*International Journal of Advanced Information in Engineering Technology (IJAIET) ISSN:* 2454-6933
*Vol.4, No.1, January 2017*

# Stand Alone Wind Energy Conversion System With Battery Ultra Capacitor Hybrid Energy Storage System

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***Abstract*—This paper presents a standalone wind energy conversion system with battery and ultra capacitor for continuous power supply. Due to intermittent nature of wind energy and load fluctuations, the power flow will be unstable. Battery is the commonly used energy storage device to stabilize the power flow. Since the power density of battery is low, charging and discharging rate is much less. Due to quick charging and discharging, stress on battery increases thereby reducing battery life. Ultra capacitors have high power density and hence it can react to quick load fluctuations. The hybrid battery- ultra capacitor energy storage system will have high energy and power density. This will increase battery life. Bidirectional DC DC converter is used to interface battery and ultra capacitor to dc link. The simulation is done in MATLAB/SIMULINK to verify the result.**

***Keywords*— *Hybrid energy storage; wind energy conversion system; battery; ultra capacitor***

## I. INTRODUCTION

Power generation all around the world has increased considerably in recent years. But millions of people living in remote areas still lack electricity. In remote areas such as mountains, remote villages, etc, where grid connection is practically or economically not feasible, the stand alone operation will be useful. Renewable energy sources such as solar and wind can be used for the stand alone operation. Wind energy has been proven to be the most cost effective and most developing non conventional energy source.

In areas having high wind flow the wind energy system can be established. But the wind flow is never constant, and it varies from time to time. Due to this intermittent nature, the power generated will be fluctuating. For an efficient power system, quality of the power supplied should be proper. It is highly desirable to have good quality and continuous power supply to load. In order to overcome these problems, energy storage systems (ESS) such as battery and ultra capacitor can be used. Since the wind speed changes from time to time the power generated also varies. Fig. 1., Shows the power generated and power demand of loads. The power generated and power demands are never equal. When the power generated exceeds the power demand, the excess power is stored in the ESS and when the power demand goes beyond the generation the ESS discharges to meet the excess demand.

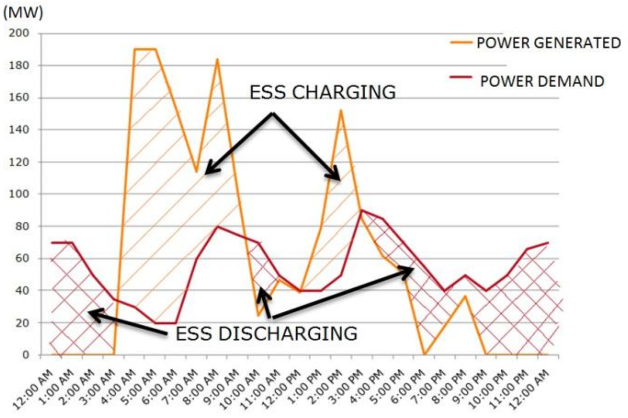


Fig. 1. Power generated and power demand curve for 24 hours

Batteries are generally used as primary energy source in hybrid ESS. It has high energy density and low power density which results in long charging cycles and low self discharges. When the battery alone is connected in the circuit it has to respond to quick changes in power flow. It cannot respond quickly to sudden fluctuations in power and these fluctuations also cause stress in the battery. This reduces the battery life considerably. Ultra capacitor has low energy density and high power density which in turn allows it to react to quick fluctuations in the system. But it cannot be connected alone in a system because of its high self discharge rate. It will not be able to supply for long period of time. Thus the hybrid battery and ultra capacitor system combines the advantages of battery and ultra capacitor. It will have high energy and power density as shown in Fig. 2. Battery can act as primary energy source by providing power for large voltage drops where as ultra capacitor can act on quick power fluctuations there by reducing stress on battery.

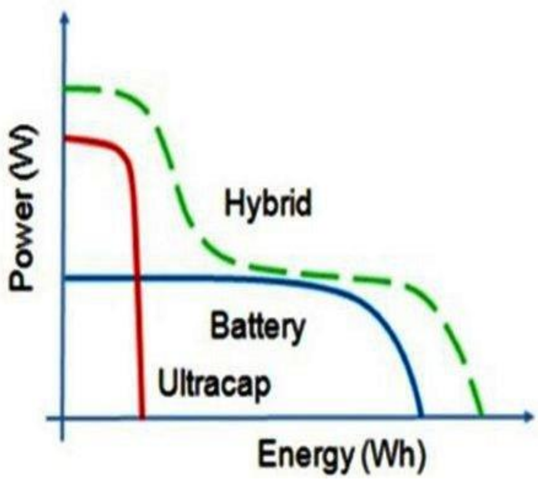


Fig. 2. Power density versus energy density curves of battery, ultra-capacitor and hybrid battery ultra capacitor ESS.

## II. PROPOSED SYSTEM

The proposed system is shown in Fig. 3. It consists of a wind turbine which is coupled to a permanent magnet synchronous generator (PMSG). The output of the PMSG is rectified using a three phase rectifier and it is given to the load through an inverter. Variation in wind speed and change in load has direct influence on the DC link voltage ($V_{dc}$). When the wind speed changes the power generated by PMSG also changes. This will change the DC link voltage. When the load increases the current drawn by the load will increase which will reduce the DC link voltage, because the power generated by PMSG will be the same for a constant wind speed. If the DC link voltage is kept constant, the power delivered to the load can be kept constant even when the wind speed or the load is changed. In order to make the power in DC link constant, battery and ultra capacitor is connected through two bi directional buck boost converters. When the power in dc link is more, it is used to charge the battery. The battery is discharged to maintain constant power in case the power in dc link drops. Ultra capacitor is connected in the circuit to reduce the sudden charging and discharging of battery and which would increase the battery life.

## III. DESIGN CONSIDERATIONS

### A. *Turbine* Modeling

According to rotor aerodynamic static relation the power extracted from the wind for a wind speed $V_W$ m/s is

$$P_W = \frac{1}{2} C_P \rho A {V_W}^3 \qquad (1)$$

Where Cp is coefficient of power, A area covered by turbine in $m^2$, and ρ is the air density.

Aero dynamic torque for the rotor speed $\omega_w$ is

$$\tau_W = P_W / \omega_W \qquad (2)$$

The coefficient of power $C_p$ is given by the expression

$$C_P(\lambda, \theta) = C_1(\frac{C_2}{\beta} - C_3\theta - C_4\theta - C_5)e^{\frac{-C_6}{\beta}} \qquad (3)$$

Where$C_1$= 0.5, $C_2$ = 116, $C_3$ = 0.4, $C_4$= 0, $C_5$= 5, $C_6$ = 21. According to Betz's law, $c_p$ reaches a maximum value of 0.59. The curve between coefficient of power and tip speed ratio of the designed turbine at β=0 is shown in Fig. 5.

The MATLAB implementation of turbine model is shown in Fig. 4.

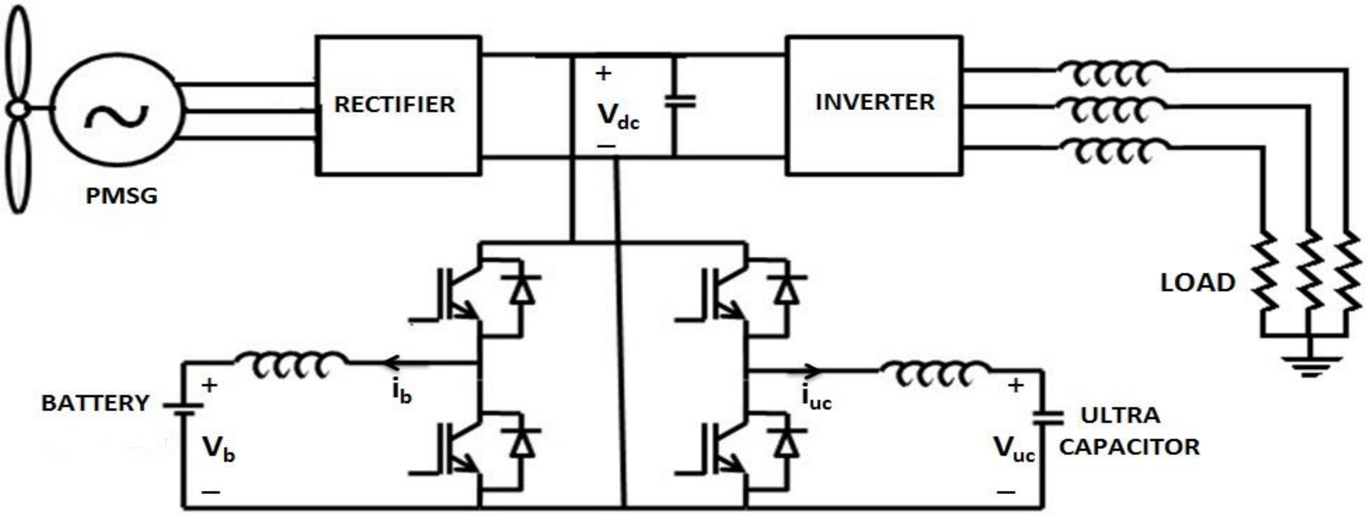


Fig. 3. Block Diagram of proposed system

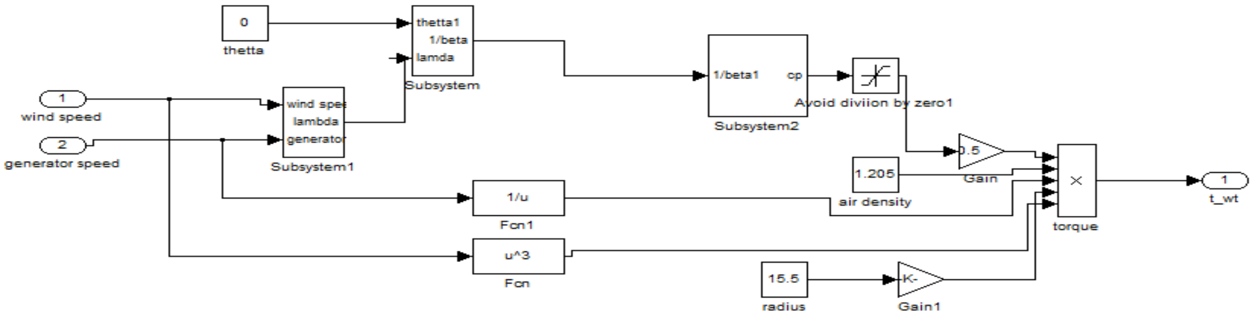


Fig. 4. MATLAB implementation of turbine model

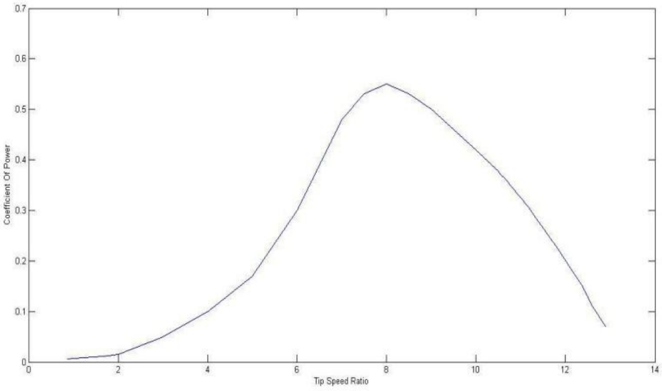


Fig. 5. Coefficient of power versus tip speed ratio curve of turbine

### B. *Permanent Magnet Synchronous Generator*

The permanent magnet synchronous generator (PMSG) is mainly advantageous due it high power density, compact size, reliability and robustness. Its size reduces due to the absence of brushes and gears.

The dynamic model of PMSG can be expressed by the following equations,

$$V_{qs} = R_s i_{qs} + L\, di_{qs}/dt + \lambda_{sf}\omega_r \cos\theta_r \qquad (4)$$

$$V_{ds} = R_s\, i_{ds} + L\, di_{ds}/dt - \lambda_{sf}\omega_r \sin\theta_r \qquad (5)$$

Its electromagnetic torque can be expressed by the equation

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left[(Ld - Lq)\ iq\ id + \lambda m\ iq\right] \qquad (6)$$

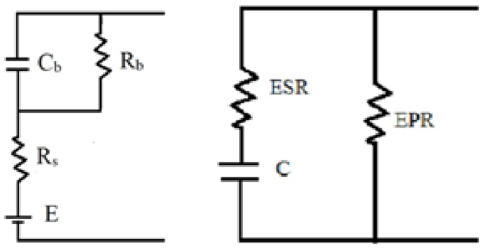
### C. *Modeling Of Battery*

The role of the battery is to maintain the dc link voltage to the reference value voltage by charging and discharging. It has low power density and high energy density. It can charge or discharge for long duration of time. These features make battery suitable to use as primary ESS. The charging and discharging of battery is done by the bi directional buck boost converter.

Fig. 6 (a). hows the equivalent circuit model of battery. Capacitor is used to show the charge storing capacity of the battery. Resistor is used to show the flow of charge. $R_s$ is the equivalent series resistance of the battery. $R_b$ is used to represent the self discharging of battery. It is usually a high value so that the self discharging of battery is low. The capacitor $C_b$ is used to represent the storage energy during charging. The value of capacitor with an energy storing capacity of battery in kilo watt hour ( kWh) is

$$C_b = \frac{kWh\ x\ 3600\ x\ 10^3}{0.5(V^2_{dcomax} - V^2_{dcomin})} \qquad (7)$$

The battery used in the simulation is 8 lead acid batteries of 12V and 150 Ah. Discharging characteristics of the battery is shown in Fig. 7.



(a) (b)

Fig. 6. (a) Equivalent circuit of battery
(b) Equivalent circuit of ultra capacitor

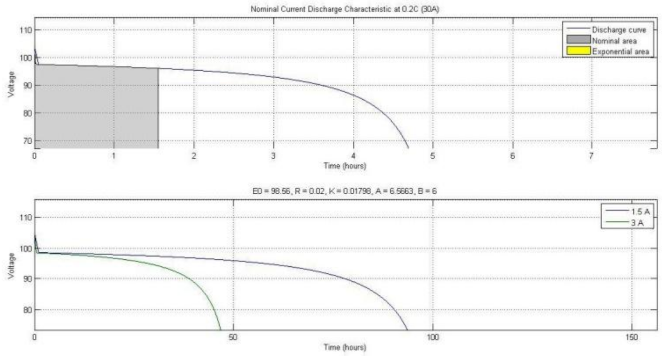


Fig. 7. Battery discharging characteristics

### D. *Modeling Of Ultra Capacitor*

The purpose of the ultra capacitor is to avoid the quick charging and discharging of the battery. The ultra capacitor has high power density and low energy density. It can react to quick fluctuations by charging and discharging quickly. Equivalent circuit is shown in Fig. 6 (b).

The voltage of ultra-capacitor declines according to equation

$$V = V_o\, e^{(-t/RC)} \qquad (8)$$

Where V and $V_o$ are the values of battery before and after discharging.

Equivalent series resistance (ESR) is generally a low value which includes contact resistance drop, electrode resistance drop etc. It is represented by

$$\text{ESR} = \frac{\text{Voc} - \text{V}}{I} \tag{9}$$

Where Voc is the open circuit terminal voltage before discharging and V is the terminal voltage at during discharging.

Equivalent capacitance of the circuit is the amount of the charge stored represented by

$$\text{C} = \frac{t}{\text{R x ln 2}} \tag{10}$$

Equivalent parallel resistance (EPR) is given by

$$\text{EPR} = \frac{-(t2-t1)}{C \text{ x} \ln(\frac{V2}{V1})} \tag{11}$$

Where V1 and V2 are the voltages at t1 and t2 respectively. The charging and discharging characteristics of ultra capacitor is shown in Fig. 8 and Fig. 9 respectively.

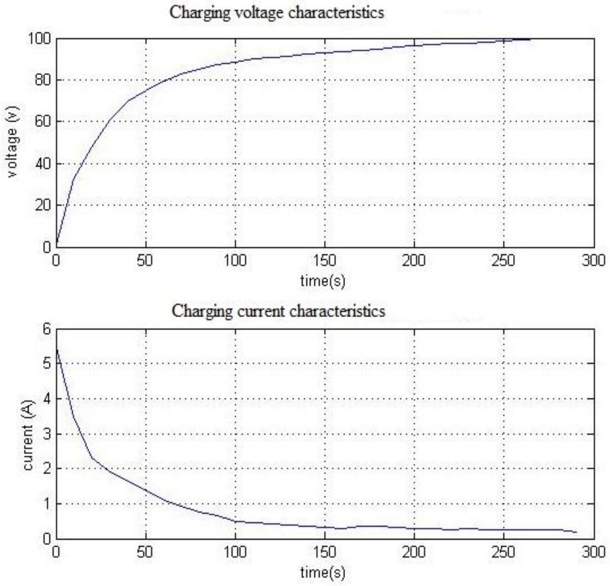


Fig. 8. Charging characteristics of ultra capacitor

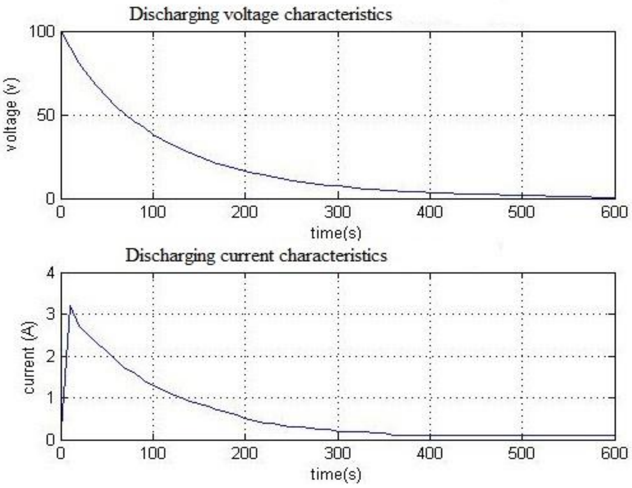


Fig. 9. Discharging characteristics of ultra capacitor

### *E. Bidirectional Buck Boost Converter*

Bidirectional buck boost converter is used to connect the battery and ultra-capacitor to DC link. Neglecting the switching losses, the equation for the bi-directional converters can be represented as

$$V_{dc} - V_b = L\,(di/dt) - i_b R_b \tag{12}$$

$$V_b = V_{dc} \text{ x } D \tag{13}$$

Where $V_{dc}$ is the DC link voltage and $V_b$ is the battery terminal voltage. $R_b$ is the internal resistance of the battery and $i_b$ is the battery current. This converter can be used in both buck and boost modes. During charging it will act as buck. The same equations can also be used for discharging also. During discharging it acts as boost mode, changing the direction of $i_b$ accordingly. The pulses given to the converters are complimentary so duty remains same. During buck mode if the duty ratio is D then in boost it the duty ratio will be (1-D). Similarly ultra capacitor bidirectional converter can also be designed.

## IV. CONTROL STRATEGY

The objective of the battery side converter is to control the charging and discharging of the battery for maintaining DC link voltage and also optimizing it to increase battery life. The objective of ultra capacitor side converter is to control quick charging and discharging to stabilize the DC link voltage.

The DC link voltage is compared with a reference voltage; the error produced is passed through a PI controller to produce reference current. This current reference will have steady state current as well as fluctuations. This current is passed through a low pass filter which filters out the steady current values. It is compared with current control loop of battery and passed through PI controller to produce reference for the PWM pulses for battery converter. The steady state current is subtracted from the current to obtain fluctuating current. It is compared with the ultra capacitor and is passed through PI controller to produce reference for PWM pulses for the ultra capacitor side converter.

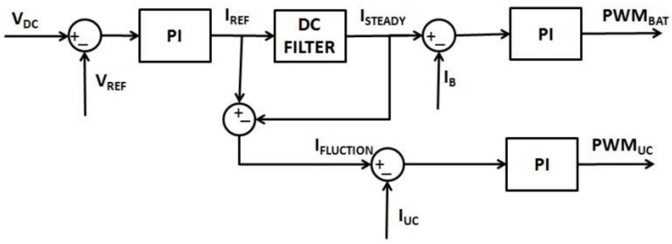


Fig. 10. Control strategy block diagram

## V. SIMULATION AND RESULTS

Simulation is done for the wind speed of 8.1 m/s and a sudden change of wind speed to 8 m/s is given at .15 s. It is shown on Fig. 13 and the waveforms are shown in Fig.11 and Fig.12 respectively. ESS used is a battery of 96 V, 150AHr and ultra capacitor of 100V. The value of dc link voltage is first 238 at 8 m/s and 241 at 8.1m/s.

When the wind speed is constant at 8.1 m/s the dc link voltage is larger than reference value 220V. The battery charging is constant. But when suddenly the wind speed drops to 8 m/s the available power from PMSG drops as a result DC link voltage drops during this sudden change the ultra capacitor discharges so that the fluctuations is captured by the ultra capacitor. This will reduce stress on the battery. The battery charging current will change slowly to reach the desired current value. All the fluctuations will be met by the ultra capacitor. This increases the battery life.

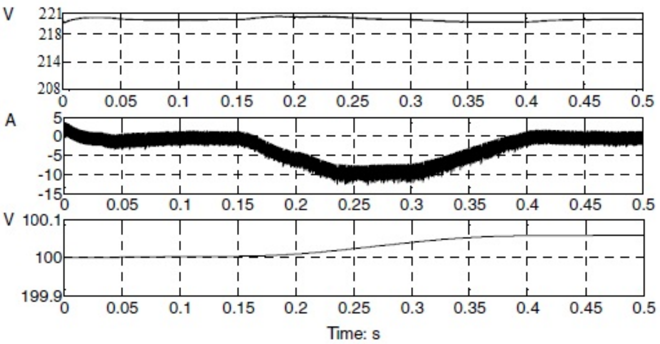


Fig. 11. Wave form of DC link voltage, ultra capacitor current and terminal voltage of ultra capacitor

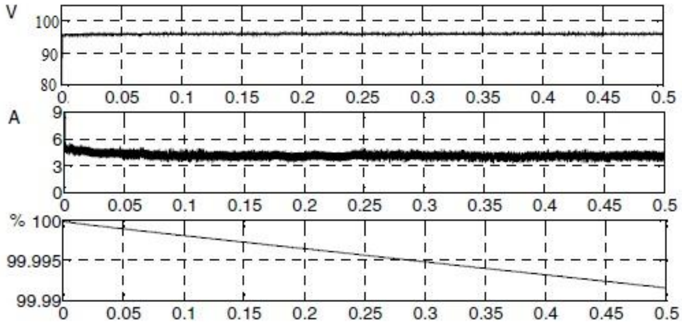


Fig. 12. Wave form of battery terminal voltage, battery current and SOC

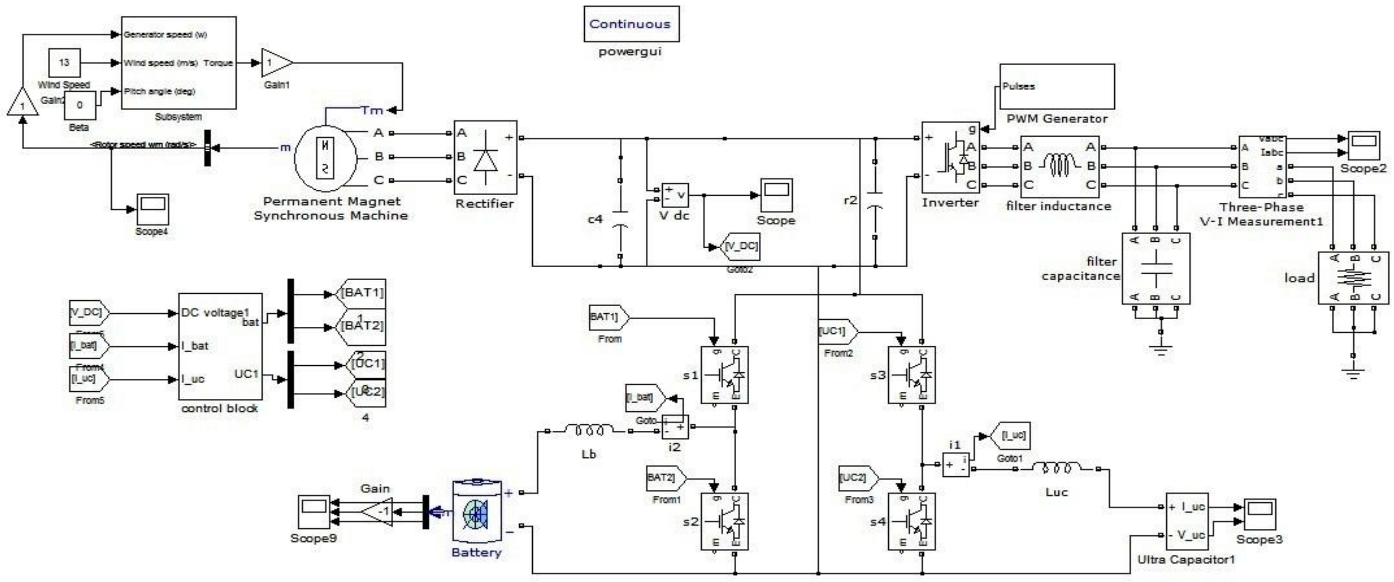


Fig. 13. Simulation diagram of complete system

## VI. CONCLUSION

In this paper, the PMSG with hybrid battery ultra capacitor storage device is analyzed. Mathematical models and controls of various systems have been provided. The proposed control strategy and designs are verified using MATLAB/ SIMULINK. The battery tracks the continuous current and the ultra capacitor supplies for fluctuating and additional currents to support battery thereby reducing sudden charging and discharging of the battery which would increase the battery life. The proposed system can be adapted in any of the renewable energy sources such as solar, tidal etc with proper modification. Evolution of such hybrid energy storage system will become mile stone in proper exploitation of renewable energy sources by diminishing the problem of power intermittency.

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