highest. The active

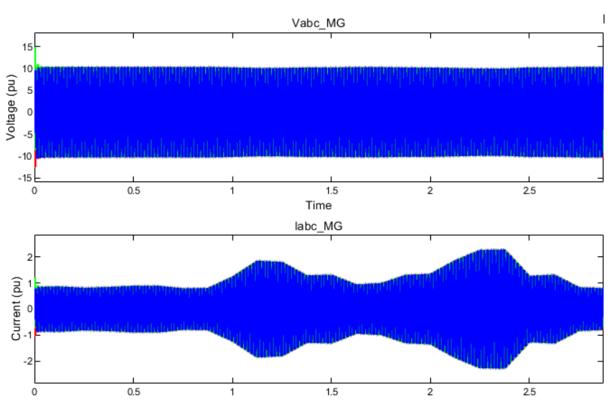

Fig. 17: The Voltage and current of three-phase load

and reactive component of the three-phase load is represented using P and Q. When the load demand is peak, the reactive power also rises which is displayed in Fig. 18.

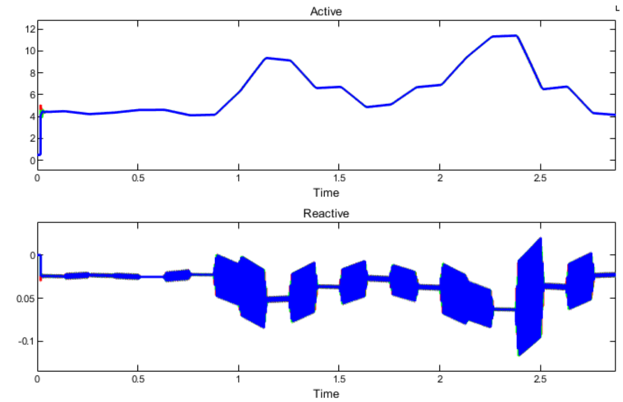

Fig. 18: Active and reactive component of the three-phase load

A. Data Table

Peak generation and load consumption data are shown in Table I. Peak generation time and peak demand time are not at the same hour. At peak generation time, Solar DNI was about $449W/m^2$. Peak load consumption hour was presumed to be 19 hours time stamp. Maximum voltage, current, and power were for that instant as shown in bellow table below.

TABLE I: Peak generation and load consumption

Peak PV Generation				
Voltage		**Current**	**Power**	
176V		175A	31KW	
Peak Load Demand				
Line Voltage (peak-to-peak)	**Line Voltage (RMS)**	**Phase Current**	**Active**	**Reactive**
481.99V	340.82V	2.25A	34.30KW	0.25KVR

VI. Conclusions

In our study, we tested the performance stability of a grid-connected renewable system. The hourly solar insolation and temperature data were used for 24 hours to imitate real-life data because renewable generation is only available in the limited daytime, and another issue with the load demand is that the peak hour is at night. Then, during off-peak hours, 31kW of energy per is harnessed from the solar model and EMS facilitates the energy generated from PV to be used to charge up both energy storage. Peak-to-peak line voltage is around 481.99V. In the time of peak hours, the inverter was able to deliver a constant RMS current of around 340.82V in the grid. The total harmonic distortion is measured over a period of time to check the performance stability of a hybrid system. The active and reactive components of the dynamic load are also tested with no issues.

The proposed model comprised a renewable generation system, HES, and the existing power grid was operational and stable considering different performance parameters. Renewable energy produces much fewer emissions than burning fossil fuels. Transitioning away from fossil fuels, which now account for most emissions, and toward renewable energy is critical for tackling the climate catastrophe. Renewable generations are now cheaper in most countries and generate three times more jobs than fossil fuels. The further step should be estimating the economic viability of the system so that this type of model can be installed all over the country.

References

[1] A. Gupta, A. Kumar, and D. K. Khatod, "Optimized scheduling of hydropower with increase in solar and wind installations," *Energy*, vol. 183, pp. 716–732, 2019.

[2] K. Amasyali and N. El-Gohary, "Building lighting energy consumption prediction for supporting energy data analytics," *Procedia Engineering*, vol. 145, pp. 511–517, 2016.

[3] T. Salameh, M. A. Abdelkareem, A. Olabi, E. T. Sayed, M. Al-Chaderchi, and H. Rezk, "Integrated standalone hybrid solar pv, fuel cell and diesel generator power system for battery or supercapacitor storage systems in khorfakkan, united arab emirates," *International Journal of Hydrogen Energy*, vol. 46, no. 8, pp. 6014–6027, 2021.

[4] N. Uloom, T. Mansur, R. Ali, N. Baharudin, and A. Abdullah, "A comparative study of hybrid energy storage system using battery and supercapacitor for stand-alone solar pv system," in *Journal of Physics: Conference Series*, vol. 2312, no. 1. IOP Publishing, 2022, p. 012075.

[5] R. T. Moyo, P. Y. Tabakov, and S. Moyo, "Design and modeling of the anfis-based mppt controller for a solar photovoltaic system," *Journal of Solar Energy Engineering*, vol. 143, no. 4, 2021.

[6] H. Hafeznia, A. Aslani, S. Anwar, and M. Yousefjamali, "Analysis of the effectiveness of national renewable energy policies: A case of photovoltaic policies," *Renewable and Sustainable Energy Reviews*, vol. 79, pp. 669–680, 2017.

[7] S. E. A. Himu, S. Sultana, M. S. H. Chowdhury, A. I. Ikram, H. R. Saium, and M. M. Hossain, "Modification of dynamic logic circuit design technique for minimizing leakage current and propagation delay," in *2022 4th International Conference on Sustainable Technologies for Industry 4.0 (STI)*. IEEE, 2022, pp. 1–5.

[8] A. I. Ikram, M. S.-U. Islam, M. A. B. Zafar, M. K. R. Dept, A. Rahman *et al.*, "Techno-economic optimization of grid-integrated hybrid storage system using ga," in *2023 1st International Conference on Innovations in High Speed Communication and Signal Processing (IHCSP)*. IEEE, 2023, pp. 300–305.

[9] D. Haji and N. Genc, "Dynamic behaviour analysis of anfis based mppt controller for standalone photovoltaic systems," *International journal of renewable energy research*, vol. 10, no. 1, 2020.

[10] V. M. Miñambres-Marcos, M. Á. Guerrero-Martínez, F. Barrero-González, and M. I. Milanés-Montero, "A grid connected photovoltaic inverter with battery-supercapacitor hybrid energy storage," *Sensors*, vol. 17, no. 8, p. 1856, 2017.

[11] Z. Cabrane, J. Kim, K. Yoo, and M. Ouassaid, "Hess-based photovoltaic/batteries/supercapacitors: Energy management strategy and dc bus voltage stabilization," *Solar Energy*, vol. 216, pp. 551–563, 2021.

[12] M. C. Argyrou, C. C. Marouchos, S. A. Kalogirou, and P. Christodoulides, "A novel power management algorithm for a residential grid-connected pv system with battery-supercapacitor storage for increased self-consumption and self-sufficiency," *Energy Conversion and Management*, vol. 246, p. 114671, 2021.

[13] NREL, "National renewable energy laboratory." [Online]. Available: https://www.nrel.gov/gis/solar.html