Modeling of Demand Management for a Wind Battery Powered Micro-grid

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***Abstract*—The wind energy is a clean energy source that is used to meet the electricity needs of consumers from small to large. The nature of intermittency prevents it from being used as a continuous source of energy. The paper presents a solution to this by storing the energy from the wind turbine to a battery and supplying to the dc loads when the energy is not available from the turbine. This paper also incorporates a Demand Management system that manages the prioritized controllable loads. The demand management system is adopted based on the voltage at the dc bus bar. The system has been modeled in MATLAB/Simulink. The proposed system proves to be efficient and economic in providing supply to the connected dc loads. The system is also effective in providing a reliable supply to critical dc loads even if wind is unavailable for long period.**

***Keywords*—Demand Management, Wind Turbine, PMSG.**

I. INTRODUCTION

The popularity of the renewable energy sources has increased much during last decades. The increased popularity is due to the reasons that include depletion of energy sources like coal, natural gas and petroleum and the resulting environmental pollution. A solution is to depend on renewable sources on large scale for the production of energy. The integration of renewable energy with the conventional AD/DC [1, 2] grid is done with the introduction of Micro-grid [3]. The wind energy, which is one among them is available in plenty at free of cost. The ability of the wind energy system to harness energy day and night has made it a superior choice over the solar energy. Several technological and non technological factors also accelerated the development of wind power all over the world that include availability of high strength fiber composites for constructing large low cost rotor blades, falling price of power electronics, variable speed operation of electrical generators to capture maximum energy, short payback period, etc.

Wind energy is the kinetic energy associated with the movement of large masses of air. The kinetic energy depends on wind speed, which in turn depends on environmental factors, humidity, pressure differences, temperature, etc. This makes the nature of wind intermittent.

Complete dependency on wind energy for meeting energy requirement is not effective due to its intermittent nature. A solution is to incorporate storage unit that feeds the loads during the period when the wind is not available. The demand for energy varies from consumers to consumers and from time to time. The increased demand can be suitably controlled and met by incorporating demand management (DM) [4-15] system. DM is a technique in which the demand of the consumers is met by suitably rearranging the loads, without making alterations in the generation side. The demand management is done by setting a set of activities to influence the demand of the consumers. It is adopted on categorized loads based on the priority.

The paper presents design and modeling of a demand management system on a wind energy system incorporating storage units. The storage units are charged and discharged depending on the generation demand gap. The demand management is performed on dc loads that are categorized into critical, variable and dummy loads, based on voltage on dc bus bar. The critical loads are those which should be operated continuously. A variable load can be switched off at any time, whereas, dummy loads are operated when generation is more than the demand. Demand management is made more effective by introducing storage units that charges when generation is greater than demand and discharged otherwise. The modeling of the system is done by using MATLAB/ Simulink [15-17].

II. VOLTAGE BASED DEMAND MANAGEMENT SYSTEM

The wind battery system consists of wind turbine, Permanent Magnet Synchronous Generator (PMSG), rectifier, boost converter, battery and controller. The wind turbine extracts the kinetic energy of wind and converts it to mechanical energy. The PMSG converts the mechanical energy to electrical energy. Due to the intermittent nature of wind, the power output of the PMSG also varies. A regulated 24V DC output is obtained by letting the ac output of PMSG through rectifier, filter, boost converter and a PI controller.

An effective demand management and a continuous supply to the loads can be provided by incorporating storage unit. The mode of operation of battery and controllable loads are based on the dc bus bar voltage which is a measure of generation demand gap.

The block diagram representation of proposed Voltage Based Demand Management System (VBDMS) on a wind battery powered micro grid is shown in Fig. 1. The subsystem included in the block diagram of VBDMS has to be designed and modeled.

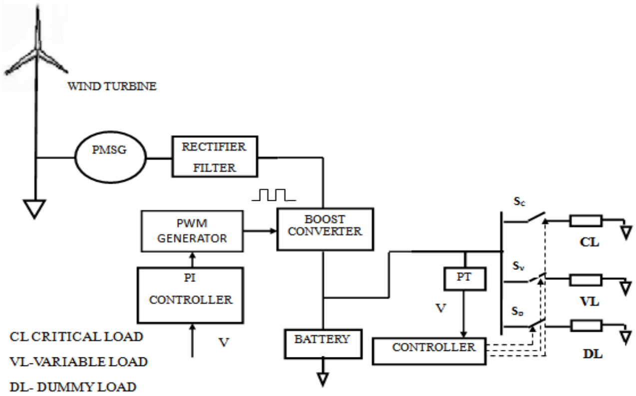

Fig.1 Block diagram representation of proposed VBDMS on a Wind Battery Powered Micro-grid

A. Wind Turbine Modeling

The wind turbine converts kinetic energy of the wind to electrical energy. The wind turbine selected is horizontal axis type with the parameters given in the Table 1. The power output of the wind turbine is given by the equation (1). The blade pitch angle is taken as zero. The turbine [18-22] modeled in MATLAB/ Simulink is shown in Fig. 2 and the subsystem of the same is shown in Fig. 3.

Table 1 Wind Turbine parameter specification

Parameter	Value	Unit
Radius(R)	1	m
Cut -in speed	3	m/s
Rated speed(v)	8	m/s
Air density(ρ)	1.205	kg/m^3
Maximum Performance coefficient(C_{pmax})	0.4412	-
Rated Power	350	W

$$Pw = \frac{1}{2} C_P(\lambda, \beta)\rho A V^3 \quad (1)$$

Cp (λ, β) =Performance coefficient of turbine

$$C_p(\lambda, \beta) = C_P(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-\frac{C_5}{\lambda_i}} \quad (2)$$

$$\frac{1}{\lambda_i} = \frac{1}{\left((\lambda+0.08\beta) - \frac{0.035}{(\beta^3+1)}\right)} \quad (3)$$

λ = Tip speed ratio
β = Blade pitch angle
ρ = Air density(kg/m^3)
A = Area of the turbine (πR^2)
R=Radius of the wind turbine (m)
V=velocity of wind (m/s)

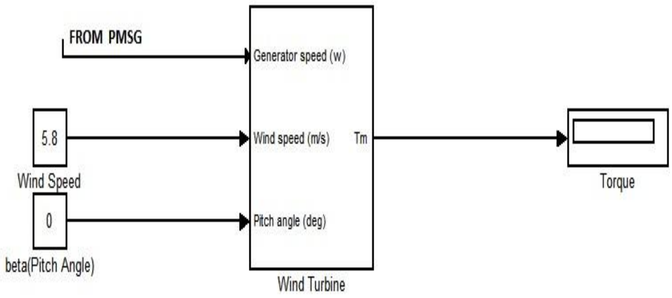

Fig. 2 MATLAB/Simulink model of wind turbine

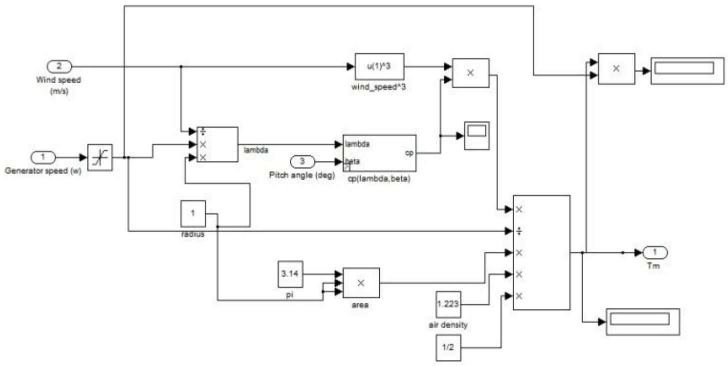

Fig. 3 Wind turbine subsystem

The performance coefficient of the turbine varies depending on the type of the turbine. The coefficients are adjusted to obtain the required performance. The output of the turbine modeled has to be given to a PMSG [23-25].

B. Permanent Magnet Synchronous Generator

PMSG converts the mechanical energy of the wind turbine to electrical energy. PMSG is preferred due to the advantages that include higher efficiency, less maintenance, absence of gear box, less weight of the nacelle. The basic parameters of PMSG are given in Table 2.

Table 2 PMSG parameter specification

Parameter	Value	Unit
Stator phase Resistance	18.7	Ω
Armature inductance	0.02682	H
Pole pairs	6	Nos.
Rated speed	500	rpm
Armature current	1.7	A
Rated torque	9.5	Nm
Rated power	500	W

The MATLAB/ Simulink PMSG model is shown in Fig. 4.

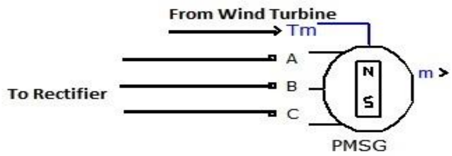

Fig. 4 PMSG model in MATLAB/ Simulink

The output of PMSG has to be given to a rectifier and filter circuit.

C. Rectifier

A three phase diode bridge rectifier converts the ac output of the PMSG to dc. An LC filter reduces the ripples contained in the dc output of the rectifier. The inductor and capacitor values selected are 533μH and 50mF respectively. The rectifier and filter circuit modeled in MATLAB/ Simulink is shown in Fig. 5.

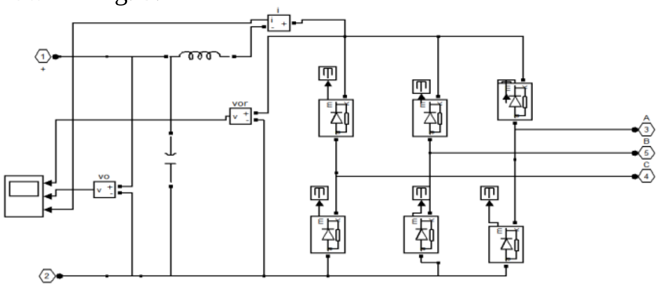

Fig. 5 Rectifier and filter model in MATLAB/ Simulink

As the wind speed keeps changing, the rectifier output continuously varies. A boost converter has to be used to regulate the dc output of the filter.

D. Boost Converter

A Boost converter with a PI controller is designed and modeled to produce a regulated 24V dc. The design of the converter is as follows:

$V_{in} = 14V - 22V$

$V_o = 24V$

$D = 1 - \frac{V_{in}}{V_o}$

$I_L = 1.8A$

$\Delta I_L = 40\% I_L = 0.72A$

Case1: $V_{in} = 14V$

$V_o = 24V$

$D = 1 - \frac{V_{in}}{V_o} = 0.42$

$L = \frac{V_{in}}{\Delta I_L}\frac{D}{f} = 0.4mH$

Case2: $V_{in} = 22V$

$V_o = 24V$

$D = 1 - \frac{V_{in}}{V_o} = 0.0833$

$L = \frac{V_{in}}{\Delta I_L}\frac{D}{f} = 0.127mH$

The selected value of L is 0.4mH.

Fig. 6 shows the MATLAB/ Simulink model of the boost converter along with PI controller.

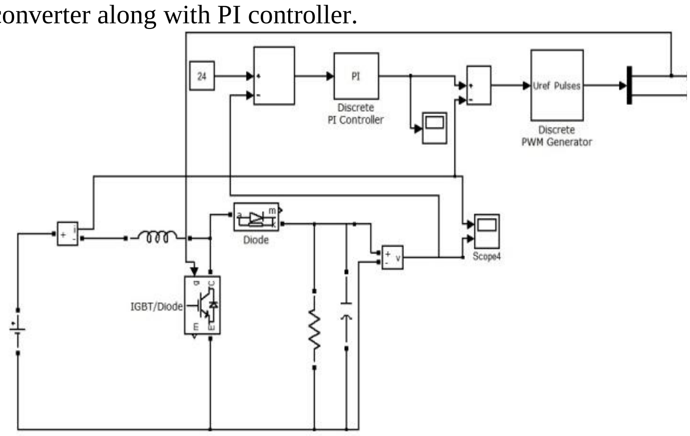

Fig. 6 Boost converter and PI controller model in MATLAB/ Simulink

The PI controller keeps the dc output voltage and inductor current of the boost converter within the limits. At the end of tuning, K_P and K_I values are selected to be 1 and 100 respectively. By proper switching, the boost converter maintains the dc voltage at 24V. The switching is done by means of pulses generated by the PWM generator initiated by the tuned PI controller. The output of the Boost converter is given to a 24 V, 7Ah lead acid battery. The specifications of the battery are given in the Table 3.

Table 3 Lead acid battery parameters

Parameter	**Value**	**Unit**
Nominal voltage	24	V
Rated Capacity	7	Ah
Initial State of charge	20	%
Maximum Capacity	7.35	Ah
Fully Charged Voltage	27.6	V
Nominal Discharge Current	0.7	A
Internal resistance	0.01	Ω
Capacity at nominal voltage	7	Ah

E. Controller

Demand management is performed on categorized load based on voltage of the dc bus bar, a measure of generation demand gap. An increase in demand reduces the bus bar voltage below the specified value of 24 V with a tolerance of ±5% making the specified range of voltage between 22.8V and 25.2V. The loads are categorized as critical load, variable load and dummy load. The switches to these loads are S_C, S_V and S_D respectively. The initial conditions of the loads and the respective switches are given in Table 4.

Table 4 Initial conditions of switches and loads

Load	**Switch**	**Switch position**	**Load operation**
Critical Load	S_C	Closed	Connected
Variable Load	S_V	Closed	Connected
Dummy Load	S_D	Open	Not Connected

The controller is coded such that when the bus bar voltage is greater than 24V, the storage unit is made to operate in Demand Management (DM) mode [26]. The battery is set to operate in Uninterruptible Power Supply (UPS) mode [26] during when the voltage is less than 22.8V. The controller decides whether to on/off the switches such that during the period when the bus bar voltage is greater than 25.2V, all the loads are turned on depending on the requirement. During the period when the bus bar voltage is within the specified range, both critical and variable loads are on. During the period when the bus bar voltage is less than 22.8V, only critical load is connected, which is fed from both wind system and the battery. The proposed Demand Management System provides a reliable and continuous supply, where the critical loads are fed even at no or less wind periods through the battery.

The control algorithm has to be developed that manages various loads so as to maintain the dc bus bar voltage around 24V.

III. Control Algorithm For VBDMS

The algorithm to perform Voltage Based Demand Management for VBDMS integrated on wind powered micro grid is shown in Fig. 7.

STEP 1: Start
STEP 2: Get V, $V_{ref\,1}$ and $V_{ref\,2}$
STEP 3: Compare $V_{ref\,1}$, $V_{ref\,2}$ and V
STEP 4: IF $V < V_{ref\,1}$
S_V is made OFF; GO TO 2
STEP 5: IF $V_{ref\,1} < V < V_{ref\,2}$
IF S_V is OFF, S_V ON; GO TO STEP 2
STEP6: If $V > V_{ref\,2}$
IF S_V is OFF, THEN S_V ON; GOTO STEP 2
ELSE Switch ON S_D; GO TO STEP 2
STEP 7: IF $V = V_{ref\,1}$ or $V_{ref\,2}$
No change; GO TO 2
STEP 8: For V=0; do steps 8 - 9
STEP 9: IF S_V is ON; switch OFF S_V; GO TO STEP 2
STEP 10: Stop

Fig.7 Control algorithm for doing DM in the proposed system

The proposed VBDMS on wind powered micro grid has to be modeled in MATLAB/ Simulink as explained in section II with the controller coded based on the algorithm explained in section III.

III. Results And Discussion

The wind battery power system on which VBDMS is incorporated consists of a wind turbine, PMSG, rectifier, filter and a boost converter with PI controller. The subsystems are designed and modeled as explained in section II. The PI controller is tuned to generate pulses via PWM generator so as to maintain dc bus bar voltage at 24V. The system simulated using MATLAB/ Simulink is shown in Fig. 8.

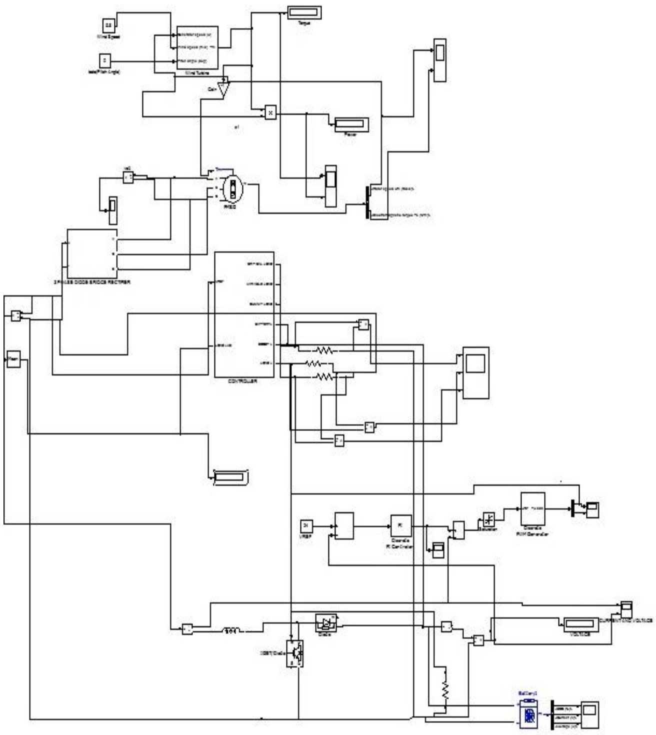

Fig. 8 MATLAB/ Simulink model of the proposed VBDMS on wind powered micro grid

For a wind speed of 10m/s the PMSG output voltage and current waveforms are shown in Fig. 9.

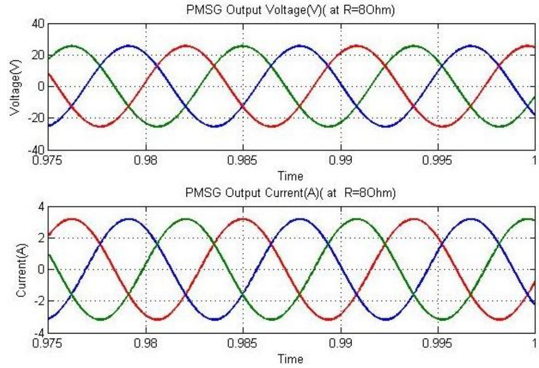

Fig. 9 Voltage and Current waveform of PMSG

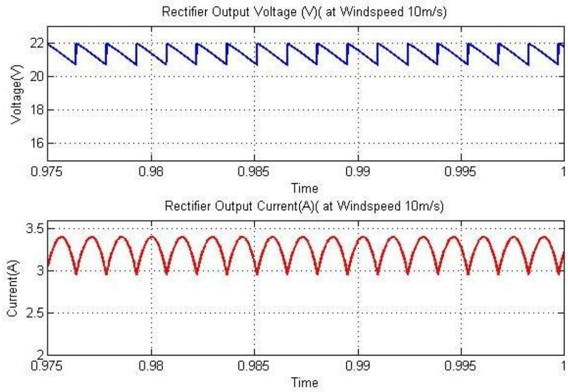

Fig. 10 Voltage and Current waveforms of Rectifier circuit

A ripple free dc output is obtained by letting the output of PMSG to a rectifier and LC filter circuit. Fig. 10 and Fig. 11 shows the rectifier and filter outputs respectively. The ripple free output is fed to the boost converter with PI controller to get a regulated 24V dc voltage, which is fed to the dc loads.

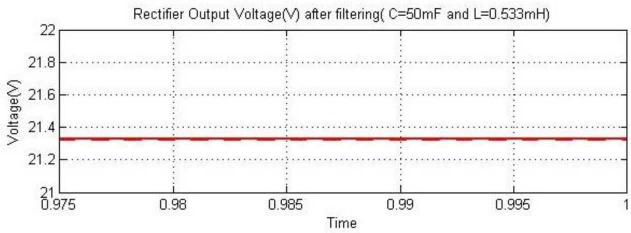

Fig. 11 Output voltage of LC filter

The dc voltage on bus bar depends on the loads connected. The bus bar voltage reduces as connected loads increase and vise-versa. Hence, voltage at the bus bar can be maintained constant by proper management of loads. This calls for the use of DM among the loads that are categorized into critical, variable and dummy loads. The categorized loads are managed based on the dc bus bar voltage. The management of loads requires a micro controller that senses the dc bus bar voltage, compares with the specified value and makes the decision whether to switch on/off the controllable loads.

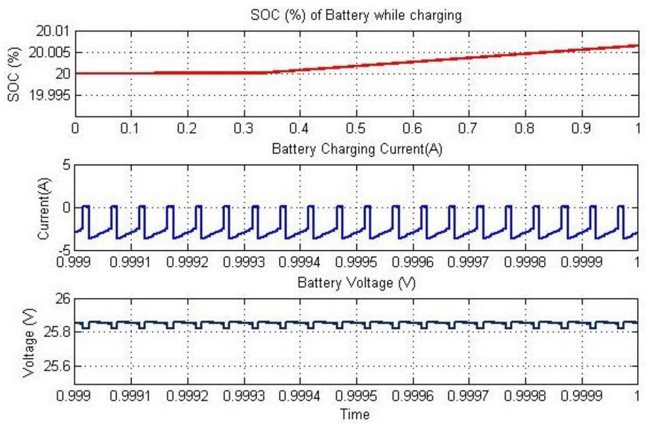

Fig. 12 State of charge, output current and voltage waveforms of storage unit under DM mode

The system also incorporates storage unit thereby increasing the effectiveness of demand management system. The mode of operation depends on the bus bar voltage, which in turn depends on the wind speed. For high wind speed, the dc bus bar voltage is greater than 24V and vise-versa. The controller is coded to be in DM mode [26] during period when bus bar voltage is greater than 24V and in UPS mode [26] when bus bar voltage is less than 24V. The mode of operation of battery unit in DM mode and UPS mode is shown in Fig. 12 and Fig. 13 respectively.

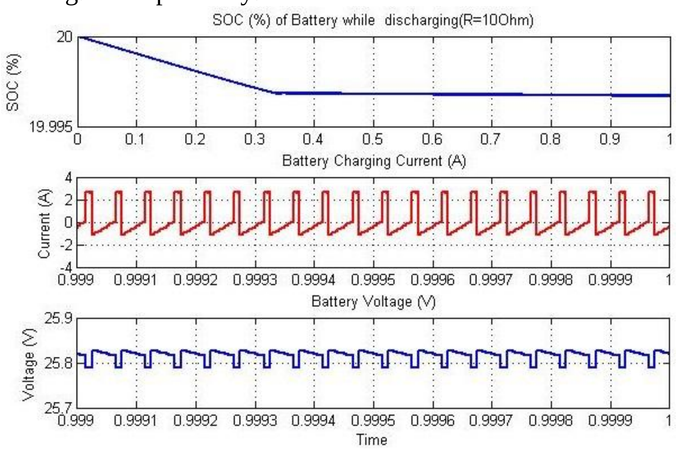

Fig. 13 state of charge, output current and voltage of storage unit under UPS mode

The controller is coded to connect all loads including dummy load during the period when the bus bar voltage is greater than 25.2V. For the bus bar voltage within the specified range, all the loads except dummy load remain connected. For the period when the bus bar voltage is less than 22.8V, only critical load remain connected. For period when wind is absent, all the loads except critical loads are disconnected and the storage unit supplies the critical load. Table 5 shows the output of the proposed VBDMS on wind battery powered micro grid, modeled in MATLAB/ Simulink.

Voltage condition	State of Switch		
	S_C	S_V	S_D
$V<V_{ref1}$	ON	OFF	OFF
Vref1< V<Vref2	ON	ON	OFF
$V>V_{ref2}$	ON	ON	ON
V=Vref1 or Vref2	ON	ON	OFF
V=0	ON	OFF	OFF

Table 5 Table showing the Output of the proposed VBDMS

IV. Conclusion

The paper presents a Voltage Based Demand management System on a wind battery powered micro grid. The system works for wind speed range from cut-in speed to maximum speed. The Voltage Based Demand Management System is done on categorized loads based on the dc bus bar voltage. The controller is coded such that during the period when voltage is greater than 24V, the battery is made to operate in demand management mode. The battery is set to operate in uninterruptible power supply mode during when the voltage is less than 24V, where the critical loads are fed both from the wind system and the storage unit. The proposed Demand Management System provides a reliable and continuous supply, where the critical loads are fed even at no or less wind periods through the battery. The work can also be extended to AC power system, by involving an inverter. A hardware setup can be implemented using dsPIC microcontroller as the controller. The controller can also be coded to control the domestic loads.

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