# A Standalone Operation of PMSG based Wind Turbine Generating Systems with Energy Management by Hybrid Energy Storage

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**Abstract**: Standalone operation of a wind turbine generating system during fluctuating wind and variable load conditions is a difficult task. Moreover, high reactive power demand makes it more challenging due to the limitation of reactive capability of the wind generating power system. A Remote Area Power Supply (RAPS) system consisting of a Permanent Magnet Synchronous Generator (PMSG), a hybrid energy storage, a dump load and a mains load is considered in this project. The hybrid energy storage consisting of a battery storage and a Supercapacitor where both are connected to the DC bus of the RAPS system. An energy management algorithm (EMA) is proposed for the hybrid energy storage in order to improve the performance of the battery storage. A coordinated control approach is introduced to manage the active and reactive power flows among the RAPS components. In this regard, individual controllers for each RAPS component have been developed for effective management of the RAPS components. The results will be carried out through MATLAB/Simulink R2014a environment.

**Keywords**: Battery storage, hybrid energy storage system, permanent magnet synchronous generator, remote area power supply, super capacitor.

## I. INTRODUCTION

Variable nature of wind and fluctuating load profiles make the operation of wind power systems challenging, particularly when they are operated in standalone mode. The frequent variation of wind speed leads to fluctuating torque of the wind turbine generator resulting in voltage and frequency excursions in the Remote Area Power Supply (RAPS) system.

Integration of an Energy Storage System (ESS) into a wind power system provides better voltage and frequency response, especially during wind and load demand variations. The application of energy storage to a standalone power system can be used to fulfill one or more of the listed requirements: (1) to improve the efficiency of the RAPS system, (2) to decrease the primary fuel (e.g., diesel) usage by energy conversion, and (3) to give better security of energy supply. The reason behind the integration of energy storage into a wind energy application is based on the factors which include total wind turbine inertia, low voltage ride through capability, power quality issues, etc. An ideal ESS should be able to provide both high energy and power capacity to handle situations such as wind gust or sudden load variations which may exist for a few seconds or even longer.

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However, among all the energy storage options available, a single energy storage system is not seen to satisfy both power and energy requirements of the RAPS system thus requiring the combination of two or more energy storage systems to perform in a hybrid manner.

The selection of an energy storage system requires good understanding of its operational characteristics. Generally, battery and super capacitor are seen to provide high energy and power requirements respectively. Therefore, the integration of a super capacitor ensures a healthy operation of the battery storage by preventing it to operate in high Depth of Discharge (DOD) regions and operating at low frequency power regions.

PMSG offers many advantages but not limited to self excitation capability which allows operation at a high power factor and improved efficiency, gear-less transmission, high reliability, good control performance, Maximum Power Point Tracking (MPPT) capability, low noise emissions, etc. The performance of the components of a hybrid RAPS system is investigated under fluctuating wind conditions.

The schematic of the proposed RAPS system is shown in Fig. 1. The PMSG performs as the main source of energy while the hybrid energy storage together with the dump load perform as auxiliary system components to maintain the active power balance for the RAPS system and to extract the maximum power from wind.
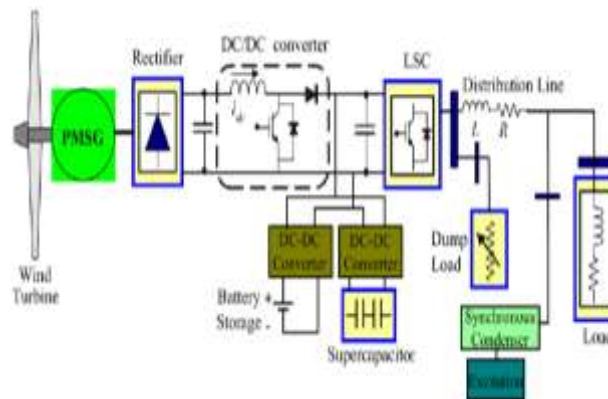
Fig. 1. PMSG based hybrid remote area power supply system with a hybrid energy storage

The existing work on remote area power supply systems with energy storage is summarized below. A multilevel energy storage consisting of a flow battery storage and a super capacitor is discussed in [7]. However, authors have presented results associated with the hybrid energy storage system rather than the system level behaviour. Different control strategies proposed for the battery-super capacitor hybrid energy storage is discussed in [9]. It only examines the different control strategies that could be applied to a hybrid energy storage system. An optimal energy management scheme for battery-super capacitor hybrid energy storage is proposed in [10]. In order to obtain the optimal solution, the authors have formulated the problem as an optimization problem for minimization of the fluctuation of the current flowing in and out of the battery. However, optimization is generally application- oriented and the optimized parameters for one system may not be suitable for another. Authors in [11] have analysed a method of improving battery lifetime in a small-scale remote area wind-power system by the use of a battery/super capacitor hybrid energy storage system. Transient analysis of integrated diesel-wind photovoltaic system with battery energy storage is discussed in [12]. However, it does not provide the details regarding the control strategies associated with the components of the system. The dynamic response of a standalone wind energy system with battery storage is discussed in [13]. However, the authors of this  project have assumed that the battery storage voltage remains constant during wind gust which is not the case in practical applications. Application of a super capacitor for a  doubly-fed induction generator in grid connected mode of operation is demonstrated in [14].

However, management and control coordination of a remote area power system consisting of a PMSG, hybrid energy storage and  a dump load have received a very little research attention. In this an entire RAPS system is modelled to evaluate the complete system performance as well as the performance of the individual components in relation to the voltage/ frequency and power sharing among the system-components. A coordinated approach for power management is proposed for the system components, to operate the RAPS system during over and under generation scenarios. A power sharing strategy is formulated for battery energy storage and super capacitor based on the demand-generation variations in the RAPS system. An energy management strategy is proposed and implemented while harvesting maximum power from the wind.

## II.  COORDINATED CONTROL APPROACH FOR THE RAPS SYSTEM

In general, in order to achieve robust voltage and frequency regulation of any power system it is vital to maintain the active and reactive balance given by (1) and (2) respectively

$$\sum P_{SOURCES} - \sum P_{SINKS} = {}^{D}E_{KE}/{}_{DT} = {}^{D\sum Jw^2}/{}_{DT} = 0 \quad (1)$$
$$\sum Q_{sources} - \sum Q_{sinks} = 0 \quad\quad\quad\quad (2)$$

Where, P- Active power, $E_{KE}$- Kinetic Energy of the system, J- Moment of inertia, ω- Angular Velocity   ,Q-Reactive power.

During over generation conditions where the power output from the wind turbine generator is greater than the load demand the hybrid energy storage .Where, it is assumed that the hybrid energy storage is capable of providing the required power into the system. The control coordination approach discussed above has been realized by developing the control strategies for each system components of the RAPS system. It is assumed that the power outputs of the wind system and the hybrid energy storage are sufficient to supply the load demand at all time. In other words, emergency situations like wind turbine generator operation below cut-in speed or above cut-out speed, have not been considered. In practical RAPS systems, a load shedding scheme can be implemented under an emergency situation where the reduced load is then supplied by the hybrid energy storage system.

## III. CONTROL ASSOCIATED WITH PMSG

As mentioned earlier, in the RAPS system shown in Fig. 1, the PMSG performs as the main source of energy and is interfaced with an uncontrolled rectifier-inverter arrangement before connecting to the mains load. In this regard, control is developed for the Line Side Converter (LSC) and DC/DC converter which is presented in the proceeding sub-sections.
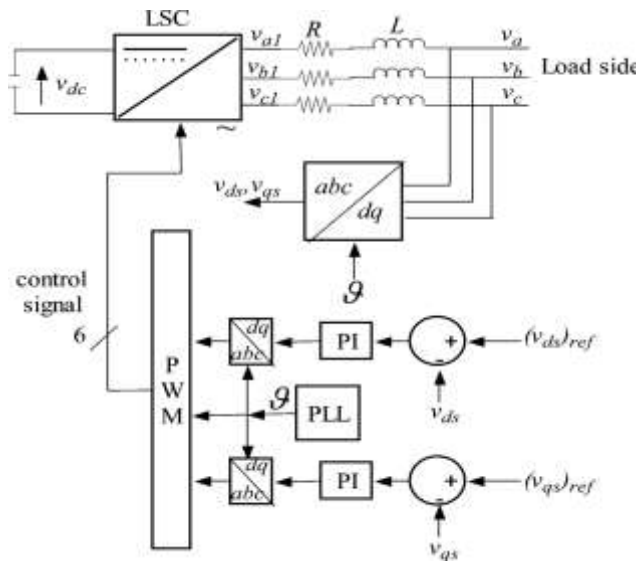
### 3.1. Line Side Converter Control



Fig. 2. Vector control scheme for the LSC

The LSC is modelled as a voltage controlled voltage source inverter. The control objective of the LSC is to regulate the magnitude and frequency of the load side voltage. In this regard, vector control has been employed to develop the control associated with the LSC. The voltage balance across the filter of the LSC shown in Fig. 2. The voltage balance across the filter of the LSC shown in Fig. 3 is expressed using (3).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L\frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \end{bmatrix} \qquad (3)$$

Where $V_{a1}, V_{b1}, V_{c1}$ voltages at the inverter output, $V_a, V_b, V_c$ voltages at load side, $i_a, i_b, i_c$ current through the filter circuit, L and R filter inductance and resistance, respectively. These quantities are then transformed into a synchronously rotating d-q (direct and quadrature) coordinates with an angular velocity ωas given by (4)–(7).

$$V_{ds1} = v_{ds} - V_{ds}{}^* + L\omega_s i_{qs} \qquad (4)$$
$$V_{qs1} = v_{qs} - V_{qs}{}^* - L\omega_s i_{ds} \qquad (5)$$
$$V_{ds}{}^* = Ri_{ds} + L\frac{d}{dt}i_{ds} \qquad (6)$$
$$V_{qs}{}^* = Ri_{qs} + L\frac{d}{dt}i_{qs} \qquad (7)$$

Where $v_{ds}$ and $v_{qs}$ are d and q components of the load side AC voltage, $i_{ds}$ and , $i_{qs}$ are d and q components of inverter current, and $V_{ds1}$ and $V_{qs1}$ are d and q components of the inverter output voltage respectively.
A virtual phase lock loop is used to define the orientation angle, for the inverter and to achieve a constant frequency of the RAPS system. As depicted in Fig. 2, the reference d–component of the voltage is maintained at 1 pu ($V_{ds}$ =1pu) whereas the reference q–component of the load voltage is set to zero($V_{qs}$=0). The PI controllers associated with LSC are tuned using the internal model control principle as discussed in [17].

### 3.2. Control Strategy for DC/DC Converter
The DC link voltage of the RAPS system is regulated using a DC/DC converter (i.e., boost converter). The rectified voltage output,Vdc presents at the full converter diode bridge is a function (i.e., linearly proportional) of the generator speed, and can be explained[1] and shown in figure 4.The proposed control scheme for the DC/DC converter is shown in Fig. 6. The outer control loop measures the DC link voltage , which is compared with the reference DC link voltage ,

and the error is compensated using a PI controller to generate the reference current through the inductor of the boost converter, as in [10]. This current is then compared with the actual current, and the corresponding error is compensated through the second PI controller to generate the switching signal for the DC-DC converter. Further, the highest boosting factor, of the boost converter is recorded at the lowest generator speed.
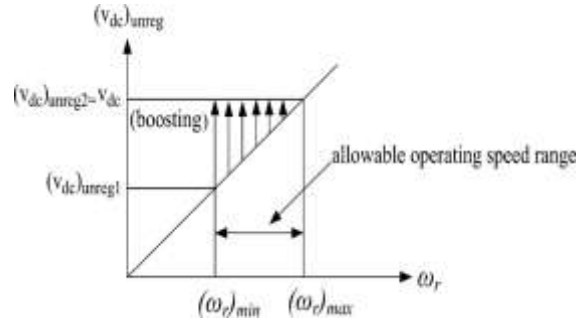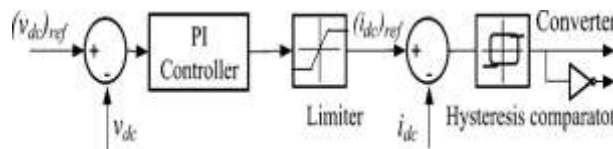


Fig. 3. Boost converter operation to regulate the DC bus voltage



Fig. 4. Control strategy of the boost converter of the PMSG based wind energy system.

## III. BATTERY STORAGE AND SUPERCAPACITOR

Nickel-Cadmium battery model given in [18] is employed in this project. The capacity of the battery storage system reduces dramatically under high DODs. Therefore, in real life situations, it is vital to regulate the State Of Charge (SOC) of the battery within the safe limits. In this project, the battery storage capacity is estimated, which is able to provide a fraction (or ) of rated current of the load demand.

$$\gamma * I_{rated} * \frac{t}{60} = Ah\ rating * K \qquad (8)$$

Where γ-fraction of the rated current of the load demand, I —rated current of the load demand, t—time duration that battery provides power into the system and k—a fraction that defines the average discharge/charge current of the battery.

## IV. ENERGY MANAGEMENT ALGORITHM (EMA) FOR HYBRID ENERGY STORAGE

In this paper an energy management algorithm is developed and implemented between the battery storage and super capacitor with a view to achieve the following objectives:
1) To help maintain the power balance of the RAPS system,
2) To operate wind turbine generator at variable-speed and
3) To improve the performance of the battery storage system by avoiding its operation with high frequency ripple currents and high rate of DODs.
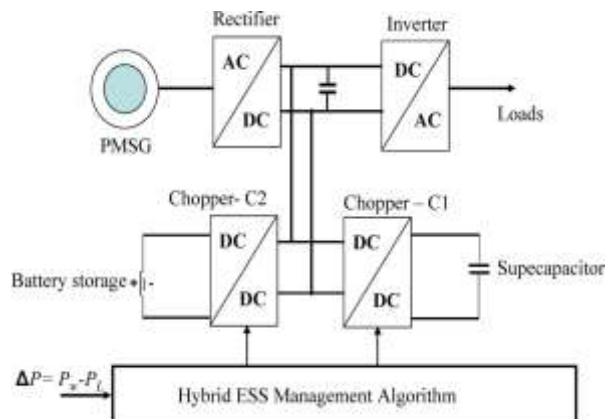


Fig 5.Proposed topology for hybrid energy storage system in a PMSG based RAPS system.
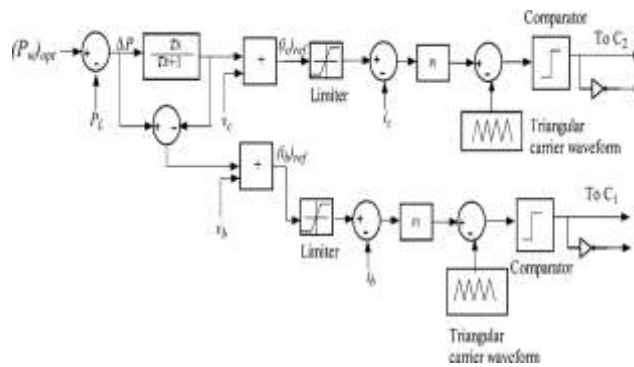
Fig 6. Energy management algorithm for hybrid energy storage system.

This will relieve the battery stress and increase the battery life. Among several options of connection topologies, boost converters have been used to interface both the super capacitor and battery storage respectively. The energy management algorithm applied for both storage options have been developed to satisfy the above-stated objectives. The energy management algorithm for the battery storage and super capacitor is depicted. The input signal to the energy management algorithm is selected as the demand-generation mismatch with a view to achieve the first objective listed above. To realize the second objective, the demand-generation mismatch is estimated using the optimal wind power, which can be derived.

## V. DUMP LOAD

The dump load is coordinated with the hybrid energy storage system to maintain the active power balance of the system. In practical RAPS systems, a dump load can be a space-heating or water-heating system. In this paper, the dump load is represented by a series of resistors which are connected across switches. The resistors operate at zero crossings of the load side voltage to ensure minimum impact on the system voltage quality. The necessary and sufficient condition under which it operates is,

$$P_d = \begin{matrix} P_d \ (Pw)_{opt} \ + \ (Pb)_{max} \ + \ P_c > P_L \\ 0 \ \text{otherwise} \end{matrix} \qquad (9)$$
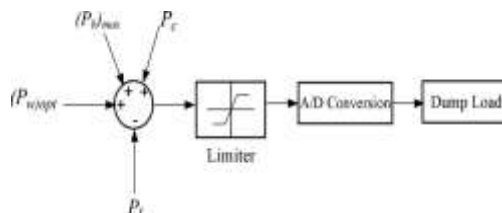


Fig. 7. Dump load controller.

## VI. SIMULATION STUDY

The proposed wind turbine system and with hybrid energy storage system is implemented in MATLAB/ SIMULINK environment.The whole system is shown in Figure 7. The simulation results are described below.
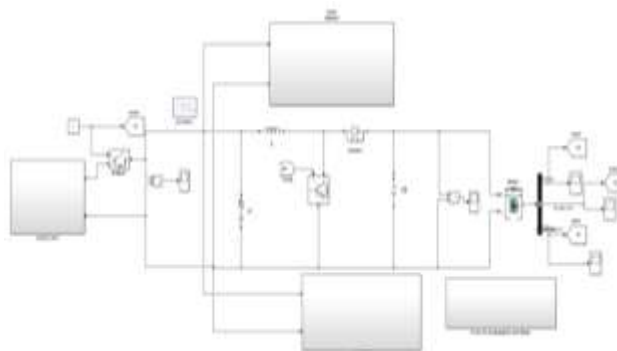


Fig 8.MATLAB/SIMULINK model.

The simulation considers the scenario when the input wind speed variation in 0.2 seconds' time series observation window, that is, drops from 7 to 0 m/s at the time of .05 seconds and the whole simulation time period is 0.2 seconds (see Figure 9).
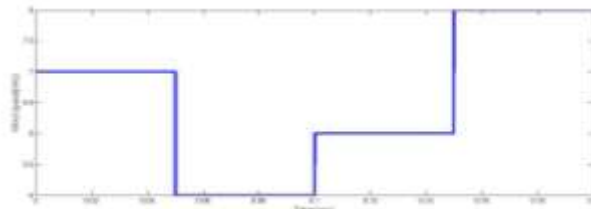


Fig 9.Wind speed used as the input of the system.

The three phase output voltage of PMSG, varying with wind speed is given below.
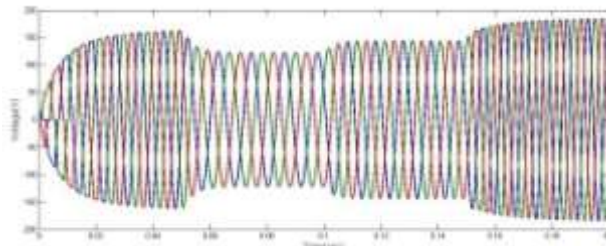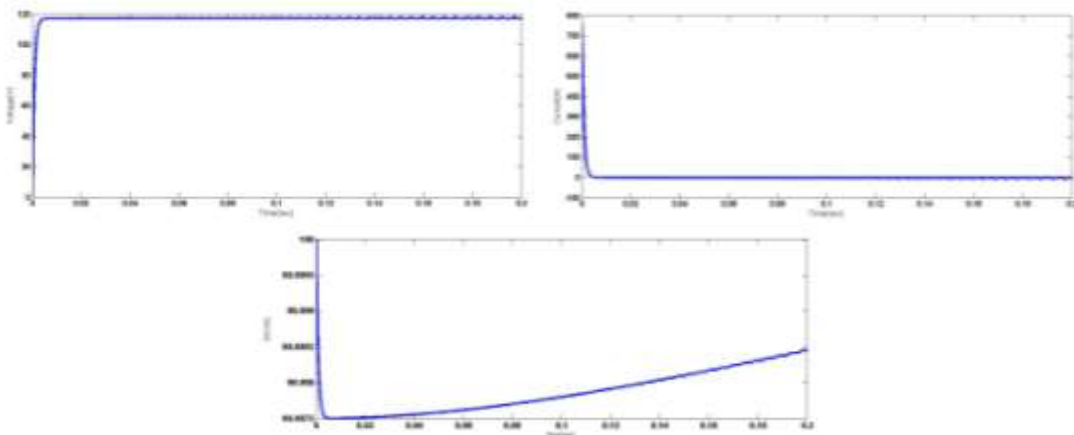


Fig 10. Output voltage of PMSG



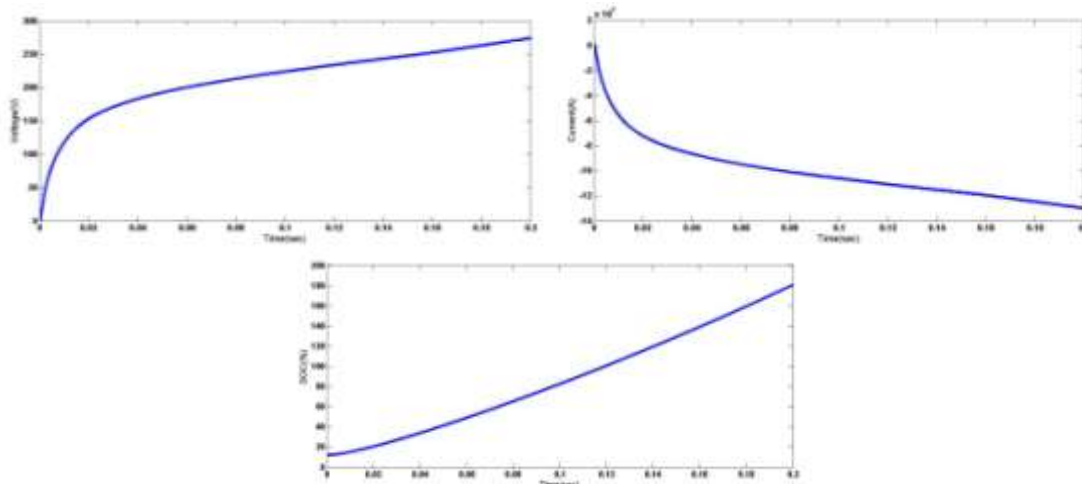Fig 11. Battery voltage, current, SOC respectively



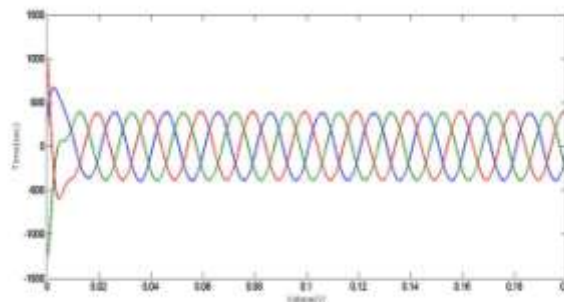Fig 12. Supercapacitor voltage, current, SOC respectively

Fig 13. Output voltage across the load

## VII.    CONCLUSION

The performance of PMSG based wind energy conversion system (WECS) has been studied during the normal operating condition. The proposed PMSG based WECS model is useful especially in rural coastal areas to effectively supply the electrical power demand of the consumers. This solution will also prove to be beneficial for the consumers to have a reliable electric power supply. This can also be beneficial for the electricity authorities or boards to meet the emergency loads of their areas in the event of an emergency shut down or an outage. Another fact is that this will help in reducing the amount of pollutants released into the environment, it also promote the energy stability and the economic security by reducing the dependability on the fossil fuels.

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