Simulation of A Wind Turbine Generator Coupled with A Battery-Supercapacitorenergy Storagesystem

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Abstract—The paper presents a model of stand-alone wind turbine system. The system consists of wind turbine, Permanent Magnet Synchronous Generator (PMSG), controller converter, hybrid energy storage, dump load and mains load. All these put together forms the Remote Area Power System (RAPS). The system is implemented using MATLAB/SIMULINK software. The hybrid energy storage consists of 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 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. 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.

Key words: Hybrid energy storage system, MATLAB, RAPS system, supercapacitor and synchronous condenser

I. INTRODUCTION

In this paper the operation of PMSG based remote area power supply with hybrid energy storage is explained in detail with block diagram and circuit modeling configurations. The coordination control, control associated with PMSG and hybrid energy storage and energy management algorithm are also discussed. Variable nature of wind and fluctuating load profiles make the operation of wind based power systems challenging, particularly when they operate in standalones 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. 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 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 security of energy supply. 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.

The WECS model consist of wind turbine, pitch angle control, permanent magnet synchronous generator (PMSG) and the converter. The general types of generator are induction generator (IG), synchronous generator (SG), doubly fed induction generator (DFIG), squirrel-cage rotor, induction generator (SCIG), wound rotor induction generator (WRIG), and permanent magnet synchronous generator (PMSG). The PMSG is used for small power generation and DFIG is used for large power generation. Hence PMSG is used for standalone systems and DFIG is used for grid connected WECS system. The model of PMSG is given in d-q model. Mostly PMSG based systems are used without the gear box. Thus cost and weight of nacelle is reduced.

II. COMPONENTS OF STANDALONE WIND POWER SYSTEM

A. Wind Turbine:

A wind turbine is the reverse of an electrical fan. A wind turbine uses wind energy to generate the electricity. A fan uses electricity to generate wind. In more sophisticated terminology, a wind turbine converts the kinetic energy of the wind into electrical energy. Wind turbines come in different sizes and types, depending on power generating capacity and the rotor design deployed. Small wind turbines with output capacities below 10 kW are used primarily for residences, telecommunication dishes, and irrigation water pumping applications.

Utility-scale wind turbines have high power ratings ranging from 100 kW to 5 MW sufficient to provide power supply given to 10 to 500 homes. Present wind farms with large capacity wind turbine installations have sprung up in rural areas and offshore regions and are capable of generating electricity in excess of 500 MW for utility companies, they present much lower generating costs and zero maintenance and operating costs, thereby realizing significant reductions in electricity generation costs, greenhouse gas emissions, and atmospheric pollution.

B. PMSG- Permanent Magnet Synchronous Generator:

Selection of a specific wind turbine generator technology is also an important design factor in a wind based RAPS system. Usually, variable speed wind turbine generator technologies are preferred in a standalone power system, as they are able to provide better voltage and frequency regulation when compared to constant speed generators such as induction generators. The doubly fed induction generators (DFIGs) and permanent magnet synchronous generators (PMSGs) are identified as preferred variable speed generator technologies for wind power applications.

However, the selection of the size and technology of a wind turbine generator for a specific application is based on several factors such as maximum load demand, financial returns, wind mill data and technical aspects covering their reactive power capability. DFIG based wind turbine generator systems are preferred for high power applications where as
PMSG based wind turbines are suitable for low or medium power levels.

C. Line Side Converter:

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 voltage balance across the filter of the LSC is expressed using (eqn1.1).

\[
\frac{V_{a}}{V_{c}} = R \left[ \frac{i_{a}}{i_{c}} + \frac{L_{d}}{L_{c}} \left( \frac{i_{a}}{i_{c}} + \frac{V_{a}}{V_{c}} \right) \right] + \frac{V_{a}}{V_{c}}
\]

where

\[V_{a}, V_{b}, V_{c}\] - Voltages at the inverter output, voltages at load side,

\[i_{a}, i_{b}, i_{c}\] - Current through the filter circuit, and - filter inductance and resistance, respectively.

These quantities are then transformed into a synchronously rotating d-q (direct and quadrature) coordinates with an angular velocity \( \omega \).

D. DC-DC Converter:

The DC link voltage of the RAPS system is regulated using a DC/DC converter. The rectified voltage output, \( V_{dc} \), represents at the full converter diode bridge is a function of the generator speed, \( \omega_{g} \). 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. The key principle that drives the boost converter is the tendency of an inductor to resist changes in current. In a boost converter, the output voltage is always higher than the input voltage. When the switch is turned-ON, the current flows through the inductor and energy is stored in it. When the switch is turned-OFF, the stored energy in the inductor tends to collapse and its polarity changes such that it adds to the input voltage. Thus, the voltage across the inductor and the input voltage are in series and together charge the output capacitor to a voltage higher than the input voltage.

![Fig. 1: Circuit Diagram of a Boost Converter](Image)

The basic principle of a Boost converter consists of 2 distinct states. In the On-state, the switch \( S \) is closed, resulting in an increase in the inductor current. In the Off-state, the switch is open and the only path offered to inductor current is through the fly back diode \( D \), the capacitor \( C \) and the load \( R \). This result in transferring the energy accumulated during the On-state into the capacitor.

E. Battery Storage and Super Capacitor:

Nickel-Cadmium battery model given in (18) is employed in this thesis. 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 \( SOC_{min} \leq SOC < SOC_{max} \). In this thesis, the battery storage capacity is estimated using (eqn1.2) which is able to provide a fraction (or \( Y \)) of rated current of the load demand [17].

\[
Y = \frac{I_{rated}}{I_{max}} = \left( \frac{Ah \ Rating}{k} \right) \leq 0.45
\]

where

\[Y\] - fraction of the rated current of the load demand,

\[I_{rated}\] — 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.

It is assumed that battery storage is used to supply 45% of the rated load current (i.e., \( Y=0.45 \)) for the time-duration of 30 min (\( t=30 \) sec). To demonstrate how the size of the battery can be estimated, assume that the rated power of PMSG, \( P_{PMSG} \) is 250 kW and the rated AC voltage, \( V_{rated} \) is 400 V. The rated current of the PMSG can be calculated as follows:

\[
I_{rated} = \frac{P_{PMSG}}{V_{rated}} = 360.844 \text{ Amps} \tag{1.3}
\]

For this condition, the Ampere-hour (Ah) rating of the battery storage system can be estimated using (eqn1.4) as below:

\[
\text{battery storage} = \frac{360.844 \times 30 \times 0.45}{0.45+60} \approx 180 \text{ Ah} \tag{1.4}
\]

The size of the super capacitor can be estimated using (eqn1.5)-(eqn1.6).

\[
E_{sc} = \frac{1}{2} C_{sc} V_{sc}^2
\]

\[
E_{sc} = \frac{1}{2} C_{sup}(V_{sc})_{max}^2 - \frac{1}{2} C_{sup}(V_{sc})_{min}^2
\]

\[
C_{sup} = \frac{(V_{sc})_{max}^2-(V_{sc})_{min}^2}{2 k_{sup}}
\]

\[
E_{sc} - \text{energy rating of the super capacitor, } (V_{sc})_{max} \text{ and } (V_{sc})_{min} \text{ - maximum and minimum operating voltages of super capacitor respectively.}
\]

To demonstrate how the size of the super capacitor can be calculated, let us assume that the safe voltage operating limits of the super capacitor is:

\[
275 < V_{sc} < 375 \tag{1.8}
\]

The size of the super capacitor is estimated in the absence of wind power where the super capacitor provides the rated power of PMSG, \( P_{PMSG} \) (i.e., 250 kW) to mains load for a time-duration, say \( t=10 \) sec. For this condition, the capacitance value of the super capacitor will be as below:

\[
C_{sup} = \frac{2 k_{sup}}{275^2 - 250^2} \approx 70 \text{ F} \tag{1.10}
\]

F. Synchronous Condenser:

In the RAPS system, 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 limitation associated with the inverters. Moreover, the PMSG is fully decoupled from the power electronic arrangement (through rectifier and inverter arrangement). Therefore, the PMSG has no inertia contribution towards the inertial requirement of the entire RAPS system.

To provide enhanced reactive power together with inertial support, a synchronous condenser can be incorporated into the RAPS system. In this system, 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 capacitor is used.

G. 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 thesis, 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.

H. Remote Area Power Supply (RAPS):
Electricity is identified as one key commodity which can be used as a medium for economic growth in rural and regional areas. In these locations, electricity is mainly used for lighting, heating and other household purposes. In addition, it can be utilised for mechanisation of farming operations which increase the economic productivity and strengthen the social cohesion. The RAPS systems are play a vital role to supply power in the remote areas like hills areas.

III. BLOCK DIAGRAM OF THE PROPOSED SYSTEM

Fig. 2: Block Diagram
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 of the RAPS system and to extract the maximum power from wind. To provide enhanced reactive power and inertial support, a synchronous condenser is integrated into the RAPS system.

IV. SIMULATION MODEL AND RESULTS OF STANDALONE WIND POWER HYBRID STORAGE SYSTEM

The simulation results are shown with clear explanation of each graph. Results for output from PMSG wind generator, Energy Storage system waveforms, and load side waveforms are given below. In order to verify the analysis and specification, the simulation investigation is carried out by using MATLAB simulink. The simulation time step used was 10 micro-seconds to capture the true behavior of the system components.

A. Simulated Waveform from Wind Turbine & Generator:
The PMSG based variable speed wind turbine generating system is used in this thesis. The generator output is 225 KW, and voltage and current values is given in the waveforms (i.e. Voltage = 250 V, Current = 900 A).

Fig. 3: Overall Simulation diagram for Energy Management in Variable speed wind generator by Hybrid Energy Storage System

B. Simulated Waveform from AC-DC Line Side-Converter:
The output waveform of rectifier is shown in the figure. This is in the oscillating manner. The smoothing elements are used to rectify the oscillations. The DC side equivalent capacitor is set to 1.8mF. The dc side capacitor is to reduce the oscillations.

Fig. 4: Waveform: (i) Time(s) vs 3 Phase Output AC Voltage = 250 V (ii) Time(s) vs 3 Phase Output AC Current = 900 A

B. Simulated Waveform from AC-DC Line Side-Converter:
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Fig. 5: Waveform: Time(s) vs DC Voltage from rectifier = 450 V
C. Simulated Waveform for Energy Storage System:
Here the Hybrid Energy Storage is used (i.e., Battery and Super capacitor). The super capacitor response waveform is given in Figure 6. During starting the generator starts with low speed rotation of rotor, it shows the under generation condition of the wind generator. Under generating conditions the battery and super capacitors supplies to the system. The super capacitor supply suddenly to system and battery supply slowly. The Energy storage supply response is shown in Figure 6, and Figure 7.

D. Simulated Waveform to be supplied to Remote Area Power Supply (RAPS):
The load regulated voltage is maintained in the range of 415V. In this graph from 0 sec to 2.5 sec time period maintained the generation and load. After that from 2.5 sec to 5 sec the over generation is occurred. During over generation the dump load is activating and to maintain this condition the synchronous condenser also takes place then maintains the balance condition after 2.5sec. The synchronous condenser gives the reactive power support to the system. The normal operating and voltage and current waveforms are clearly shown in Figure 8.

The simulation results of the system are given in this chapter. Thus the results conclude that the designed PMSG based Remote Area Power Supply system with Hybrid Energy Storage system is well suited for the real time applications. The standalone operations of power generation and utilizations the proposed system is well suitable.

V. CONCLUSION
In this paper, the standalone operation of a PMSG with a hybrid energy storage system consisting of battery storage and a supercapacitor, a synchronous condenser and a dump load is presented. 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. 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. The performance of the battery storage is improved with the implementation of the proposed energy management algorithm, as supercapacitor absorbs the ripple or high frequency power component of demand generation mismatch while leaving the steady component for the battery storage. The supercapacitor 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.

REFERENCES


