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Design and Comparison of Grid Connected Permanent Magnet Synchronous Generator Non-salient Pole and Salient Pole Rotor Wind Turbine

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***Abstract*-- Variable speed wind turbines are widely used wind energy conversion system (WECS). Among them doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG) are mostly used. PMSG based wind turbines are getting more popular in recent times because of their several advantages over other types. Direct drive capability and low speed operation are some of its significant advantages over other type. In the dq0 reference frame, this analysis discusses the implementation and simulation of a Simulink-based operated permanent magnet synchronous generator (PMSG) wind turbine. The current control subsystem makes use of PID controllers to regulate the wind turbine's velocity, direct and quadrature stator currents, and blade pitch tilt. The pitch angle controller monitors both the generator's speed and active strength, restricting both in the event of high-speed wind conditions. PMSGs exhibit constant excitation that is uncontrollable. As a result, a properly designed damper winding is needed to ensure stable operation in the absence of a frequency controller. This article analyzes and compares the performance of three-phase non-salient pole permanent magnet ac machines and salient pole machine fitted with damper windings in rigid network operation. The recommendations for network-connected generators are determined by evaluating the results of a circuit-based mathematical models of the PM-machine.**

***Index Terms*-- Wind turbine, Variable speed, PMSG, Rotor, Salient pole, Grid.**

I. INTRODUCTION

Wind energy conversion system (WECS) is designed to run at a variable speed over a large speed range in order to produce peak power at low wind speeds and at a constant speed and power output at high wind speeds. Then, the traditional synchronous generator is used to generate alternating current electricity with a variable frequency over a broad frequency spectrum. Since it is less expensive than other generators, it is also financially sustainable [1-2]. The synchronous generator can be connected to a diode or operated rectifier to generate direct current and the profound portion of the rotor current with a power factor of around unity. The key disadvantages of this configuration are that the WTG's motor cannot be started, and its rotor current can be turbulent [3]. The primary advantage of salient pole machines is their lower manufacturing costs - particularly in applications that area and size are insignificant. To some extent, advantages just 'appear' - due to apples and pears comparisons: cylindrical rotor machines target fast-rotating applications where salient pole machines simply disintegrate due to mechanical stress [4]. One workaround is the claw pole generator, which trades mechanical stability for efficiency. They are more important than cylindrical machines with equivalent performance when it comes to salient pole machines [5-6]. A greater moment of inertia aids in demonstrating equilibrium in this case. With equal moments of inertia, this advantage vanishes.

The wind energy market is gradually shifting towards PMSG due to its direct drive feature and wide operating range [7]. For the direct drive PMSG low speed high torque generator with full scale converter is used. Low speed operation and the absence of gear box offers lower maintenance expenses and easily manageable and controllable features though the manufacturing cost is higher. The rise in temperature gradually decreases the flux density of the permanent magnets. To operate efficiently, complex control strategy with expensive power converter system is a requirement for PMSG wind turbines [8-9].

The paper is divided into the following sections. Section II presents the mathematical model of wind turbine and generators. Section III briefly describes PMSG WECS and comparative discussion about non salient pole and salient pole rotor. Simulation analysis is discussed in section IV. And section V summarizes and concludes the paper.

II. PMSG WIND TURBINE MODEL

2.1 Aerodynamic model

Wind turbine is used to convert the kinetic energy of the wind to mechanical power. The wind speed sequence consists of four components [8].

$$v_w(t) = v_a(t) + v_r(t) + v_g(t) + v_t(t) \qquad (1)$$

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Here, v_a is the constant wind component, v_r is the ramp wind component, v_g= gust wind component, v_a= turbulence or base noise wind component. All of them are in m/s. The wind power extracted from the wind can be expressed as [10-11]:

$$P_m = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta){v^3}_w \tag{2}$$

here, P_m is the power extracted from the wind, ρ= air density (kg/m^3), R= Blade radius (m), v= wind speed (m/s), $C_p(\lambda,\beta)$= Power coefficient of the wind turbine, β= Blade pitch angle (deg), λ= Tip speed ratio. The function of C_p in terms of tip speed ratio (λ), and blade pitch angle (β) can be expressed as:

$$C_p(\lambda,\beta) = 0.5176[\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}} + 0.0068\lambda] \tag{3}$$

With,

$$\frac{1}{\lambda_i} = \left(\frac{1}{\lambda+0.08\beta}\right) - \left(\frac{0.035}{\beta^3}\right) \tag{4}$$

Here, β is the pitch angle (deg), which is the angle between rotational plane and blade cross section. λ= tip speed ratio which can be defined as , $\lambda = \frac{\omega R}{v_w}$. Here, R= rotor radius (m), ω= angular velocity of rotor (rad/sec) and v_w= wind speed (m/s). Fig. 1 shows the relationship between turbine power and speed. It is shown that power captured by the wind turbine is maximum at a particular rotational speed while pitch angle is kept constant [12].

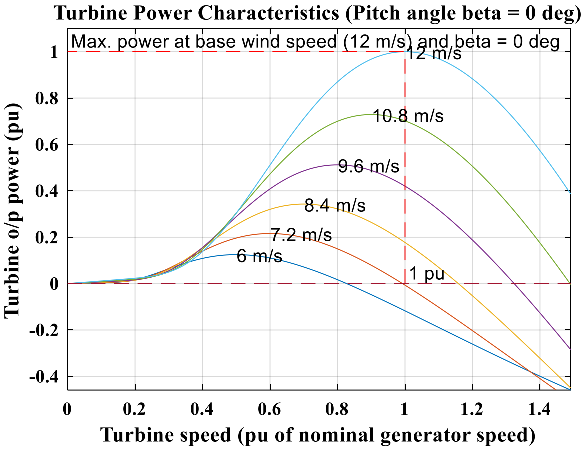


Fig. 1: Turbine speed power curve.

The maximum value of C_p ($C_{pmax} = 0.48$) is achieved for β= 0 degree and $\lambda = 8.1$. This is the nominal value for λ. $C_{pmax} = 0.48$, means that the power extracted from wind wind turbine is less than the Betz's limit which is 59.3% . It is because of the aerodynamic losses that depends on rotor construction such as number or shape of blade, weight, stiffness etc.

2.2 Mathematical model of PMSG

The PMSG mathematical model is expressed in rotating reference frame (*dq*) frame. All the quantities in the rotor reference frame are referred to the stator. The *d* axis and *q* axis current equations can be defined as [12-14]:

$$\frac{d}{dt}i_{sd} = \frac{1}{L_{sd}}v_{sd} - \frac{R}{L_{sd}}i_{sd} + \frac{L_{sq}}{L_{sd}}\omega_m i_{sq} \tag{5}$$

$$\frac{d}{dt}i_{sq} = \frac{1}{L_{sq}}v_{sq} - \frac{R}{L_{sq}}i_{sq} - \frac{L_{sd}}{L_{sq}}P\omega_m i_{sd} - \frac{\lambda P\omega_m}{L_{sq}} \tag{6}$$

The equation of electromagnetic torque is,

$$T_e = 1.5P\left[\lambda i_{sq} + \left(L_{sd} - L_{sq}\right)i_{sd}i_{sq}\right] \tag{7}$$

The difference between salient pole rotor and non-salient pole (round) rotor is that there is no variation in phase inductance in round rotor.

$$L_{sq} = L_{sd} = \frac{L_{ph}}{2} \tag{8}$$

But for the salient pole rotor the *dq* inductance would be,

$$L_{sd} = \frac{L_{ph(max)}}{2} \tag{9}$$

$$L_{sq} = \frac{L_{ph(min)}}{2} \tag{10}$$

Here, $L_{ph(max)}$ and $L_{ph(min)}$ are maximum *d* axis inductance and minimum *q* axis inductance respectively. Active and reactive power equations are:

$$P_s = V_{sd}i_{sd} + V_{sq}i_{sq} \tag{11}$$

$$Q_s = V_{sq}i_{sd} - V_{sd}i_{sq} \tag{12}$$

Here, i_{sq} and i_{sd} are *q* and *d* axis currents respectively. v_{sq} and v_{sd} are *q* and *d* axis voltages respectively. L_{sq} and L_{sd} are *q* and *d* axis inductances respectively. ω_m= angular velocity of the rotor; R= resistance of the stator winding; P= no. of pole pairs; T_e= electromagnetic torque and λ= amplitude of the flux induced by the permanent magnets of the rotor in the stator phases.

2.3 Pitch angle controller

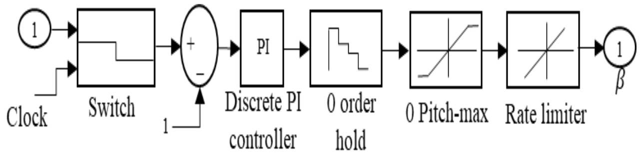


Fig. 2: VSWT pitch angle (β) controller.

Aerodynamic control system is necessary to control mechanical power. Pitch angle controller generally works to change the blade angle that prevents the rotor speed from exceeding the rated speed. It also protects the generator from overloading at high wind speed [15-16]. In Fig. 2 input generator speed is compared with the nominal value through PI controller which is used to manage the tracking error.

III. SYSTEM DESCRIPTION

3.1 System description of VS-PMSG wind turbine

The variable speed PMSG wind turbine is connected to the AC grid through a back to back (AC-DC-AC) full power converter [17]. The converter system is a bidirectional power converter that consists of IGBT based pulse width modulated (PWM) VSCs connected through DC link as in Fig. 3. The complete system consists of wind turbine with drive train models, PMSG, generator side controller and grid side controller. Both of the converters are built by IGBT. They are controlled by generator side and grid side controller. The generator side controller is associated to the stator terminal and the grid side controller is connected to the grid system through step up transformer. The generator side controller transforms the three phase AC voltage generated by PMSG to DC voltage. And the grid side controller transforms the DC voltage into three phase AC voltage of the grid frequency.

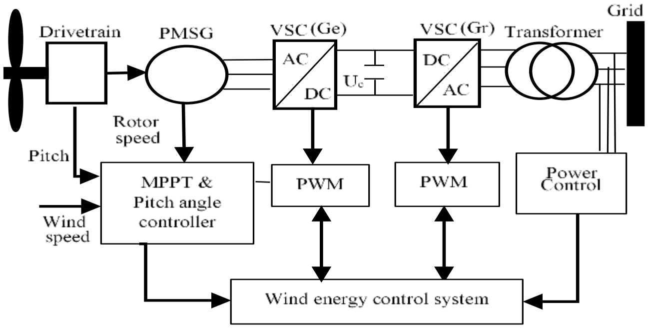
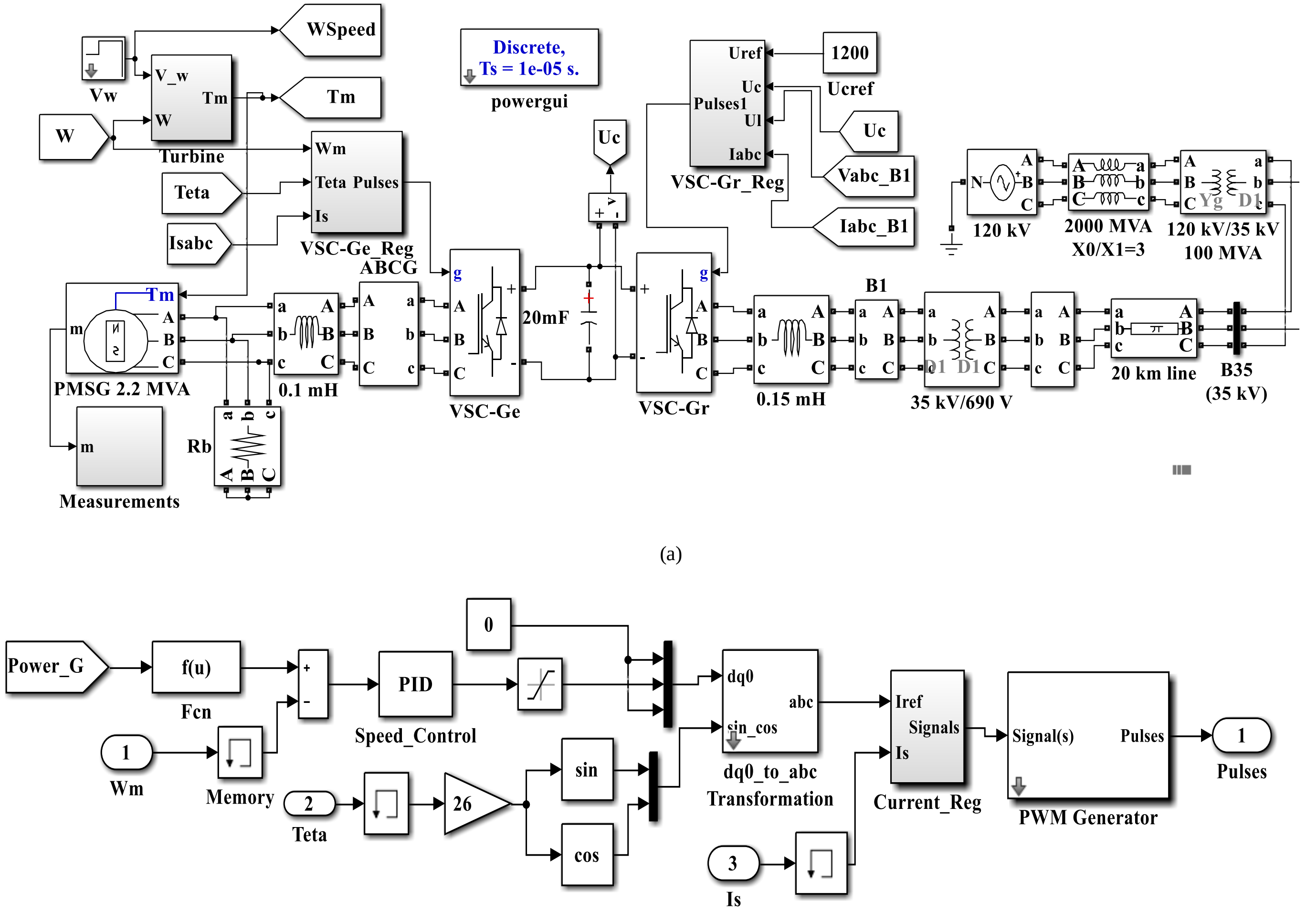


Fig. 3: General structure of the PMSG WECS.

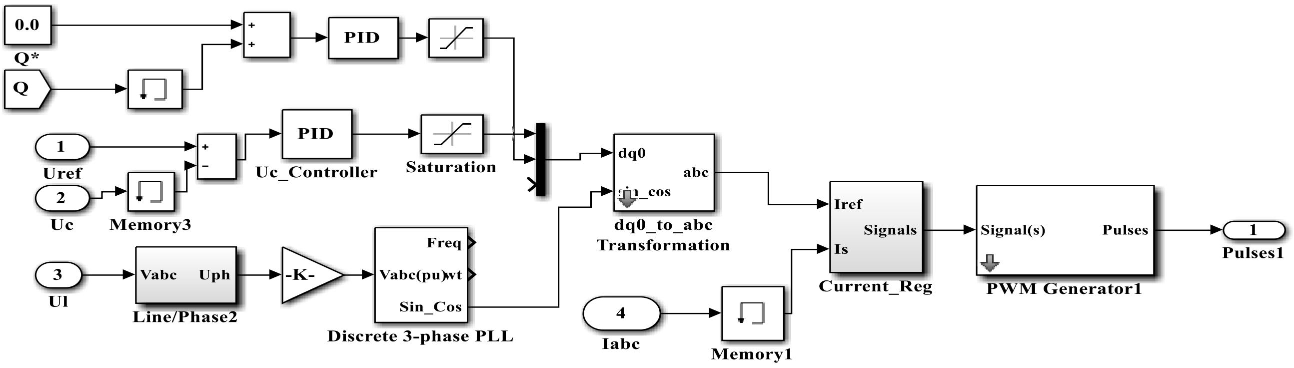
Multipole PMSG both the non-salient or round pole rotor and salient pole rotor has been considered for the system. Parameters considered for the system is given in Table I. The PMSG is used to convert the mechanical energy extracted by the wind turbine into electricity. As the generator side and grid side is coupled through the converter, so it is possible to keep the grid side frequency constant while the change in wind speed varies the generator electrical frequency. This process makes variable speed operation possible. Power converters filter out harmonics thus reducing flicker level which improves power quality and keep it smooth. The capacitor that is in between the inverter and rectifier is called DC link capacitor. Decoupling the control of the two converter is possible because of it [18-19].

Matlab/Simulink model of the PMSG WECS, VSC of the generator side and VSC of the converter side is illustrated in Fig. 4(a), (b) and (c) respectively. VSC_Ge_Reg and VSC_Gr_Reg block contains the reference values for simulation. The value of proportional gain (K_p), integral gain (K_i) and derivative gain (K_d) are 180, 3200 and 1 respectively. VSC_Ge_Reg also contains rotating speed controller.



(a)

(b)



(c)

Fig. 4: Matlab/Simulink design of the (a) PMSG wind turbine system, (b) Generator side voltage source converter and (c) Grid side voltage source converter

The DC link voltage voltage (U_c) is kept constant by controlling the grid side converter. It is achieved by supplying active power to the grid and controlling reactive power flow to the system. Even in low wind speed it is possible to extract power by controlling pitch angle controller. It also protects the system from wind gust [20].

3.2 Non-salient (round) pole rotor vs salient pole rotor

Self-excitation is a key feature of PMSG. The rotor of PMSG contains the magnets that creates the rotor magnetic field of the generator. Non-salient pole rotors and salient pole rotors are the two rotor types in PMSG. Each of these types have their own benefits and downsides. The main difference between round pole rotor and salient pole rotor is the air gap between the stator and rotor. Round pole rotor generators have uniform air gap. Because of that the reluctance of the magnetic path is same in all direction. As a result reactance (X_s) remains same. The air gap of salient pole rotor is non uniform. So, reactance also varies with the rotor position. In the case of round pole generator only *d* axis of geometric symmetry exists but salient pole machines have both *d* axis and *q* axis of geometric symmetry. According to the two reaction theory by Blondel because of the non-uniform air gap reluctance on the *q* axis (X_q) is greater than reluctance on the *d* axis (X_d) [19]. Non-salient or round pole rotor machines are used in high speed applications. They have advantages such as robust construction, less windage loss. The number of pole pairs are higher compared to the salient pole rotors generators. Salient pole rotor generators are more suitable for low speed applications [22-23].

IV. SIMULATION ANALYSIS

The complete variable speed WECS was designed and simulated by Matlab/Simulink using the parameters given in Table 1. The surface magnet generator (SPMSG) is utilized in the Simulink model of non-salient pole PMSG, in which $L_d = L_q$; therefore, the generator current component I_q is defined with the wanted torque, and the component I_d is equal to zero. The model of wind turbine salient pole PMSG is a copy of PMSG non-salient pole except for the fact that instead of SPMSG, the interior permanent magnet synchronous generator (IPMSG) is utilized where ($L_d \neq L_q$). The blocks which compute the reference are added in the subsystem VSCGe_Reg in the WECS model. There, Gain1 block recalculates the actual reference for i_{sq} into the relative unit. Fcn1 block solves the quadratic equations and the block Gain2 carries out the calculations inverse to the block Gain1. The power, voltage and rotating speed are kept same in both the cases of the generators. In the case of IPMSG number of pole pairs is higher which reduces rotor flux. Fig. 5 shows the wind speed variation. Under nominal condition (wind speed 12 m/s) with the increase in wind speed upto 15 m/s at *t*= 7s and its abatement to 7 m/s at *t*= 20s. Fig. 6 to Fig. 8 shows the rotor speed, pitch angle and torque changes respectively. It can be seen that with the increase in wind speed the angular velocity of the rotor speed of PMSG also increases. The speed limit is obtained with the pitch angle variation. The value of torque is negative because it is clockwise. Fig. 9 to Fig. 11 shows the simulation result of PMSG non-salient pole and salient pole generator voltage, current and power respectively. Nominal current of PMSG can be determined as:

$$I_n = \frac{\sqrt{2}\times 2.2\times 10^6}{\frac{690}{\sqrt{3}}} = 2606\ \text{A}$$

Here, Transparent power *S*= 2.2 MVA under the nominal voltage of 690 V and frequency of 9.75 Hz. Nominal rotating speed of non-salient pole and salient pole generator is, $\omega_n = 2\times\pi\times(9.75/26) = 2.355\ \text{rad/s}$ and $\omega_n = 2\times\pi\times(9.75/30) = 2.041\ \text{rad/s}$ respectively.

Here, 26 and 30 are the number of pole pairs taken from TABLE I. And the nominal torque of non-salient pole and salient pole rotor is,

$$T_{en} = 2.2\times\frac{10^6}{2.355} = 934.2\ \text{kNm and}$$

$$T_{en} = 2.2\times\frac{10^6}{2.041} = 1077.9\ \text{kNm}$$

In order to have minimum IPMSG current with same torque current component I_d should be controlled. The turbine has the power of 2 MW at the base wind speed of 12 m/s in both the system. Back to back VSCs are connected utilizing IGBT and PWM with the frequency of 2160 Hz in both system. VSC-Ge control system contains rotating speed controller. The reference speed can be defined as, $\omega_r = K_m\sqrt[3]{P_g}$. Here, P_g is the measured PMSG power and K_m is the coefficient which depends on accepted units and on the turbine parameters. In this case under consideration in pu K_m= 1. The value is optimal if P_g is equal to the optimal value at the given wind speed. During steady state operation in both of the cases reactive power at generator side is kept nearly zero. If the wind speed rises, *Pg* also increases. The rotating speed increases until it reaches the value that corresponds to the maximum at the new wind speed. Fig. 11 shows the simulation result of DC link voltage of non-salient pole and salient pole PMSG. It is produced by grid side converter and the phase voltage fed to the grid. The value of the DC link voltage is around 1200V. It remains constant and well controlled in both cases.

Fig. 13 shows the wave forms of active and reactive power of grid side non-salient pole and salient pole rotor PMSG respectively. Changes in wind speed can be resulted in the fluctuation of the power components. It can be seen that total harmonic distortion is not more than 2% in the network current. Though both of the system contains converters that are rated 100%, it can be seen that active power injected to the grid by salient pole PMSG WECS is smother compared to the other.

TABLE I

Parameters of simulated PMSG wind turbine.

Parameters	Value		Unit
Rated power	2		MW
Frequency	50		Hz
DC link capacitance	20		mF
Rated speed	12		m/s
Rated voltage	690		V
	Non salient	*Salient*	
Pole pairs	26	30	
Stator phase resistance	0.78	0.8	mΩ
Armature inductance	1.57	L_d=1.5; L_q=2.6	mH
Flux linkage	9.18	7.9	Wb

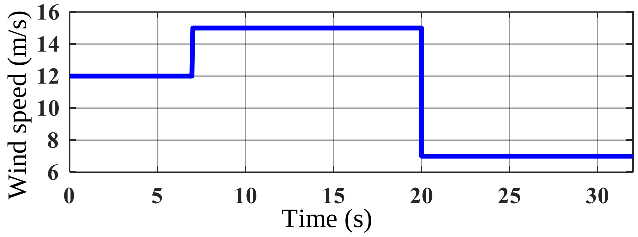


Fig. 5: Variation of wind speed.

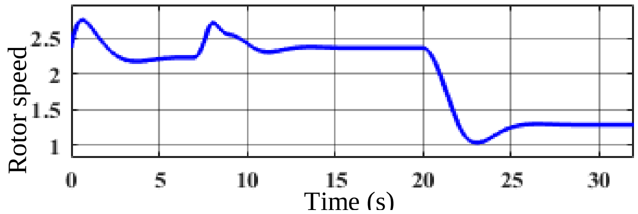


Fig. 6: Rotor speed.

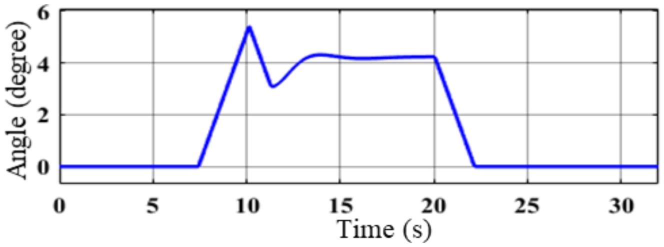


Fig. 7: Pitch angle.

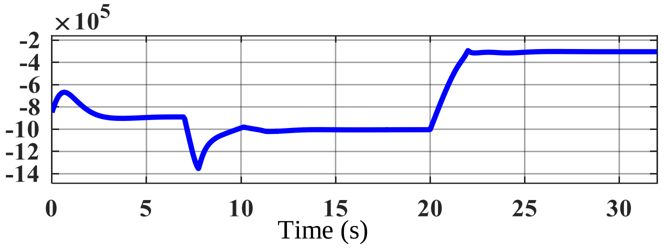
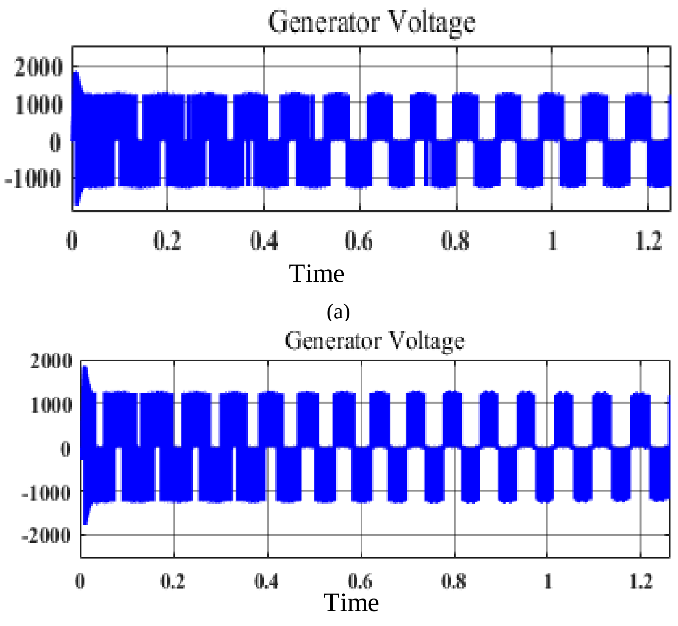


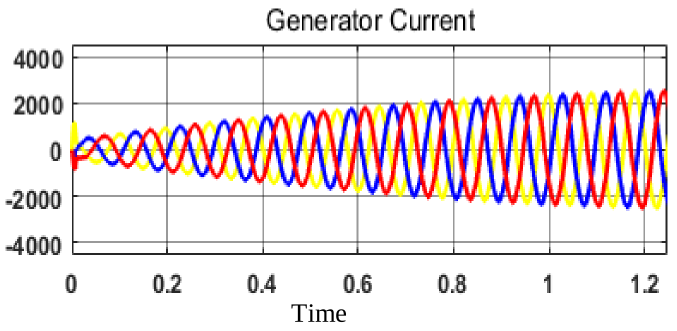
Fig. 8: Wind turbine torque (Nm).



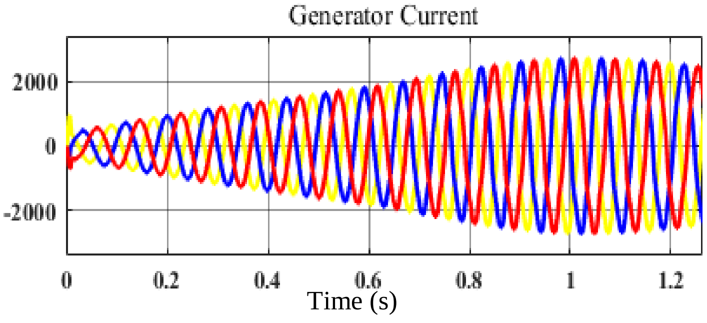
(a)

(b)

Fig. 9: Generator side voltage of (a) non-salient pole PMSG, (b) salient pole PMSG.

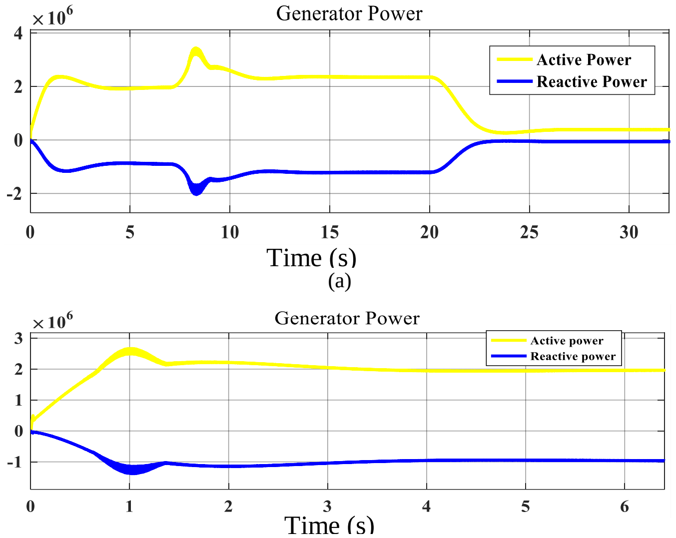


(a)



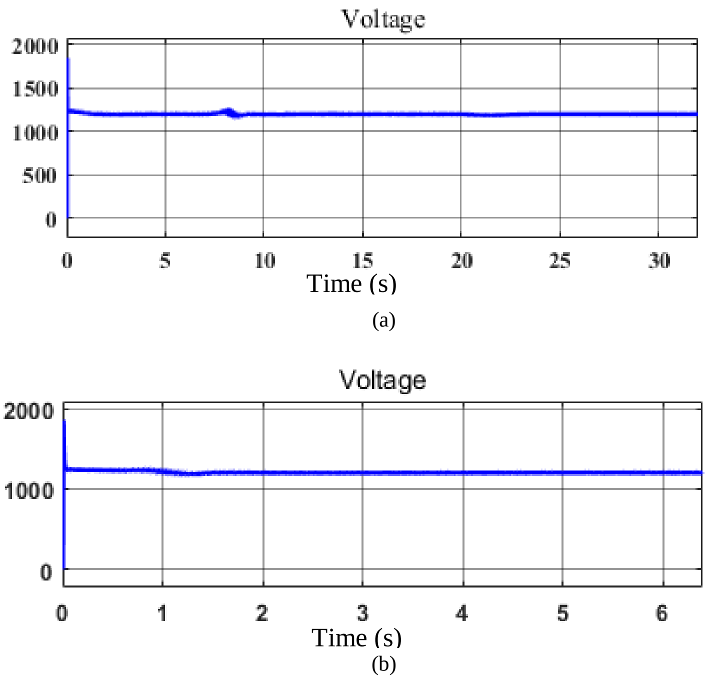
(b)

Fig. 10: Generator side current of (a) non-salient pole PMSG, (b) salient pole PMSG.



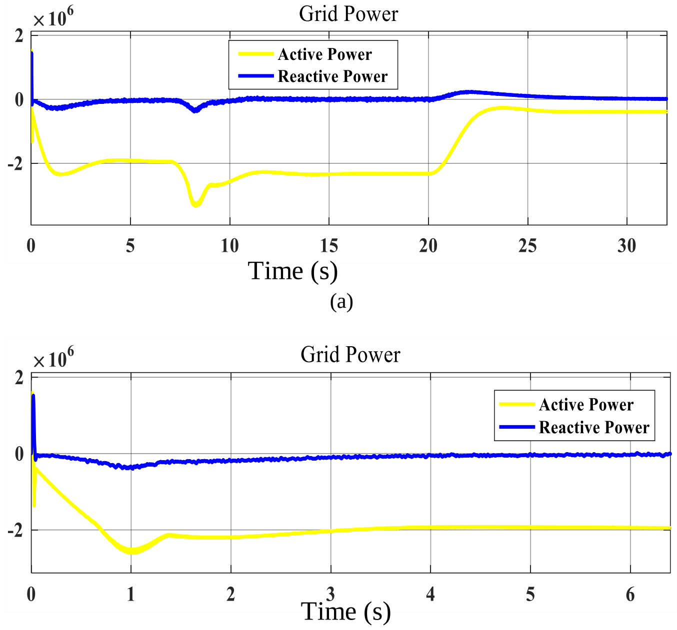
(b)

Fig. 11: Active and reactive power of generator side (a) non-salient pole PMSG, (b) salient pole PMSG.



(b)

Fig. 12: DC link voltage of (a) non-salient pole PMSG, (b) salient pole PMSG.



(b)

Fig. 13: Active and reactive power of grid side (a) non-salient pole PMSG, (b) salient pole PMSG.

V. CONCLUSIONS

This paper presents the model of a VS WECS using PMSG non-salient pole and salient pole rotor. The differences between these two types of generators in WT system and their impacts on the output have been discussed. The objective of this study is to compare the performance and give an overview of these two rotor types of grid connected generators. Non salient pole rotor PMSG offers robust structure with high speed performance and high power quality whereas salient pole rotor PMSG offers low speed performance with comparatively low cost. Though the power quality is higher in non-salient pole rotor PMSG but the power generation is limited due to only magnetic torque. Salient pole rotor PMSG have reluctance torque and magnetic torque which helps it to generate high power. It offers smooth power flow even in low wind speed. If issues such as power quality, reliability and efficiency are considered then direct drive PMSG non salient pole wind turbine offers better solution.

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