Research Paper

Dynamic Control Algorithm for Energy Management In Hybrid Power Systems With A Novel Design for Power Quality Improvement

Engineering

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ABSTRACT   *This paper describes modeling and simulation of microgrid connected renewable energy based Hybrid Power System (HPS) in the aspect of improving power quality. Since optimal utilization of primary energy sources will increase the level of supply reliability, a dynamic control algorithm is proposed for economic energy management. In order to meet sustained load demands during varying natural conditions, different renewable energy sources and power conditioning units are need to be integrated with each other. The paper focuses on the combination of Photo Voltaic (PV) cell, Wind Turbine (WT), Fuel Cell (FC), and Battery systems for power generation. To improve power quality of the power system, the proposal is to use DC Motor-Synchronous Generator Set instead of conventionally used static Inverters. A Diesel engine is also coupled to synchronous generator as a standby prime mover to improve the reliability of the overall system during varying natural conditions like wind velocity, irradiance, temperature and etc. The proposed control algorithm acts as a bridge between load fluctuations and generating capacity for managing available resources economically. The results show that the proposed hybrid power system can effectively manage the optimal utilization of primary energy sources and improves the power quality in both islanding mode and as well as grid connected mode.*

I. Introduction

Energy demand in isolated mode or grid connected mode of applications is steadily increasing. Thus, it is very important to meet the continually increasing demand of power. On the other hand, there is a social interest for global environmental concerns such as green house effect and global warming and a reduction in fossil fuel resources. The solution for these issues can be considered from the recent research and development of alternative energy sources which has excellent potential as a form of contribution to conventional power generation system. i.e., to introduce renewable energy, such as Photovoltaic, Fuel cell and wind energy. This is clean and abundantly available in nature, offers many advantages over conventional power generation system, such as low pollution, high efficiency, diversity of fuels, reusability of exhausts, and onsite installation. The system consists of PV panels, wind power system and fuel cell system. Electrolyzers are used to absorb the rapidly fluctuating output power with load and generate hydrogen.

The generated hydrogen is stored in the hydrogen tank and used as fuel for fuel cells, which reduces the fuel cost. Combining several different types of power sources will form the system called "Hybrid Power system" (HPS). HPS combine two or more energy conversion devices, or fuels for the same device, that when integrated, overcome limitations inherent in either. They are available in two modes; namely islanding (isolating) mode and grid connected mode. In general, a hybrid power system might contain AC diesel generators, coupled diesel system, an AC distribution system, a DC distribution system, loads, power sources, energy storage, power converters, load management options, or a supervisory [20].

In the system, the output of the renewable sources cannot feed the load directly, because their voltage fluctuations are so large that they will damage the concerned load. So first it needs to be conditioned, for that generally dc-dc/ac-dc converters are used. Thus the varying voltage can be brought to required value and specified variations limits by varying the duty ratio of the converters, and then connected to DC bus.

II. Proposed System

The DC bus voltage is now used to drive the DC motor coupled to the synchronous generator. Electrical power should be produced exactly at the same time when it is demanded by various classes of consumers. It may not be possible for renewable energy sources to produce sufficient energy to drive DC motor

coupled to synchronous generator at all the time, since their operation depends on varying natural conditions. It is obvious that WT output power varies with the wind speed, the PV cell output power varies with both the temperature and irradiance, and FC output power varies with input fuel. So, diesel engine is also coupled to synchronous generator to avoid shortages of power.

In the proposed system [14] shown in figure.1, the DC motor, Alternator and Diesel Engine are mechanically connected using an electrical clutch. The DC bus is used for integrating all the sources and storage of energy. To have an optimum, efficient and reliable operation of the complex system consist of various power sources, a control is needed [23]. Hence microgrid controller which also acts as Energy management unit is designed using the algorithm proposed in the later sections (figure.15). Modeling and simulations for both islanding (primary load- always connected) mode and grid connected mode (secondary loads) are conducted using MATLAB/Simulink [1] to verify the effectiveness of the proposed system. Total Harmonic Distortion (THD) is a measure of harmonics in the output waveforms. This parameter is a substitute to study about power quality, used for the proposed system, evaluated and shown in Table.1.
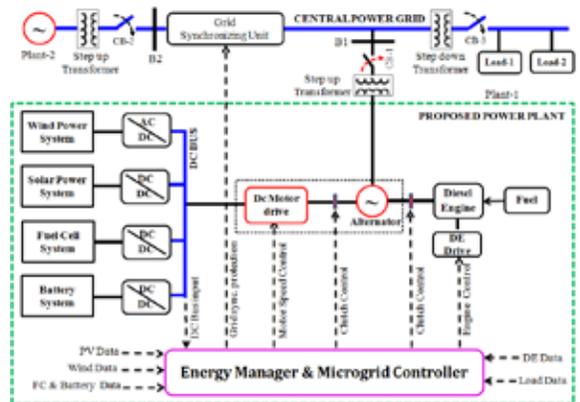

Figure.1.   Proposed   System   Block   diagram

III. Modeling and Simulation
A. Fuel cells
A fuel cell shown in figure.2 is a device that uses hydrogen as a fuel to produce electrons, protons, heat and water. Fuel cells are

electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. It must respond quickly to changes in load and have low maintenance requirement as well as a long cell life [2].The basic building block of a fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on either side. In the Schematic of fuel cell, gaseous fuels are fed continuously to the anode, and an oxidant i.e., oxygen from air, is fed continuously to the cathode compartment, the electrochemical reactions take place at the electrodes to produce an electric current. A fuel cell is individual small unit of around 1.2V. A group of units are connected in series and in parallel to get required voltage and current ratings, that group is called fuel cell stack [3].
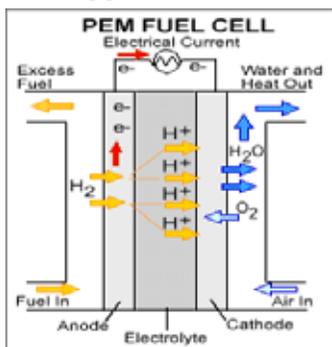
Figure.2. A Fuel Cell constituents

Fuel cell operation is based upon the combustion reaction, $2H_2 +O_2 \leftrightarrow 2H_2O$ (1)
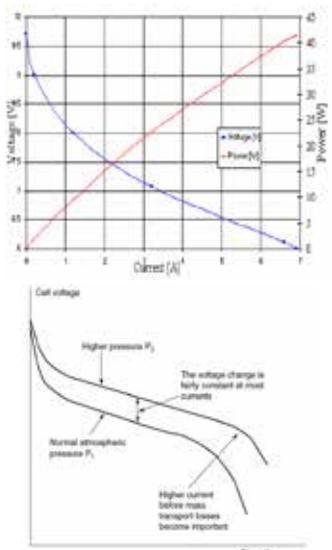

Figure.3. (a) Overall Performance (b) V-I characteristics of Fuel Cell

Fuel cell is modeled in Matlab/Simulink with the help of modeling equations given as the thermodynamic potential E is defined via a Nernst equation in expanded form as [3]

$E=1.229-0.85*10^{-3}*(T-298.15) +$

$4.3085*10^{-5}*T* (lnP_{H2}+lnP_{o2})$ (2)

The concentration of dissolved oxygen at the gas/liquid interface can be defined by a Henry's law

$Co_2=Po_2 / (5.08*10^6 \exp (-498/T))$ (3)

The parametric equation for the over-voltage due to activation

and internal resistance developed from the empirical analysis is given as

$\acute{\eta}_{act} = -0.9514+0.00312T – 0.000187\,T\,ln(i) +$

$\qquad 7.4*10^{-5}\,T\,ln\,(Co_2)$ (4)

$R_{act} = 0.01605 – 3.5*10^{-5}\,T + 8*10^{-5}\,I$ (5)

$R_a = - \acute{\eta}_{act} / i$ (6)

The combined effect of thermodynamics, mass transport, kinetics, and ohmic resistance determines the output voltage of the cell as

$V = E – v_{act} + \acute{\eta}_{ohmic}$ (7)

The steady state fuel cell model described above indicates that the current drawn, cell temperature, H_2 pressure, and O_2 pressure will affect the fuel cell output voltage. A drop in fuel cell voltage can be compensated by an increase in fuel pressure.

The ohmic voltage loss in the fuel cell is given by

$\acute{\eta}_{ohmic} = -i*R_{int}$ (8)

The fuel cell system consists of a stack of 100 similar cells connected in series. Therefore, the total stack voltage is given by

$V_{stack} = 100* V_{cell}$ (9)

The amount of hydrogen and oxygen consumed in the fuel cell depends upon the input and output flow rates and the current drawn out of the fuel cell. It also depends upon the volume of the electrodes. If the incoming and outgoing flow rates (mol/s) are known, then the gas pressure within the fuel cell humidifier can be determined using the mole conservation principle. Figure 4, shows the Simulink model of fuel cell.

For the fuel cell anode

$(V_a/RT)(dPH_2/dt)\dfrac{Va}{RT}\dfrac{dPH2}{dt} = m'_{H2\,in} – (\rho_{H2}\,UA)_{out} – (I/2F)$ (10)

Similarly, the equation for the cathode is

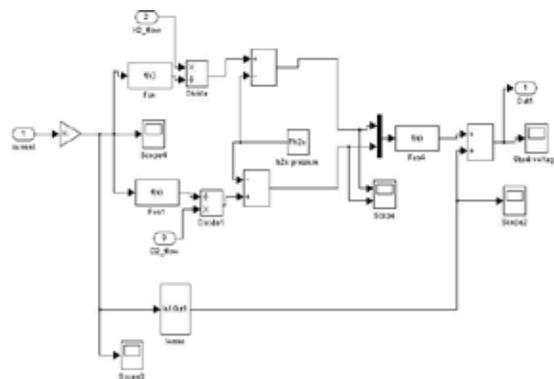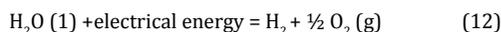$(V_a/RT)(dPO_2/dt)\dfrac{Va}{RT} = m_{o2\,in} – (\rho_{o2}\,UA)_{out} – (I/4F\dfrac{i}{4F})$ (11)

Figure.4.Simulink model of fuel cell

B. Electrolyzer
The decomposition of water into hydrogen and oxygen can be achieved by passing an electric current between two electrodes separated by an aqueous electrolyte [5], [6]. The total reaction for splitting water is;

$H_2O\,(1) +$electrical energy $= H_2 + ½\,O_2\,(g)$ (12)

A water electrolyzer consists of several electrolyzer cells con-

nected in series [10]. The current vs. voltage characteristics of an electrolyzer depend upon its working temperature, According to Faraday's law, the production rate of hydrogen in an electrolyzer cell is directly proportional to the transfer rate of electrons at the electrodes, which in turn is equivalent to the electrical current in the circuit.

$$\acute{\eta}H_2 = \acute{\eta}_F\, \acute{\eta}_c\, i_e/2/F\ (mol/s) \tag{13}$$

Faraday efficiency (in percent) can be given as

$$\acute{\eta}_F = 96.5\ \exp\ (0.09/I_e - 75.5/i_e^2) \tag{14}$$

The two equations above give a simple electrolyzer model. For simplification, dynamic modeling of the electrolyzer and fuel cell's auxiliary equipment, such as hydrogen storage vessel, compressor, piping, valves etc., was not considered.
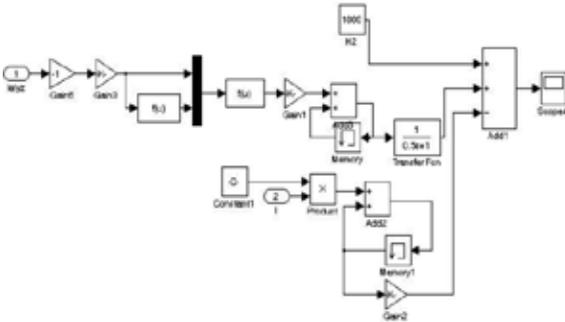
Figure.5. Electrolyzer subsystem model.

C. PV Panel
Photovoltaic/solar cell is the device which converts sunlight into electricity directly of which magnitude of current and voltage depends on many factors like temperature, solar irradiation, and wave length of incident photon etc. the solar cell produces DC supply.

A solar cell module is the basic element of each photovoltaic system. It consists of many jointly connected solar cells. A number of solar cell models have been developed, but the one diode electrical equivalent circuit [10] is commonly used for cell based or module based analysis (figure 6). It consists of a diode, a current source, a series resistance and a parallel resistance. The current source generates the photo-current that is a function of the incident solar cell radiation and temperature [7], [8].
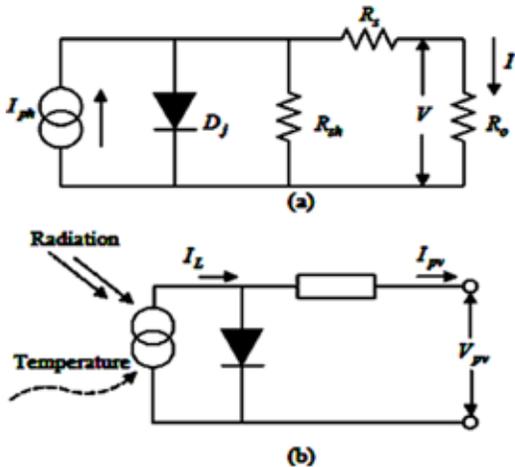

Figure.6. Solar Cell equivalent circuit.

This voltage loss is expressed by a series resistance (R_s). Furthermore leakage currents are described by a parallel resistance (R_{sh}). However, the series resistance is very small and the parallel resistance is very large [8]. So we can ignore Rs and R_{sh}.
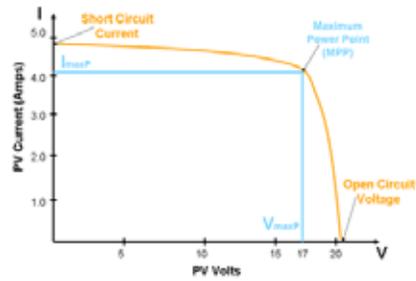

Figure.7. V-I characteristics of Solar Cell

PV panel is modeled in Simulink [10]. Figure.8 shows Simulink model of PV panel. The modeling equations used to develop the PV panel model are;

The solar cell current equation is

$$I_p\ (t) = I_s\ \{1 - C_1[\exp(\frac{V_{pn}}{C_2 V_o}) - 1\} \ +$$

$$I_{PV}(t) = I_{sc}\left\{1 - C1\left[\exp\left(\frac{V_{mp}}{C_2 V_{oc}}\right) - 1\right]\right\} \ +$$

$$\frac{E_t\ (t)}{E_s}[\alpha(T_a\ (t) + 0.002E_t\ (t) + 1] - I_{pn}$$

$$\frac{E_{tt}(t)}{E_{st}}[\alpha(T_a(t) + 0.002E_{tt}(t) + 1] - I_{mp} \tag{15}$$

The solar cell voltage equation is

$$V_p\ = V_{pn}\ [1 + 0.0539\log(\frac{E_t\ (t)}{E_s}) + \beta(T_a(t) + 0.0\ E_t\ (t)$$

$$(16)$$

$$C_1 = (1 - \frac{V_{pn}}{I_s})\exp[\frac{-V_{pn}}{C_2 V_o}]$$

$$(17)$$

$$C_2 = (\frac{V_{pn}}{V_o} - 1)\,/\ln(1 - \frac{I_{pn}}{I_s})$$
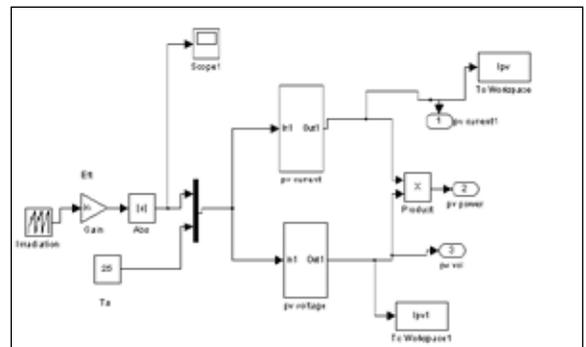
$$(18)$$

Figure.8. Simulink model of PV panel

D. Wind Power

The power output of wind turbine is relating to wind speed with a cubic ratio [21], [22]. i.e., it depends on the wind velocity at the location and the blade pitch angle. Figure.9 shows the Simulink model of Wind turbine power generating system. The equivalent model for the wind turbine generating system can be considered as the combination of asynchronous machine (Induction generator in general) driven by a wind turbine. This generates alternating (AC) voltage. So it is needed to be converted into DC before going to connect to DC bus. Hence a rectifier circuit is connected as shown in the figure.9.

The power curve of the wind turbine studied is nonlinear [10]. The dynamics of the wind turbine due to its rotor inertia and generator are added by considering the wind turbine response as a second order slightly under-damped system [7], [9]. Using this simple approach, a small wind turbine dynamic can also be modeled as
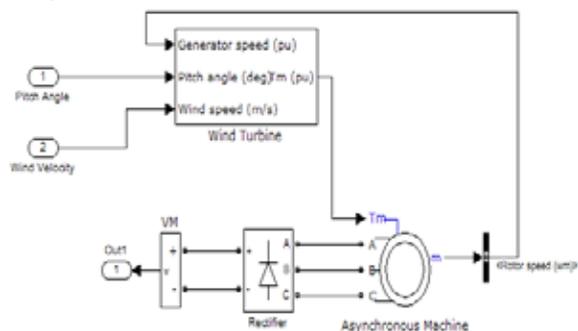
$$P_g(s)/P_{wt}(s) = 0.25/ (s^2+0.707s+0.25) \qquad (19)$$

Figure.9. Simulink model of WT generating system

E. DC Motor-Synchronous Generator set
In order to improve power quality, the DC bus voltage is used to drive motor-synchronous generator set instead of giving to conventionally used static inverters [15], [16]. This is modeled in Matlab/Simulink as figure.10. The speed control circuit [1] is shown in figure.11.
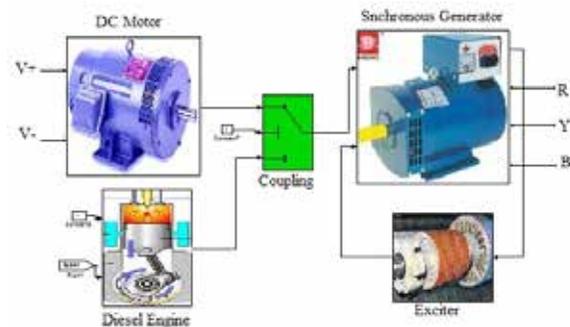
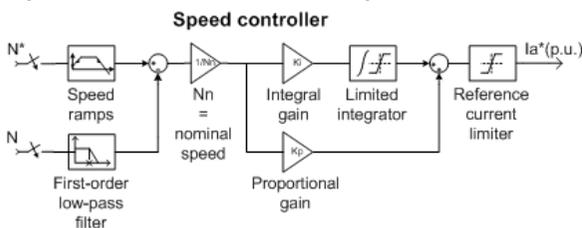Figure.10. Model of DC motor, Diesel engine-Generator set

Figure.11. Speed controller circuit for DC Motor.
F. Diesel Engine setup

To ensure continuous prime mover energy to synchronous generator, the diesel engine set up is coupled as a stand by prime mover. To simulate the complete dynamics of a diesel engine system, a very large order model will be required. However for most studies on speed dynamics of internal combustion

engines, it is sufficient to use a lower order model [11]. Similar approaches have been adopted in diesel engine simulation studies. Figure.13 shows the generic block diagram of a typical diesel engine system, and figure. 13 show the Simulink model of overall diesel engine setup along with its governor.
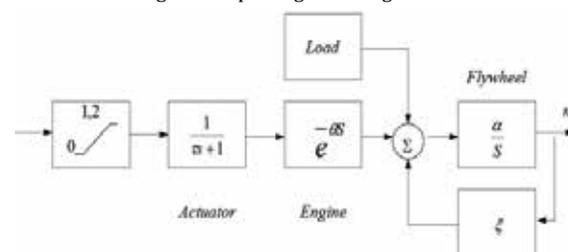
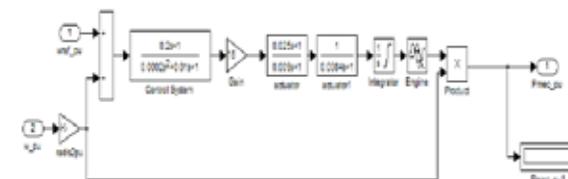**Figure.12. Block diagram of a typical diesel engine system**

Figure.13. Governor & Diesel engine subsystem in Matlab/Simulink
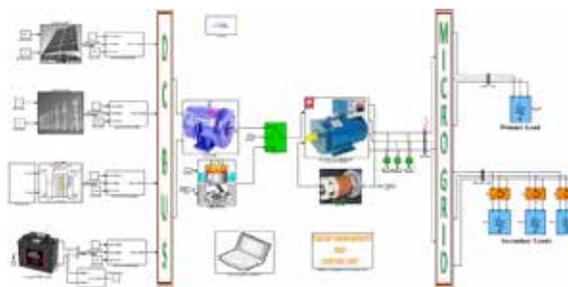
G. Proposed Hybrid power system model in Matlab/Simulink

Figure.14. Proposed Hybrid power system model using Simulink

IV. ENERGY MANAGEMENT AND CONTROL SYSTEM
The energy management [13] system (EMS) switches the mode of power supply, and controls the load share according to the condition of wind power, solar radiation, Fuel cell power and load requirement.

In general wind speed and solar radiation changes at random, in that conditions energy management plays important role. Generated power of hybrid system is compare with the load. If generated power exceeds the load, then excess power will be collected by the electrolyzer of the fuel cell. The electrolyzer can produce H_2 gas and is stored in H_2 reservoir tank. Energy management unit monitors the H_2 reservoir tank. If H_2 reservoir tank is full, and hence excess power is used to charge the battery. The storage batteries compensate the load supply when the output power from the wind power generator , Solar and fuel cell is deficient. And its charging status is also monitored by the EMS on-time. If the load is more than the generated power, then the load is connected to the grid. In that case the EMS checks for the frequency and controls it.

In the relatively low capacity of the micro-gird power systems [17], [18], there are flexible choices for demand side to increase the efficiency of the system operation and economics. Therefore, using demand side management to opportunely control load, would reduce the need of generation capacity and increase the utilization [4] of renewable generation devices and accordingly increase the efficiency of generation investment. Integration of the all blocks by using EMS can provide flexible

energy consumption management solution for improving power quality of the renewable energy hybrid micro grid power system. The hybrid power system is based on multi-agents theory [12], so the control subsystem is regarded as an agent. It is composed of several local controllers act as agents and these are connected to central EMS system. Energy management system controls and manages the operation of multi-source, such as power grid, wind turbine generation, solar photovoltaic, Fuel cell, storage batteries and loads, also to acquire data and communicate with others.
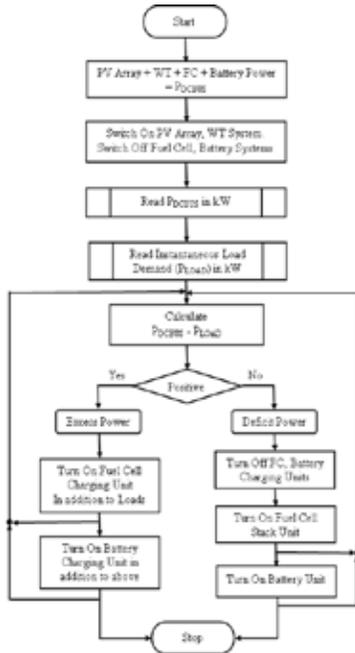

Figure.15. Proposed Algorithm for Energy Management and Control.

V. SIMULATION RESULTS OF THE HYBRID POWER SYSTEM

All the components such as PV panel, PEM fuel cell, Wind Turbine system, Storage Batteries and DC-DC converters, etc., which are individually modeled, and are integrated for simulation. With respect to the variation in natural conditions, the outputs of PV, FC, and Wind turbine systems are primarily controlled by varying duty cycles of DC-DC converters, and are connected to DC Bus. Switching between these primary energy sources is controlled by Energy Management and control unit as discussed above. The Simulation results for different effective input parameters are shown as follows.
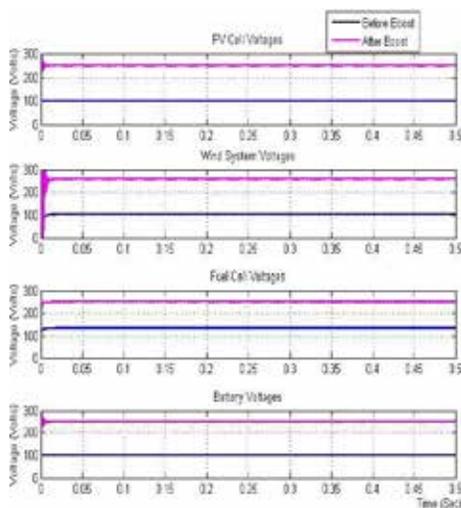

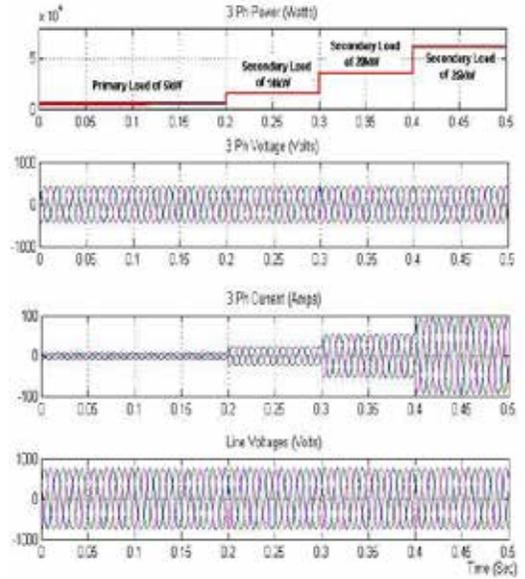**Figure.16. Voltages of Primary Energy Sources connected to DC Bus.**

Figure.17. Generated Voltage, Current, and Power values of the HPS
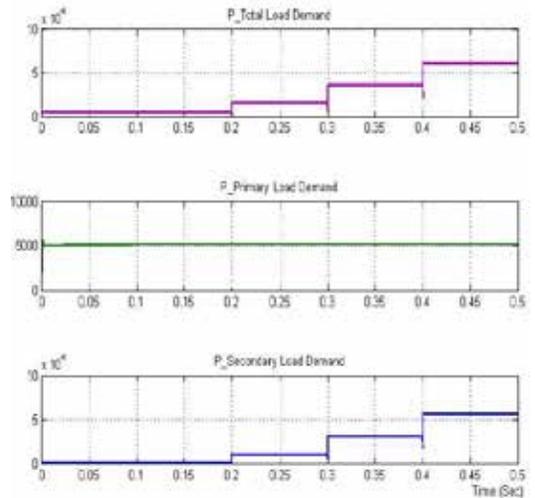

Figure.18. Load Demand of various classes of consumers scheduled as Primary and Secondary loads for the HPS.
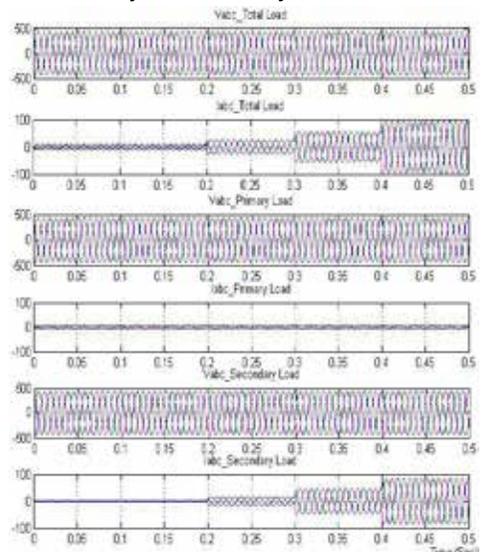

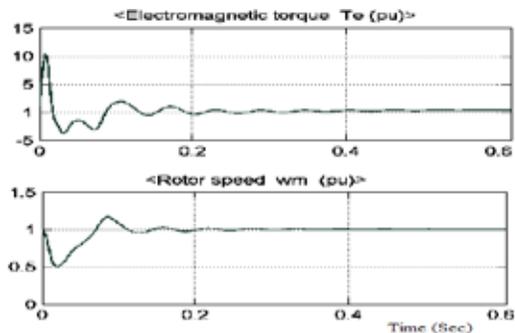**Figure.19. Voltages and Currents of various classes of loads.**

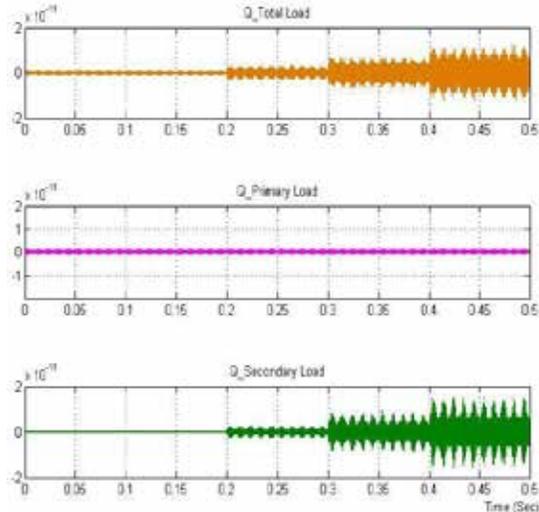Figure.20. Alternator rotor speed (pu) and Torque (pu).

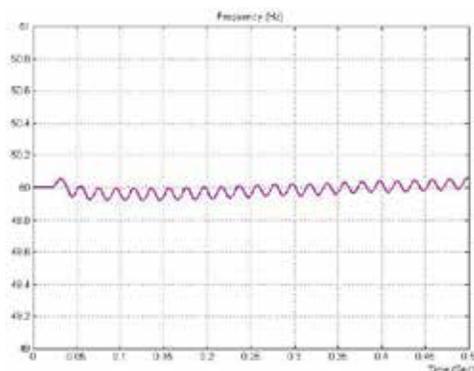Figure.21. Reactive Power drawn by various classes of loads.

Figure.22. The overall system frequency controlled for all load variations.
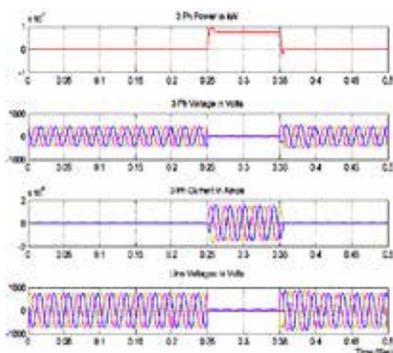

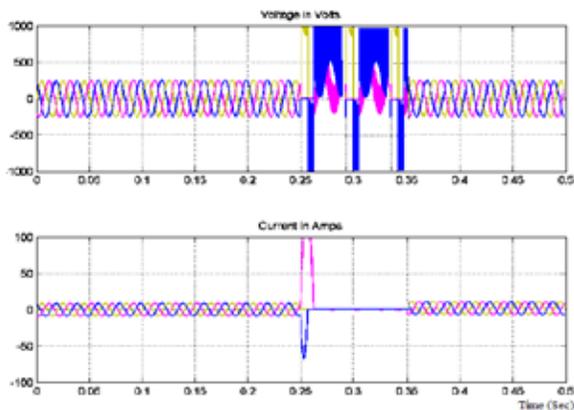Figure.23. Effect of 3 Phase Fault (0.25-0.35 sec) on system parameters

Figure.24. Fault clearance through the operation of automatic circuit breakers controlled by micro grid controller.

TABLE-I
THE PARAMETERS ACHIEVED BY THE PROPOSED DESIGN FOR THE HYBRID POWER SYSTEM.

S. No	Parameter	Error Tolerance Obtained	Remarks
1.	Frequency	± 0.4% Maximum	Satisfactory (As per IEEE standards the acceptable limit is ± 2.5%)
2.	Speed	± 0.2% Maximum	Satisfactory
3.	Total Harmonic Distortion (THD)	0 % at SteadyState	Satisfactory
4.	Terminal Voltage of the system	0 % at SteadyState	Satisfactory (As per IEEE standards the acceptable limit is ± 10.0%)
5.	Reactive Power Control.	Achieved	Satisfactory
6.	Fault Protection System.	----	Satisfactory

VI. CONCLUSIONS

This paper introduces an original philosophy for improving power quality in Hybrid Power Systems, which ensures continuous and reliable supply to loads. The Total Harmonic Distortion (THD) obtained (Table.1) strongly supports it. This facilitates the application of HPS for grid connected mode. The method developed is based on the use of DC Motor-Synchronous generator set instead of using inverters to convert DC to AC Voltages feeding to central utility power grid. The main control tasks (voltage/ frequency control) are done by the central microgrid controller. The proposed control algorithm manages the switching between available resources according to the load fluctuations.

Voltage, Speed, Frequency variations at the output/grid is found to be within the acceptable range, which is shown in Figures 17-22. The Table.1 compares the obtained values with the international standards, and found to be satisfactory. Therefore, this system can tolerate the rapid changes in load and environmental conditions, and suppress the effects of these fluctuations and provides optimum utilization of available resources for economic power generation.

REFERENCE

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