

## Research Article

### Scalar Controlled Boost PWM Rectifier for Micro Wind Energy Systems

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**Abstract:** Uses of Permanent Magnet Synchronous Generators (PMSG) are increasing in variable speed micro-Wind Energy Conversion Systems (WECS). In stand-alone or grid-connected Micro-WECS, extraction of maximum power is vital. To extract maximum power output and to obtain a constant DC bus voltage from variable magnitude and variable frequency voltage output of PMSG and generally a two stage scheme namely i) conventional diode bridge rectifier and ii) DC-DC Boost/Buck/Buck-Boost converters are used. In this study, a single stage Scalar Controlled PWM (SCPWM) Boost Rectifier is proposed in order to minimize the current harmonics and to improve the power factor on source side. The modeling and simulation of PMSG based wind generator and SCPWM Boost rectifier was developed in MATLAB. The harmonic content in the input current waveform of the proposed SCPWM rectifier is compared with the conventional three-phase bridge rectifier. The Simulation results show the effectiveness of the PWM Boost rectifier in terms of effective utilization of source, improved efficiency and harmonic mitigation for PMSG based Wind Generator. Simulation results demonstrate the effectiveness of the proposed system in reducing the current and voltage THD on source side.

**Keywords:** AC-DC converter, boost PWM rectifier, current harmonics, harmonic distortion, micro-WECS, PMSG

## INTRODUCTION

Growing energy demands, depleting Fossil fuel and rise in fuel cost, environmental issues increases the interest of using Renewable Energy Sources. Use of Wind Energy Conversion Systems (WECS) increases the power quality and stability issues in the power network. This requires intensive research on the modeling of WECS, Power Converters, their control methods. Use of power electronic converters enables the power extraction from wind with good quality and maximizes the output power. Variable speed WECS enable the operation of the wind turbine at its maximum power Coefficient ( $C_p$ ) over a wide range of wind speeds and provide increased energy capture than Asynchronous Generators (Induction Generators). Variable-speed WECS requires power converters for achieving maximum power from the wind turbine and to generate quality power with stability (Kim *et al.*, 2010). PMSG is preferred for small wind power generation less than 100 kW, because of its reliability, high efficiency and low cost (Arifujjaman, 2013).

Generally, a PMSG based WECS consists of an AC-DC, DC-AC power converter and to convert the variable magnitude variable frequency generator output to the fixed frequency fixed grid voltage as shown in Fig. 1 (Xu and Luo, 2009). AC-DC conversion system

consists of two stages namely:

- Diode Bridge Rectifier
- DC-DC Boost Converter

The system efficiency of PMSG with diode bridge rectifier is low because of higher order current harmonics in source side.

In Micro-wind generating system extracting the maximum real power is more important. Most of control techniques employed for variable speed WECS are discussed in the literature is based on Diode Bridge Rectifier (Chen *et al.*, 2009; Urtasun *et al.*, 2013; Rolan *et al.*, 2009). AC-DC rectification systems operate at low power factor and inject significant amount of lower order harmonics into the power system. The adverse effects of low power factor operation and harmonics on the utility are well understood. To mitigate the harmonics and improve power factor, PWM based rectifiers provide better solutions. Most of the control techniques discussed in the literature for PWM rectifiers is based on d-q transformation (Singh *et al.*, 2004; Ametani, 1972). The control signals and digital control algorithm cannot be directly applied to analog controlled system, which is preferred in many low power applications. The analog controller based boost rectifier can be easily implemented for low power end user applications.

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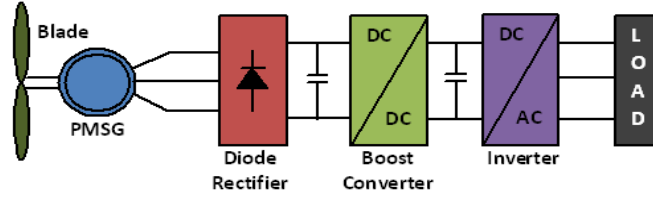


Fig. 1: Typical configuration of PMSG wind energy conversion system

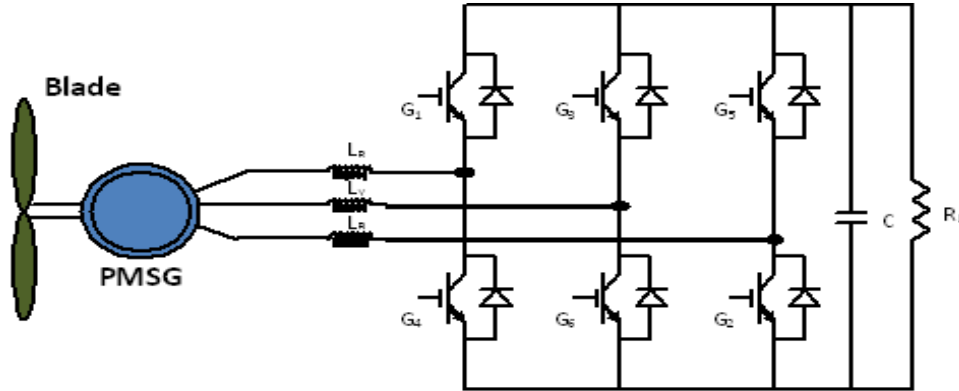


Fig. 2: Scheme of PMSG with PWM boost rectifier

In this study an attempt has been made to improve the PMSG based WECS performance, SCPWM Rectifier is proposed. The proposed method offers the advantages of control simplicity, input voltage sensor less operation and improved system efficiency. The proposed SCPWM Boost Rectifier based PMSG-WECS system is shown in Fig. 2.

### MODELING OF WIND TURBINE

The aerodynamic power converted by the wind turbine is depending on the power coefficient such as (Soetedjo *et al.*, 2011; Aziz *et al.*, 2011):

$$P_t = \frac{1}{2} \rho C_p(\lambda, \beta) \pi R^2 V_w^3 \quad (1)$$

where,  $\rho$  is the air density ( $\rho = 1.225 \text{ kg/m}^3$ ),  $R$  is the blade length and  $V_w$  is the wind speed. The power coefficient is depending on the pitch angle  $\beta$  and the tip speed ratio. The tip speed ratio is given by:

$$\lambda = \frac{\Omega R}{V_w} \quad (2)$$

where,  $\Omega$  is the rotational speed of the wind turbine. The power coefficient is given by the expression:

$$C_p(\lambda, \beta) = 0.5 \left( 116 \frac{1}{\delta} - 0.4\beta - 5 \right) e^{-21 \frac{1}{\delta}} \quad (3)$$

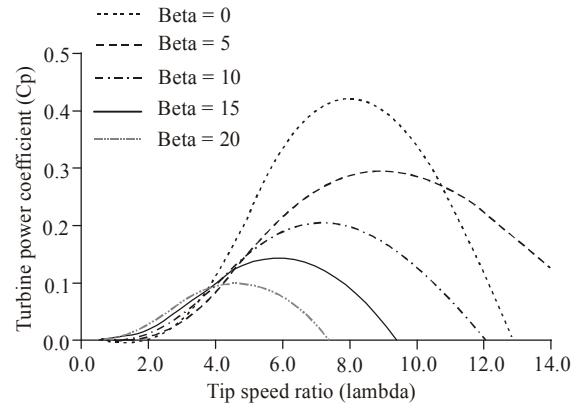


Fig. 3: Tip speed ratio vs. power coefficient at different pitch angles

with,

$$\frac{1}{\delta} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^2}$$

The  $\lambda$  vs.  $C_p$  characteristics of the wind turbine for different pitch angles were obtained from the simulation in MATLAB and is shown in Fig. 3. From the characteristics it is perceived that there exist the maximal value of power coefficient  $C_{p\_max}$  corresponding to the optimal value of the tip speed ratio  $\lambda_{opt}$  for each value of pitch angle  $\beta$ . From Fig. 3 and the nominal tip speed ratio  $\lambda_{opt}$  corresponding to maximum power coefficient of 0.425 for null pitch angle is found to be 7.9. The maximal power can be expressed as:

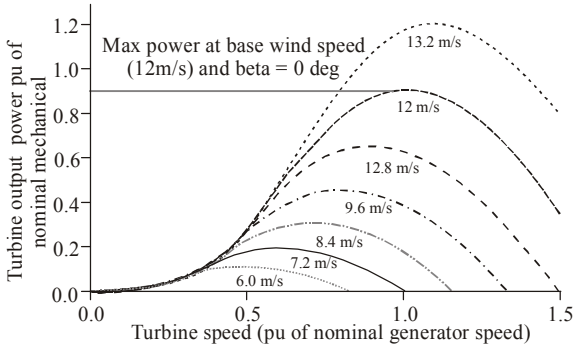


Fig. 4: Turbine power vs. turbine speed at different wind velocities

$$P_{t\_opt} = \frac{1}{2} \rho C_{p\_max} \frac{\pi R^5}{\lambda_{opt}^3} \Omega_{ref}^3 \quad (4)$$

The speed reference for maximizing the power captured by the wind (MPPT strategy) is given by:

$$\Omega_{ref} = \frac{\lambda_{opt} V_w}{R} \quad (5)$$

Form Fig. 4, it is clear that the maximum power can be achieved at different rotor speeds for different wind speeds. The rotor speed is adjusted to achieve the Maximum Power Point operation of the Wind Turbine.

### MODELING OF PMSG

The mathematical model of the PMSG in the synchronous reference frame is given by:

$$\frac{di_d}{dt} = \frac{1}{L_{ds} + L_{ls}} (-R_s i_d + \omega_e (L_{qs} + L_{ls}) i_q + u_d) \quad (6)$$

$$\frac{di_q}{dt} = \frac{1}{L_{qs} + L_{ls}} (-R_s i_q - \omega_e (L_{ds} + L_{ls}) i_d + \psi_f + u_q) \quad (7)$$

where,

$R_s$  = The stator resistance ( $\Omega$ )

$L_{ds}, L_{qs}$  = The inductances of the generator on the d and q axis (H)

$L_{ls}$  = The leakage inductances of the generator (H)

$\psi_f$  = The permanent magnetic flux (Wb)

$\omega_e$  = The electrical rotating speed (rad/sec) of the generator and defined by  $\omega_e = p \omega_m$

where, p is the number of pole pairs of the generator.

The electromagnetic torque of the PMSG is expressed by the following equation:

$$\tau_e = 1.5 p ((L_{ds} - L_{ls}) i_d i_q + i_q \psi_f) \quad (8)$$

Based on the mathematical model, 8.5 kW PMSG was modeled in MATLAB/SIMULINK environment.

### SCALAR CONTROLLED PWM RECTIFIER

The Scalar control based three-phase PWM rectifier is proposed in this study for controlling DC output voltage of PMSG. The primary advantages of the scalar control technique are simple implementation of control algorithm and sensor less input voltage operation. To derive the necessary control equations, conventional three-phase H-bridge configuration is used as shown in Fig. 2. The DC link voltage is maintained at a desired reference voltage by using a feedback control loop. The DC link voltage is measured and compared with a reference voltage  $V_{ref}$ . The error signal is used to generate the switching pulses to turn on and off the six switching devices of the rectifier. The power flow from and to the AC source can be controlled according to the DC link voltage requirements. The three reference current waveforms are generated using the three input source current waveform and the capacitor voltage (Chattoadhyay and Ramanarayanan, 2005; Prasad *et al.*, 1990). The current reference waveforms are compared with the carrier to generate the switching pulses for the converter. The generated three switching pulses are given to the top of the switch gates  $G_1, G_3$  and  $G_5$  in Fig. 2. The complimentary signal is given to the other switches  $G_2, G_4$  and  $G_6$  in Fig. 2. The objectives of the SCPWM converter:

- Sinusoidal input current at Unity Power Factor (UPF)
- Regulation of DC bus voltage and Low harmonic content in input current

The first control objective of getting sinusoidal input current  $i_s(t)$  is achieved by using a current modulator. The second control objective of maintaining constant DC bus voltage  $V_C$  is achieved with an outer voltage controller. The voltage controller is responsible to maintain the power balance between the AC and DC side of the converter. The output of the voltage controller and  $V_m$  commands a particular current from the AC source to meet the load demand on the DC side. The current modulator does the function of maintaining sinusoidal input current in phase with the voltage. The output of the voltage controller  $V_C$  controls the degree of modulation. The modulation technique is based on the concept of resistance emulation (Anand *et al.*, 2004).

**Mathematical model:** The single-phase equivalent circuit of the SCPWM Boost Rectifier is shown in Fig. 5.

On applying volt-second balance on the line inductance (L), the relation between the input voltage  $V_s(t)$  and the DC bus voltage  $V_C$  is given in Eq. (9):

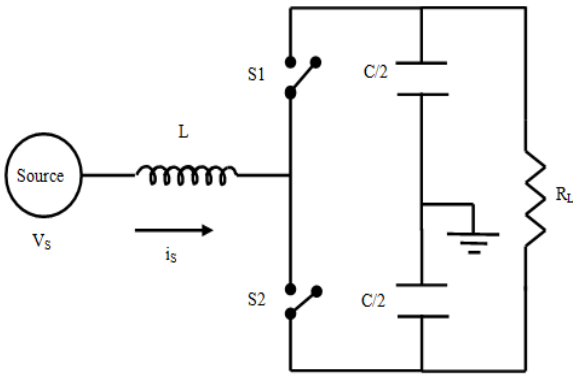


Fig. 5: Single phase equivalent circuit of PWM boost rectifier

$$V_s(t) = \frac{V_c}{2} [1 - 2d(t)] \quad (9)$$

where,  $d(t)$  is the duty ratio of switch S2 shown in Fig. 4. The control desires that the input current and  $i_s(t)$  to be in phase with the input voltage  $V_s(t)$  and emulate a resistance. The emulated resistance  $R_e$  indicates the amount of power drawn from the source:

$$V_s(t) = i_s(t)R_e \quad (10)$$

From Eq. (9) and (10), the duty ratio is obtained as:

$$d(t) = \frac{1}{2} - \frac{i_s(t)R_e}{V_c} \quad (11)$$

Equation (11) is modified in terms of the control variable as:

$$d(t) = \frac{1}{2} - \frac{i_s(t)R_e}{V_m} \quad (12)$$

where,  $R_e$  is the current sense resistor and  $V_m$  is the output of the voltage controller. By varying the duty ratio of the switches as per the modulation law given in Eq. (12) and sinusoidal input current at UPF can be achieved. In the proposed scalar control, the modulation law is implemented without using transformations, resulting in minimum computation. The current waveform follows the voltage waveform as per the principle of resistor emulation law and responds to frequency components present in the voltage. The control block diagram of the scalar control based three-phase boost rectifier is shown in Fig. 6. The output of the voltage controller is given to the input of current modulator. The output from the current modulator is used as a current reference and the pulses are generated by comparing with carrier signal. The signals associated with switching pulse generator are shown in Fig. 7.

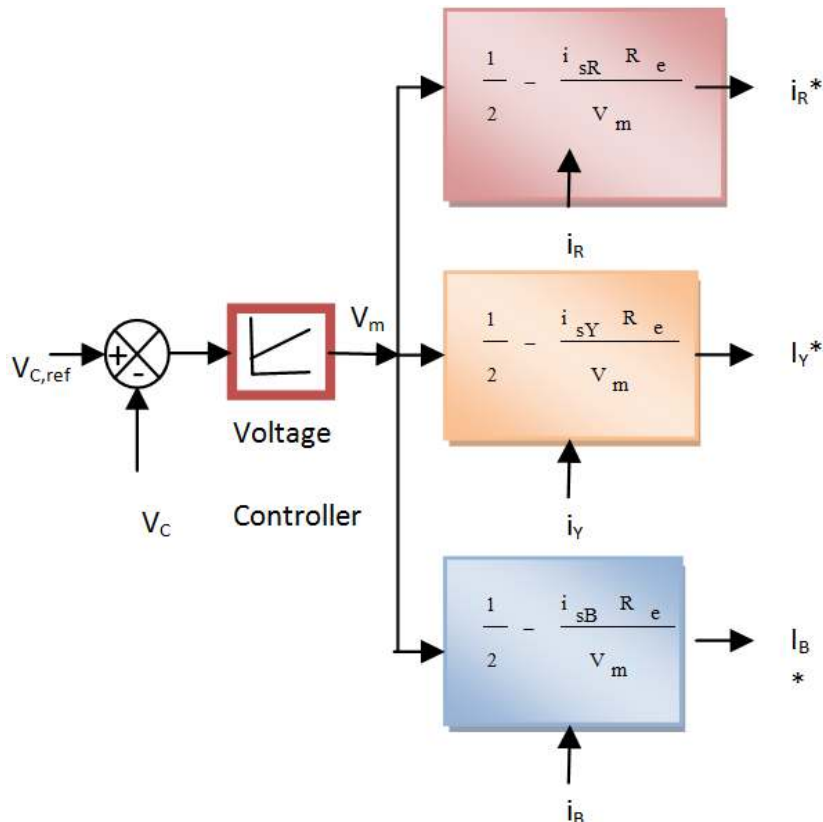


Fig. 6: Control structure for scalar controlled PWM boost rectifier

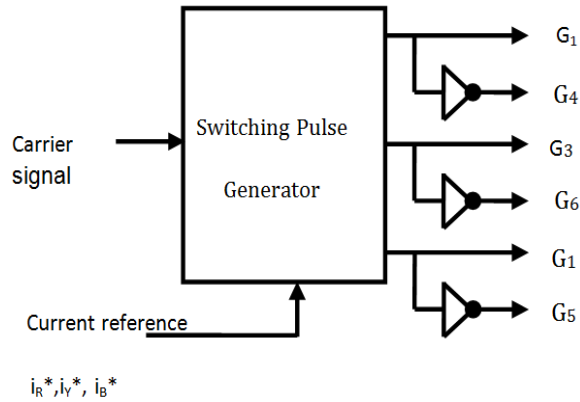


Table 1: System parameters

Parameters	Value
Power rating of PMSG	8.5 kW
Stator resistance	0.425 Ω
Stator inductance	0.833 mH
Number of poles	10
DC link capacitor	1650 μF
Boost inductor	15 mH
Carrier frequency	10 kHz
$V_{DC,ref}$	510 V

Fig. 7: Block diagram of PWM pulse generator

MATLAB. Simulation studies are carried out using the system parameters given in Table 1.

To investigate the performance of PMSG with diode bridge rectifier and SCPWM rectifier the following parameters are considered:

### RESULTS AND DISCUSSION

In order to find the performance of the PMSG with SCPWM rectifier the test system is compared with the conventional single stage diode bridge rectifier based system and the test systems are simulated using

- Source current THD
- Source voltage THD
- DC bus voltage magnitude
- Output real power

To identify the system frequency the test system is simulated with the balanced resistive load. The

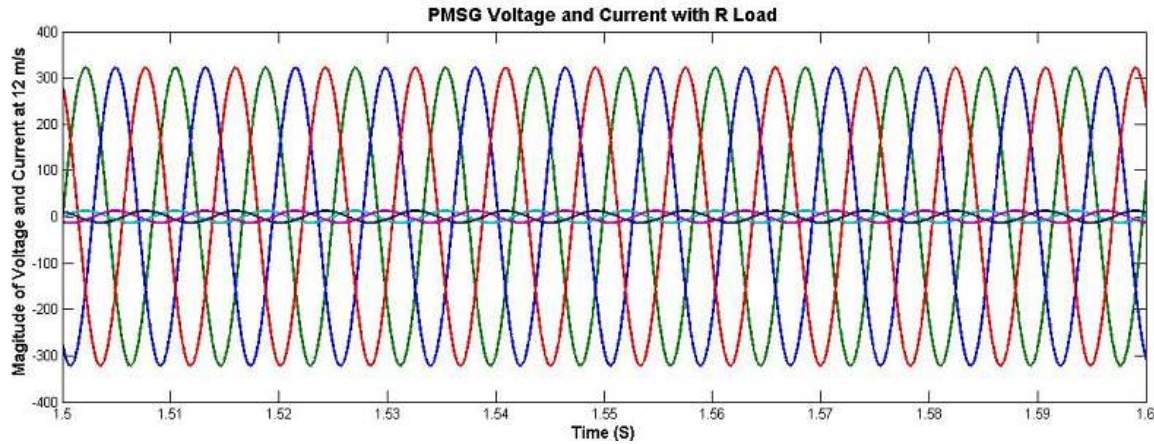


Fig. 8: Three-phase voltage and current waveform of PMSG with R load

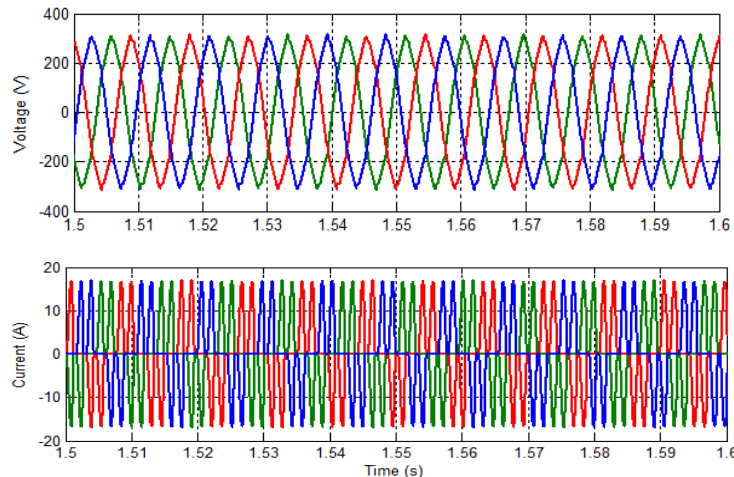


Fig. 9: Three-phase voltage and current waveform of PMSG with diode bridge rectifier

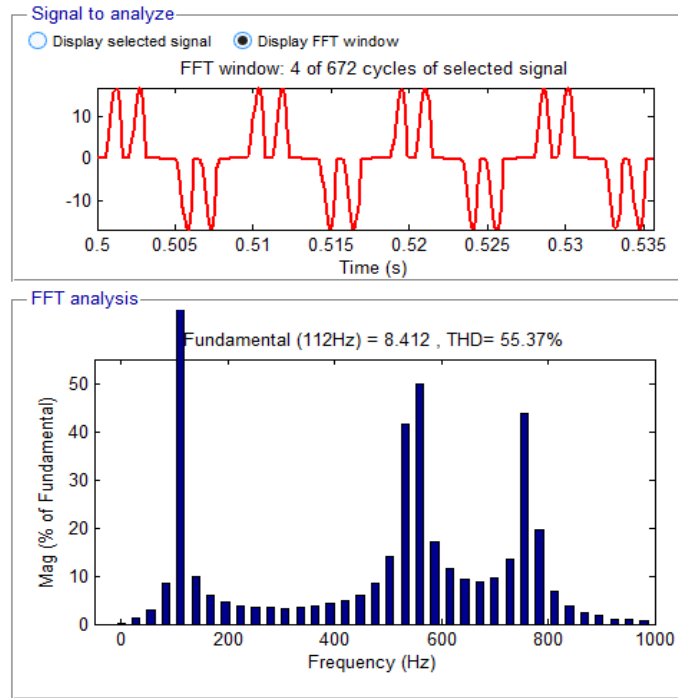


Fig. 10: R-phase PMSG source current waveform and its THD spectrum with diode bridge rectifier

Table 2: THD performance comparison with diode bridge rectifier and SCPWM rectifier

Method of conversion	Voltage % THD			Current % THD		
	$V_R$	$V_Y$	$V_B$	$I_R$	$I_Y$	$I_B$
With diode bridge rectifier	4.7	3.1	3.1	55.4	56.7	56.7
With boost PWM rectifier	1.2	1.3	1.3	3.4	4.1	4.0

corresponding three-phase voltage and current waveforms are shown in Fig. 8. It is found that PMSG is generating pure sinusoidal output when R load is considered and the system frequency is 112 Hz at 12 m/sec wind speed. Under this condition, the rms value of the output phase voltage is found to be 210 V.

To investigate system with different converters, wind speed is considered as 12 m/sec and the DC side load resistor is considered as 60  $\Omega$ . The voltage and current waveforms of PMSG with diode bridge rectifier are shown in Fig. 9. The R-phase current waveform and its corresponding THD spectrum are plotted using the power GUI tool in MATLAB, which is shown in Fig. 10. It shows that the source current is completely non-linear and the THD value is 55% of its fundamental. Due to this non-linear current flow from the source, the voltage waveform is also distorted and its corresponding THD value is shown in Table 2. The DC bus average voltage is constant but the value is only 487 V. The result shows that the source current harmonics affects the performance of PMSG in reducing the real power output and consequently reduces the efficiency of the system. The above analysis clearly indicates that WECS with the diode bridge rectifier, the real power output will reduce due to the distortion power in source side.

Further to compare, the performance of the PMSG based WECS system with SCPWM rectifier, the test system is simulated using the same dc side load. The output voltage and current waveforms are shown in Fig. 11. The PMSG based WECS with PWM rectifier the R-phase source current THD is 3.4% and the corresponding THD spectrum is shown in Fig. 12. It shows that the source current THD value is drastically reduced by using the PWM rectifier. This study clearly demonstrates the effectiveness of the proposed PWM rectifier topology in PMSG system. Further and the PWM based PMSG system's real power values are compared with the conventional diode bridge rectifier based system. The test result shows that the real power output for the same load is 4335 W. Using the PWM rectifier the dc bus reference voltage is considered as 510 V, so the output DC voltage is tracking the reference closely. In this case, to maintain the output DC voltage as 510 V the source real power output is increased by 9% compared to conventional rectifier.

Further to investigate the proposed system with variable wind input power the test system is simulated by varying the input power with step variation of wind speed at 0, 2 and 4 sec of magnitude 12, 11 and 12 m/sec, respectively. Under the variable input condition the PMSG with conventional diode bridge rectifier and SCPWM rectifier are analyzed.

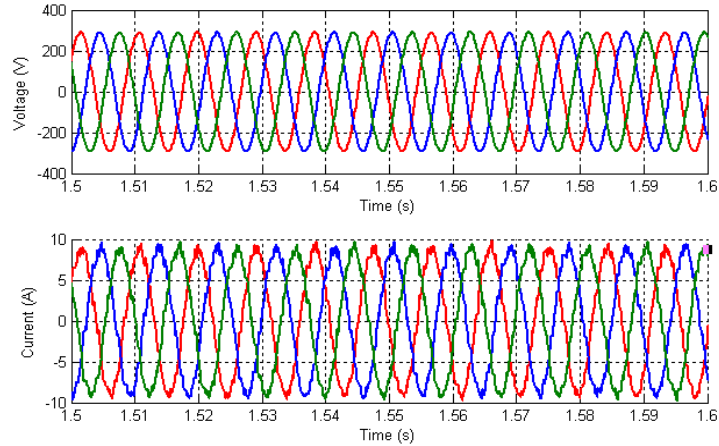


Fig. 11: Three-phase voltage and current waveform of PMSG with SCPWM rectifier

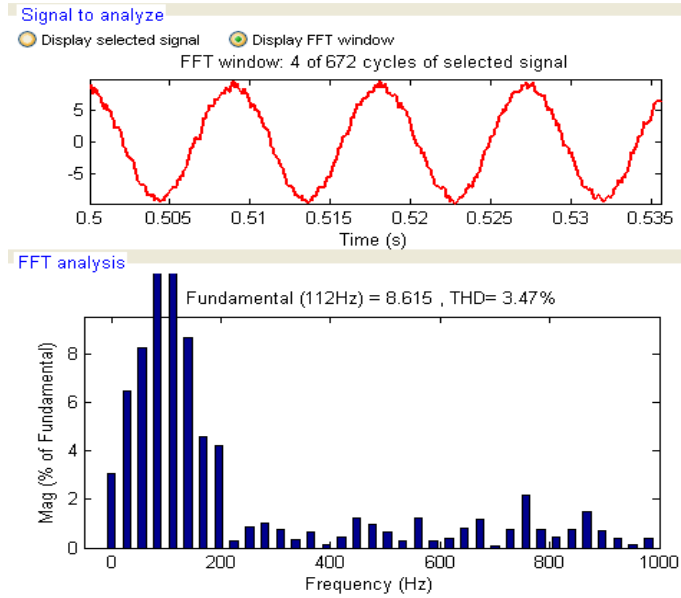


Fig. 12: R-phase PMSG source current waveform and its THD spectrum with SCPWM rectifier

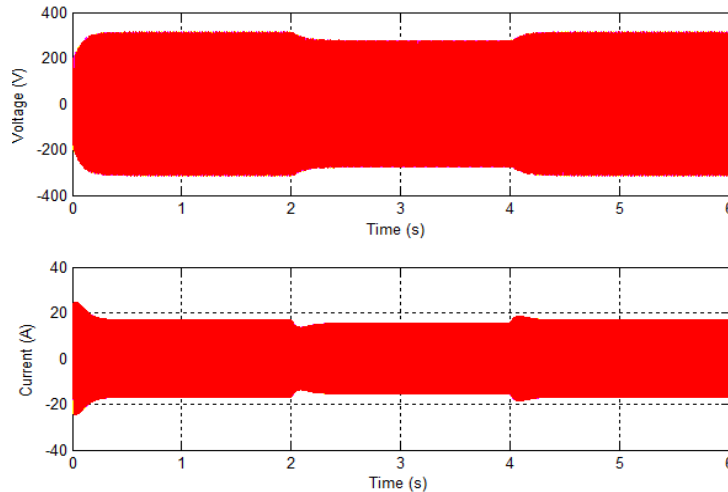


Fig. 13: Three-phase voltage and current waveform of PMSG with diode bridge rectifier

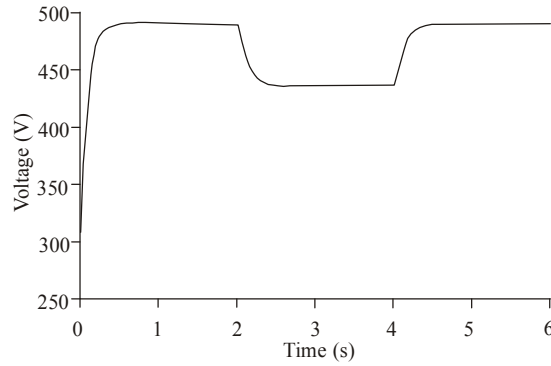


Fig. 14: DC output voltage of diode bridge rectifier

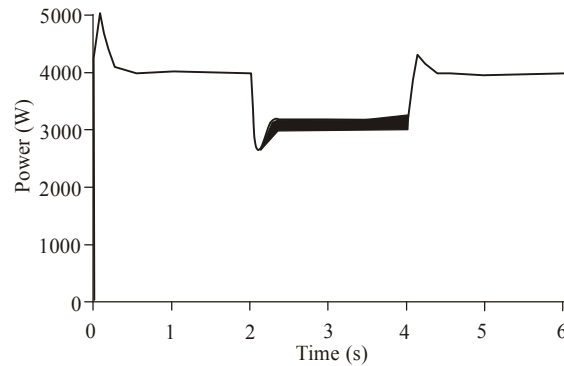


Fig. 15: Real power of PMSG with diode bridge rectifier

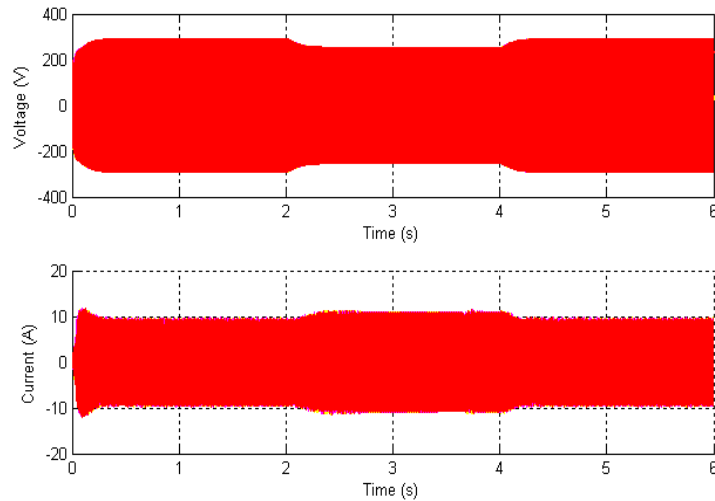


Fig. 16: Three-phase voltage and current of PMSG with SCPWM rectifier

When wind speed is 11 m/sec, the rms value of PMSG output voltage is decreased to 195 V and it is shown in Fig. 13. The dc bus voltage variation is shown in Fig. 14. The result shows that when the wind speed is varied from 12 to 11 m/sec the rectifier output voltage is varied from 487 to 434 V and the corresponding real power output from the generator is varied from 3950 to 3139 W. Under the variable wind input condition, the PMSG output power variation is also plotted and it is shown in Fig. 15. To get constant DC voltage from the

variable AC output it is necessary to use DC-DC converter topologies. It is another one major drawback of using diode bridge rectifier based WECS topology.

To investigate the proposed SCPWM Boost Rectifier based PMSG-WECS system under the variable wind speed conditions the same test system is considered. Under variable wind speed condition the PMSG output voltage and current waveforms are shown in Fig. 16. The dc bus voltage under variable wind input is shown in Fig. 17. The DC bus voltage is



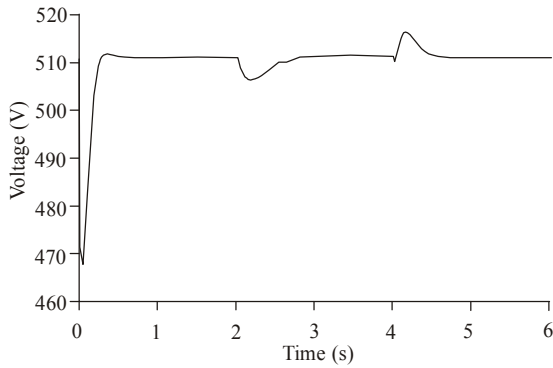


Fig. 17: DC output voltage of SCPWM rectifier

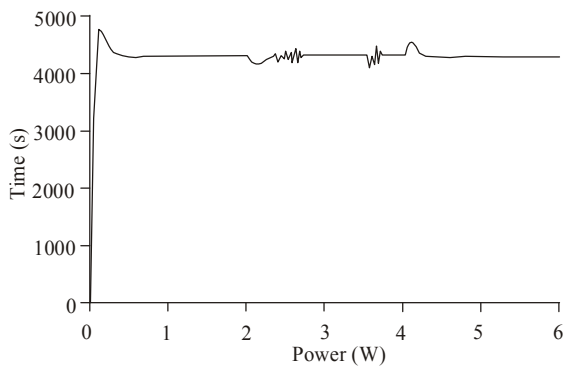


Fig. 18: Real power of PMSG with SCPWM rectifier

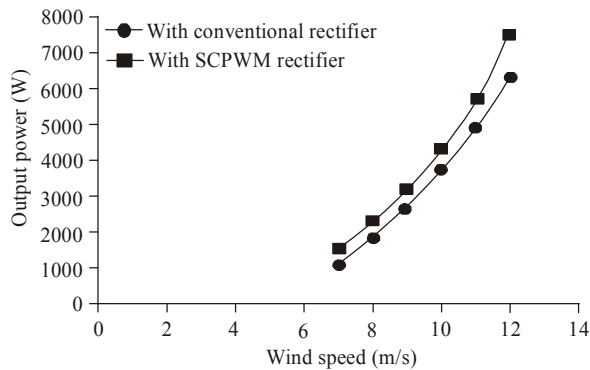


Fig. 19: Comparison of PMSG output power

maintained as constant irrespective of the variable wind speed. It shows that without using a separate DC/DC converter, the DC bus voltage is maintained constant effectively. With the proposed SCPWM rectifier the output voltage magnitude is decreased when the input power is decreased from 12 to 11 m/sec but the input current is increased during this period to maintain the dc bus voltage as constant. Even under variable wind input condition, the percentage of current THD is below 5%. It is well below the IEEE-519 standard. The real power output is also shown in Fig. 18. The above analysis shows that for the constant load with variable

wind source condition the output power maintained as constant.

In Table 2 Voltage THD and Current THD of PMSG with Diode Bridge Rectifier and with SCPWM Boost Rectifier is listed. It is found that the Current THDs are reduced well below 5% in all phases in the proposed method. Further the test system is simulated to compare the performance of the proposed system with variable load condition. The output power with conventional and SCPWM rectifier at different wind speeds is shown in Fig. 19. The test result shows that under all variable wind input conditions and the output power of SCPWM rectifier based WECS is more than that of conventional rectifier and also it tracks near to its corresponding maximum power output. This analysis clearly indicates that the SCPWM rectifier reduces the source current harmonics and so increases the efficiency by increasing the real output power of PMSG and maintains the constant DC voltage at the output.

### CONCLUSION

In this study modeling and simulation of 8.5 kW PMSG based WECS with SCPWM Boost Rectifier was modeled in MATLAB. The proposed model is investigated with single stage conventional diode bridge rectifier and SCPWM rectifier with constant and variable wind speed conditions. The results show that the SCPWM rectifier based WECS require only one conversion stage to get constant DC output voltage. Using the proposed PWM rectifier by reducing the current THD and voltage THD the system efficiency is improved. In micro-grid distributed generation system, the proposed PWM rectifier control algorithm can be easily implemented using analog controls. The simulation results demonstrate the effectiveness of the SCPWM rectifier in terms of reducing the current THD, increasing the system efficiency and maintaining the Constant DC output voltage.

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