PMSG Based Wind Energy Conversion System Containing Reactive Power Control Scheme

[1]Ziyaulhaq Bokda, [2] Prof. Manish Pandya
[1]M. Tech Research Scholar, [2]Associate Professor, PIET, Vadodara
[1]Parul Institute of Engineering & Technology,
[1]Parul University, Vadodara, India

Abstract: This paper shows the working of a reactive power management technique for network connected PMSG based wind power system with unification of WPCS to the grid-network through 3-phase AC-DC-AC converters PWM voltage source converters in order to organize volatile speed functioning of PMSG with independent reactive power support. This system is an irregular speed scheme which for PMSG. Control of the generation side converter works for control of active power or fetching best possible Power of the machine while controlling of the output side converter maintains the voltage at the DC link at constant value and it also supplies the control of reactive power to the grid. At the end, Simulink/MATLAB model run for MPPT control on machine side. Voltage control at DC-link and reactive power restrains on grid side. At last, the outputs define that the controllers are able to fetch maximum power and control the reactive power of wind generation under different wind and load conditions. Simulation was performed with a 2.68 kW DD-WT based wind energy generation system.

Index Terms- **Direct Driven Permanent Magnet Synchronous Generator (DD-PMSG), Grid side converter (GSC), Machine side converter (MSC), Wind Turbine(WT), Wind Energy Conversion System (WECS), Back to back converter (BTB), Maximum Power Point Tracking (MPPT), Reactive power control, Variable speed wind turbine.**

I. INTRODUCTION

Among the various resources of renewable energy, wind power sector achieved most rapidly growing sector in recent times. Wind generation system is a vital area to reducing carbon emissions. Currently, through gigantic growth in wind power generation, wind power effortlessly adapted to energy form by using of wind turbines. [1]. But, the existence of gearbox in WT that pairs the turbine to the PMSG makes difficulties. The gearbox often affected by significant problems, needs repairs and drops the total productivity of whole the system [2], [14].

PMSG has been utilized mostly in the wind power area because its benefits over others [3]. Monitored reactive power, half-scale converter and various ride through competencies are studied the prime benefit of this generation scheme [4]. Day by day, the progress in bulky wind power ability, larger the power concentration, necessity of better reliability and bad LVRT capacity of the half-scale converters, various kinds wind power schemes established.

The DD- PMSG is able to increase the reliability of wind power system. As it is beneficial to others, DD-PMSG met further interest in the current time [5]. it has additional benefits over other formations of wind energy production system like excessive power density, reduced losses, better productivity, low repairs rate there is no gearbox, slip rings and full-controlled power converters who enhances the grid capability. Direct drive functioning can be attained with noiseless operation.

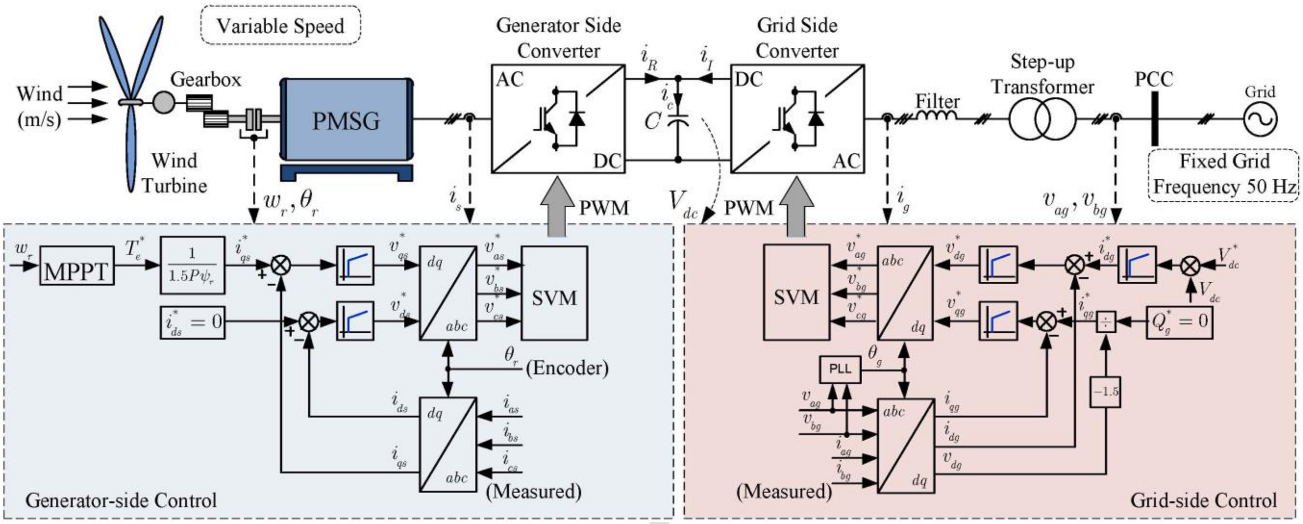
Using PM in the generator rotor makes the influencing current supply through the stator needless for regular air-gap flux. The current that is in the stator essential for barely generating the torque in PMSG. Hence, for the similar output, the machine will work with better power factor and will be better over other generators.

Some Scholars are working to develop various schemes for MPPT control of PMSG so that best possible power can be transmitted to DC Link from the source of the system. Various kinds of regulation techniques like duty cycle scheme, optimum relationship-based method, look-up table for maximum speed of machine rotor, optimal control of the torque and power, optimal TSR, Perturb & Observe and peak climb searching control etc. suggested for optimum wind energy generation. To fetch the best possible output from flexible wind velocity operation in WECS is essential. The general control schemes of maximum power chasing needed to attain optimal wind power consumption.

The DD-PMSG, based wind power system contains a machine coupled directly to wind turbine. The machine stator coupled to the full scale AC-DC-AC converter and VSC is linked to the power grid/loads to acquire the amplitude and frequency necessities. Wind power system with BTB converters chosen nowadays, as the power converters fully delinked the generation from grid disturbances.

In this paper, simulation of the WT and generator have been done in Matlab/Simulink. For irregular speed generation system, a voltage based control scheme with regular PI is applied to chase the optimal power from wind. PWM scheme applied to maintain the input side converter and control of the BTB converter is also modelled in Matlab/Simulink [6]. The control of load side converter is described and simulated through Simulink. The control of DC link voltage has applied through PWM load side inverter.

II. PMSG MODEL AND CONTROL



A voltage source converter based PMSG wind turbine have few parts i.e. a direct-driven WT, a PMSG, and converters as shown in Fig. 1 [7], [14]. In the WECS, the turbine draws wind power which supplied to the PMSG. A completely controlled

Figure 1 Representation of PMSG based WECS with BTB converter control

converter interfaced among generator and grid to decouple them. SPWM scheme applied for switching the BTB converters: a generator side converter, and a load side inverter, having voltage at dc link voltage amongst it [8], [9].

The generator control system has two segments: the PMSG and the WT part. At the PMSG side, BTB converters are regulated by the regular control theme. The generator side converter is regulated by means of speed adjustment to fetch the optimal power production from turbine.

Conventional Proportional and Integral control applied to produce torque reference. The GSC sustains the voltage at dc-link unvarying and maintain the reactive power. At the generation part, a speed controller and a torque controller applied. Here, at minimal wind flow velocity, the speed controller offers a power or a torque constant at the generator side controller founded over MPPT. The power controller rises or cuts the pitch angle of turbine blades for the purpose of protection of the WT over evaluated power at huge wind speed conditions [11], [21].

III. MODEL OF PMSG WIND TURBINE

3.1 Shaping the Wind Turbines

The WT power dragged by a turbine is stated by the following equation [14].

$$P_m = 0.5C_p(\lambda, \beta)\, \rho_{air} A_{blade}\, v^3{}_{wind} \qquad (1)$$

Here P_m is mechanical power related to the power fetch from the wind by blades, C_p, is the power coefficient and ρ_{air} is density air in kg/m^3 which is about 1.225 kg/m^3, A_{blade} gives the covered area by blades of the rotor [m^2] and v_{wind} is the speed of wind (m/s).

The C_p is a related with the pitch angle β and of the TSR (λ) . The TSR λ is the ratio of tip speed of blade and v_{wind} value, given by

$$\lambda = \frac{\omega_m \cdot R}{v_{wind}} \qquad (2)$$

In this Equation, R is the blade radius and ω_m is the rotor speed. The C_p displays the power fetching efficiency of the WT. It is a nonlinear link to λ and the pitch angle. The max calculated value of power coefficient is 0.59, but practically it lies around 0.4 to 0.45. There are many equations for power coefficient in different literatures. One of them used to model Cp (λ, β) and based on the modelling the WT characteristics. The Cp (λ, β) expressed through TSR and the pitch angle.

$$C_p(\lambda, \beta) = c_1\left({c_2}/{\lambda} - c_3\beta - c_4 \right) e^{-c_5/\lambda} + c_6\lambda \qquad (3)$$

$$\text{And,} \quad \frac{1}{\lambda} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \qquad (4)$$

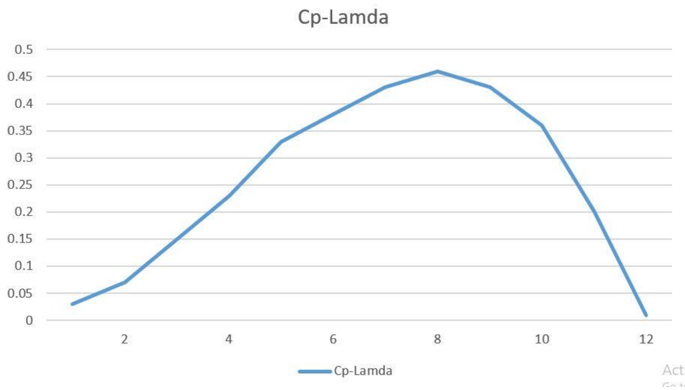


Figure 2 Cp by λ curve

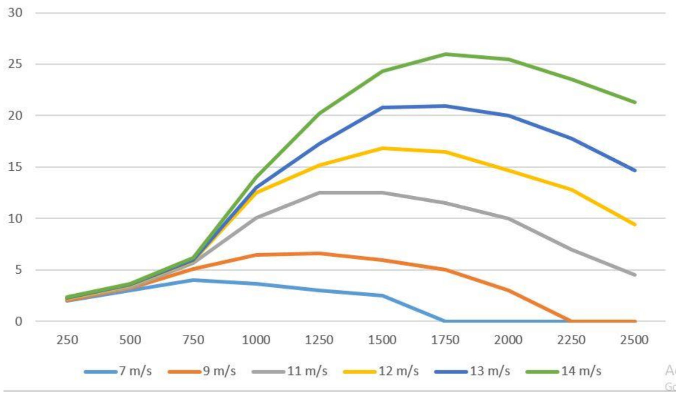


Figure 3 Turbine power vs speed characteristics

The values of constants c1 to c6 are defined as C1=0.5176, C2=116, C3=0.4, C4=5, C5=21 and C6=0.0068. The optimal power is calculated by the coefficient C_p if wind speed v_{wind} is known. Generally, the C_p is related with λ which expressed in equation (3).

The WT graphs of Pm to power coefficient and TSR and Turbine power by speed curves as shown in Fig. 2. And above statement describes the values of the C_p constants. The WT power is found by the C_p and TSR for fixed value of the blade covered area, air density, and wind speed. The power conversion coefficient and the TSR depend on the aerodynamic curve of the WT. The optimum turbine power lies at a point of λ_{opt} and C_{pmax} as shown in Fig. 3.

3.2 Modeling of PMSG

The equations for voltage at stator transient using generator convention in the synchronous reference frame are,

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = -R_s \begin{pmatrix} i_d \\ i_q \end{pmatrix} - \frac{d}{dt}\begin{pmatrix} \psi_d \\ \psi_q \end{pmatrix} + \omega_e \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \psi_d \\ \psi_q \end{pmatrix} \qquad (5)$$

where R_s is the resistance of stator winding, V_d, V_q, i_d, i_q, ψ_d and ψ_q are the stator voltages for direct and quadrature axis components, current of stator and flux of generator. If the rotor flux is aligned with d-axis then the stator flux linking shown follows,

$$\begin{pmatrix} \psi_d \\ \psi_q \end{pmatrix} = \begin{pmatrix} \psi_f \\ 0 \end{pmatrix} + \begin{pmatrix} L_{ls} + L_{dm} & 0 \\ 0 & L_{ls} + L_{qm} \end{pmatrix}\begin{pmatrix} i_d \\ i_q \end{pmatrix} \qquad (6)$$

Here ψ_f gives flux linkage which is formed by the permanent magnet of PMSG, leakage inductance L_{ls}, L_{qm} and L_{dm} are quadrature axis and direct axis mutual inductances. The electromagnetic torque equation is as below:

$$T_e = \frac{3}{2}P\left(\psi_d i_q - \psi_q i_d\right) = \frac{3}{2}P\left(\psi_f i_q + \left(L_d - L_q\right) i_d i_q\right) \qquad (7)$$

If P is the pair of pole of generator, $L_d = L_{ls} + L_{dm}$ and $L_q = L_{ls} + L_{qm}$. in steady-state, voltage equation for stator is as follows,

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = \begin{pmatrix} 0 \\ \omega_e \psi_f \end{pmatrix} + \begin{pmatrix} -R_s & -\omega_e L_q \\ \omega_e L_d & -R_s \end{pmatrix}\begin{pmatrix} I_d \\ I_q \end{pmatrix} \qquad (8)$$

Direct axis and the quadrature axis steady-state currents are given by eqn. (9) and (10) from the eqn. (8).

$$I_d = (V_q - \omega_e \psi_f)/(\omega_e L_d) \qquad (9)$$

$$I_q = -V_d/\omega_e L_q \qquad (10)$$

For, Non-salient pole generator, inductances of the direct and quadrature axis are same ($L_d = L_q = L_s$). The T_e of the PMSG is given by

$$T_e = \frac{3}{2}P\psi_f i_q \qquad (11)$$

It means that PMSG torque be upheld by controlling q-axis component of the stator. For the optimum output torque and best competence, current at the d-axis is taken zero.

IV. CONVENTIONAL CONTROL OF MSC

The generator side control of the PMSG is regulated the torque of the generator reactive power based on current control of stator. The conventional control technique having layered-loop with faster inside hoop, The stator direct and quadrature axis current and slower external hoop for torque/stator control. The quadrature axis loop is for WT power/torque regulation and the d-axis loop is for other control like optimum proficiency. The control method of inner circle is;

$$V_d = -\left(R_s i_d + L_d \frac{di_d}{dt}\right) - \omega_e L_q i_q \tag{12}$$

$$V_q = -\left(R_s i_q + L_q \frac{di_q}{dt}\right) + \omega_e L_d i_d + \omega_e \psi_f \tag{13}$$

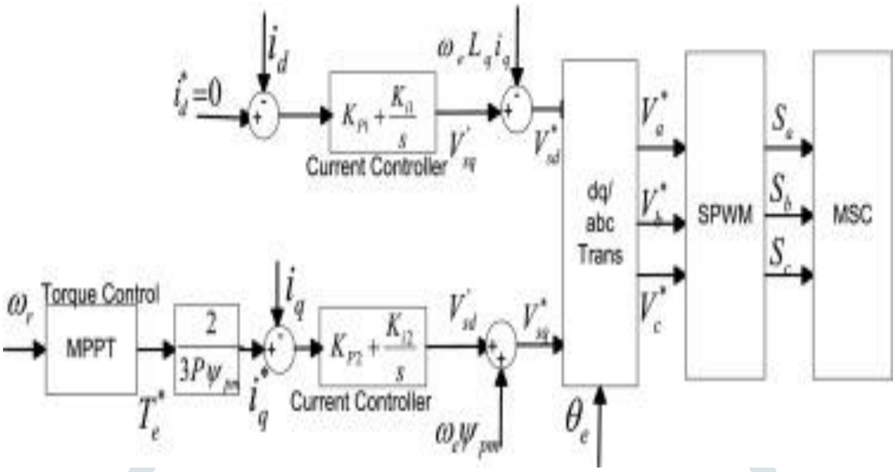


Figure 4 Vector control of MSC

The 1st span of equations (12) and (13) shows that stator d-q axis currents maintained by regulating the direct and quadrature axis voltages, and the second part denotes the compensation terms. The block diagram of the control of machine side converter is shown in Fig. 4. The MPPT is applied to produce the reference generator power of electromagnetic torque based on generator speed. Below the speed of PMSG β is maintained to reference value zero and WT speed is moved in according to uneven wind speed like that the λ (TSR) is maximum. The base power is calculated from generator speed ω_m.

The MPPT is applied from the P_t-ω_m curve. Stator direct axis reference current is taken zero while stator q-axis reference current is estimated from base electromagnetic torque. The $i^*{}_d$ and $i^*{}_q$ matched with measured i_d and i_q respectively which evaluate the error. Conventional PI controller is applied to overcome this error. Output of this PI controller is the expected direct and quadrature axis voltage $V'{}_d$ and $V'{}_q$ respectively. After compensation, projected direct and quadrature axis base voltages $V^*{}_d$ and $V^*{}_q$ is transformed to abc frame and then SPWM applies switching to MSC. PI controllers has some problems like compensation terms required the generator parameters and rotor speed. plus, tough to balance the parameters and inadequate to handle the system nonlinearity.

V. CONVENTIONAL CONTROL OF GSC

5.1 GSC Modelling

The dc-link capacitor amongst machine side converter and load side converter, three-phase voltage source inverter work as the voltage at the PCC in the WPS shown in Fig. 1. The voltage stability through the grid filter is;

$$\begin{pmatrix} V^*{}_{Gd} \\ V^*{}_{Gq} \end{pmatrix} = R_f \begin{pmatrix} i_{Gd} \\ i_{Gq} \end{pmatrix} + L_f \frac{d}{dt} \begin{pmatrix} i_{Gd} \\ i_{Gq} \end{pmatrix} + \omega_G L_f \begin{pmatrix} -i_{Gq} \\ i_{Gd} \end{pmatrix} + \begin{pmatrix} V_d \\ V_q \end{pmatrix} \tag{14}$$

Where ω_G is the grid frequency,$V_{d,}$ $V_{q,}$ $V^*{}_{Gd}$ and $V^*{}_{Gq}$ are the VSI and PCC voltages, respectively, i_{Gd} and i_{Gq} are current components passing through VSI and grid, L_f and R_f are the inductance and resistance of filter[12][13].

In the PCC voltage frame. The rapid active and reactive powers on the load side are relative to the direct and quadrature axis current of the grid, and steady-state powers are relational to the direct and quadrature axis output voltages.

The instantaneous and steady-state powers equations are;

$$p(t) = V_d i_d + V_q i_q = V_d i_d \tag{15}$$

$$q(t) = V_q i_d - V_d i_q = -V_d i_q \tag{16}$$

$$P = V_d V^*{}_q / X_f \tag{17}$$

$$Q = V_d (V^*{}_d - V_d) / X_f \tag{18}$$

5.2 GSC Control

The generalized control scheme for load side converter of the PMSG has layered loop arrangement having speedy inside current control loop and slow external current feedback loop. The direct axis current loop controls the voltage at dc-link and the q-axis current loop control the reactive power or p.f. on the load side. Control method for inside loop is given by

$$V^*{}_d = \left(R_f i_d + L_f \frac{di_d}{dt}\right) - \omega_G L_f i_q + V_d \qquad (19)$$

$$V^*{}_q = \left(R_f i_q + L_f \frac{di_q}{dt}\right) + \omega_G L_f i_d \qquad (20)$$

The first part of above eqn. (19) and (20) shows that stator direct and quadrature axis currents can be synchronized by regulating the d-axis and q-axis voltages, and the 2nd part of it denotes the compensation spans. The figure of the vector control of generator side controller is shown in Fig. 5.

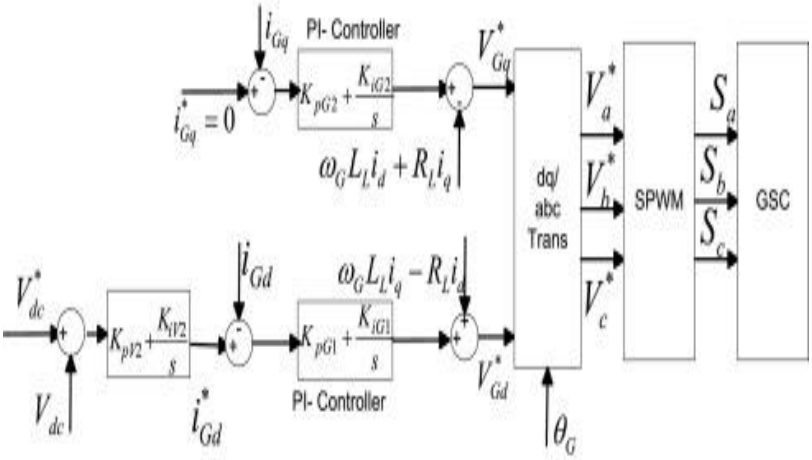


Figure 5 Vector control of GSC

The load side converter is regulated based voltage based control to adjust the voltage at the dc-link and reactive power of the system. Grid quadrature axis base current set to be zero and direct axis base current is projected from the external loop of V_{dc}. Reference $V^*{}_{dc}$ is compared with the found value of V_{dc} which produce the base $i^*{}_{Gd}$. projected base direct and quadrature axis currents $i^*{}_{Gd}$ and $i^*{}_{Gq}$ compared with direct axis and quadrature axis currents i_d and i_d which are measured earlier L filter. Errors are input to PI controller which tweak the error. After compensation, projected direct and quadrature axis reference voltages $V^*{}_{Gd}$ and $V^*{}_{Gq}$ is transformed to abc frame using rotor angle θ_G then SPWM generates the switching pulses of GSC.

5.3 DC-Link Voltage Control

For PMSG wind power system, the max. power fetched from wind has to be supplied to grid via dc-link capacitor and load side converter. The dc-link voltage control is key part for PMSG system as it is completely varying from DFIG system. Conventional control offers better performance and better dc-link voltage regulation. Thus, controlling of BTB converters can be decoupled by generator side controller for MPPT control and the load side controller for the voltage of the dc-link regulation so that power fetched from the wind can be moved to the grid with stable dc-link voltage.

5.4 Controlling Reactive Power

The load side converter works in reactive power control. In this scheme, quadrature axis base current is too originated from reactive power regulator. In the ac system voltage support control mode, quadrature axis base current is originated from voltage regulator on grid side. The load side converter creates the needed reactive power depending on how much voltage drop across the Filter and PCC. If the load side converter reaches to its physical restraints due to a maximum active power moved from the generator to the grid via load side converter, load side converter works in ideal state to control dc-link voltage in importance through necessity of reactive power to grid [18].

VI. DISCUSSIONS OF SIMULATION RESULTS

We have conducted various simulations the system in Matlab/Simulink with different values of parameters in order to examine stated control scheme. The PI controllers' workability examined with various conditions. The WT and PMSG parameters in Table 1. we are controlling the dc-link voltage constantly at 340 V, the capacitance value at dc-link capacitor is about 1650 μF, and the switching frequency for the MSC and the GSC is 5 KHz, the grid side voltage is 220 V(rms)/50 Hz [18], [38].

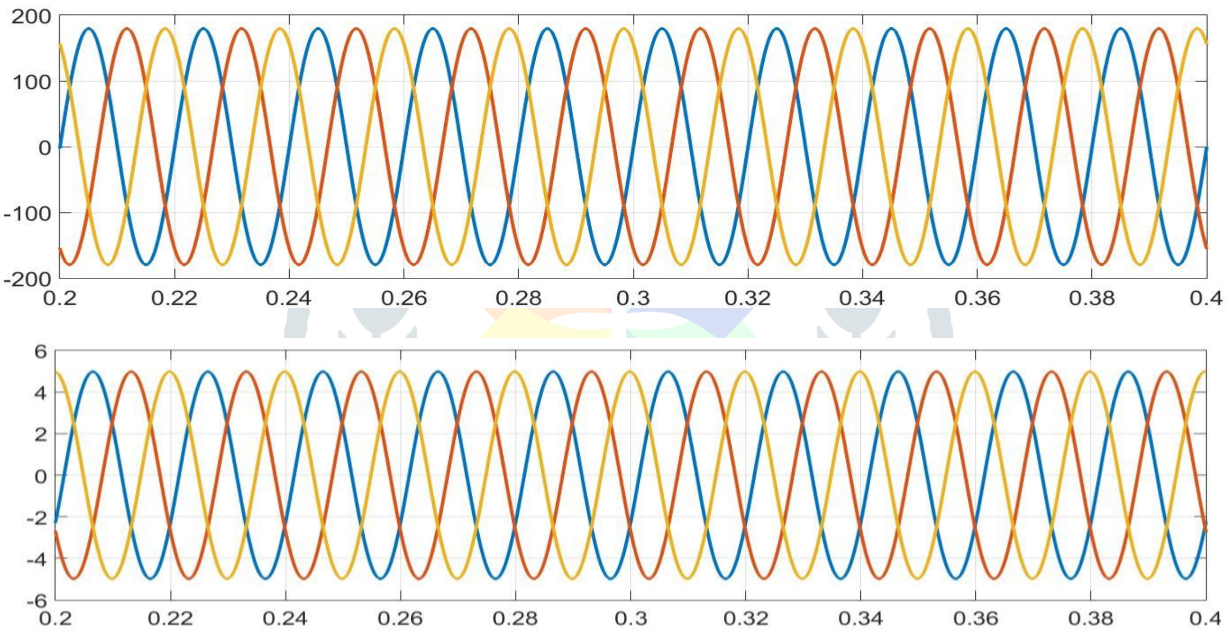
6.1 Normal Grid Condition at Rated Speed

In such condition, PI controller reaction is checked through base wind speed of 15.5 m/s. The PMSG is operated in the MPPT way where its active power is regulated. The current in direct axis kept to zero to get max. attraction of power or torque per ampere on MSC side. The current at q-axis maintained to zero for maximum active power transfer from generator to grid through B2B converters and regulate the dc-link voltage on GSC side. The Simulation results are illustrated in Fig.6 (a-g).

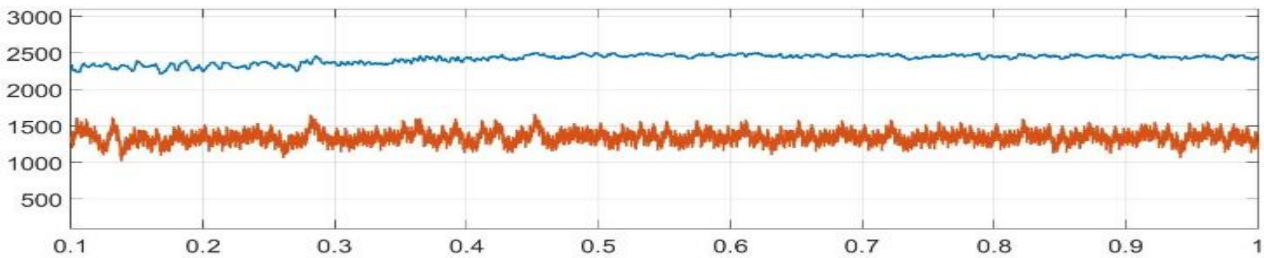
Table 1 Parameters of PMSG

Rated Power	2.68 [kW]
Voltage / Frequency	220 [V] / 60 [Hz]
Rated Flux	0.468 [Wb]
Rated Current	9.8 [A]
Torque Constant	1.72 [N.m/A]
Rated Speed	1200 [rpm]
Pole Pair	3
Moment of Inertia	0.00331 [Kg· m$^{3]}$
Stator Resistance	0.49 [Ω]
Stator Inductance	5.35 [mH]

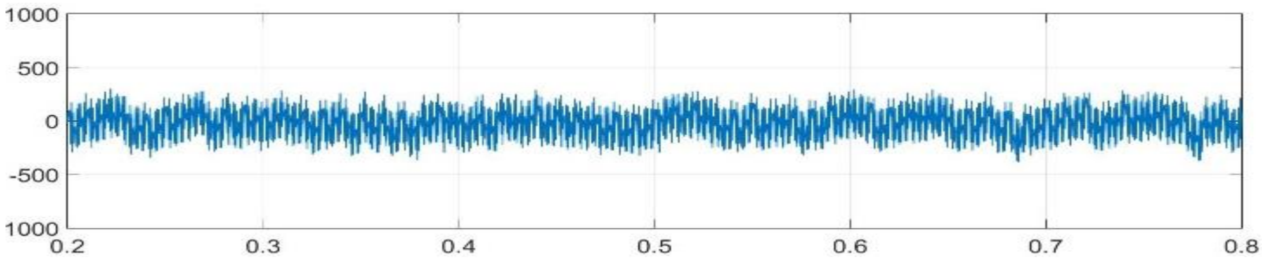
Fig. 6 shows the system operation at base wind speed of 15.5 m/s. Fig. 6 (a) displayed, grid voltage is 127 V (rms) and grid current is 6.96 A (rms). Generator power is 2.7 KW and grid power is 2.67 kW while reactive power on grid side is zero displayed in Fig.6. Grid direct axis current is 9.85 A, and quadrature axis current is zero, shown in Fig.6. Wind turbine and generator torques are 22 Nm and 22.4 Nm respectively, shown in Fig.6 and generator speed is 1200 rpm, shown in Fig.6. DC-link voltage is regulated at 340 V at rated wind speed.



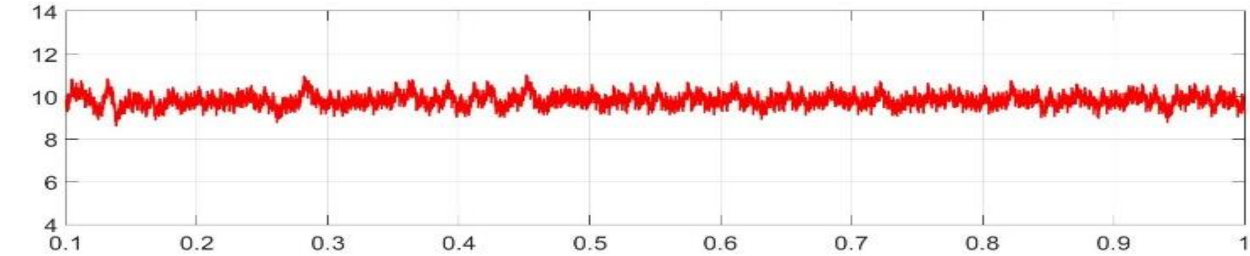
(a) Grid side voltage and current



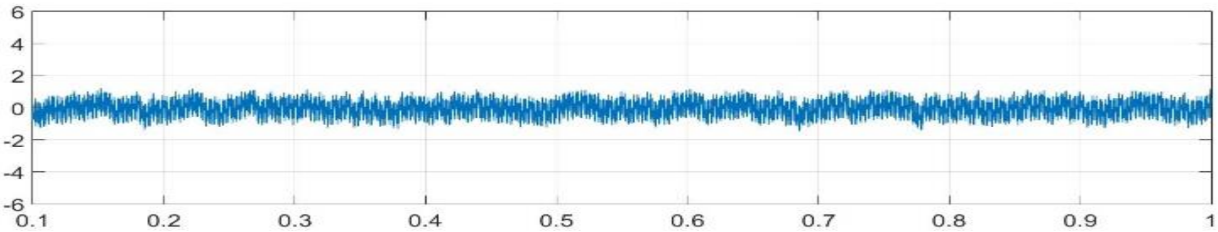
(b) Active power at Generator (blue) and Grid (red)



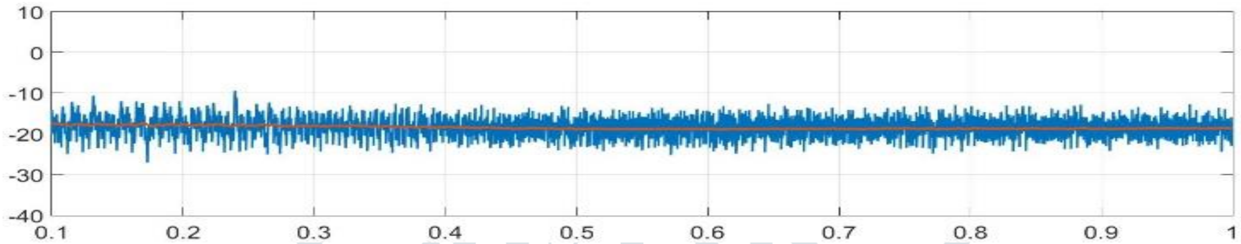
(c) Reactive power at Grid



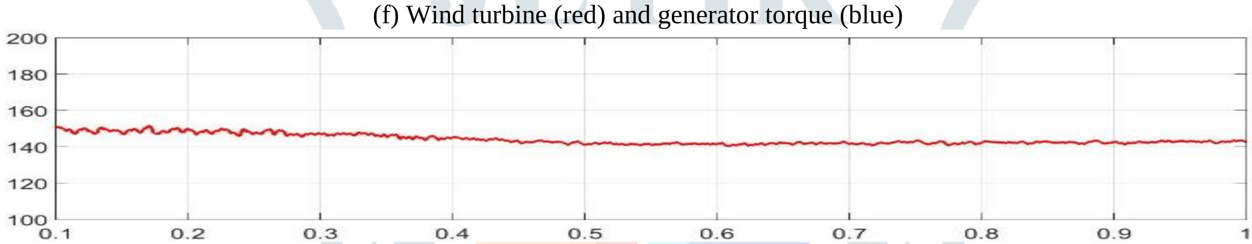
(d) Grid direct axis current



(e) Grid quadrature axis current



(f) Wind turbine (red) and generator torque (blue)



(g) Generator speed

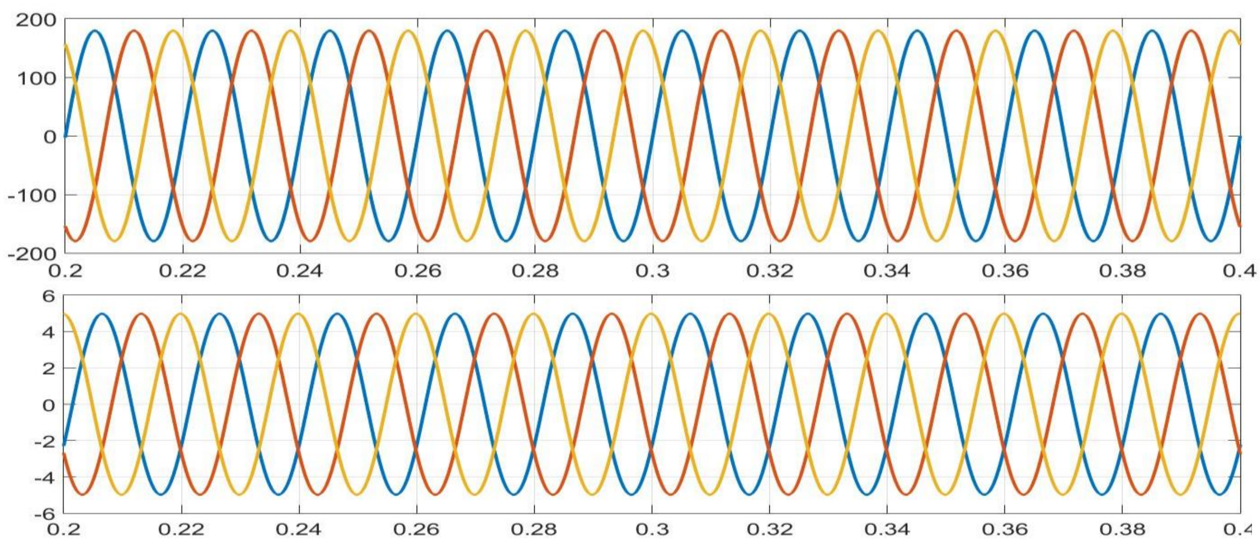
Fig. 6 Wind Turbine performance at normal grid condition

6.2 Normal Grid Condition with RL load at Fixed speed

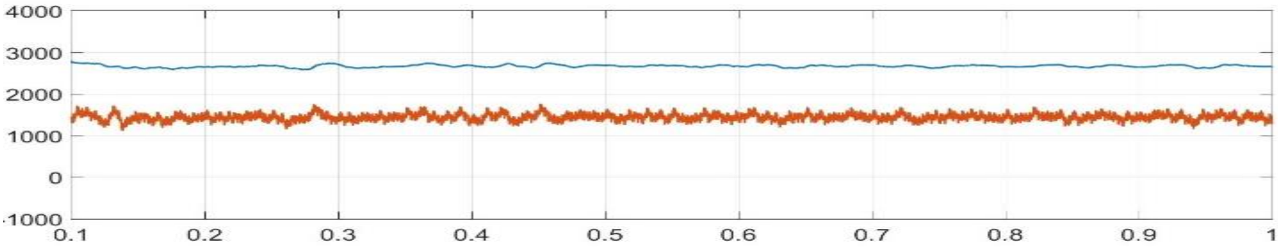
Fig. 7 shows the system operation at rated wind velocity of 15.5 m/s with active load of 1.2 kW and reactive load of 0.6 kVAr. Load voltage is 220V and load current is 4.81 A with p.f. of 0.9 lagging shown in Figure7(a).

Hence, the RL load connected next to the GSC and before the Grid. Thus, active & reactive powers are differing at load side converter and grid. Active power and reactive power flows subject to the load demand. Load side converter active power is about 2.67 kW and active power at grid side shows around 1.45 kW as the load of 1.2 kW is connected in between as shown in Fig. 7.

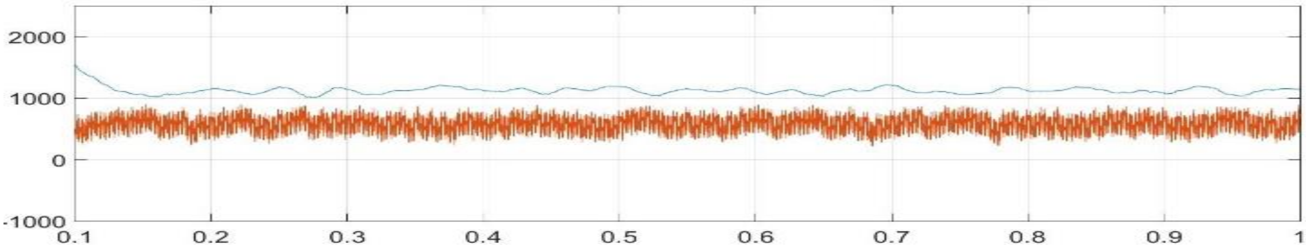
Due to the reactive power is controlled at GSC side for optimum active power transfer from generator to the grid and to acquire unity power factor control, required reactive power 0.5 kVAr to the load is from the grid in place of the load side converter, which shows in Fig. 7. Regulated dc-link voltage 340 V, Grid voltage of 127 V, and current of 4.2 A with unity power factor, Wind turbine and generator torque, generator speed and d-axis grid current are same as previous case.



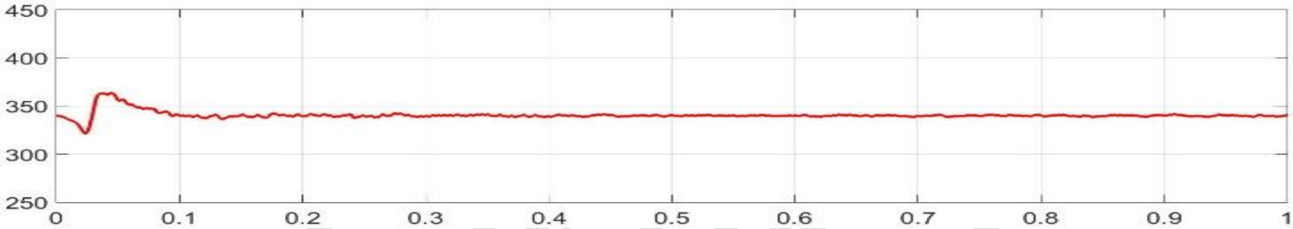
(a) Load voltage and current with 0.9 lagging power factor



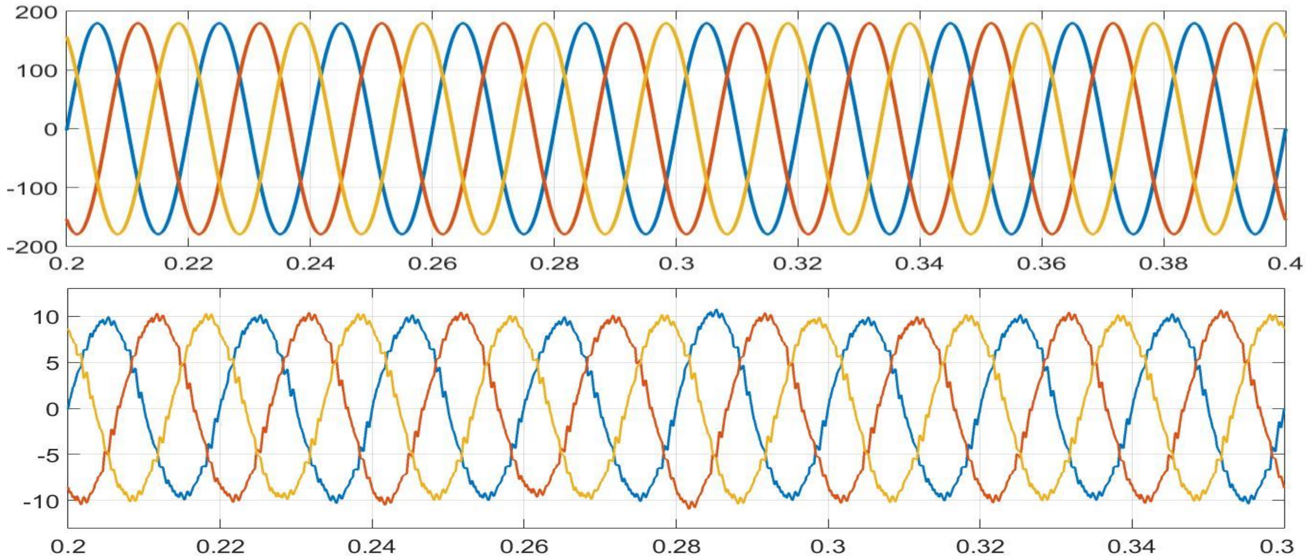
(b) GSC (blue) and grid (red) active power



(c) GSC (blue) and grid (red) reactive power



(d)Voltage across dc-link Capacitor



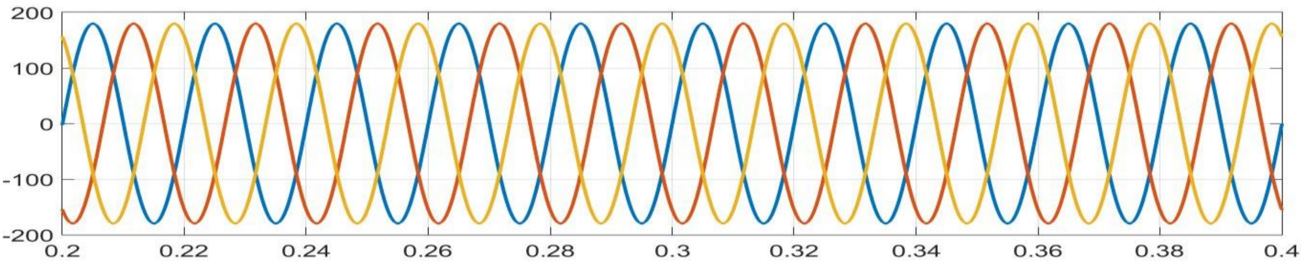
(e) Inverter voltage and current with unity power factor

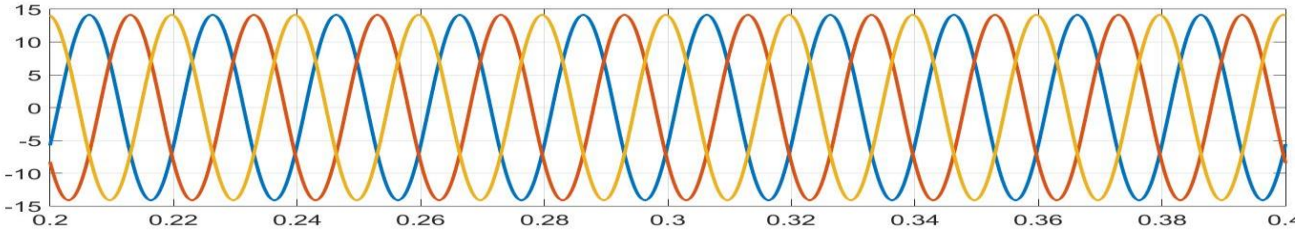
Fig. 7 Wind generation performance at normal grid condition with R-L load at rated wind speed 15.5 m/s.

6.3 RL load at Wind Speed 11.5 m/s

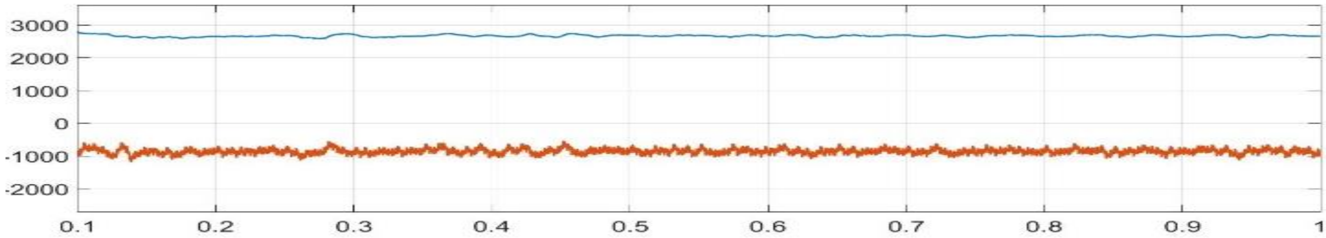
Fig. 8 shows the system performance at 11.5 m/s wind speed with 3.5 kW active and 1.5 kVAr reactive power load. Here, output of load side converter is 1.1 kW active power and the load needs 3 kW active and 1.5 kVAr reactive power. Fig. 8 shows, the 1.675 kW active and 1.5 kVAr reactive power is from the grid while 1 kW active and zero reactive power from load side converter.

Hence, the load voltage is 127 V and load current is 10.66 A, and p.f. is 0.894 lagging, GSC side voltage is 128 V and current is 2.68 A. load side converter direct axis current is 3.18 A, WT and generator torques are 10.2 Nm and 10 Nm respectively and generator speed is 1011 rpm shown in Fig. 8, dc-link voltage is 340 V constant and power coefficient is 0.48 constant.

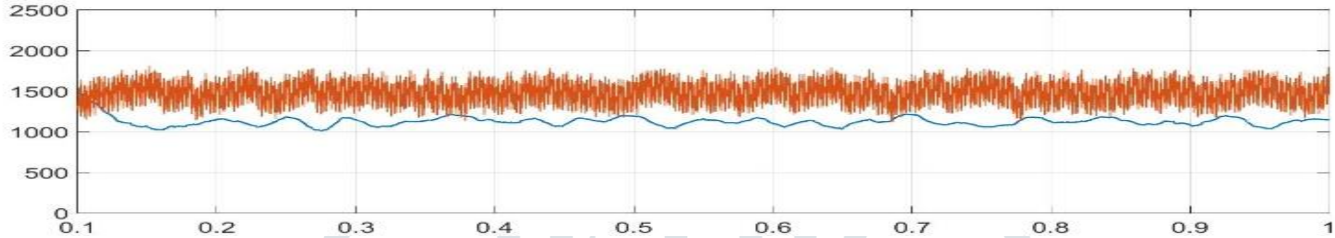




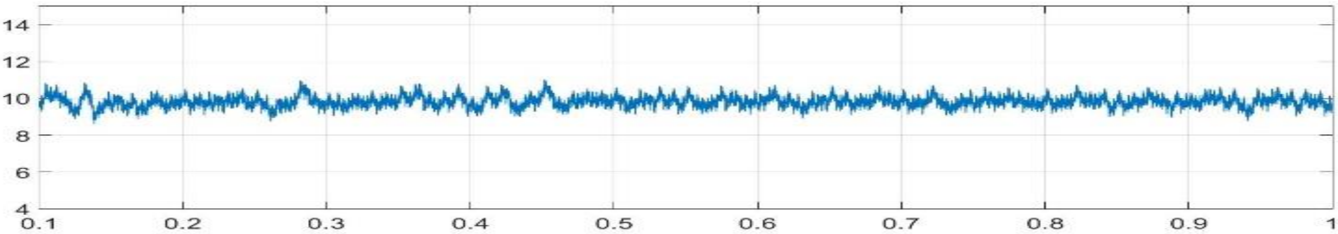
(a) V and I at load with 0.89 lagging power factor



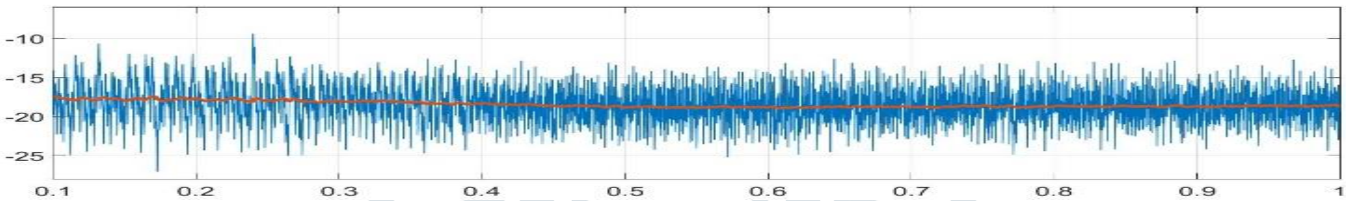
(b) Active power at GSC (blue) and grid (red)



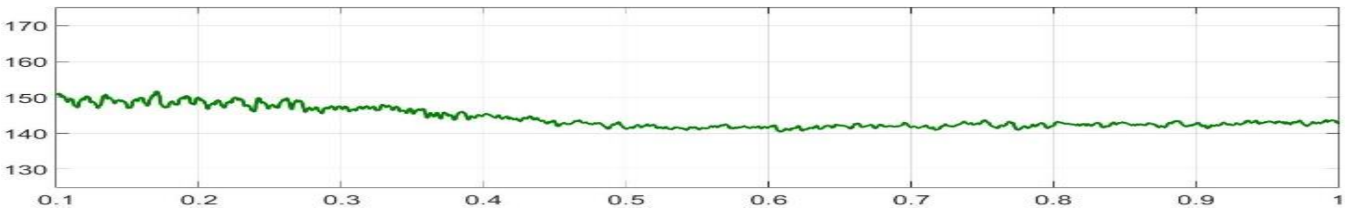
(c) GSC (blue) and grid (red) reactive power



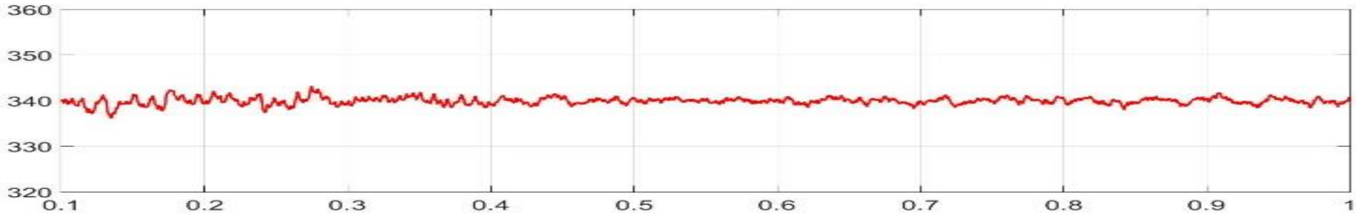
(d) GSC d-axis current



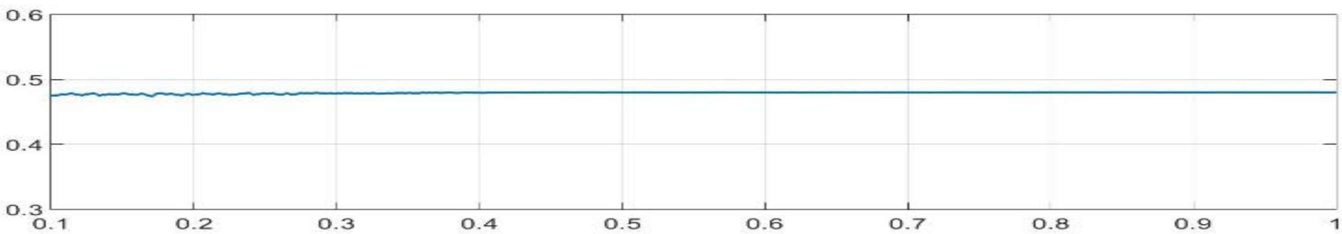
(e) Wind turbine (red) and generator torque (blue)



(f) Generator speed



(g) dc-link voltage



(h) Power coefficient (C_p)

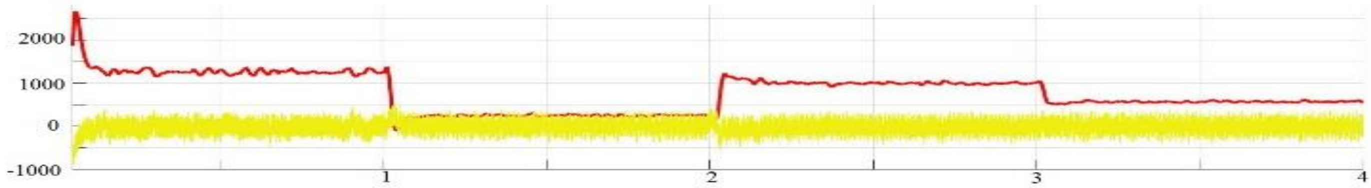
Fig. 8 Performance with R-L load at 11 m/s wind speed.

6.4 Constant Load and Varying Wind Speed

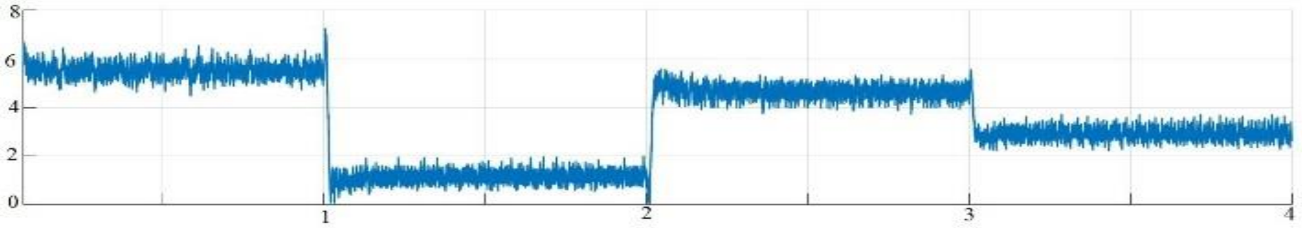
Fig. 9 shows the system operation at 17 m/s, 12 m/s, 15.5 m/s and 14 m/s of continuously changing wind speed with constant load 900 W. Wind turbine torque, generator torque, grid current, GSC active and reactive power, grid active and reactive power, load voltage, load current, generator speed, dc-link voltage, grid direct axis and quadrature axis current and C_p are shown from Fig. 9.

(a) WT and generator torque

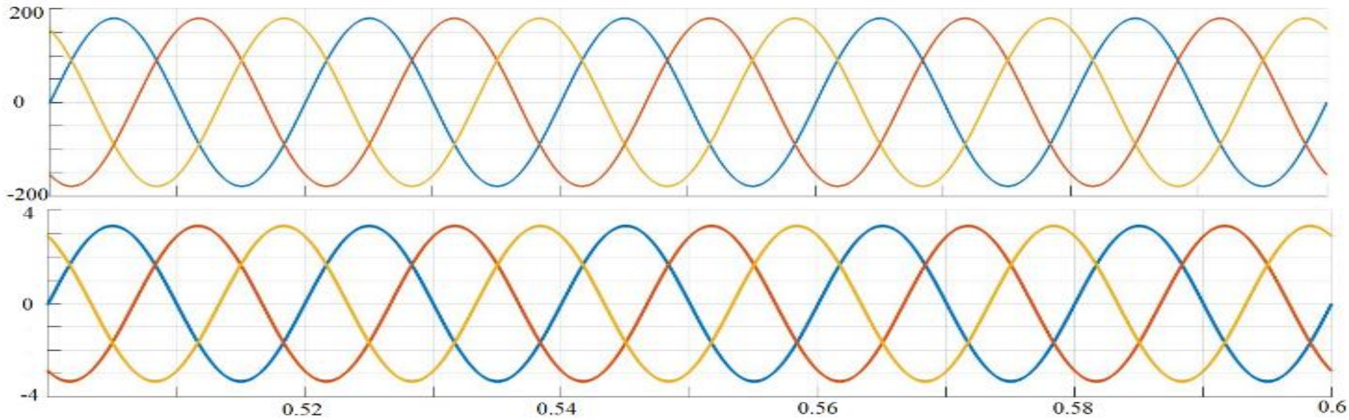
(b) Active power at GSC side and grid side



(c) Reactive power at GSC and grid

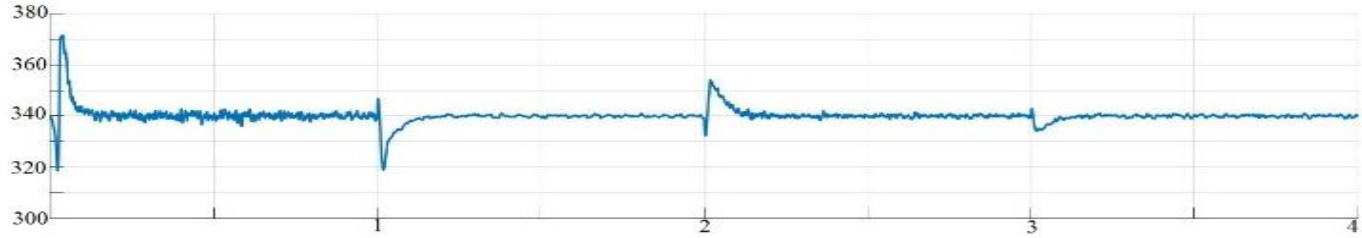


(d) Grid RMS current

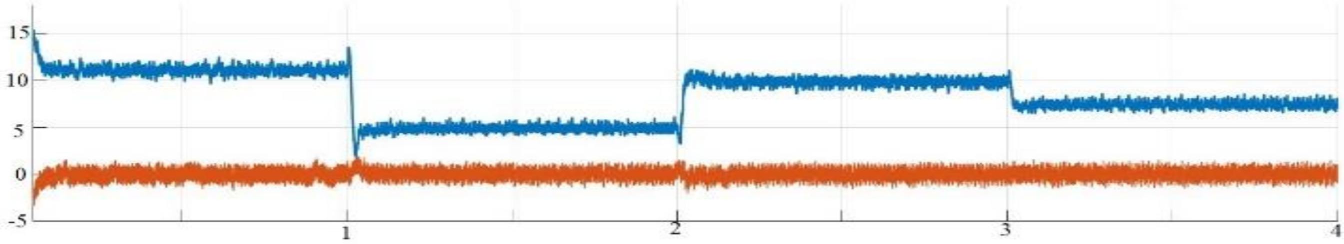


(e) voltage and current(Load) waveforms

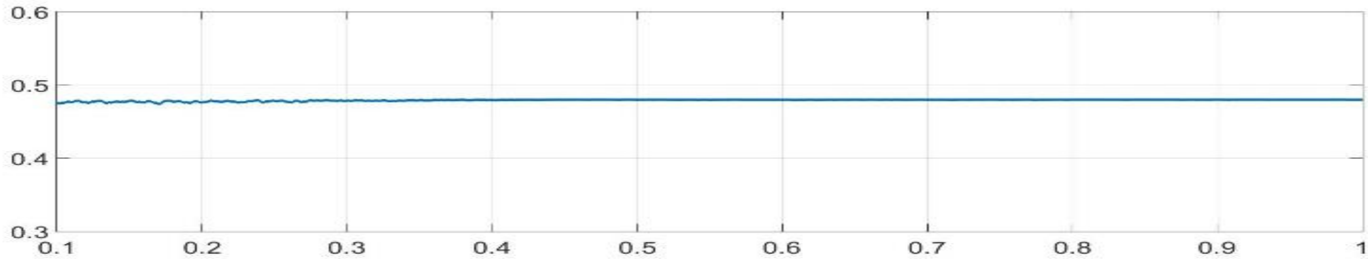
(f) Generator speed



(g) DC-link voltage



(h) Grid direct and quadrature axis current



(i) Power coefficient (C_p)

Fig. 9 Wind Turbine performance with fixed load at different variable wind speed.

VII. CONCLUSION

This study has analyzed the conventional PI scheme of flexible speed DD-PMSG for grid assistance. This work shows how the control of generator side converter and load side converter modelled through the conventional voltage oriented control scheme and applied with the MPPT on machine side. Reactive power and dc-link voltage regulation on load side converter of a PMSG based wind power system.

Full work with various conditions verifies that the PMSG WPCS which is based on the conventional vector control method, can satisfy the PMSG WT system with better performance for fixed and flexible wind situations and also for varied load positions. The controller can optimize the output power of VSWT through various wind and load situations. The test outputs of the planned control strategy have proved outputs results for a 2.68 KW PMSG system with different load settings.

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