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Management of Variable Speed Wind Turbine Generating System with Battery Super Capacitor and Synchronous Condenser for Raps Networks

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Abstract- **Standalone operation of a wind turbine generating system under 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 system. A Remote Area Power Supply (RAPS) system consisting of a Permanent Magnet Synchronous Generator (PMSG), hybrid energy storage, a dump load and a mains load is considered in this paper. They grid energy storage consists of a battery storage and a super capacitor where both are connected to the DC bus of the RAPS system. An energy management algorithm (EMA) is proposed for the hybrid energy storage with a view to improve the performance of the battery storage. A synchronous condenser is employed to provide reactive power and inertial support to the RAPS system. A coordinated control approach is developed 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. Through simulation studies carried out using detailed model in MATLAB Simulink, it has been demonstrated that the proposed method is capable of achieving: a) robust voltage and frequency regulation (in terms of their acceptable bandwidths), b) effective management of the hybrid storage system, c) reactive power capability and inertial support by the synchronous condenser, and d) maximum power extraction from wind.**

I. INTRODUCTION

Variable nature of wind and fluctuating load profiles particularly when they operate in standalone mod The random variation of wind speed lead 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 based power system provides an opportunity for better voltage and frequency response, specially during wind and load demand variations.

The application of energy storage to a standalone power system can be used to fulfil one or more of the following requirements: to improve the efficiency of the entire RAPS system, to reduce the primary fuel (e.g., diesel) usage by energy conversion, and to provide better security of energy supply. The justification 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.

For a wind turbine based RAPS system, 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. However, among all the energy storage options available, a single type of energy storage 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 option requires good understanding of its operational characteristics. In general, 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 to operate at low frequency power regions Permanent Magnet Synchronous Generator (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. In this paper, the performance of the components of a hybrid RAPS system is investigated under fluctuating wind and variable load conditions. The schematic of the proposed RAPS system is shown in Fig.1.1. 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

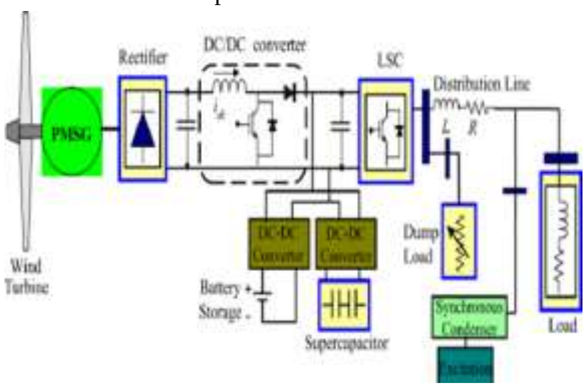


Fig: 1 pmsg based hybrid remote area power supply system with a hybrid energy storage

To provide enhanced reactive power and inertial support synchronous condenser is integrated into the RAPS system the existing work on remote area power supply systems with energy storage is summarized below. An isolated operation of PMSG with a battery storage system is discussed in

It only covers a RAPS system consisting of PMSG and battery storage. A multilevel energy storage consisting of flow battery storage and a super capacitor is explained in 8. However, authors of this paper have presented results associated with the hybrid energy storage system rather than the system level behavior.Different control strategies proposed for the battery- supercapacitorhybrid energy storage are discussed in . It only examines the different control strategies that could be applied to a hybrid energy storage system. In, an optimal energy management scheme for battery-super capacitor hybrid energy storage is proposed. In order to obtain the optimal solution, the authors of have formulated the problem as an optimization problem for minimization of the fluctuation of the current flowing in and out of the battery and the energy loss seen by the super capacitor.

However, optimization is generally application-oriented and the optimized parameters for one system may not be suitable for another. Authors in have presented 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 integrate diesel-wind-photovoltaic system with battery storage is studied in . 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 analyzed in However; the authors of this paper have assumed that the battery storage voltage remains constant during wind gust which is not the caseIn practical applications. Application of a super capacitor for a doubly- fed induction generator in grid connected mode of operations demonstrated in However, management and control coordination of a remote area power system consisting of a PMSG, a hybrid energy storage a dump load and a synchronous condenser have received a very little research attention

PERMANENT MAGNET SYNCHRONOUS GENERATOR

A permanent magnet synchronous generator is a generator where the excitation field is provided by a permanent magnet instead of a coil. The term synchronous refers here to the fact that the rotor and magnetic field rotate with the same speed, because the magnetic field is generated through ashaft mounted permanent magnet mechanism and current is induced into the stationary armature Synchronous generators are the majority source of commercial electrical energy

$$\Sigma P_{sources} - \Sigma P_{sinks} = \frac{dE_{KE}}{dt} = \frac{d\Sigma J\omega^2}{dt} = 0 \quad (1)$$

$$\Sigma Q_{sources} - \Sigma Q_{sinks} = 0 \quad (2)$$

$$P_w \pm P_b \pm P_c = P_L + P_d \quad (3)$$

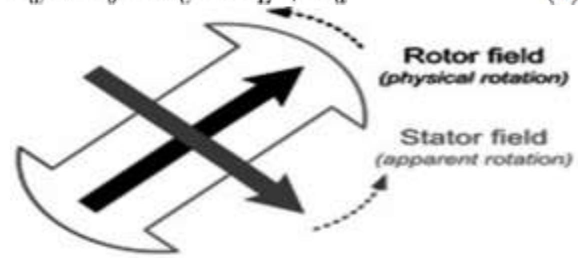


Fig.2 synchronous generator rotor

In this paper, 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 in the RAPS system, 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 of the RAPS system. The key objective of the proposed control methodology is to operate the hybrid energy storage in such a manner that battery storage is used to mitigate low frequency fluctuation and the super capacitor is to mitigate high frequency fluctuation

II COORDINATED CONTROL APPROACH FOR THE RAPS SYSTEM

over generation conditions where the power output from the In general, to achieve robust voltage and frequency regulation of any power system it is vital to maintain the active and reactive Balance given by and respectively

Where P—active power,EKE —kinetic energy of the system—moment of inertia of rotating machine,W —angular velocity of the rotating machine and Q—reactive power. In relevance to the RAPS system shown in Fig. 1, the active power flow has to be coordinated among the wind turbine generator, battery storage, super capacitor and dump load which is given by

Where PW —wind power output,Pb—battery storage output,PC—supercapacitor output,Pd — dump load power and PL—active power demand.

To ensure the power balance of the RAPS system a coordinated control approach is developed as shown in Fig. 2. During wind turbine generator PW greater than the load demand, the hybrid energy storage (i.e., battery storage and super capacitor) should absorb the excess power PW-PL, according to the energy management algorithm discussed in Section V. If the ESS capacities reach their maximum limits (i.e., SOCMAXand(VSC) where is the maximum state of charge of the battery (VSC)MAX and is the maximum operating voltage of the super capacitor), the dump load PD is operated to absorb the excess power. If the dump load reaches its maximum rating (PD) MAX, the pitch angle control of the wind turbine generator has to be activated. During the under-generation conditions,

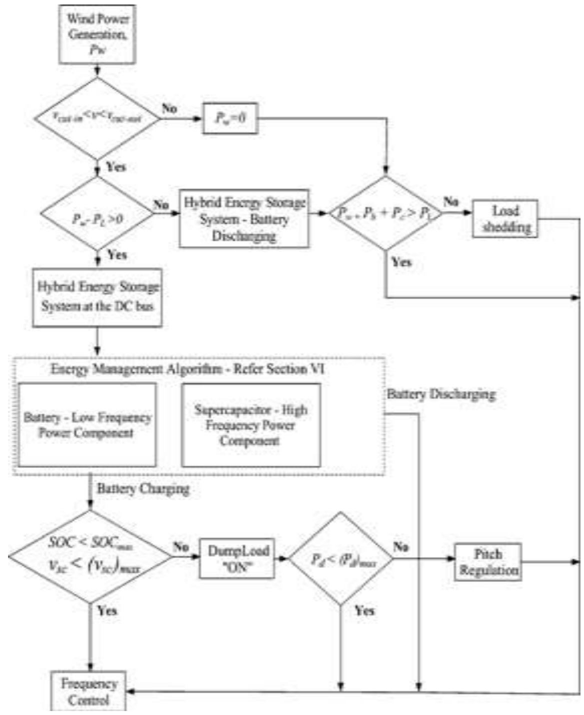


Fig. 3.Proposed control coordination methodology

where PW_ PL < 0is 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 wind system and hybrid energy storage are sufficient to supply the load demand at all time. In other words, emergency situations such as 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 during an emergency situation where the reduced load is then supplied by the hybrid energy storage system.

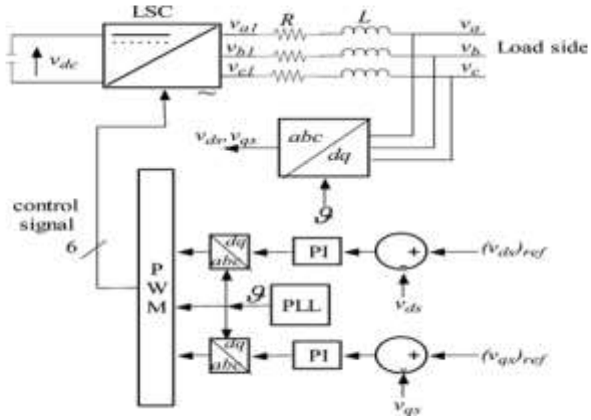
The reactive power sharing is made between the synchronous condenser and inverter as given by (4).

$$Q_{inv} + Q_{syn} = Q_L \qquad (4)$$

Where Qinv _ inverter reactive power, Qsyn_ reactive power from synchronous condenser and QL- reactive power demand of mains load

III: CONTROL ASSOCIATED WITH PMSG

Fig.4 Vector control scheme for the LSC 16



As mentioned earlier, in the RAPS system, the PMSG performs as the main source of energy and is interfaced with an uncontrolled rectifier-inverter arrangement before

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_{a1} \\ v_{b1} \\ v_{c1} \end{bmatrix}. \quad (5)$$

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.

LINE SIDE CONVERTER CONTROL

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 LST voltage balance across the filter of the LSC shown in Fig. 3 is expressed using (5).where –VA1,VB1,VC1 voltages at the inverter output, -VA,VB,VCvoltages at load side,IA,IB,IC, - current through the filter circuit,L and – R filter inductance and resistance, respectively. These quantities are then transformed into a synchronously rotating-q (direct and quadrature) coordinates with an angular velocities given by 6–9.

here vds and vqs_ q components of the load side AC voltage, ids and iqs —d and q components of inverter current and vds1 and vqs1 —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. 3, the referenced– component of the voltage is maintained at 1 Pu (pu)

$$v_{ds1} = v_{ds} - v_{ds}^{*} + L\omega_s i_{qs} \quad (6)$$

$$v_{qs1} = v_{qs} - v_{qs}^{*} - L\omega_s i_{ds} \quad (7)$$

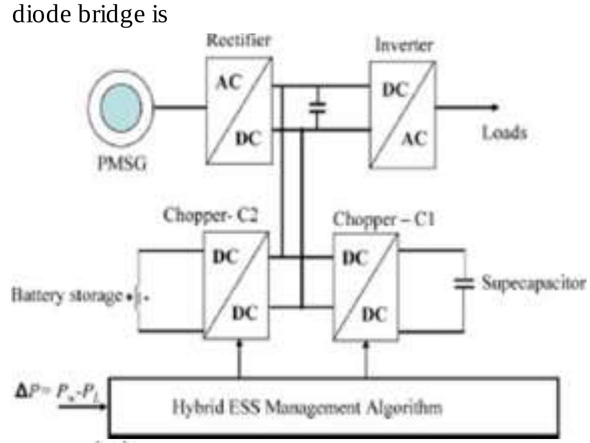
$$v_{ds}^{*} = Ri_{ds} + L\frac{di_{ds}}{dt} \quad (8)$$

$$v_{qs}^{*} = Ri_{qs} + L\frac{di_{qs}}{dt} \quad (9)$$

Whereas the reference q–component of the load voltage is set to zero. The PI controllers associated with LSC are tuned using the internal model control principle as discussed in

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, presents at the full converter diode bridge is



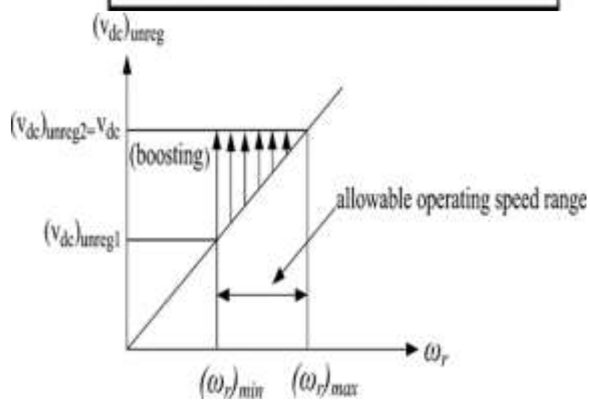


Fig. 3.2 Boost converter operation to regulate the DC bus voltage.

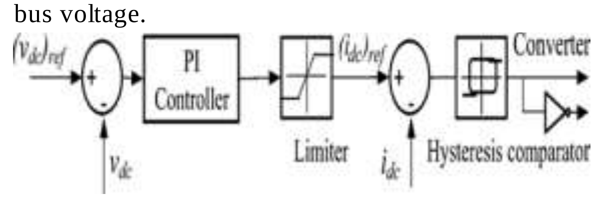


Fig. 3.3 Control strategy of the boost converter of the PMSG based wind energy system.

A function (i.e., linearly proportional) of the generator speed and can be explained using Fig. 4.The proposed control scheme for the DC/DC converter is shown in Fig. 5. The outer control loop measures the DClink voltage, which is compared with the reference DC link voltage, and the error is compensated using a PIcontroller to generate the reference current through the inductor of the boost converter, as in. 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 and can be given as in Equation

$$(i_{dc})_{ref} = \Delta v_{dc} \left(k_p + \frac{k_i}{s} \right) \tag{10}$$

$$(b_f)_{\max} = \frac{(v_{dc})_{ref}}{(v_{dc})_{unreg1}}. \tag{11}$$

Where (idc)ref is the reference current through the inductor of the boost converter,(vdc) ref is the regulated DC bus voltage, kp,kiare proportional and integral components of the PI controller and (vdc)uneg1 is lowest unregulated voltage present at the output of diode bridge rectifier.

IV. HYBRIDE ENERG STOAGE SYSTEM (ESS) MANAGEMENT ALGORITHM

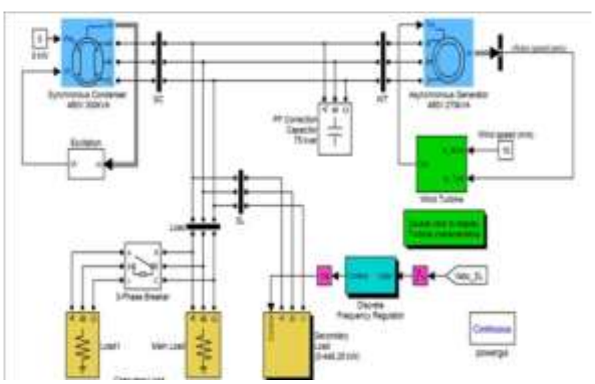


Fig.5.1 Proposed topology

This optimum wind power is used to derive the input signals for the battery storage and super capacitor.

Where pa - aero dynamic power, pw - power output of the turbine,cp- power coefficient of the turbine, A—area swept by the rotor blades, v—wind speed, —air density, R—radius of blade,— tip-speed ratio, —pitch angle, —optimal mechanical power output from the wind turbine.

By controlling the power flow into the battery storage and super capacitor using the maximum power tracking algorithm

$$P_a = \frac{1}{2} C_p(\lambda, \beta) A \rho v^3 \tag{24}$$

$$\lambda_{opt} = \frac{(\omega_r)_{opt} R}{v} \tag{25}$$

$$(P_w)_{opt} = k_{opt}[(\omega_r)_{opt}]^3 \tag{26}$$

$$K_{opt} = \frac{1}{2}(C_p)_{opt} \rho A (\frac{R}{\lambda_{opt}})^3 \tag{27}$$

it is possible to impose an appropriate torque, TPMSG on the PMSG shaft given by to extract the maximum power from the wind. Also, the corresponding optimum generator speed is given by

Where KT - equivalent linkage flux of the PMSG andidc—current through the inductor of the boost converter. The third objective is achieved by splitting the demand-generation mismatch into two frequency components by means of a high-

$$T_{PMSG} = K_T i_{dc} \tag{28}$$

$$(\omega_r)_{opt} = \sqrt{\frac{K_T}{k_{opt}} i_{dc}} \tag{29}$$

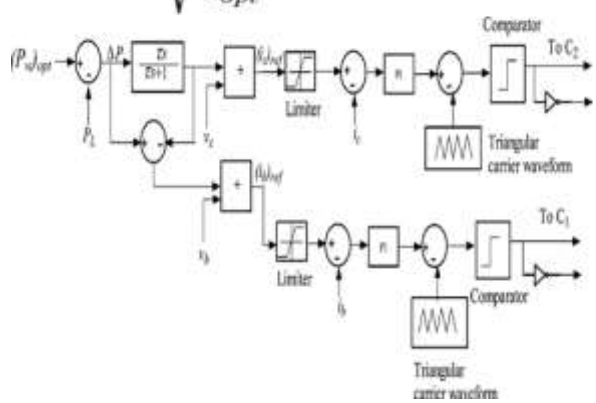


Fig. 5.2 Energy management algorithm for hybrid energy storage system

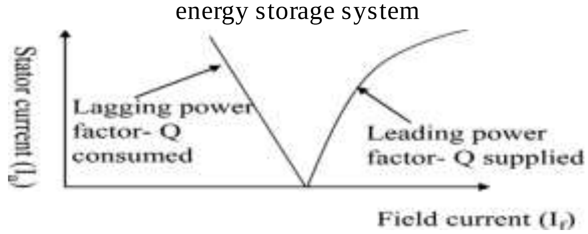


Fig. 5.3 The V curve of synchronous

V SIMULATION RESULTS AND DISCUSSIONS

The proposed strategy was implemented with the detailed model of the MATLAB Simulink SimPower and also with the highly accurate models of the system components. The simulation time step used was 5 micro-seconds to capture the true behaviour of the system components. To prove the robustness of the proposed method, wind gusts and load step changes in wind profile and load profile respectively are used to synthesize the worst system conditions in a RAPS system. Such worst-case scenarios are used to show how well the proposed control strategy behaves in relation to the voltage and frequency regulation

VI.SIMULATION RESULTS AND DISCUSSION

Fig.8.1.simulink model of proposed system

The load side voltage shows slight fluctuations at and which correspond to load step changes. The highest voltage variation is seen to occur due to load step down at and is limited within of its rated value. Also, it can be seen that wind changes have no or minimal influence on the load side voltage variations. The operating frequency of the system is regulated within rated value, i.e., pu with some minor fluctuations due to load step changes as shown in Fig. 8.1. The DC bus voltage is shown in Fig. 11 which is regulated well at its rated value.

The wind power variation of the system is shown in Fig. 12 According to the wind turbine characteristics; the corresponding maximum power output of the wind generator is 0.83 pu at rated wind speed of 12 m/s. Until, the power output of the PMSG stays at 0.83 Pu and during this time period, the load active power demand is set to 0.4 Pu as depicted in Fig. 12. This simulates an over generation condition where the excess power from the wind given by is shared Between the hybrid energy storage and dump load. However, the power sharing between hybrid energy storage units occurs according to the energy management algorithm discussed in

Section V. The battery storage power is shown in Fig. 12and it is seen that until, the battery reaches its full capacity Whereas the super capacitor absorbs the high fluctuating power component of demand-generation mismatch as shown in Fig. 12 When the battery storage reaches to its full capacity, the excess low frequency power component is absorbed by the dump load as shown in Fig. 12 After, the wind speed reduces to 9 m/s thus lowering wind power output to nearly 0.375 Pu as depicted in Fig. During this time, the RAPS system experiences an under- generation scenario, where the Deficit power, is supplied through the battery storage. The dump load operation is disabled

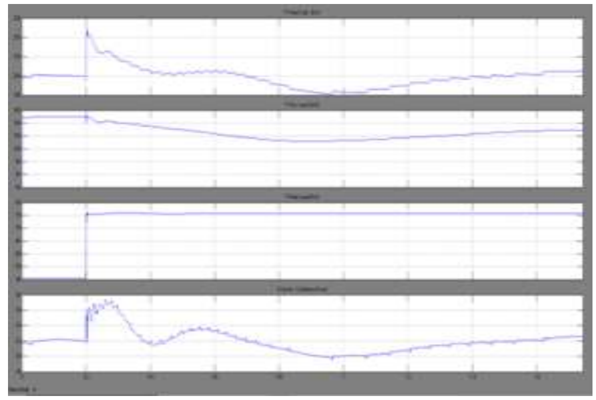


Fig.8.2.(Response of the RAPS system under variable wind and load conditions. a)Wind Speed , (b) Voltage at load side , (c) Frequency at load side , and (d) DC link Voltage .

Also, the sudden wind speed changes cause rapid variations of the wind power output which is seen to be absorbed by the super capacitor. After, the real power demand is increased by 0.3 Pu for which RAPS system further experiences an under generation condition. In this scenario, the battery storage increases its discharge rate. After, the wind speed is increased to 10 m/s thus increasing the power output from the wind generator. However, the RAPS system still experiences an under-generation condition where the power deficit is supplied through the battery storage. With this load step down which occurs at, the system experiences an over- generation condition causing the battery storage to move from discharging to charging mode of an operation to maintain the power balance of the RAPS system. Throughout the operation, the super capacitor absorbs the high frequency power component of demand-generation mismatch during transient conditions which occur due to wind and load step changes as evident from To examine the effectiveness of integrating an hybrid energy storage into a PMSG based RAPS system, a comparative study has been carried out in relation to the battery storage current. The behaviour of the battery current without having a super capacitor Is shown in It can be seen that the battery current consists of high frequency component which will shorten the lifespan of the battery storage system. In addition, high depth of discharge rates which occur during transient conditions including wind and load step changes will further cause damage to the battery storage system. The battery storage current with integration of the hybrid energy storage is shown in .It is clearly visible that the high frequency component (i.e., above 0.5 Hz) is absorbed by the super capacitor and provides a smoother transition from one operational mode to another with

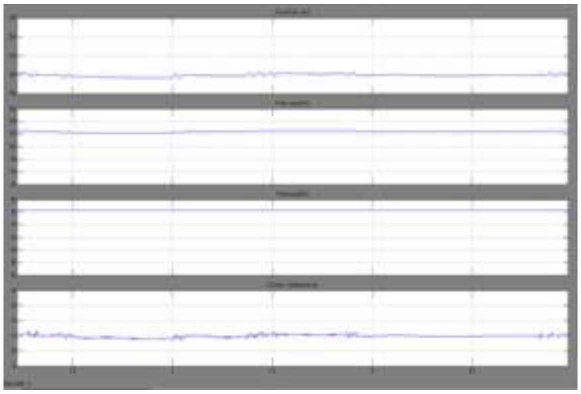


Fig.8.3Power sharing of the RAPS system at variable wind and load conditions
(a)Wind Power, (b) Battery power, (c) Super capacitor power (d) Dump load power and (e) Load demand.

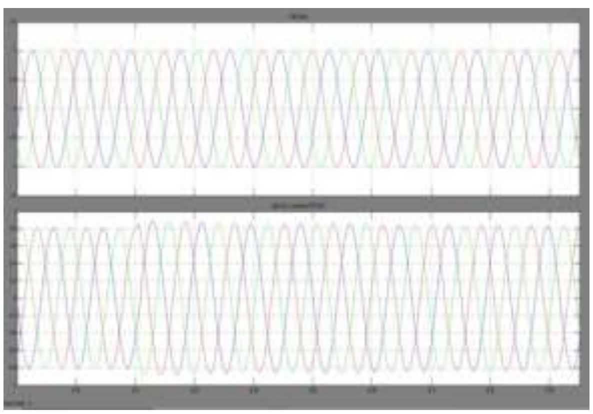


Fig.8.4.PMSG output voltages and currents

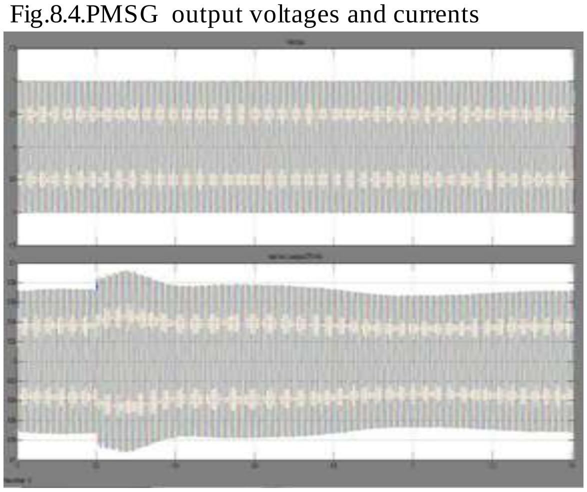


Fig.8.5Current and voltages at load side

Lower depth of discharge for the battery storage. The maximum power extracted from wind is shown in Fig. 15. It can be seen in Fig. 15 that the PMSG runs on its maximum power extraction mode of operation throughout its entire operation

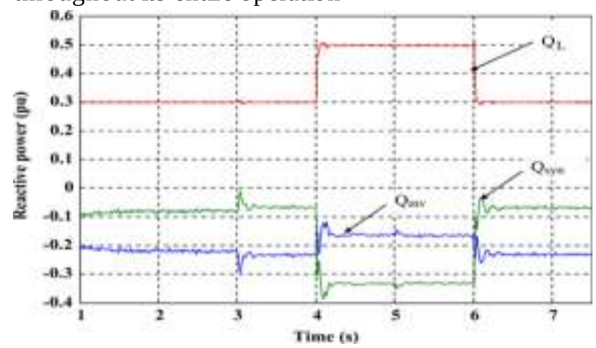
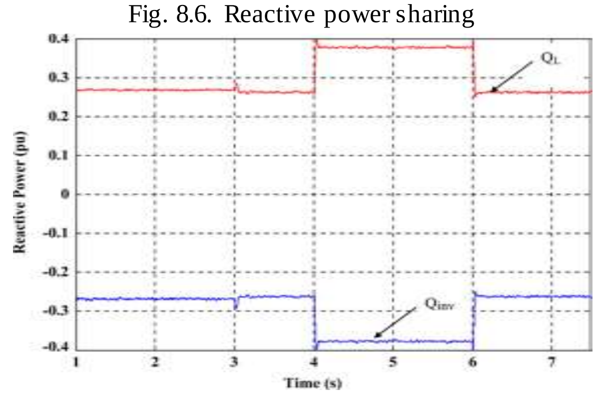


Fig. 8.6. Reactive power sharing



Set to 0.3 Pu. The highest reactive power support is provided through LSC where the rest is supplied by the synchronous condenser during the load step change at, the reactive power demand is increased to 0.5 pu where the highest proportion of reactive power is now supplied through synchronous condenser while the rest is provided through LSC inverter. The reactive power supply through LSC alone. It can be seen that the LSC inverter is not capable of providing the required reactive power into the system thus causing a reduction of load side voltage as shown in Fig. 18. This is mainly due to the capacity, limitations associated with the inverter.

VII.CONCLUSION

This paper has investigated the standalone operation of a PMSG with a hybrid energy storage system consisting of battery storage and a super capacitor, a synchronous condenser and a dump load. The entire RAPS system is simulated under over-generation and under-generation conditions covering the extreme operating conditions such as load step changes and wind gusts. The suitability of the adopted control strategy for Each system component is assessed in terms of their contributions towards regulating the load side voltage and frequency.

Investigations have been carried out in relation to the voltage and frequency regulation at load side, DC bus stability, maximum power extraction capability of wind turbine generator and the performance of the hybrid energy storage system. From the simulated behaviour, it is seen that the proposed approach is capable of regulating both voltage and frequency within tight limits for all conditions including the worst-case scenarios, such as wind gusts and load variations. Also, the performance of the battery storage is improved with the implementation of the proposed energy management algorithm, as super capacitor absorbs the ripple or high frequency power component of demand generation mismatch while leaving the steady component for the battery storage. Moreover, the super capacitor helps in avoiding battery operation in high rate of depth of discharge regions.

The proposed control algorithm is able to Manage power balance in the RAPS system while extracting the maximum power output from the wind throughout its entire operation. With the integration of the synchronous condenser, it has been proven that the RAPS system is able to maintain the load voltage within acceptable limits for all conditions including the situation when reactive power demand becomes very high.

7.1 SYSTEM CONFIGURATION PARAMETERS

PARAMETERS OF RAPS SYSTEM- BASE 100 KVA

TABLE I PAR METERS OF RAPS

Rating of wind turbine generator	100 kW
Rating of battery storage system	75 Ah
Rating of Supercapacitor	30 F
Rating of dump load	25 kW
Rated DC link voltage of back-to-back converter	750 VDC
Battery storage system voltage	250 VDC
Supercapacitor max voltage	375 VDC
Rated load side voltage	400 V
Load side operating frequency	50 Hz

TABLE II: PARAMETERS OF PMSG

Rated power output (P_{PMSG})	100 kW
stator resistance (R_s)	0.0275 ohms
stator inductance (L_s)	4e-3 H
Flux linkage (Φ_s)	1.125 Vs
Torque constant (T_k)	9 Nm/A_{pk}
voltage constant (V_k)	535.45 $(v_{pk})_{LL}/Krpm$
Inertia (J)	0.3 (Jkg^2)
Number of pole pairs (P)	4

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