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A SUSTAINABLE APPROACH TO POWER SUPPLY USING SOLAR-PUMPED HYDRO TURBINE STORAGE

Chukwudi Emmanuel Boma

Department of Electrical and Electronics Engineering, Rivers State University, Port-Harcourt, Rivers State, Nigeria

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Abstract: This study investigates the enhancement of power supply efficiency through a solar-pumped hydro turbine storage system. Renewable energy sources, while environmentally friendly, often suffer from intermittent generation, posing challenges for continuous electricity supply. To address the variability of photovoltaic (PV) power—especially during nighttime and adverse weather conditions—energy storage via pumped hydroelectricity is vital. Pumped hydro storage systems offer multiple benefits such as voltage support, load shifting, grid stability, and improved system resiliency, making them essential for future energy infrastructures. However, managing power effectively remains a challenge for renewable energy producers. This work employs an intelligent valve system governed by a fuzzy logic controller to dynamically monitor solar irradiance and reservoir water levels, thereby controlling a centrifugal pump to maintain consistent water flow and meet load demand. The hybrid system is modeled in MATLAB/Simulink, integrating subsystems including a solar array, DC-DC boost converter, induction motor, and centrifugal pump. Simulation results demonstrate that the fuzzy logic controller adeptly responds to irradiance and water level changes, efficiently actuating the control valve to regulate flow direction. The local controller also achieves maximum power point tracking (MPPT) with over 99.5% efficiency from the PV panels, substantially boosting power supply reliability. The findings confirm that the proposed fuzzy logic-based control strategy effectively stabilizes the pumped hydro storage operation, ensuring a continuous and reliable power supply aligned with load requirements and enhancing overall system resiliency.

Keywords: Fuzzy Logic Controller, Solar Pumped Hydro Storage, MATLAB/Simulink, Maximum Power Point Tracking, System Resiliency

1. INTRODUCTION

Poor energy supply in growing and undeveloped nations, especially in Africa, gave birth to the increasing use of renewable energy sources (RES) as a clean and alternative means of power supply for urban and rural regions. Nigeria has the renewable energy mass to produce energy that can handle to a great extent, the whole West African region though, it is not self-reliant in terms of power generation, transmission, and distribution.

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In Nigeria, the development of the power industry has been stagnated by a lack of political will to pursue conventional ways of power generation that rely on fossil fuels. The power sector as we speak, faces numerous technical and socio-economic challenges, such as inadequate power generation capacity, low power distribution rate to customers, limited capital for investment, restricted access to infrastructure, inefficient usage, ineffective regulation, insufficient transmission and distribution facilities, high technical losses, and vandalism [1].

Ref [2] has it that a significant majority of the world's power is now being produced via traditional methods. Renewable and nuclear energy make up a negligible percentage. This worsened the already dire condition of the climate. From the research, over 1.06 billion individuals, or 14% of the world's population, lack access to electricity. It was also revealed that the capacity of renewable energy grew from 1000GW in 2007 to 2195 GW in 2017. It is no doubt that Nigeria has abundance of natural resources that, if made used of, have the chance to provide a power supply that surpasses current demand.

It was observed that huge Nigerian population, about 60%, do not have access to electric lighting. Even individuals with access are encountering erratic power supplies due to epileptic outages [3]. Due to the worldwide issue of climate change and the expected shortage of fossil fuels, many nations are working towards creating a sustainable and environmentally friendly energy system to support economic growth and progress [4].

Ref [5] asserts that renewable energy sources are inexhaustible and need less upkeep, hence cutting production costs. It is ecologically sustainable, cost-effective, and emission-free. Nevertheless, the energy output is not as substantial as that generated by fossil fuels. The initial cost of setting up a solar plant is relatively high but it is expected to reduce as its adoption rate increases. Renewable energy is heavily reliant on natural factors, as the generation of power via renewable energy resources is contingent upon meteorological conditions. Insufficient atmospheric conditions can impede the generation of sufficient power by renewable energy systems.

One effective method to address the issue of intermittency in renewable energy is by implementing a hybrid system that combines several renewable energy sources with an energy storage system. Energy storage devices play a crucial role in a hybrid renewable energy system (HRES) by ensuring the maintenance of power quality and dependability. It serves as a protective barrier during situations of power demand and supply imbalance. Several energy storage technologies are now in use, including fuel cells, batteries, flywheels, supercapacitors, and hydro pumps [6].

Pumped hydroelectric storage is a technology that utilizes two reservoirs situated at different elevations to store energy. One reservoir is located at a higher elevation while the other is at a lower elevation. During periods of low electricity demand (off-peak), water is pumped into the upper reservoir. Subsequently, when there is a significant energy demand, the water that has been stored in the higher reservoir is discharged and flows through the hydro turbines to generate electricity [7].

Ref [8] have conducted a comparison between grid-tied solutions and an off-grid-pumped hydro system for power generation. They utilized an internal reforming solid oxide full cell (IRSOFC) and a horizontal axis wind turbine (HAWT) in their analysis. The wind turbine employed was positioned along the horizontal axis, as the name suggests. The stability of the output from the horizontal axis wind turbine (HAWT) is seen to be inconsistent. Nevertheless, the authors contended that by integrating the HAWT and IRSOFC approaches while effectively managing the fuel rate of the IRSOFC, the combined system exhibited consistent power output.

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Ref [9] suggested a hybrid system that comprises a pumped storage hydro-electric power, wind energy and solar PV and developed a mathematical model to describe the operation of the model proposed. The hydropower plant makes use of water from the sea as its lower reservoir while a tank is built and installed high up to serve as the upper reservoir. An investigation of the impact of the proposed hybrid system on the grid utility has been carried out under different scenarios. The obtained results after the investigations revealed the ability of the proposed hybrid system to minimize the energy exchange with the grid.

Ref [10] examined hybrid pumped hydro storage and proposed a methodology that utilizes multicriteria evaluation. The system is made up of three sources: a pump, a turbine, and a combination of three distinct capacities - 2MW, 4MW, and 6MW. Additionally, there are varying volume capacities of reservoirs, as well as PV solar and wind powers of 0.54-1.6MW and 4-5MW, respectively. The optimal solution is determined to be a hybrid system consisting of hydro, wind, and PV solar panels with capacities of 4 MW, 5 MW, and 0.54 MW respectively. This system, along with a reservoir volume of 378,000 cubic meters, has the highest return on investment and achieved around 72% satisfaction in meeting yearly consumption needs. The authors contended that integrating pumped hydro storage with PV and wind power offers a genuine approach to enhance dependability and flexibility, ultimately achieving energy autonomy.

Ref [11] conducted a study on the integration of wind power with small hydroelectric power facilities. The concept underlying the project is that incorporating a renewable energy source into any vulnerable section of the power grid will improve the overall stability of the system. Hydropower reservoirs, regardless of whether they are pumped storage facilities or conventional plants, serve as extensive energy storage systems.

Ref [12] presented a model aimed at achieving the most efficient functioning of a pumping system that combines diesel and solar power sources, employing subterranean water for pumped hydro storage. The purpose of the design is to minimize the expenses associated with energy in the nearby regions. The model is essentially created to decrease the output of the diesel generator and efficiently regulate the power distribution from the solar (PV) system. The simulation of the designed model demonstrated a significant energy cost decrease of over 71% when compared to employing a diesel generator.

Ref [13] introduced a hybrid energy conversion system that combines wind and solar power, with the inclusion of a hydro-based energy storage system. The planned system consisted of wind turbines, photovoltaic panels, and pumped hydroenergy storage (PHES). The authors employed a genetic algorithm to enhance the efficiency of the pumped hydro energy storage in the proposed hybrid plant. This action is taken in order to minimize the disparity between the amount of energy produced and the amount of energy required. The minimum storage capacity of the pumped hydro energy storage is predicted to be 3,930,615 kilowatt-hours (KWh). The top reservoir has a capacity of roughly 43170 cubic meters. The suggested system is designed to facilitate the objective of attaining environmentally friendly and cost-effective energy, therefore alleviating the impact of climate change.

The objectives are:

i. To design an advanced controller in MATLAB/Simulink that can ensure efficient operation of pump hydro storage system using fuzzy logic technique.

ii. To design and model a local controller that can extract maximum power from the PV array using fuzzy logic maximum power tracking technique.

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iii. To examine the pump capacity of the storage reservoir.

2.0 MATERIALS AND METHOD

2.1 Materials

i. PV Array
ii. Boost Converter
iii. Inverter
iv. Induction Motor
v. Centrifugal Pump
vi. Water Reservoir

2.2 Method

The fuzzy logic technique was used to design an intelligent hydraulic valve that senses fluctuation in solar insolation and water level to control the direction of flow for flexible operation of centrifugal pump used in hydro pump storage system.

2.3 Description of the Proposed System

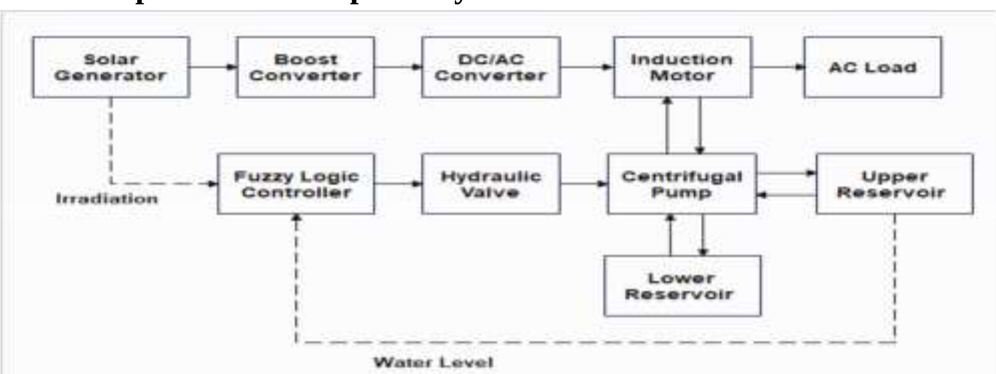

Figure 1: Block Diagram of the Proposed System Hydro-Pump Storage System

Figure 1 shows the block diagram of the proposed hydro pump storage system consisting of a solar generator, a reservoir, a centrifugal pump and an intelligent hydraulic valve. The fuzzy logic controller senses fluctuations in solar insolation and water level and controls the centrifugal pump in both forward and reverse directions.

When the irradiance is low and the water level is high, the fuzzy logic controller will actuate the control valve to change the direction of rotation of the centrifugal pump from pump mode to turbine mode. Similarly, when the irradiance is high and the water level is low, the fuzzy logic controller will actuate the control valve to change the direction of rotation of the centrifugal pump from turbine mode to pump mode**.** By so doing, the pump storage reservoir provides a buffer when there is no sunlight to mitigate the intermittency that arises with renewable energy resources. Plate 1 shows the aerial view of the proposed site located 921m at (4⁰55’27’’N 6⁰49 ’53’’E).

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Plate 1: Aerial View of the Proposed Site

2.4 Pump Hydro System Modeling

2.4.1 Determination of Tank Volume

$$V_{tank} = \frac{\pi d^2}{4} * h_s \qquad (1)$$

Where d: diameter of tank

h_s: vertical rise

2.4.2 Determination of Inlet Flow Rate of Water

$$Q_{inlet} = \frac{V_{tank}}{t} \qquad (2)$$

Where

V_{tank}: volume of tank t: time taken for pumping water

2.4.3 Determination of Outlet Flow Rate of Water

$$Q_{outlet} = \frac{V_{tank}}{t} \qquad (3)$$

Where

V_{tank}: volume of tank t: time taken for discharging water

2.4.4 Determination of Total Dynamic Head (TDH)

$$THD = h_p + h_s + F_l \qquad (4)$$

$$F_l = \left[L_t + \sum \left(n_f * f_e\right)\right] * \frac{f_h}{100} \qquad (5)$$

Where

h_p: pumping level h_s: vertical rise

F_l: frictional loss in pipe

L_t: Ttotal length of pipe

f_e: Fittings of the pipe, in feet, which has a standard value in feet, depending on the pipe’s diameter

n_f: Number of same fittings in the system

f_h: Friction loss of head per 100 feet of pipe, depending on the pipe’s diameter and flow rate

2.4.5 Determination of Pump and Motor Size

Pump hydraulic power $(P_h) = \frac{Q * \rho g * THD}{1000}$ (6)

where

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Q: flow rate m^3/s
ρ:density of water kg/m^3
g: acceleration due to gravity in m/s
THD:total dynamic head in m
Induction Motor size $(P_m) = \frac{P_h}{\eta}$ (7)
where
P_h: hydraulic power
η: pump efficiency 80%

2.4.6 Determination of Storage Capacity

The power required to pump water into the tank is given by

$$P_{in} = \frac{dE}{dt} = PQ \quad (8)$$

where
E: energy stored in the tank
t: time
P: pressure of the fluid at the base of the tank
Q: volumetric flow rate of the liquid into the tank
Volumetric flow rate of the liquid into the tank

$$Q = \frac{dV}{dt} = A\left(\frac{dh_s}{dt}\right) \quad (9)$$

where
A: cross-sectional area of the tank
Assuming the water level above height hp is sufficient to generate the needed pressure, then anything above hp will be used for storing hydroelectric energy. Therefore, pressure at the base of the tank is given by $P = \rho(h_p + h_s)$ (10)
where
ρ: density of the liquid
g: acceleration due to gravity h_p: pumping level h_s: vertical rise
Substituting (9) and (10) into (8) and integrating

$$\int_0^E dE = \int_0^{hs} \rho g(h_p + h_s)A dh_s$$

The energy storage capacity of the tank at the full capacity of pumped water is given by

E=$\rho g A * (h_p h_s + \frac{hs^2}{2})$ (12)[(11)]
where
ρ: density of the liquid
g: acceleration due to gravity
A: area of the tank h_p: pumping level
h_s: vertical rise

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The same amount of water is used for electricity generation, therefore, power provided by the stored energy is given by

$$P = \frac{E}{t} \quad (13)$$

where

E: Energy storage capacity of the tank

t: discharge time

2.4.7 Photovoltaic System Modeling

The mathematical equation that describes the relationship between photovoltaic voltage and current includes the short circuit current, reverse saturation current, temperature, irradiation, diode ideality factor, electron charge, Boltzmann's constant, series resistance, and shunt resistance. Figure 2 depicts a solar array's equivalent circuit used for solar analysis.

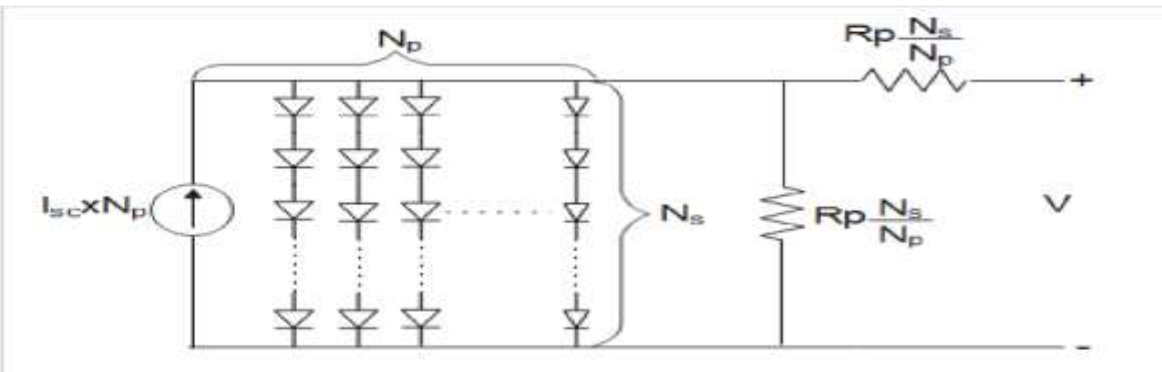

Figure 2: Model of a Photovoltaic Array (Source: [9])

2.4.8 Review on Fuzzy Logic Local Controller for Boost Converter

The control technique described in this work utilizes fuzzy logic control due to its adaptable nature, simplicity, and capacity to address issues with imprecise and incomplete input [14]. The architecture of fuzzy logic controllers (FLC) consists of four phases, as seen in Figure 3 below.

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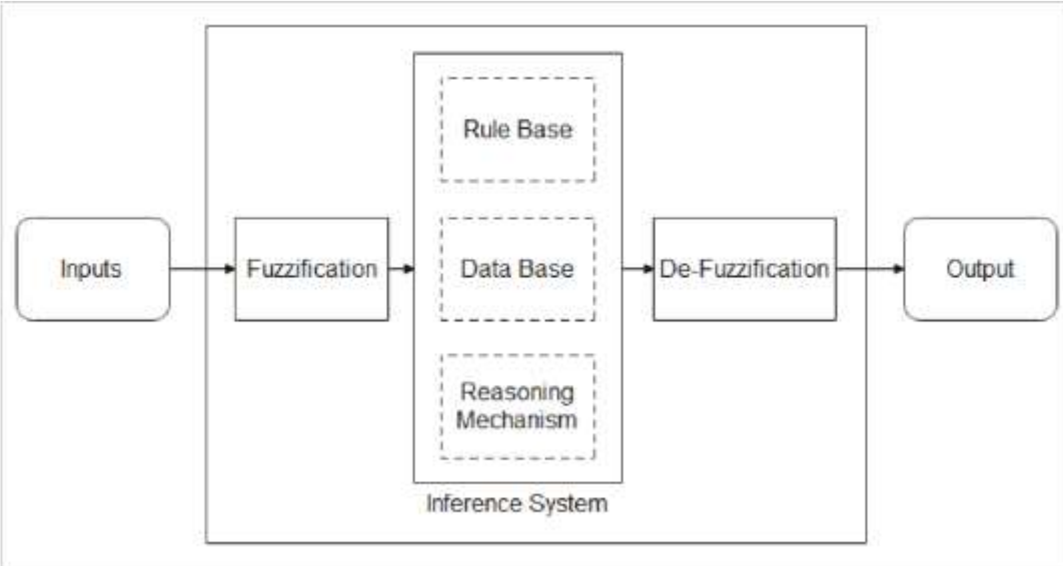

Figure 3: Fuzzy Logic Controller

The current and shunt resistance of a photovoltaic array is given by

$$I_{ph} = I_{sc} - I_o\left[e^{\left(q\frac{V+IR_s\frac{N_s}{N_p}}{aKTN_s}\right)} - 1\right] - \left(\frac{V+IR_s\frac{N_s}{N_p}}{R_s\frac{N_s}{N_p}}\right) \quad (14)$$

where

I_{ph}: Photovoltaic current (A)

I_{sc}: Short circuit current (A)

I_o: Reverse saturation currents of the diode (A) V: Photovoltaic voltage (V) q: Electron Charge ($1.67x10^{-19}C$)

K: Boltzmann Constant ($1.38x10^{-23}J/K$)

T: Junction temperature (K) a: diode ideality factor

Rs: Series resistance (Ω)

Rp: Series resistance (Ω)

$$R_p = \frac{\left(V_{mpp}+I_{mpp}R_s\frac{N_s}{N_p}\right)}{\frac{N_s}{N_p}[V_{mpp}(I_{sc}-I_d)]-P_{mpp}} \quad (15)$$

where

P_{mpp}: maximum power point power

I_{mpp}: maximum power point current

V_{mpp}: maximum power point voltage

2.4.8 Power of a Photovoltaic Array (P_A)

$P_A = N_s * N_p * V_{mpp} * I_{mpp}$ (16)

where

P_{mpp}: maximum power point power

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I_{mpp}: maximum power point current
V_{mpp}: maximum power point voltage

3.0 RESULTS AND DISCUSSION

3.1 Result of an Advance Controller That Can Ensure Efficient Operation of Pump Hydro Storage System Using Fuzzy Logic Technique.

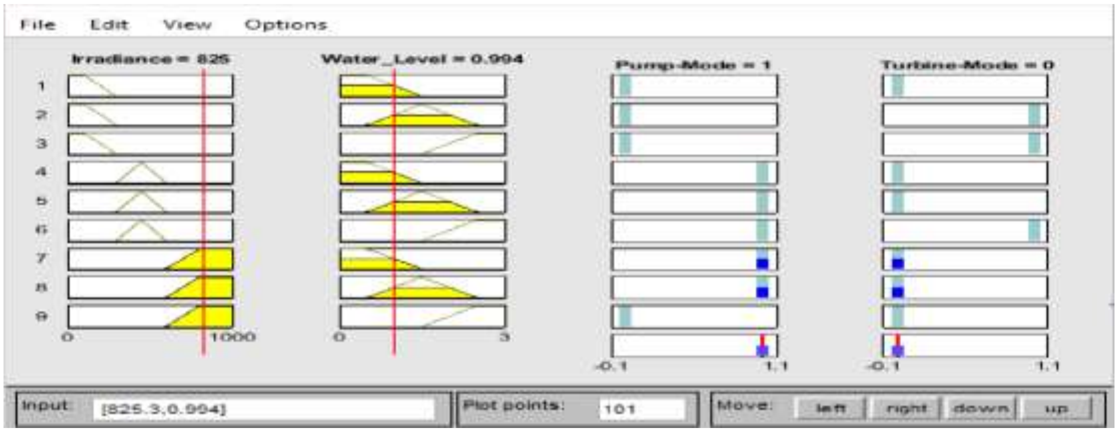

Figure 4: Fuzzy Logic Rule Viewer for Actuating Pump Mode

Figure 4 displays the rule viewer that describes the intelligent control of the centrifugal pump. The Rule Viewer allows for the interpretation of the entire fuzzy inference process at once. The Rule Viewer also shows how the shape of certain membership functions influences the overall result. For this study, nine (9) rules are considered but for actuating the pump mode of the centrifugal pump, rules 7 and 8 are used to roadmap the process. Output 1 indicates valve opening while 0 indicates valve closing. The fuzzy logic controller checks for variations in irradiance and water level and if irradiance is high and water level is low or moderate, the controller will energize the control valve to change the direction of rotation to pump mode

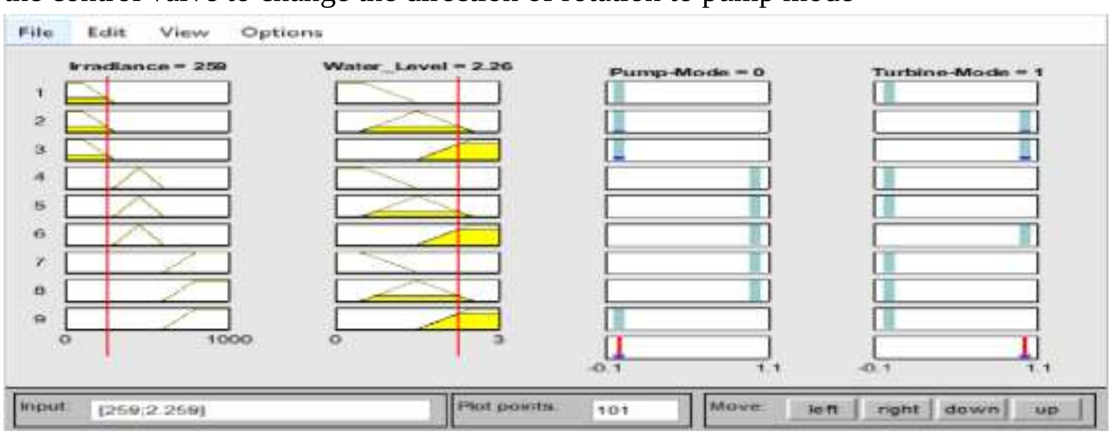

Figure 5: Fuzzy Logic Rule Viewer for Actuating Turbine Mode

In the same vein, Figure 5 shows the rule viewer display for energizing the turbine mode of the centrifugal pump. Nine (9) rules were considered but rules 2 and 3 are used to roadmap the process by opening the turbine valve and closing the pump valve. The fuzzy logic controller checks for variation in irradiance and water level and if irradiance is low and water level is moderate or high, the controller will actuate the control valve to change the direction of rotation to turbine mode. The Rule Viewer allows for the interpretation of the entire fuzzy inference process at once. The Rule Viewer also shows how the shape of certain membership functions influences the overall result.

3.2 Result of Local Controller That Can Extract Maximum Power from PV Array Using Fuzzy Logic Maximum Power Tracking Technique

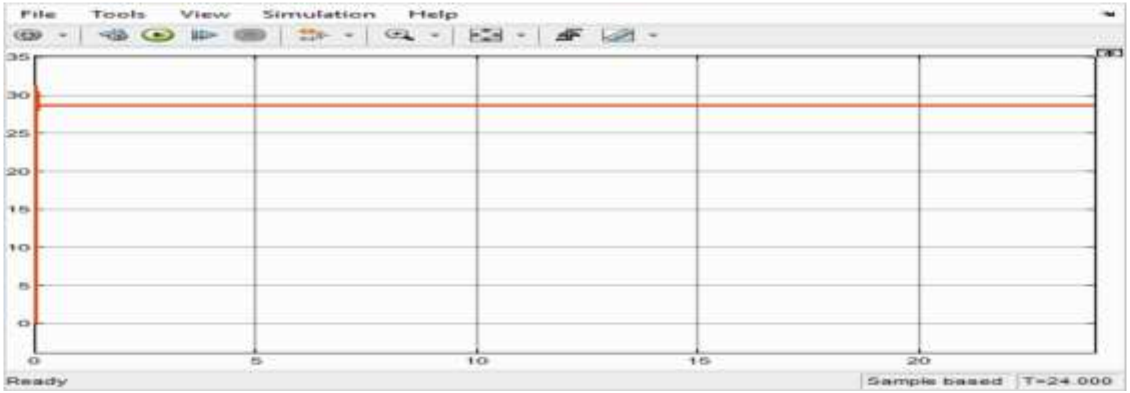

Figure 6: Plot of PV Array Output Power at MPPT

Figure 6 shows the plot of PV array output power at a standard irradiance of 1000w/m^2 and a constant temperature of 25^{o}C. Atmospheric condition which determines the effectiveness of a PV array for instance, operating temperature, solar insolation, and shading array configuration. When the PV module is irradiated, an unregulated DC voltage is produced which is fed to the boost converter for regulation. A quick look at the power plot shows that the maximum power was tracked at a very fast rise time and stabilizes at the maximum power point with no oscillations which are some of the advantages of the fuzzy logic controllers, high efficiency, fast tracking time, and high stability at the maximum power point despite fluctuations in irradiance and other external conditions.

3.3 Result of Pump Capacity of the Storage Reservoir

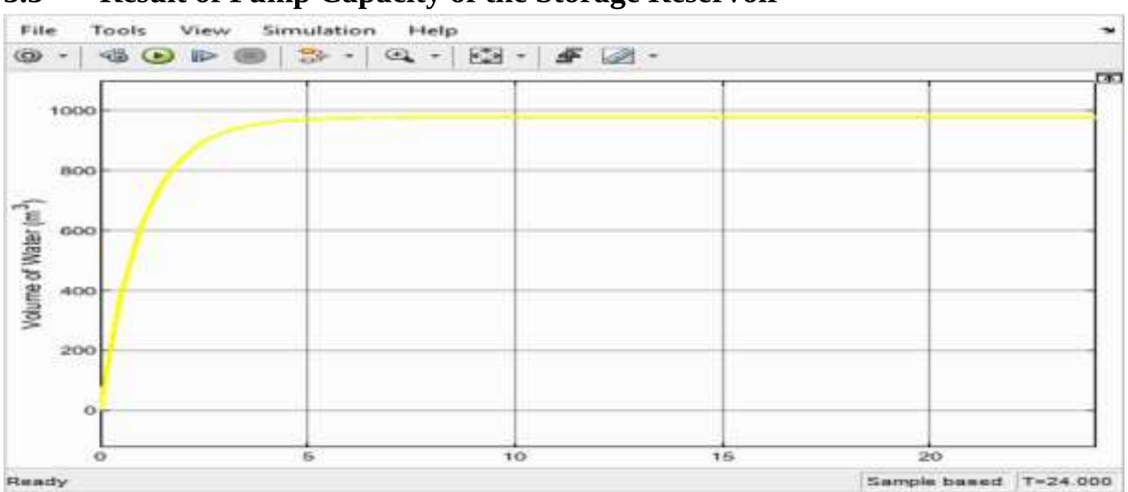

Figure 7: Plot of Reservoir Capacity during Pumping Mode

Figure 7 shows the reservoir capacity during pumping mode. The storage strength of the reservoir is 77. 3kWh. The induction motor is capable of pumping 942.5m^3 of water per day for eight hours. It also shows that the graph is close to the estimated value. After eight hours of operation, the stored water can now be discharged from the reservoir to drive a 15kW turbine generator for electricity generation. The stored water discharges through the water filtration system back into the lower reservoir from where the pump draws its water.

4.0 CONCLUSION

This study x-rayed the conceptual and operational aspects of a hybrid photovoltaic system with a Pumped Hydro System. The hydroelectric power, derived from the mechanical motion of water, is a very valuable renewable energy source. Hydro technologies have reached a high level of development, with a long history, and are capable of generating significant amounts of energy without producing carbon emissions. Pumped-storage technology is a very significant and promising form of energy storage technology known for its exceptional efficiency. Pumped storage hydropower is widely recognized as a very effective large-scale energy storage technology, as it enables the storing of surplus energy for future utilization. Furthermore, it also facilitates the incorporation of renewable energy into the power systemin solar irradiation and reservoir water level. The system effectively controls a centrifugal pump to provide a continuous supply of water and maintain consistency with the load demand.

The hybrid system is developed in the MATLAB/Simulink environment utilizing several subsystem models, including a solar array DC-DC boost converter, an induction motor, and a centrifugal pump. The system dynamic model is constructed using the system's dimensions. The obtained result demonstrates that the fuzzy logic controller effectively monitored the changes in irradiance and water level. It is able to activate the control valve to alter the flow direction. Additionally, the local controller successfully extracted maximum power from the PV panels, achieving a tracking efficiency of over 99.5%. This demonstrates that the suggested fuzzy logic controller efficiently regulated the operation of the pumped hydroelectricity system to guarantee a consistent energy supply that aligns with the fuzzy rules and maintains load demand consistency.

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