Proc. of the 1st International Conference on Electrical, Communication and Computer Engineering (ICECCE)
24-25 July 2019, Swat, Pakistan

Dynamic Operation and Supervisory Control of a Photovoltaic/Fuel cell/Super-capacitor/Battery Hybrid Renewable Energy System

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Abstract— **This work provides the dynamic operation and supervisory control of a hybrid renewable energy system which supplies power in stand-alone as well as in grid-connected mode. It contains a photovoltaic as a primary source controlled via fuzzy and a Proton Exchange Membrane Fuel Cell (PEMFC) as a secondary source controlled via Proportional Integral Differential (PID) controller. The high intermittency nature of photovoltaic is addressed through the integration of super-capacitor and battery bank in the proposed architecture. The overall strategy of the proposed system is achieved using dynamic power switches of the power converters. The strategy maximizes the use of available photovoltaic /fuel cell/ super-capacitor/battery power and reduces stress on the public grid under all conditions for 24 hours. The proposed test-bed is simulated under real weather pattern and load variations. Simulations conclude the effectiveness of the proposed architecture.**

Index Terms— ***PV, hydrogen energy, hybrid storage, fuzzy logic, supervisory control, MATLAB***

I. INTRODUCTION

In recent years, the continuous increase in crude oil price due to global warming, different countries around the globe have begun to invest extensively in research and an infrastructure regarding Renewable Energy Sources (RES). Numerous RES, for example, Photovoltaic (PV) energy is bounteously accessible in nature and economical. The use of PV systems is increasing in all countries including developed and under-developed. On the surface of sunny countries there is only 1/10,000 of the one percent of the world's basic power consumption. PV based power systems are scalable and can be extended with the existing power converters [1], [2], [3]. Nonetheless, due to stochastic nature, the output of PV is a function of weather [4]. Any kind of fluctuations in weather can results low efficiency [5]. To hurdle this problem, normally a hybrid system is used. The purpose of hybrid system is to get maximum benefits in terms of reliability, and efficiency from different power sources and/or storage system [6], [7].

Regarding hybrid power systems an enormous literature is appeared in hundreds of papers and books. For example, a PV system integrated with FC is simulated in [8] [9]. In [10], [11], [12], the authors have developed a coordinated control algorithm for PV with super-capacitor/battery in a micro-grid and/or hybrid system. In [13], a hybrid system combining wind/battery with diesel is developed. Though, in this work, the researchers have still received power from diesel generator in their system. In [10], the authors have reviewed a solar hybrid system integrated with hydro in the context of Europe. Similarly, in [14], the researchers have developed a hybrid power plant integrating PV/wind with FC simulated in LabVIEW. The control of complete system is performed using appropriate power control strategy to extract highest power value from the turbine via variable speed controls. Similarly, it takes maximum energy from the PV using Maximum Power Point Tracking (MPPT). Similarly, FC based generation system is designed in [15], [16]. Likewise, many authors have developed and presented various aspects of hybrid power system such as cost and sizing [17], [18], power quality [19], [20], power fluctuations [21], and energy management [22]–[24].

This paper gives a hybrid renewable energy system which includes of PV, hydrogen cell, Super-capacitor (SC), and battery while considering the real weather data and load conditions. System modelling is done in MATLAB. The proposed system works under Dynamic Power Switches Control System (DPSCS), which successfully deals with all the energy sources and capacity framework as per weather and demand. The proposed design and strategy validate 24 Hrs power transfer with high continuity.

This research is arranged as: Section II describes the architecture of system and its control. Next, Section III focuses on the proposed algorithm. Simulations are explained in Section IV. Conclusion is stated in Section V.

II. ARCHITECTURE AND CONTROL OF SYSTEM

The system which is taken in this work has two bus architecture as illustrated in Figure 1. PV, FC, SC and battery are attached with DC bus. Similarly, domestic load and grid are synchronized to AC bus. The energy transfer happens between these components via the proposed DPSCS. The output power of PV is controlled via Proportional Integral (PI) and fuzzy controllers as shown Figures 2 (a) and 2 (b). Similarly, FC is controlled via DC–DC converters with PID controller as given in Figure 3. The objective of fuzzy controller is to minimize the MPPT error "e". This error is critical to control the boost converter connected to PV. The

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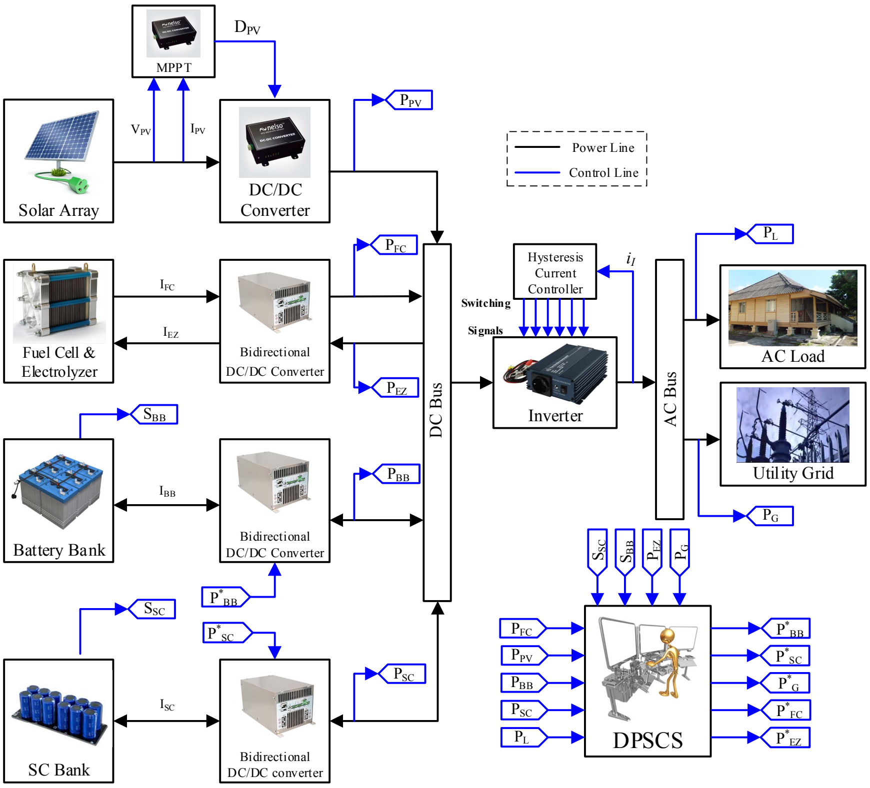


Fig. 1: Structure of the proposed system

battery and SC are attached to the DC bus using bi-directional DC-DC converter. The power transfer from different power sources to the DC side is occurred via DC-DC converter. Both the SC and battery are controlled via PID controllers as illustrated in Figure 4. The inverter is controlled through hysteresis current control algorithm with two PI controllers. The PI controllers via phase locked loop reduces the error to provide the required powers as shown in Figure 5.

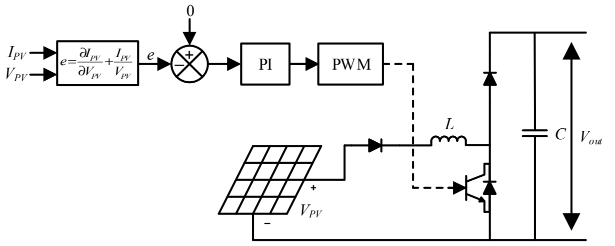


Fig 2 (a): Control of PV using PID

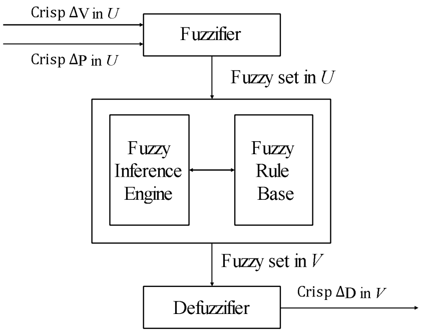


Fig 2 (b): Fuzzy control of PV

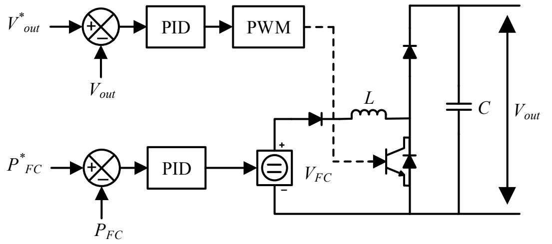


Fig 3: Control of PEMFC

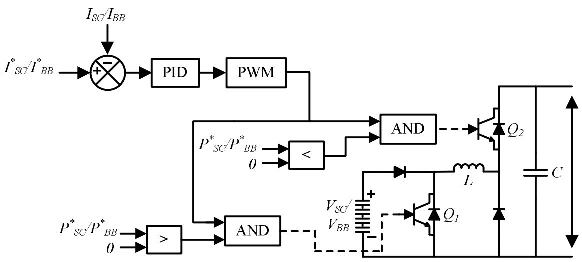


Fig 4: Control of SC/battery

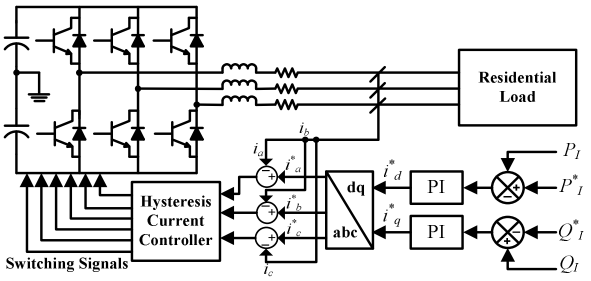


Fig 5: Inverter control

III. WORKING OF DPSCS

The PV and FC (PEMFC) which are taken in simulation are capable to generates 261 kW and 200 kW power, respectively. A battery (50 Ah) and SC (165 F) are attached with FC in the system. Both SC and battery utilize the surplus power from DC side and then provide in case of need. Besides, the load tracking issue of FC is balanced by SC. Depending on load, the DPSCS generate the references for the power converters linked to the system's components. The approaches are used in the DPSCS are described as below.

- PV system has made choice 1 over other sources to deliver the required power.
- If PV generates more power than it will be sent to the battery first, and then to SC for charging.
- If still there is an excess power, then it will be used for electrolysis.
- Likewise, if the demand is high than the total power provided by PV, then the proposed DPSCS will take power from battery and then SC provided their SoC> 20%.
  - If the demand is still not meet from the combine power of PV/SC/battery, then the remaining power will be taken from the FC.
  - If still there is a demand, grid will provide the remaining power.

The process of proposed algorithm is illustrated in Figure 6.

IV. SIMULATION

The weather statistics taken in simulation are real time measured weather data [25]. From Figure 7, the sun appears at 6.3 Hrs and sets around 20 Hrs. Correspondingly, the temperature is below 27 °C at nighttime, and it goes to 37 °C at daytime.

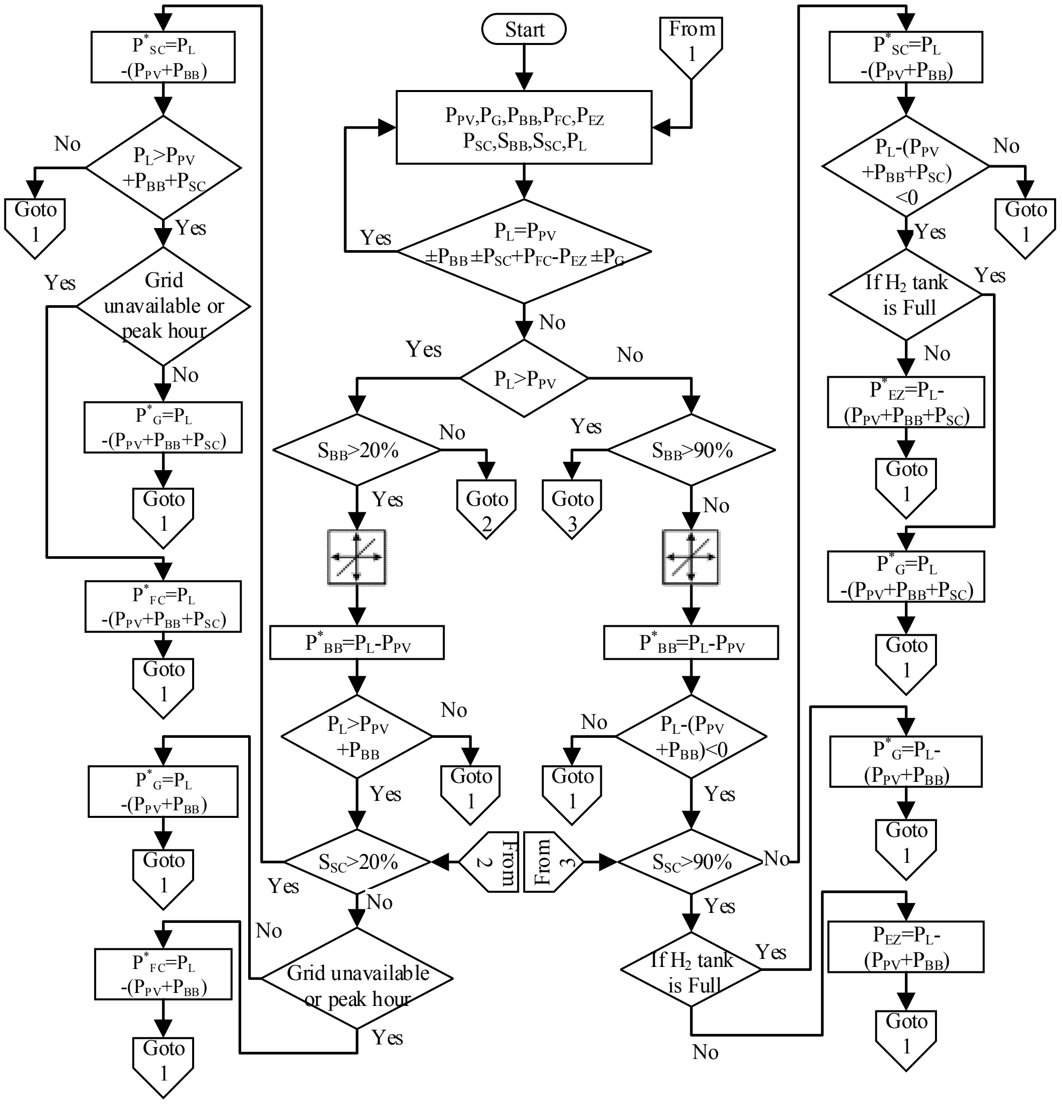


Fig 6: Working of DPSCS

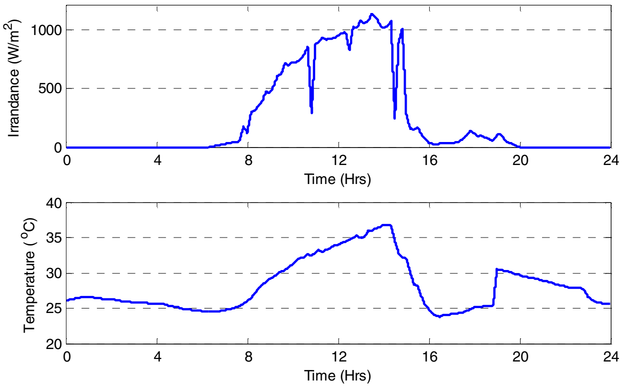


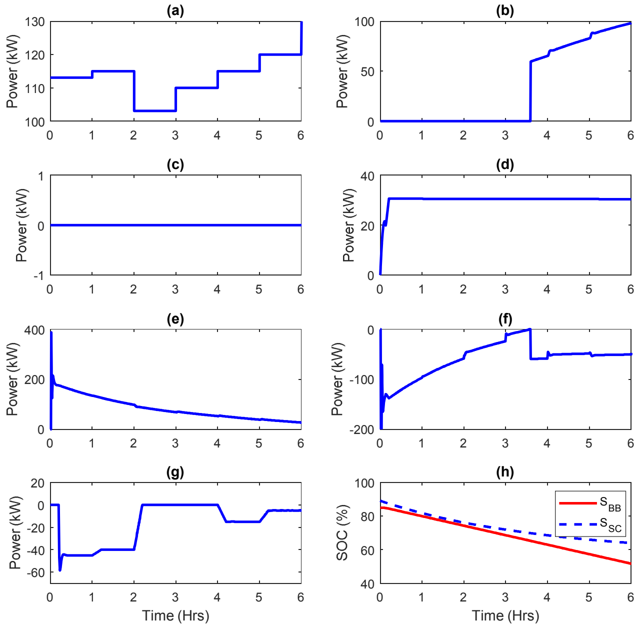
Fig 7: Weather data

The available powers generated from various energy sources are illustrated in Figures 8-11. These results are explained in four sections according to time intervals. The first section begins early morning at 0:00-6:00 Hrs, and similarly the second section starts at 6:00-12:00 Hrs. Initially, from the Figure 8, the proposed system experiences a load of 113 kW. At the start, a very slow response can be seen at a transient from the battery.

On the other hand, SC possesses high-power density, so, 210 kW output power overshoots are available from SC. Further, excess power is also available in the period from the energy sources. The surplus power was effectively utilized by the ELZ. The net available power from battery and SC is more than the demand which can be observed in simulation at t=1-3.5 Hrs. All the surplus power is consumed through ELZ to generate hydrogen. The proposed DPSCS commands FC to deliver the power at t=3.5 Hrs, because SC and battery cannot meet the required RL demand. Due to night hours, a minimum PV output power can be observed at t=3.5-6.3 Hrs, and a 30 kW power is taken from the battery. In this period, the system experiences a maximum load of around 132 kW. Also, the fuel cell and SC, and grid are giving a maximum power of 113 kW and 53 kW, 15 kW, respectively. The surplus power produced in this period is around 50 kW, which is dumped by ELZ to avoid oscillations in the system.

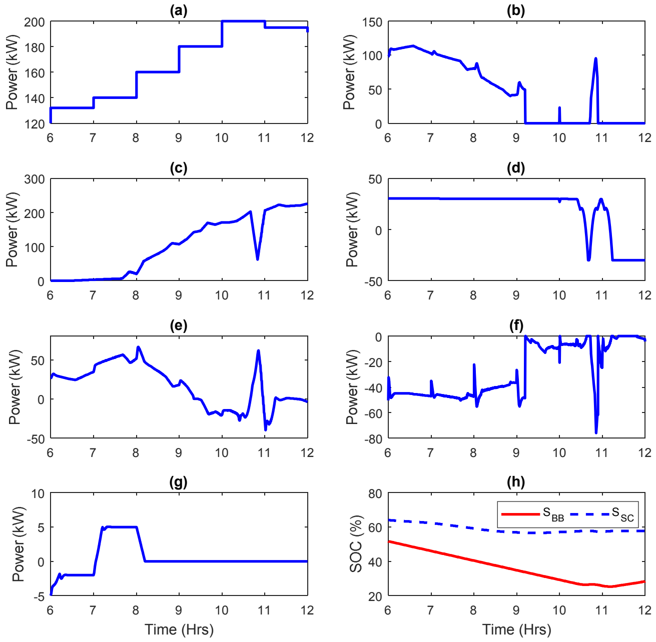
In Figure 9, it is depicted that the PV system starts to give power at 6.3-9.2 Hrs, but the required demand is not satisfied from it. The grid is in island mode in this period while SC, FC, and battery are providing the power to satisfy the RL demand. The net power of PV and battery is an adequate to satisfy the demand at 9.2 Hrs and there is no use of FC and SC in the given interval. At t=10.67 Hrs, the RL demand is lower than the PV output power. Thus, the proposed algorithm changes the battery to charging mode. During next interval, i.e., at t=10.67-11:00 Hrs, the irradiance goes down very quickly.

Therefore, the proposed algorithm manages power from SC, then from FC and battery. Due to slow dynamic response, maximum power is available from battery after a short interval, while SC & FC are effectively managed the power shortage. At t=11:00 Hrs, battery and SC are changed to charging, because the output power of PV meets the RL demand. At t=12:00-14.39 Hrs, excess power is available from PV and 20 kW is supplied to grid as shown in Figure 10.



(a). Load demand (b). PEMFC power (c). PV power (d). Battery power (e). SC power (f). ELZ power (g). Grid power (h). SoC of SC and Battery

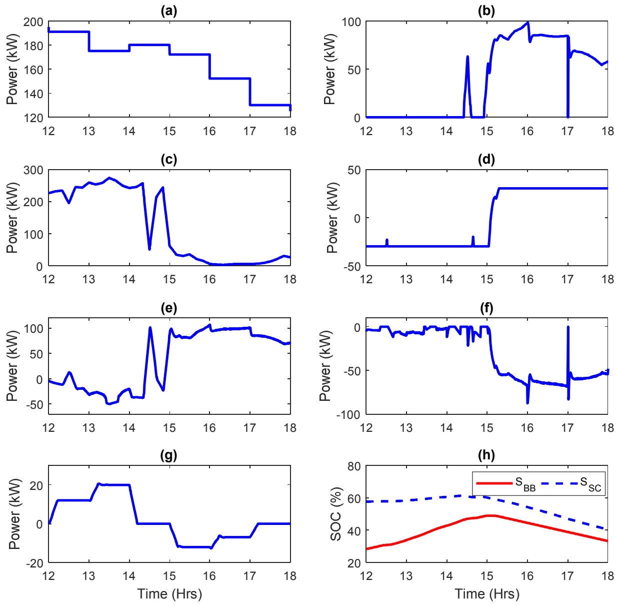
Fig 8: Output powers of different sources for 0-6 hours



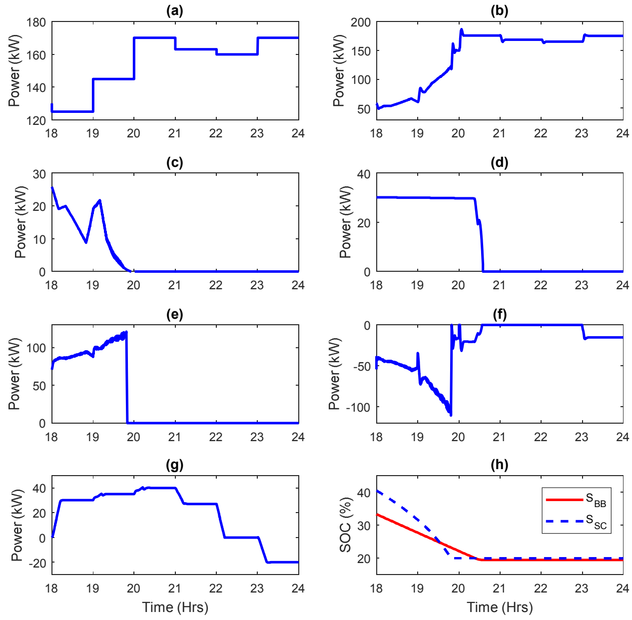
(a). Load demand (b). PEMFC power (c). PV power (d). Battery power (e). SC power (f). ELZ power (g). Grid power (h). SoC of SC and Battery

Fig 9: Output powers of different sources for 6-12 hours

The battery is charged at a maximum power, i.e., 30 kW and extra power is supplied to charge the SC and/or use in ELZ. In next interval, i.e., at t=14.40-14.6 Hrs, the PV power rapidly goes down to 57 kW which do not meet the required demand and the DPSCS takes power from FC and SC to meet the required demand. At t= 15-17 Hrs, the RL demand is more than the PV power, therefore, grid, SC and battery in combined to achieve the power gap where ELZ consumed the excess power. At 17:00-18.0 Hrs, the fuel cell also contributes and provide 119 kW power with battery and SC in combined. At this interval, the State of Charge (SoC) of SC goes down to its lowest value, therefore, the DPSCS stops the power flow from SC.



(a). Load demand (b). PEMFC power (c). PV power (d). Battery power (e). SC power (f). ELZ power (g). Grid power (h). SoC of SC and Battery
Fig 10: Output powers of different sources for 12-18 hours



(a). Load demand (b). PEMFC power (c). PV power (d). Battery power (e). SC power (f). ELZ power (g). Grid power (h). SoC of SC and Battery

Fig 11: Output powers of different sources for 18-24 hours

The SoCs of storage system (battery and SC) are given in Figure 8-11 (h). At the beginning, the SoC of SC was 90% and the SoC of battery was 85%, and their SoCs changes according to the requirement. For example, at t=11.2 Hrs The SoC of battery goes down to 25% and the SoC of SC reaches to 57%. Finally, their SoCs goes down to 20% and DPSCS stops power taken from them. After t=19.82 Hrs in Figure 11, it is observed that the battery/SC's SoC goes down to their lowest critical value at t=20.0 and 20.5 Hrs, and PV power is almost zero at this interval, so, the DPSCS switched off the battery/SC from the system due to its SoCs critical value. The total RL burden is managed from fuel cell and grid's power. The fuel cell effectively supplies all the required power and keep the system operationally stable.

The control of PV system using proposed fuzzy and PI controllers is given in Figure 12. At different interval, it can be noticed, that the proposed fuzzy controller (denoted as blue in Figure 12) performance is much better in PI controller.

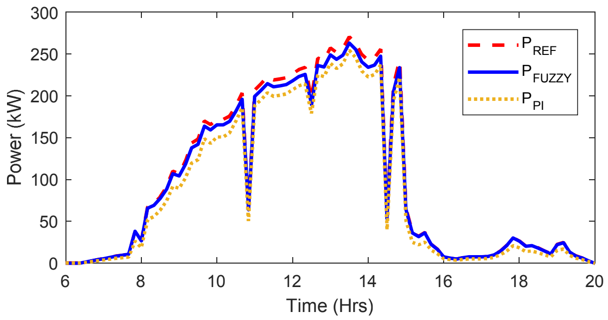


Fig 12: Fuzzy vs PI control of PV

V. CONCLUSION

This manuscript concludes hybrid renewable energy system controlled via dynamic power switches power converters. This system was composed of PV, hydrogen energy (FC), SC and battery. The primary source (i.e., PV) was controlled using fuzzy logic for maximum power. The proposed DPSCS overcomes the limitation of an individual power source and presents a PV/FC/SC/Battery hybrid system which provides power to load for 24 Hrs. The performance of the proposed system was checked under real-measured weather data and load variations. Simulation confirms the feasibility of the established test-bed.

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