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Wind-Turbine Asynchronous Generator Synchronous Condenser with Excitation in Isolated Network

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ABSTRACT

In this paper 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.The frequency is controlled by the Discrete Frequency Regulator block. This controller uses a standard three-phase Phase Locked Loop (PLL) system to measure the system frequency. The measured frequency is compared to the reference frequency to obtain the frequency error. This error is integrated to obtain the phase error. The phase error is then used by a Proportional-Differential (PD) controller to produce an output signal representing the required secondary load power. This signal is converted to an 8-bit digital signal controlling switching of the eight three-phase secondary loads. In order to minimize voltage disturbances, switching is performed at zero crossing of voltage.

KEYWORDS: *Keyword 1, Keyword 2, Keyword 3, Keyword 4, Keyword 5*

I. Introduction

Variable nature of wind and fluctuating load profiles make the operation of wind based power systems challenging, particularly when they operate in stand alone mode. The random 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 [1]. Integration of an Energy Storage System (ESS) into a wind based power system provides an opportunity for 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 following requirements:

(1) to improve the efficiency of the entire RAPS system,

(2) to reduce the primary fuel (e.g., diesel)
usage by energy conversion, and (3) to provide better securityof energy supply [2]. The justification behind the integration of an 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. [3]. 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 variationswhich may exist for a few seconds or even longer [4]. 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 [5]. 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. [6] [9] [10]. 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. 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.

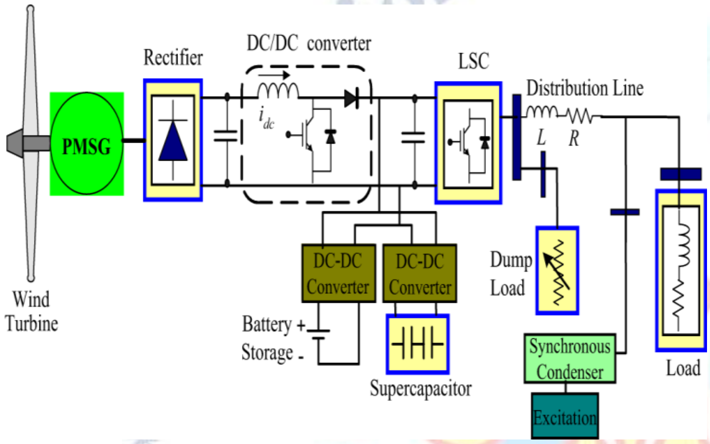

Fig. 1. PMSG based hybrid remote area power supply system with a hybridenergy storage.

II. COORDINATED CONTROL APPROACH FOR THE RAPS SYSTEM

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 (1) and (2) respectively [15].

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

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

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

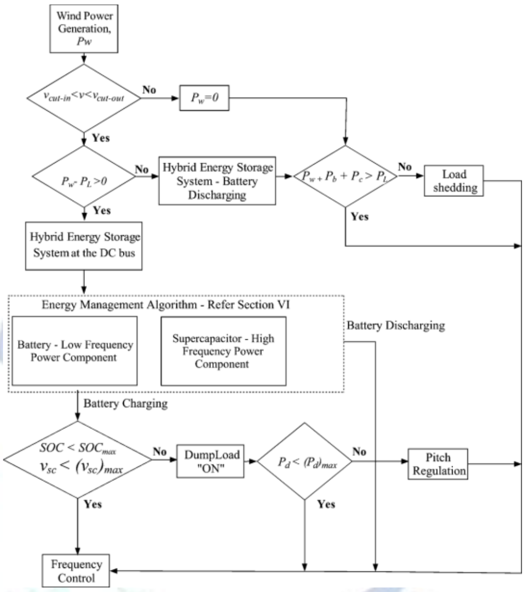

Fig. 2. Proposed control coordination methodology.

III. SYNCHRONOUS CONDENSER

In the RAPS system shown in Fig. 1, the PMSG inverter control may not be able to provide robust voltage control especially when it needs to serve reactive power loads. This is mainly due to the capacity limitation6 associated with the inverters. Moreover, the PMSG is fully decoupled from the power electronic arrangement (i.e., through rectifier and inverter arrangement). Therefore, the PMSG has no inertia contribution towards the inertial requirement of the entire RAPS system. In this regard, to provide enhanced reactive power together with inertial support, a synchronous condenser can be incorporated into the RAPS system. The operational characteristics of a synchronous condenser are shown in Fig. 9. In this paper, the synchronous condenser is used to operate at leading power factor region to supply reactive power into the RAPS system. For the simulation purposes a synchronous machine with an exciter is used, where the active power input to the synchronous machine is set to zero. An IEEE type 1 voltage regulator and exciter system are used to control the field voltage of the synchronous condenser [7],[8].

IV. 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

$$P_d = \begin{cases} P_d & (P_w)_{opt} + (P_b)_{\max} + P_c > P_L \\ 0 & \text{otherwise} \end{cases} .$$

The operation of the dump load is limited to the case where excess power is available in the system.Also, the dump loadwill start absorbing the additional power only after battery storage reaches its rated capacity (i.e.,). The maximum power

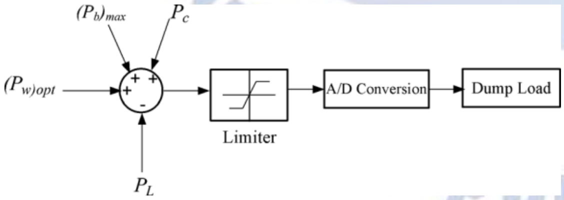

Fig. 3. Dump load controller.

that can be dissipated through a dump load can be expressed as in (31). A simplified control schematic diagram of the dump load controller is shown in Fig. 5.

$$(P_{dump})_{\max} = (2^n - 1)P_{step}.$$

V. SIMULATION RESULTS AND DISCUSSIONS

The proposed strategy was implemented with the detailed model of the MATLAB Simulink Sim Power 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 showhowwell the proposed control strategy behaves in relation to the voltage and frequency regulation. The performance of the proposed RAPS system shown in Fig. 1 is investigated under (a) variable load and (b) fluctuating wind speed conditions. In this regard, the simulated behaviour of the voltage and frequency at load side, DC link stability, performance of the hybrid energy storage and maximum power extraction capability from wind were examined. The parameters of the RAPS system and PMSG based wind turbine generator are listed in Appendices A and B respectively.

The responses of RAPS system components have been tested under variable wind and load condition. Fig. 11 shows the voltage and frequency behavior of the RAPS system, whereas Fig. 12 shows the power sharing among different system components. The wind condition under which the system has been simulated is shown in Fig. 11(a). It can be seen that the wind velocity is set initially at 12 m/s. After , the wind velocity drops to 9 m/s, then it is increased to 10 m/s at . The load demand is initially set at 0.5 pu which is having a power factor of 0.8. (i.e., real power demand is 0.4 pu). At time , the load is increased to a value of 0.86 pu with a power factor of 0.8. The same additional load (i.e., 0.36 pu having a power factor of 0.8) is now disconnected from the system at as shown in Fig. 12(e). The AC voltage at point of common coupling is shown in Fig. 11(b). It can be seen that

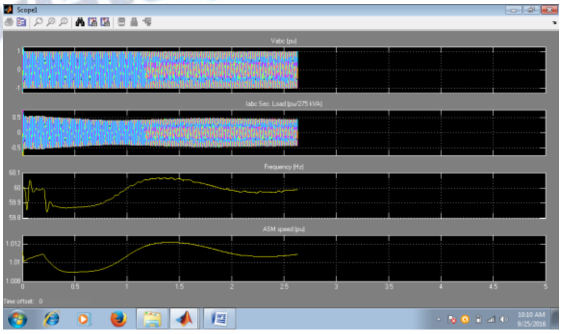

Fig. 4. Response of the RAPS system under variable wind and load conditions.

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. 4(c). The DC bus voltage is shown in Fig. 4(d) which is regulated well at its rated value. The wind power variation of the system is shown in Fig. 5(a). 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. 5(e). 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.5(b) and 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. 5(c). 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. 5(d). After , the wind speed reduces to 9 m/s thus lowering wind power output to nearly 0.375 pu as depicted in Fig. 5(a). 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 as shown in Fig. 5(d).

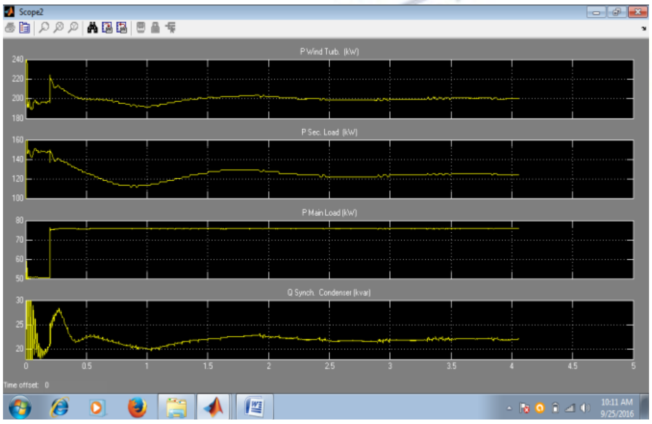

Fig.5. Power sharing of the RAPS system at variable wind and load conditions.

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 Fig. 13. 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 includingwind 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 Fig. 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 lower depth of discharge for the battery storage. The maximum power extracted from wind is shown in Fig. It can be seen in Fig. that the PMSG runs on its maximum power extraction mode of operation throughout its entire operation.

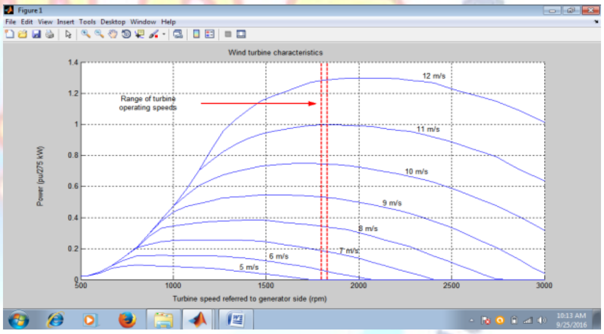

Fig 6:output of simulation

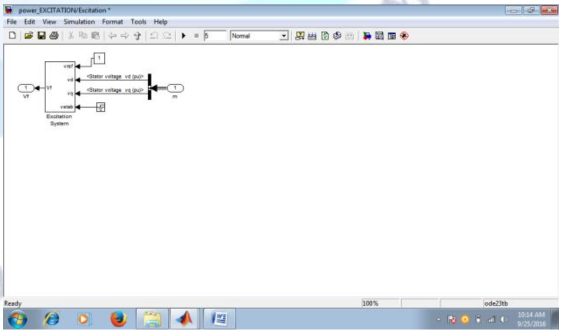

Fig 7:power excitation

VI. CONCLUSION

This paper has investigated the standalone operation of a PMSG with a hybrid energy storage system consisting of a 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 reach 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.

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