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ENERGY MANAGEMENT OF A HYBRID POWER SYSTEM FOR VARIABLE SPEED WIND TURBINE AND VARYING TEMPERATURE

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ABSTRACT

This paper deals with Energy management of a wind and solar hybrid generation system for interconnection operation with electric distribution system. This system consisting of a Permanent Magnet Synchronous Generator (PMSG), Solar PV, hybrid energy storage, a dump load and an interfacing grid. The hybrid energy storage consists of battery storage and a super-capacitor where both are connected to the DC bus of a system. An energy management algorithm (EMA) is proposed for the hybrid energy storage with a view to improve the performance of the battery storage. Moreover, high reactive power demand makes it more challenging due to the limitation of reactive capability of the wind generating system. A synchronous condenser is employed to provide reactive power. A coordinated control approach is developed to manage the active and reactive power flows among the components. In this regard, individual controllers for each system component have been developed for effective management of the system components. The simulation is carried out using detailed model in MATLAB/SIMULINK model. The performance of the model demonstrated that the proposed method is capable of achieving: a) Good voltage and frequency regulation, b) Effective Management of the Hybrid Storage System, c) Reactive Power Capability by the synchronous condenser.

Keywords: PMSG, PV array, hybrid energy storage system, grid interface inverter, synchronous condenser.

INTRODUCTION

Variable nature of wind and fluctuating load profiles make the operation of wind based power systems challenging, particularly when they operate in Grid connected mode. The random variation of wind speed leads to fluctuating torque of the wind turbine generator resulting in voltage and frequency excursions [1]. This paper deals with power control of a Wind and Solar hybrid generation system for interconnection operation with electric distribution system. Power control strategy is to extract the maximum energy available from varying condition of wind speed and solar irradiance while maintaining power quality at a satisfactory level. Integration of an Energy Storage System (ESS) into a wind and solar 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 grid can be used to fulfill one or more of the following requirements: (1) to improve the efficiency of the system, (2) to reduce the primary fuel (e.g., diesel) usage by energy conversion, and (3) to provide better security of energy supply [2]. The justification behind the integration of energy storage into a wind and solar energy application is based on the factors which include total wind turbine inertia, low voltage ride through capability, power quality issues, etc. [4]. 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 [5]. 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]. In this paper, the performance of the components of a hybrid system is investigated under fluctuating wind, varying irradiation and variable load conditions. The schematic of the proposed system is shown in Figure-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. The grid interface inverter transfers the energy drawn from the wind turbine and PV array into the grid by keeping common dc voltage constant. An isolated operation of a PMSG with a battery storage system is discussed in [7]. It only covers a system consisting of PMSG and battery storage. However, authors of this paper have presented results associated with the hybrid energy storage system rather than the system level behavior.

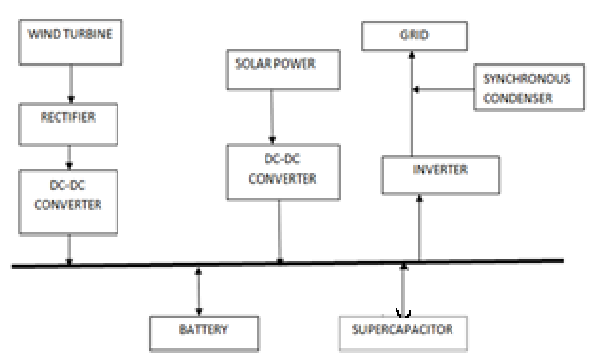

Figure-1. Block diagram of a hybrid system with grid interfacing.

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The existing work on remote area power supply systems with energy storage is summarized below. An isolated operation of a PMSG with a battery storage system is discussed in [8]. A multilevel energy storage consisting of flow battery storage and a super-capacitor is explained in [9]. 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-super-capacitor hybrid energy storage are discussed in [10]. It only examines the different control strategies that could be applied to a hybrid energy storage system. In [11], an optimal energy management scheme for battery and super-capacitor hybrid energy storage is proposed. Authors in [12] have presented a method of improving battery lifetime in a small-scale wind-power system by the use of a battery/super capacitor hybrid energy storage system. Our world is witnessing a lot of energy crisis today and environment pollution is on a rising scale. In order to solve these problems emphasis is being placed on renewable sources of energy. Photovoltaic energy is of great importance in this regard as it is clean and inexhaustible and widely available. 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. An energy management strategy is proposed and implemented while harvesting maximum power from the wind. Reactive power management has been realized through integrating and operating a synchronous condenser in a coordinated manner with other energy resources of the system. As the conventional energy sources are diminishing fast, the solar energy offers a very promising alternative, because it is free, abundant, pollution free and distributed throughout the earth. The use of PV technology meets several challenges such as increasing the efficiency of PV conversion, ensuring the reliability of converters etc. The paper is organized as follows: Section II presents a coordinated control approach for the system. Section III discusses the control strategy applied for the PMSG. The proposed energy management algorithm established among the battery storage and super-capacitor is explained in Section IV. The detailed information of battery storage and super-capacitor is given in Section V. The operations of synchronous condenser and dump load are illustrated in Section VI. The simulated results of the proposed system are presented in Section VII. Conclusion is given in Section VIII.

COORDINATED CONTROL APPROACH OF THE SYSTEM

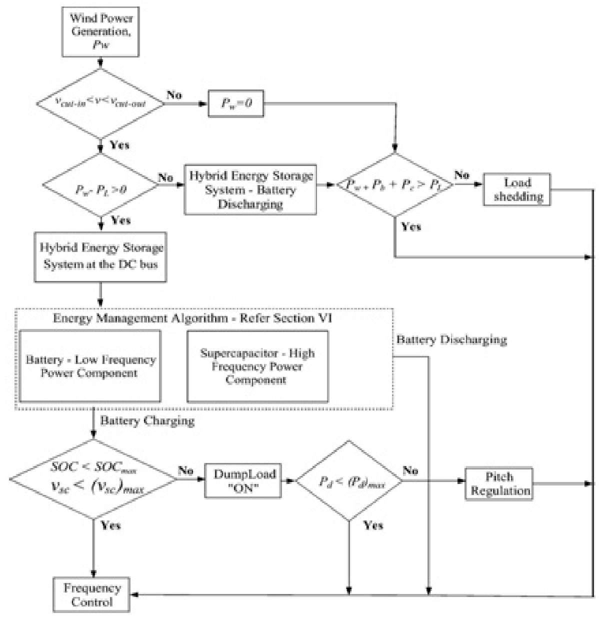

Figure-2. Proposed control topology.

Two Mass Drive Train Model

The Two mass drive train model implemented in SIMULINK is shown in Figure-3. It is a turbine and shaft coupling system. This subsystem will give shaft torque T_ shaft(pu), W_wt as outputs and T_wt(pu),generator speed(pu) as input. It is an example of closed loop control system where feedback is provided just before the gain (=1). In this paper, the WECS is represented with the two-mass drive train model. The differential equations governing it mechanical dynamics are presented as follows:

$$2Ht\frac{dWt}{dt} = Tm - Tsh \tag{1}$$

$$\frac{1}{Welb}\frac{d\theta tw}{dt} = wt - wr \tag{2}$$

$$2Hg\frac{dWr}{dt} = Tsh - Tg \tag{3}$$

where Ht is the inertia constant of the turbine, Hg is the inertia constant of the PMSG, θtw is the shaft twist angle, Wt is the angular speed of the wind turbine in p.u. , Wr is the rotor speed of the PMSG in p. u. , Welb is the electrical base speed, Tsh and the shaft torque is

$$Tsh = Ksh\,\theta tw + Dt\; d\theta tw/dt \tag{4}$$

Where Ksh is the shaft stiffness and Dt is the damping coefficient.

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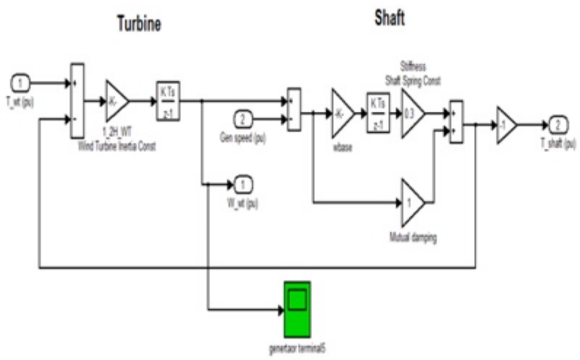

Figure-3. Two mass drive train model.

Pitch Angle Controller

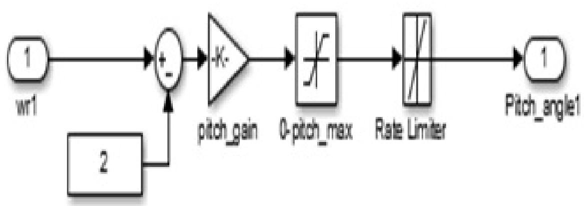

Figure-4. Pitch angle controller.

The Pitch angle controller designed in MATLAB/SIMULINK is shown in Figure-4. Here, pitch compensator is also designed with Proportional gain (Kp):1.5, Integral gain (Ki):6, output max. Limit: 45, min. limit: 0, Pitch Gain: 500.

MPPT Technique associated with wind turbine

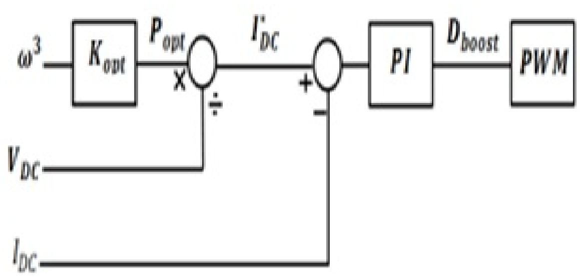

Figure-5. MPPT algorithm implementation for wind turbine.

This MPPT Technique is used to extract the maximum power from the wind energy.

Dc-Dc Converter

DC-to-DC converter is an electronic circuit which converts a source of direct current (DC) from one voltage level to another. DC to DC converters are important in portable electronic devices such as cellular phones and laptop computers, which are supplied with power from batteries primarily.

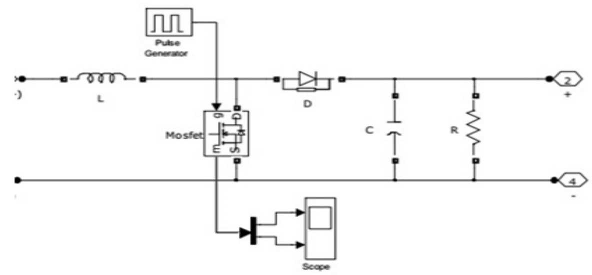

Figure-6. Boost converter model.

The key principle that drives the boost converter is the tendency to resist inductor changes in current by creating and destroying a magnetic field. In a boost converter, the output voltage is always higher than the input voltage. When the switch is closed, electrons flow through the inductor in clockwise direction and the inductor stores some energy by generating a magnetic field.

CONTROL ASSOCIATED WITH PMSG

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 modeled 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 inverter output, load side voltages, current through the filter circuit and their R, L values are converted into a synchronously rotating coordinates with an angular velocity ω_s. A virtual phase lock loop is used to define the orientation angle, θ for the inverter and to achieve a constant frequency of the Hybrid system. As depicted in Figure-7, 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.

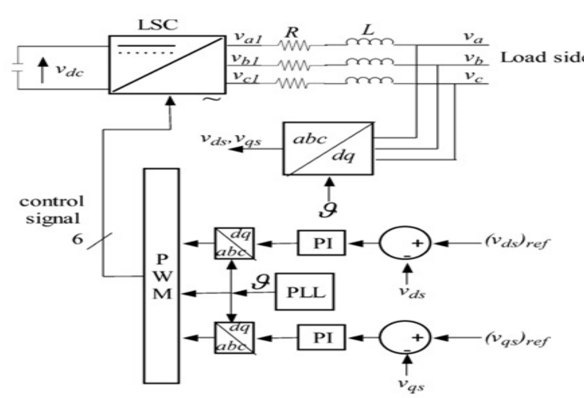

Figure-7. Vector control scheme for the LSC.

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Control Strategy for DC/DC Converter

The DC link voltage of the Hybrid system is regulated using a DC/DC converter (i.e., boost converter). The outer control loop measures the DC link voltage V_{dc}, which is compared with the reference DC link voltage $V_{dc\ ref}$, and the error is compensated using a PI controller to generate the reference current through the inductor of the boost converter $I_{dc\ ref}$. 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 b_f, of the boost converter is recorded at the lowest generator speed $\omega_{g\ min}$.

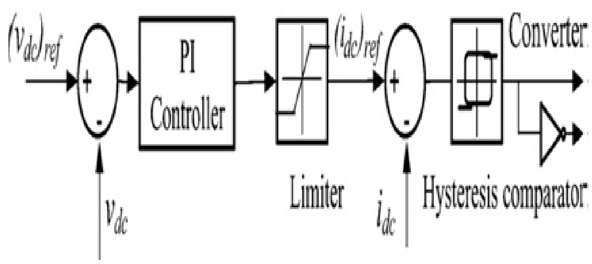

Figure-8. Control strategy of the boost converter.

ENERGY MANAGEMENT ALGORITHM

Among several options of connection topologies, bidirectional 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 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 estimate during the optimal wind power.

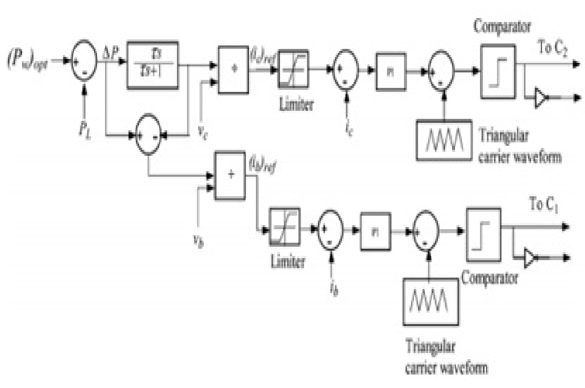

Figure-9. EMA algorithm.

BATTERY STORAGE AND SUPERCAPACITOR

Nickel-Cadmium battery model given in [3] is employed in this paper. 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 [13]. In this paper, the battery storage capacity is estimated which is able to provide a fraction (or) of rated current of the load demand. Application of a super capacitor for a doubly-fed induction generator in grid connected mode of operation is demonstrated in [14].

SYNCHRONOUS CONDENSER AND DUMP LOAD

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 limitations 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 system. In this regard, to provide enhanced reactive power together with inertial support, a synchronous condenser can be incorporated into the system. In this paper, the synchronous condenser is used to operate at leading power factor region to supply reactive power into the 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 [15].The dump load is coordinated with the hybrid energy storage system to maintain the active power balance of the 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.

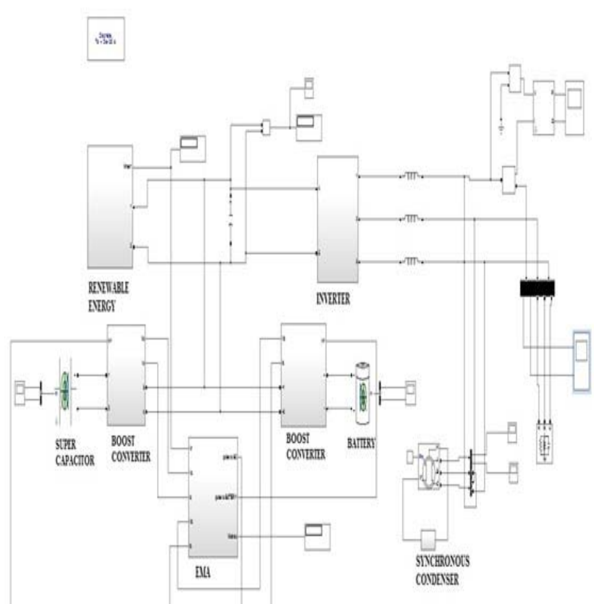

Figure-10. MATLAB/SIMULINK model.

SIMULATION RESULTS

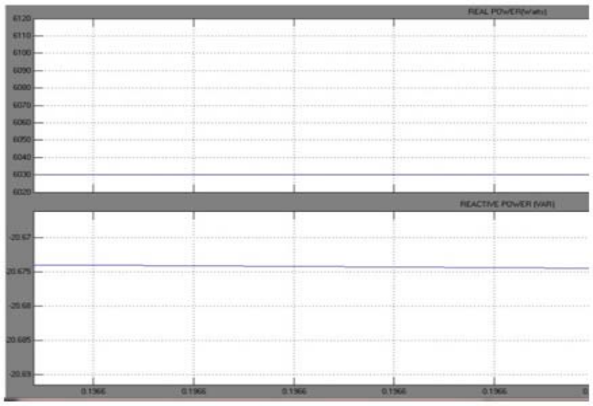

Figure-11. Real and reactive power.

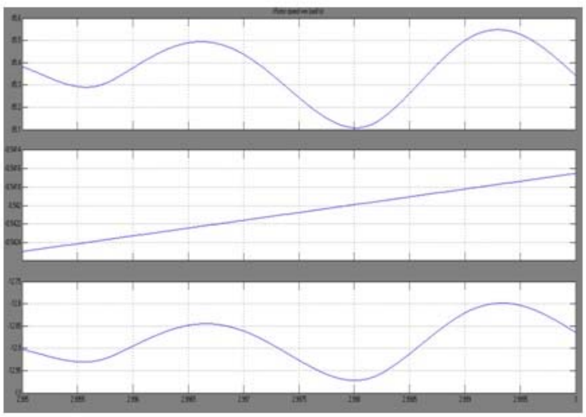

Figure-12. Rotor speed.

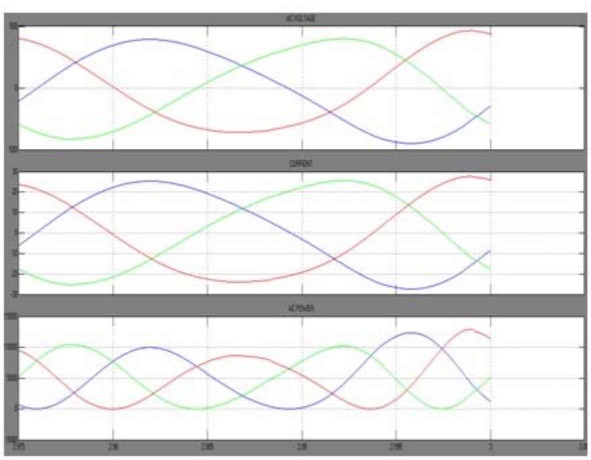

Figure-13. Current, voltage and power waveform.

The performance of the proposed system is investigated under (a) variable load and (b) fluctuating wind speed conditions. In this regard, the simulated behavior 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.

CONCLUSIONS

This paper has investigated the 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 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 behavior, 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 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 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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