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Design and Implementation of Control Strategies for an Energy Management with Multi Distribution Energy Resources

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Abstract:
In recent years, growing interest in renewable energy sources (RES) has prompted microgrids to develop towards more intelligent and modernized entities. Microgrids integrate the distributed generators including conventional and renewable sources to supply predicted load of end-users in a decentralized manner. However, intermittency and undispatchability of RES outputs induce system robust problems. Energy from RES might be unavailable due to bad weather conditions when electricity is needed. Energy storage system (ESS) is usually integrated in microgrids to compensate power mismatch. Energy sustainability of energy systems is a multi-objective, multi-constraint problem, where the energy system requires the capability to make rapid and robust decisions regarding the dispatch of electrical power produced by generator assets. This process of control for energy system components is known as energy management. This project presents a study of a standalone hybrid microgrid system that is a compound that utilizes renewable sources that are Wind Generator (WG), Solar Array (SA), Fuel Cell (FC) and Energy Storage System (ESS) using a battery. The power electronic converters play a very important role in the system; they optimize the control and energy management techniques of the various sources. The performance of the mentioned system is studied using MATLAB/Simulink software environment.

Keywords:
Distribution Energy Resources, Energy Management, Microgrid, Power Electronic Interface, PI and Fuzzy Control.

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I. INTRODUCTION

Energy is a fundamental aspect to people's life, and is essential not only for individuals but also for various sectors. It can be supplied from various resources which can be divided into two categories; renewable and non-renewable. In recent years, growing interest in renewable energy source (RES) has prompted microgrids to develop towards more intelligent and modernized entities. Wind and Solar are the most exploited renewable resources. According to the Renewables Global Status Report-REN21 [1] wind power and solar PV can be considered as the leading sources for the new power generation capacity in the India, USA, Europe and China during 2019. The report indicates that renewable energy replaces fossil and nuclear fuels in four distinct markets: power generation, heating and cooling, transport fuels, and rural/off-grid energy services.

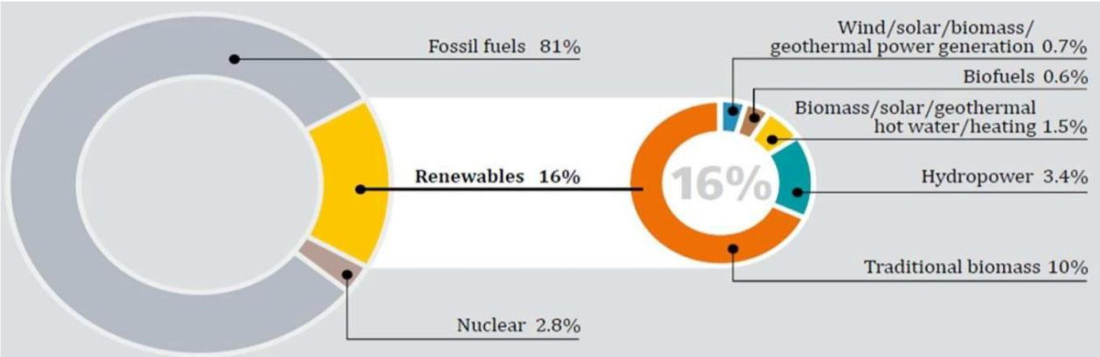


Figure1:Renewable Energy share of Global Final Energy Consumption (REN21)

Microgrids integrate the distributed generators including conventional and renewable sources to supply predicted load of end-users in a decentralized manner. Recent advances in technology have made the use of Microgrids more economical. Hence it becomes imperative to harness and optimize power generation through the use of locally abundant sources such as Solar, Wind, Biogas and tidal farms to form a grid powered by multiple renewable sources. This allows for a myriad of architectures that can be tailor fit for specific regional situations.

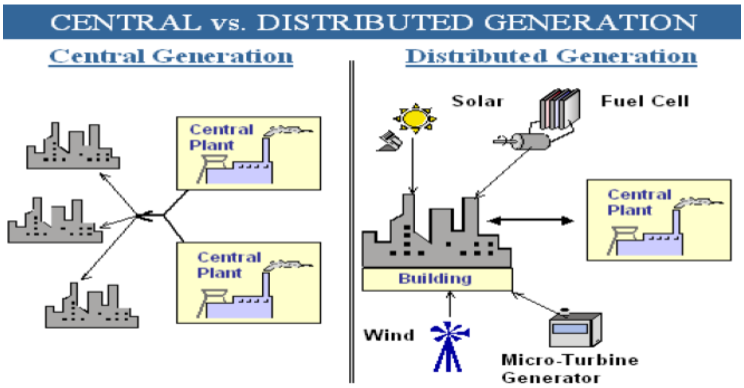


Figure2: Central generation vs. Distributed Generation representation

Smart grid is a new type of power supply mode which integrates renewable energy power generation technology (wind power generation, photovoltaic power generation, biomass energy etc.), energy management system (EMS) and distribution infrastructure. It not only improves energy efficiency and the security of power supply, but also reduces the power loss and the impact on the environment. At the same time, the microgrid should have an independent control system, which can adjust its operation status according to the load and power grid signals independently.This process of control for energy system components is known as energy management. In this context, microgrids are considered as the key building blocks of smart grids [2] and have aroused great attention in the last decade for their potential and the impact they may has in the coming future [3], [4]. The Microgrid (MG) concept has been discussed by several authors [5], [6]. Additionally, in a MG scenario due to the stochastic nature of both the renewable sources and the power consumed by the load, the inclusion of Energy Storage System (ESS) (e.g. batteries, flywheels, ultra-capacitors) and Energy Management Systems (EMS) are highly recommended in order to improve the system stability and its performance [7], [8]. In general, MGs are capable to work in both grid-connected and stand-alone modes [9], [10]. They are defined as low voltage systems comprised of loads, Distributed Generation (DG) units and storage devices that are connected to the mains at a single Point of Common Coupling (PCC) [11]. Additionally, the EMS design should take into account the MG power architecture and, in particular, the power management capability of the MG elements (i.e. which sources, loads and storage elements can be controlled). Once the power architecture and the predefined objectives are known, the EMS design can be undertaken by applying different methods [14], [15]. Moreover, in [12] the design of the EMS focuses on controlling through a predictive control technique the ESS to compensate the hourly deviations of a forecasted energy plan in a grid-connected MG. Several management strategies were proposed for a standalone HES mode in ref [13]; the authors have tested the performances of three HES management strategies in a remote area comprising PV/wind/PEMFC. The PV and wind were utilized as primary sources whereas PEMFC was employed as a secondary or backup source [14].Two-layer Energy Management Strategy (EMS) for a PV/wind/battery microgrid hybrid system has been introduced in [15], where they have forecasted the PV wind power availability and requirement load using convex optimization in the upper EMS layer.

II. PROPOSED HYBRID ENERGY SYSTEM

Distributed Energy Resource (DER) systems are small-scale power generation or storage technologies (typically in the range of 1 kW to 10,000 kW) used to provide an alternative to or an enhancement of the traditional electric power system. DER systems may include the following: Solar Photovoltaic (PV) systems, Wind power systems, Fuel cells and Battery Storage Systems etc. Hybrid Energy Systems (HES) are inter-connected from wind power, photovoltaic power, fuel cell and micro turbine generator to generate power to local load and connecting to grid/micro grids. The hybrid PV/wind power system has higher reliability to deliver continuous power than individual source. These sources supply different loads connected to storage elements to compensate for the intermittency of renewable energy sources and yield higher overall energy efficiency. In order to draw the maximum power from PV arrays or wind turbines and to deliver the stable power to the load, a substantial battery bank is needed. HES can be connected to the electrical grid or work as a standalone microgrid. The system being considered is as shown in Fig.3 and its modeling is described in following section.

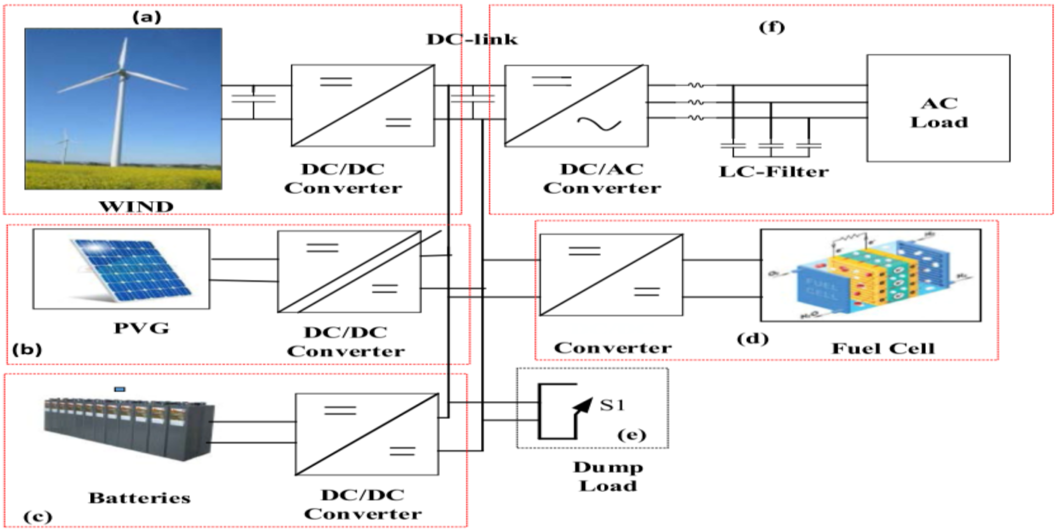


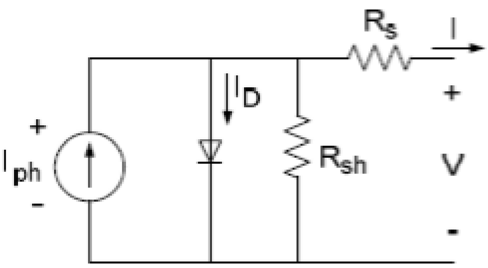
Figure3: Structure of the proposed renewable hybrid energy system

2.1 Modeling of Solar PV System:

A photovoltaic system converts sunlight into electricity. Photovoltaic (PV) effect is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. The basic device of a photovoltaic system is the photovoltaic cell or a solar cell that converts the energy of sunlight directly into electricity by the photovoltaic effect.

2.1.1 Mathematical Modeling of PV

The complex physics of the PV cell can be represented by the equivalent electrical circuit as shown in the fig.4.and its characteristics have shown in the fig.5.



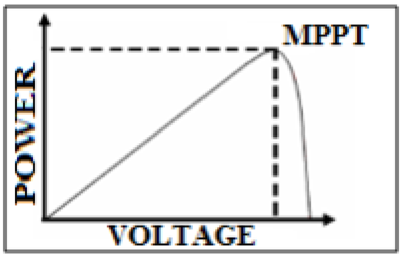


Figure4: PV cell equivalent circuit

Figure5: PV Characteristics of a Module

The basic equation from the theory of semiconductors that mathematically describes the I-V characteristic of the ideal PV cells as follows:

$$I = I_{pv,cell} - \frac{I_{o,cell}[\exp\left(\frac{qv}{akT}\right)-1]}{I_d} \qquad \text{----- (1)}$$

$$I_d = I_{o,cell}\{\exp\left[\frac{qv}{A} * k * T\right] - 1\} \qquad \text{----- (2)}$$

Where,

$I_{pv,cell}$ =the current generated by incident light (amps)
I_d =diode current (amps)
$I_{o,cell}$ =is the reverse saturation or leakage current of the diode (amps)
q = is the electron charge [1.60217646 x 10^{-19} C]
k = is the Boltzmann constant [1.3806503 x 10^{-23} J/K]
T = is the temperature of the *p-n* junction [K]
a = is the diode ideality constant.

Consequently, the instantaneous PV generator efficiency can be expressed as follows:

$$\eta_g = \eta_r \eta_{pt} \left\{1 - \beta_t (T_a - T_r) - \beta_t G_t \left(\frac{NOCT-20}{800}\right)\left(1 - \eta_r \eta_{pt}\right)\right\} \quad \text{----- (3)}$$

η_{pt}, β_t, $N_{OCT}$are parameters that depend on the type of module, and given by the manufacturer of the modules.

2.2 Modeling of Wind Energy System:

Among the renewable energy technologies for electricity production, wind energy technology is the most mature and promising one. The use of wind energy conversion systems (WECS) is increasing world-wide. Moreover, the economic aspects of wind energy technology are promising enough to justify their use in standalone applications as well as grid connected operations.

2.2.1 Modeling of Wind Turbine

The wind turbine (WT) converts wind energy to mechanical energy by means of a torque applied to a drive train. A model of the WT is necessary to evaluate the torque and power production for a given wind speed and the effect of wind speed variations on the produced torque.Wind turbine's Power characteristic equation describes the mechanical Power that is generated by the Wind as given by the equation below.

$$P_m = C_p(\lambda, \beta) \frac{\rho A}{2} V_{wind}^3 \quad \text{----- (4)}$$

The performance coefficient Cp (λ, β), which depends on tip speed ratio λ and blade pitch angle β, determines how much of the wind kinetic energy can be captured by the wind turbine system. Figure 2.8 and 2.9 are illustrations of a Power coefficient curve and Power curve for a typical fixed pitch (β =0) horizontal axis Wind turbine. It can be seen from figures 6 and 7 that the Power curves for each Wind speed has a shape similar to that of the Power coefficient curve.

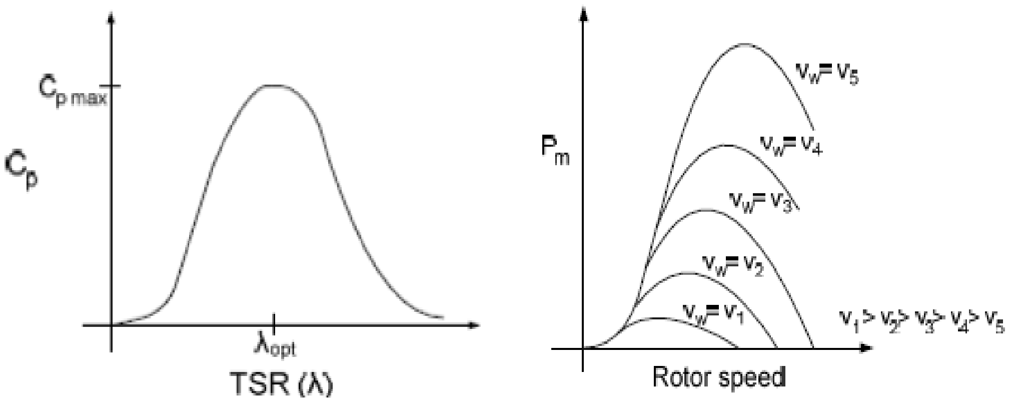


Figure6 and 7: Power Coefficient Curves of a typical Wind Turbine

2.3 Modeling of Battery Energy System:

Batteries are one of the most cost-effective energy storage technologies available, with energy stored electrochemically. A battery system is made up of a set of low-voltage/power battery modules connected in parallel and series to achieve desired electrical characteristics. Common rechargeable battery technologies used in today's PV systems include, the valve regulated lead-acid battery, nickel–cadmium and lithium-ion batteries.

2.3.1 Modeling of Battery Storage:

At any hour the state of battery is related to the previous state of charge and to the energy production and consumption situation of the system during the time from t-1 to t. During the charging process, when the total output of PV and wind generators is greater than the load demand, the available battery bank capacity at hour t can be described by

$$C_{bat}(t) = C_{bat}(t-1).(1-\sigma) + \left(E_{PV}(t) + E_{WG}(t) - \frac{E_L(t)}{\eta_{inv}}\right)\eta_{bat} \quad \text{----- (5)}$$

On the other hand, when the load demand is greater than the available energy generated, the battery bank is in discharging state. Therefore, the available battery bank capacity at hour t can be expressed as:

$$C_{bat}(t) = C_{bat}(t-1).(1-\sigma) - \left(\frac{E_L(t)}{\eta_{inv}} - \left(E_{PV}(t) + E_{WG}(t)\right)\right) \quad \text{----- (6)}$$

Where C_{bat} (t) and C_{bat} (t - 1) are the available battery bank capacity (Wh) at hour t and t-1, respectively.At any hour, the storage capacity is subject to the following constraints:

$$C_{bat\ min} \leq C_{bat}(t) \leq C_{bat\ max}\ . \qquad \text{----- (7)}$$

Where C_{batmax} and C_{batmin} are the maximum and minimum allowable storage capacity.Advances in battery technologies offer increased energy storage densities, greater cycling capabilities, higher reliability, and lower cost.

2.4 Fuel Cell:

A fuel cell is a device that converts the chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent. Fuel cells can produce electricity continuously for as long as these inputs are supplied. Fuel cells are used for primary and backup power for commercial, industrial and residential buildings and in remote or inaccessible areas. They are also used to power fuel-cell vehicles, including forklifts, automobiles, buses, boats, motorcycles and submarines. A typical fuel cell produces a voltage from 0.6 V to 0.7 V at full rated load. To deliver the desired amount of energy, the fuel cells can be combined in series to yield higher voltage, and in parallel to allow a higher current to be supplied. Such a design is called a fuel cell stack.

2.5 Energy Management Strategy:

To manage the electrical energy generated by the hybrid system, a developed supervisor was devoted to the optimization of both the energy produced via renewable sources and that of the battery. If the renewable sources do not give enough power and the capacity of the battery is sufficient (SOC >SOCmin), the battery will then supply the missing power (discharge mode) up to a precisely defined limit, otherwise load shedding is essential to protect the battery. However, if the hybrid power exceeds the load demand, the excess power will be stored in the battery, but if it reaches its maximum (SOCmax), the surplus will be dissipated in a load shedding. Therefore, managing flow of energy throughout the proposed hybrid system is essential to ensure the continuous power supply for the load demand.The supervision algorithm implemented can be represented by the following flowchart:

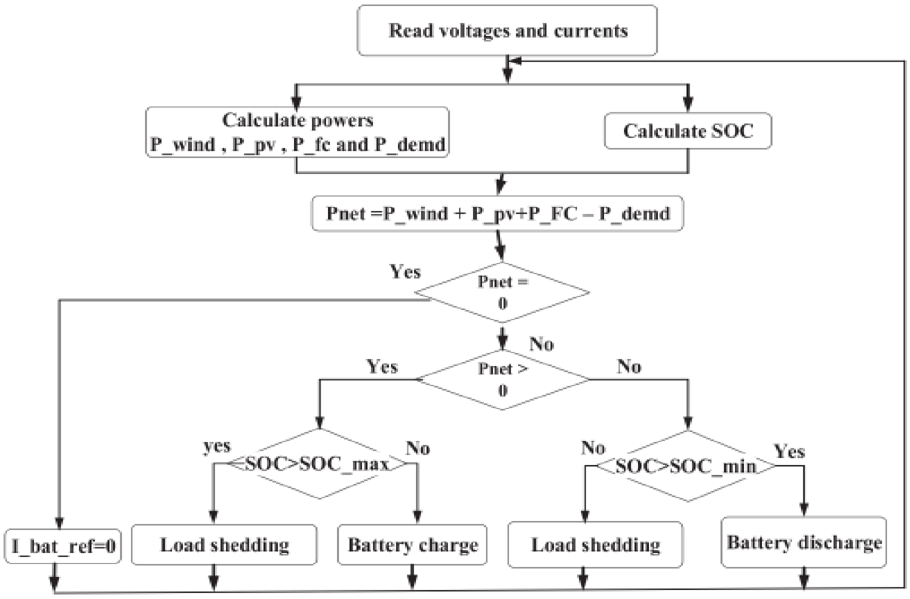


Figure8: Hybrid system power management algorithm flowchart

The main task of the three-phase load-side inverter is supplying the load under stable voltage and frequency. The following fig. shows three-phase load voltage control strategy used for the system with PI Controller and similarly implemented with fuzzy controller for better performance.

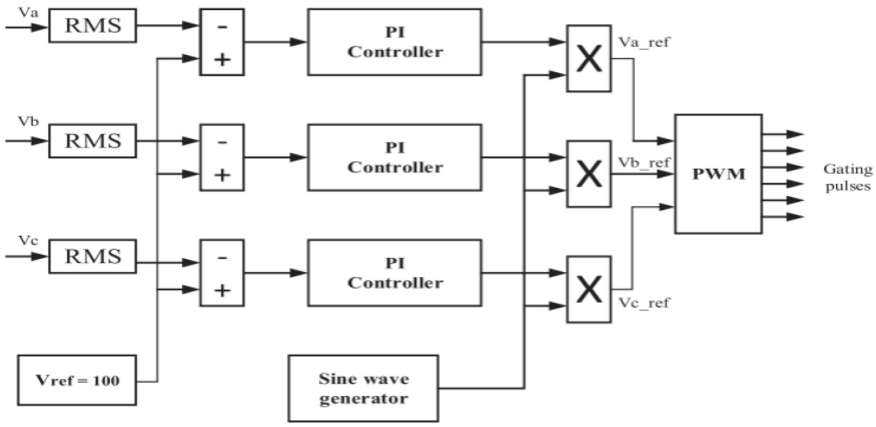


Figure9: Three-phase Load Voltage Control Strategy

III. RESULTS AND DISCUSSION

The following fig. shows the implementation of hybrid energy system and inverter control strategy with conventional PI and fuzzy controllers in MATLAB/Simulink software.

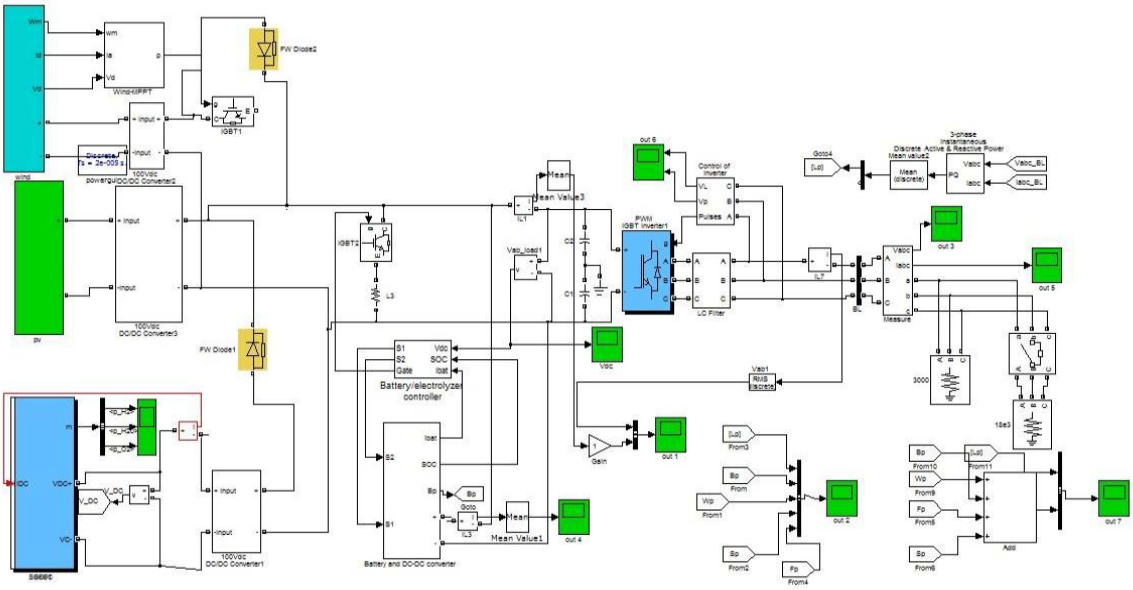


Figure10: Overall Simulation Diagram of a Hybrid System

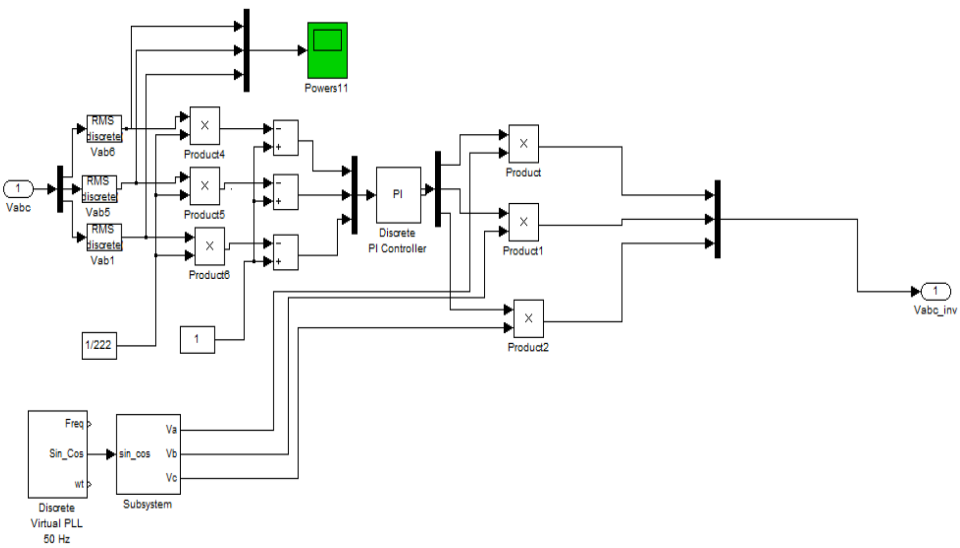


Figure11: Inverter Control Strategy with PI controller

The following results are obtained with PI control strategy.

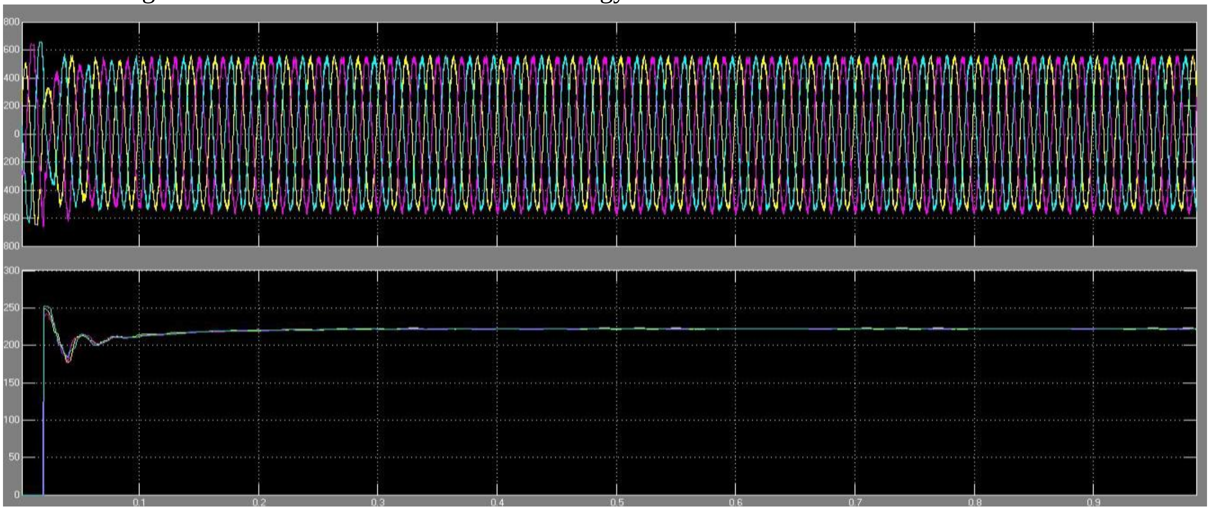


Figure12: Inverter Voltage and DC Link Voltage

The below fig. shows the power outputs of all energy sources of hybrid system considered and also load power.

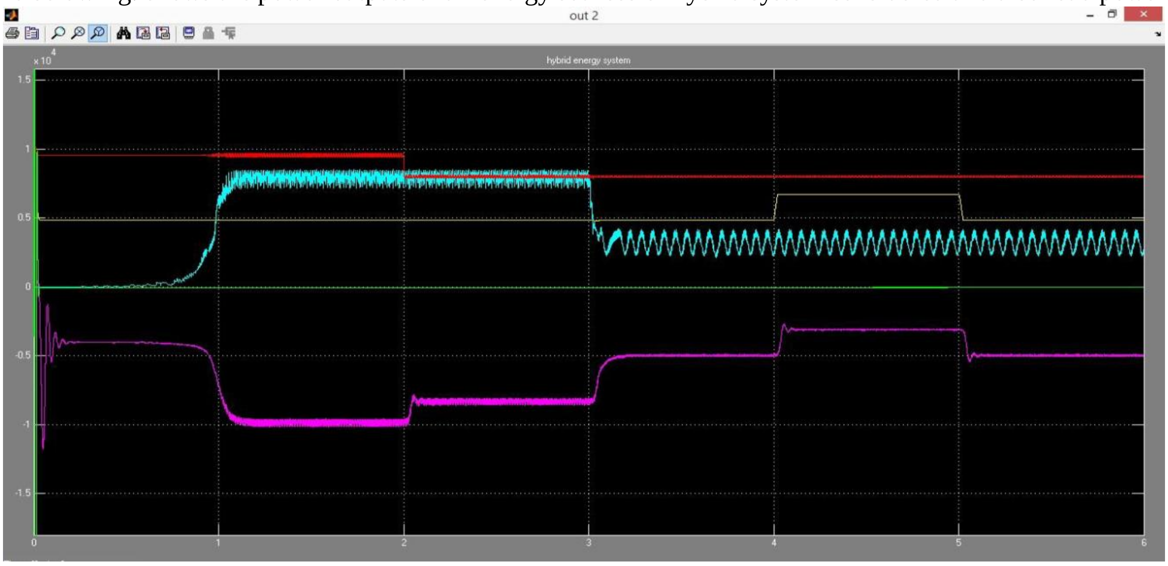


Figure13: Source Powers and Load Power with PI controller

The fig. below shows the energy outputs of the hybrid system and the load power, which is met by sum of all the sources power for the energy management of the proposed system.

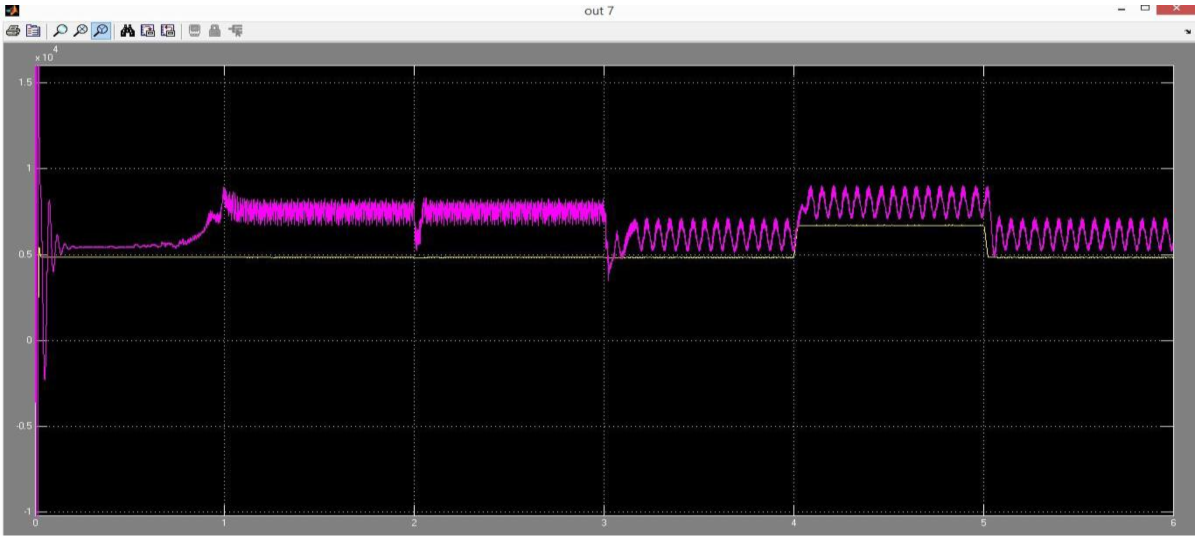


Figure14: Energy Management graph of Hybrid System with PI control strategy

Fuzzy Logic Implementation:The inputs of FLC are defined as the Voltage Error and Change of Error and Duty cycle is the output to the Fuzzy Logic Controller. Five triangular membership functions are chosen the for input variables and the output variable, namely: NB, NS, Z, PS and PB, representing negative big, negative small, zero and positive small and positive big respectively as given in the below table.

Table1: Fuzzy Rules Representation

e \ de	NB	NS	Z	PS	PB
NB	PB	PS	NS	NS	NB
NS	PS	PS	NS	PB	NB
Z	NB	NB	NS	PS	PB
PS	NS	NS	PB	NB	PS
PB	NS	NS	PB	PB	PB

The below fig. shows proposed inverter control strategy with Fuzzy controller that can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear PI control technique.

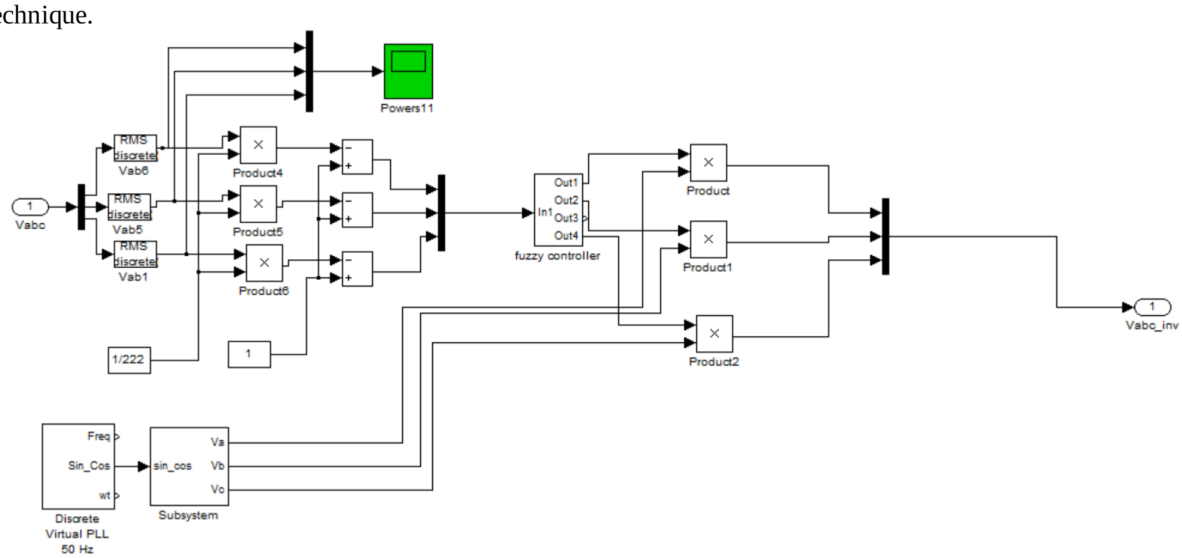


Figure15: Inverter control with Fuzzy extension methodology

The following results are obtained with Fuzzy control strategy.

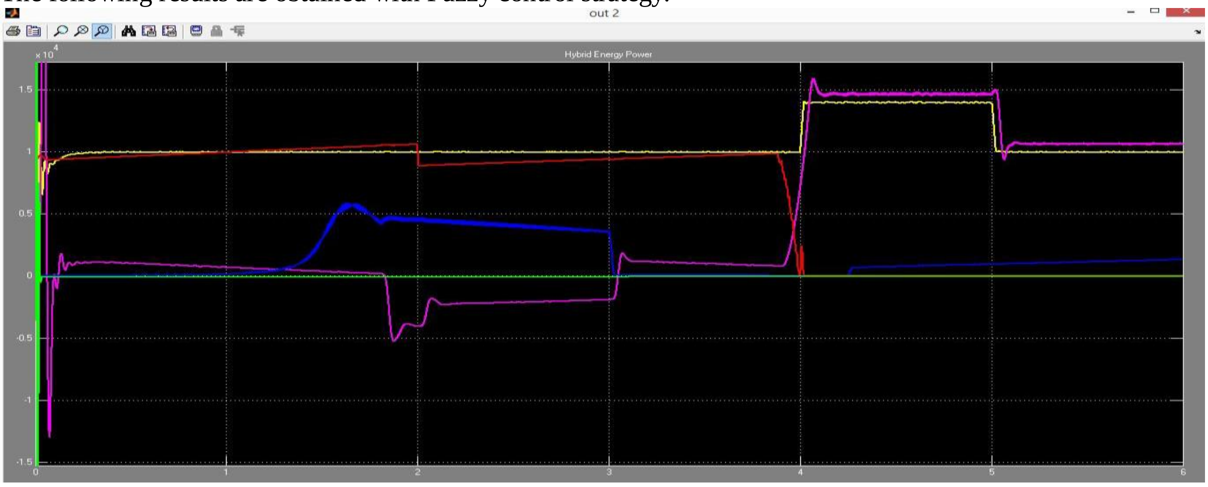


Figure16: Power Outputs of Energy Sources and Load Power with Fuzzy Controller

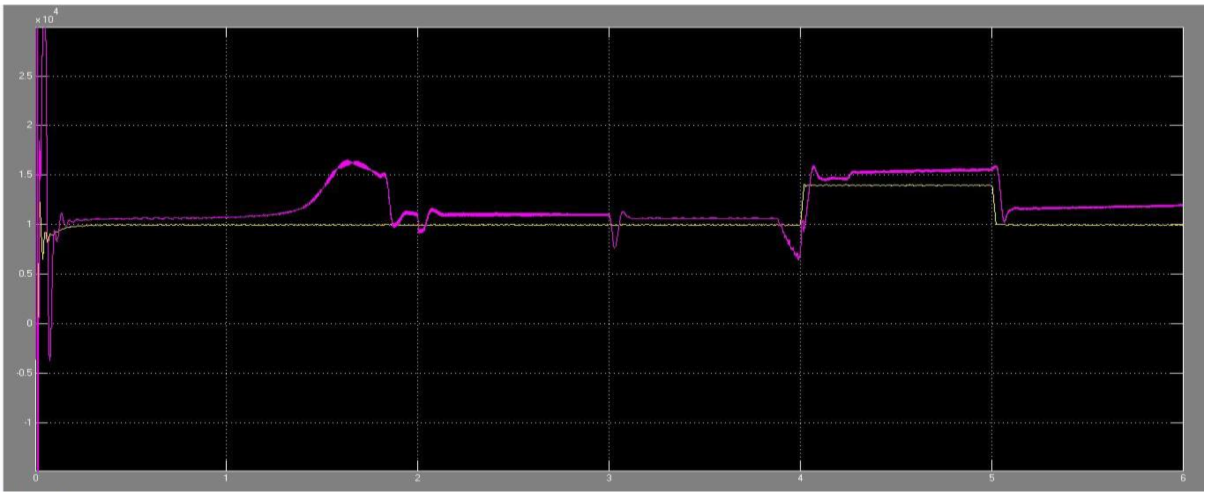


Figure17: Energy Management results of Hybrid System with Fuzzy control strategy

From the above results, it can be said that Fuzzy logic controller have superiority over the PI control strategy applied for the Inverter control of considered hybrid system for the power/energy management.

IV. CONCLUSION

In this paper, it is devoted to the realization of power/energy management of the renewable hybrid system taking into account: a wind turbine, photovoltaic, fuel cell/battery systems and a variable Load. The power electronic converter i.e., inverter control of the system optimizing the control and energy management techniques of the various sources was proposed. The AC output voltage regulation was achieved using a Proportional Integral (PI) controller to supply a resistive load with constant amplitude and frequency. Moreover, Fuzzy logic control was implemented for output regulation which archives better performance than PI controller and was very promising for potential applications in hybrid renewable energy management systems.

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