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A Performance of the Grid Connected Permanent Magnet Synchronous Generator

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Abstract — **The main purpose of this paper is to develop a wind energy conversion system model to analyze the behaviour of a permanent magnet synchronous generator (PMSG) for variable speed application. In this work, the MATLAB/Simulink programming and graphical environment has been used to develop the wind energy conversion system modelling and simulation. This modelling includes the wind turbine and the PMSG models. Using this simulation tool, the dynamic analysis and performance evaluation has been achieved for a 5.7KW PMSG. All the system components and system response have been observed closely under different wind speeds.**

Keywords — **Wind farm, PMSG, AC-DC-AC Converter, Open Loop Control Technique**

I. INTRODUCTION

The increasing penetration of wind energy into the power grid is reshaping the way that wind farms are operated in. During certain periods of large wind generation and light load conditions, most of the power in the system can be covered by the wind. The share of wind power in relation to the stiffness of electricity grid and other power plants is reaching the level where wind power may cause problems to system operators, such as voltage variations, grid voltage unbalance, and grid instability. Wind farms can no longer be considered as a simple energy source. Now they have to be operated as power plants and be able to provide reactive power, remain connected during system faults, and adapt their control to the needs of the system. One of these concerns is the issue of low-voltage ride-through (LVRT) in which the wind turbines are expected to stay connected and supply reactive power to the grid during and after the voltage dip has ended.

II. WIND TURBINE CONCEPT

The amount of the kinetic energy in the air flow can be determined based on the size of wind turbine and the wind speed [1], [2]. The elementary momentum theory gives an explanation of energy conversion in ideal circumstances. The amount of the kinetic energy of a fluid mass ($\dot{m}$) with a mass density (ρ), moving at a velocity (υ) through the area A is

$$E = \frac{1}{2}(\dot{m} * \upsilon^2)$$

and the mass flow is

$$\dot{m} = A * \rho * \upsilon$$

The power available in the wind is equal to the amount of energy yield passing per second.

$$P_{wind} = E * \dot{m} = \frac{1}{2}(\rho * A * \upsilon^3)$$

Where,

A: blade swept area [m²]
ρ : air density [kg/m³]
υ : wind velocity [m/s]

The mechanical power captured by the wind turbine is written as

$$P_{mech} = C_p * P_{wind} = \frac{1}{2} * \rho * A * C_p(\lambda, \beta) * \upsilon^3$$

and the tip-speed ratio is defined as

$$\lambda = \frac{r * w}{\upsilon}$$

Where,

r: rotor radius [m]
w: rotor angular velocity [rad/s]
C_p: coefficient of power conversion.

The maximum value $C_{p\ max}$ is obtained at the Particular λ_{opt} with constant blade pitch angle. In order to fully utilize the wind energy, λ should be maintained at λ_{opt}, which is determined from the blade design. The maximum power $P_{mech\ max}$ extracted from the wind is expressed

$$P_{mech\ max} = \frac{1}{2} * \rho * \Pi * r^2 * C_{p\ max} * \upsilon^3$$

III. WIND TURBINE GENERATOR

There are three main types of wind turbines currently in use: the fixed speed wind turbine with Squirrel Cage Induction Generator (IG), the variable speed wind turbine with Doubly Fed Induction Generator (DFIG), and the variable speed wind turbine with Permanent Magnet Synchronous Generator (PMSG) [1][2]. A brief distinction of the 3 types of wind turbine driven generators is given below.

A. Fixed Speed Squirrel Cage Induction Generator

This generator consumes reactive power and cannot contribute to voltage control. For this reason, although static capacitor control may allow wind farms with this type of generators are doomed to disappear from wind turbines. Below is the schematic diagram of the fixed speed squirrel cage induction generator used in wind turbine technology as shown in Fig. 1[1], [2], [3]

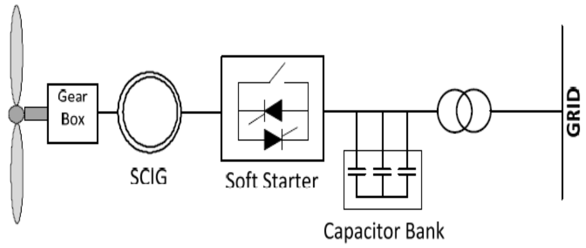


Fig. 1 Squirrel Cage Induction Generator

B. Variable Speed Doubly Fed Induction Generator

This generator can be controlled to provide frequency and voltage control with a back-to-back converter in the rotor. This type of generator presents some difficulties to ride-through voltage dips, because voltage dip generate high voltages and currents in the rotor circuit and the power converter could be damaged [1], [2]. This is the most extended variable speed wind turbine technology and manufacturers already offer this type of wind turbines with fault ride-through capabilities.

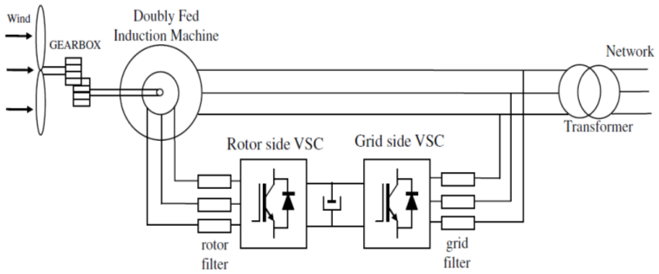


Fig. 2 Doubly Fed Induction Generator

C. Variable Speed Permanent Magnet Synchronous Generator

This generator is connected through a back-to-back converter to the grid. This provides maximum flexibility, enabling full real and reactive power control and fault ride-through capability during voltage dips [1], [2].

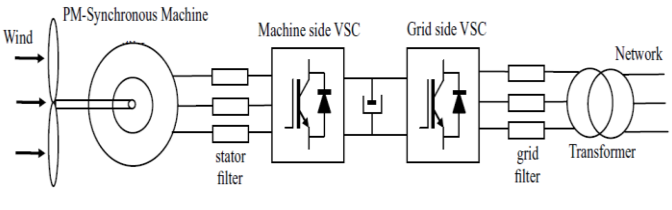


Fig. 3 Permanent Magnet Synchronous Generator

The synchronous generator–permanent magnet has the following main characteristics [1]

- Full operating speed range
- No brushes on the generator (reduced maintenance)
- Full scale power electronic converter
- Complete control of active power and reactive power exchanged with the grid
- Possibility to avoid gear
- Multi-pole generator
-

IV. PERMANENT MAGNET SYNCHRONOUS GENERATOR (PMSG)

Permanent magnet have been extensively used to replace the excitation winding in synchronous machines with the well known advantages of simple rotor design without field windings, slip-rings and excitation system. Hence, avoiding heat dissipation in the rotor winding and providing higher overall efficiency. Recently the PMSG is gaining lot of attention for WECS due to compact size, higher power density, reduced losses, high reliability and robustness [5], [10].The block diagram of PMSG based wind turbine is shown in Fig. 4 Moreover there is a need of low speed gearless generator, especially for off-shore wind applications, where the geared doubly fed induction generator or induction generator will require regular maintenance due to tearing-wearing in brushes and gear box. Both the brushes and gear box can be eliminated from WECS by using directly coupled low speed generators. Further, the elimination of gear box can increase the efficiency of wind turbine by 10%.

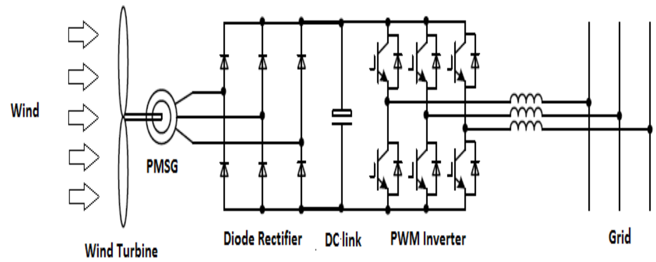
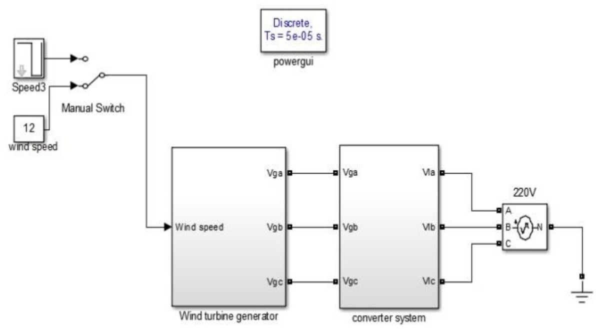
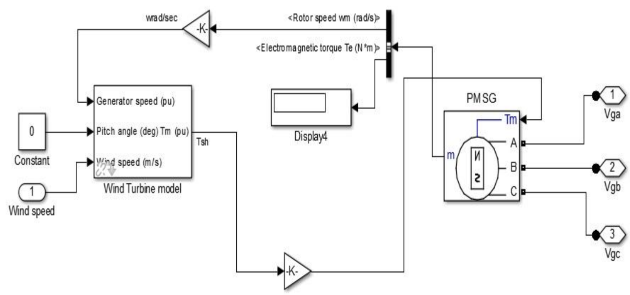


Fig. 4 Block diagram of PMSG based directly driven Wind Turbine



(a) Simulation block diagram of WECS



(b) Simulation of the wind connected PMSG

Fig. 5 Simulation block diagram of WECS (a) & Simulation of the wind connected PMSG (b)

The low speed PMSG requires:

- Higher number of poles to get suitable frequency at low speed
- Big rotor diameter for the high wind turbine torque

In case of asynchronous generators having large no. of poles, the magnetizing current is very high due to their low magnetizing reactance. Hence, for low speed operation, PMSG with large number of poles are highly beneficial.

A. Diode Rectifier

A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction. The process is known as rectification. For three-phase AC six diodes are used. Double diodes in series, with the anode of the first diode connected to the cathode of the second, are manufactured as a single component for this purpose. Some commercially available double diodes have all four terminals available so the user can configure them for single-phase split supply use, half a bridge, or three-phase rectifier. Many devices that generate alternating current (some such devices are called alternators) generate three-phase AC [5], [6]. For a three-phase full-wave rectifier with ideal thyristors, the average output voltage is

$$V_{dc} = V_{av} = \frac{\sqrt[3]{3}V_{peak}}{\pi}\cos\alpha$$

Where,

V_{dc}, V_{av}: the DC or average output voltage,
V_{peak}: the peak value of the phase input voltages,
Π: 3.14159
α: firing angle of the thyristor.

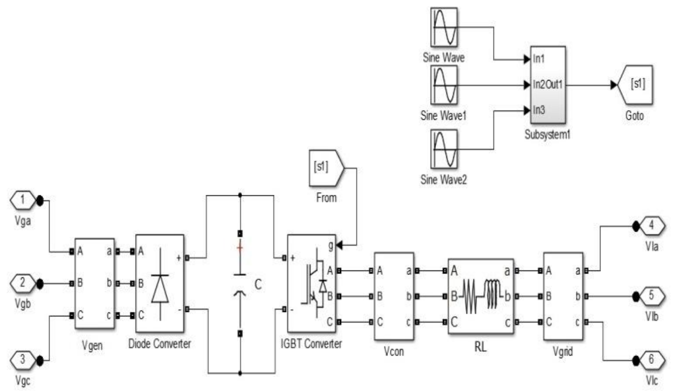


Fig. 6 Simulation of the PMSG based WECS with Diode Rectifier & Three Phase Inverter

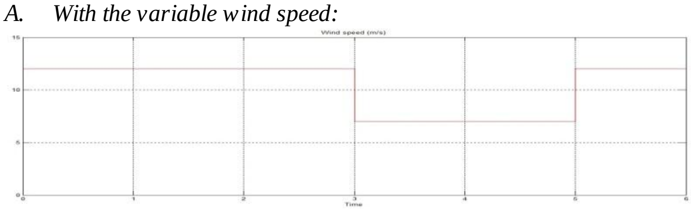
B. Three Phase Inverter

Three-phase inverters are used for variable-frequency drive applications and for high power applications such as HVDC power transmission. A basic three-phase inverter consists of three single-phase inverter switches each connected to one of the three load terminals. For the most basic control scheme, the operation of the three switches is coordinated so that one switch operates at each 60 degree point of the fundamental output waveform. This creates a line-to-line output waveform that has six steps. The six-step waveform has a zero-voltage step between the positive and negative sections of the square-wave such that the harmonics that are multiples of three are eliminated as described above. When carrier-based PWM techniques are applied to six-step waveforms, the basic overall shape, or envelope, of the waveform is retained so that the 3rd harmonic and its multiples are cancelled. To construct inverters with higher power ratings, two six-step three-phase inverters can be connected in parallel for a higher current rating or in series for a higher voltage rating. In either case, the output waveforms are phase shifted to obtain a 12-step waveform [6]. If additional inverters are combined, an 18-step inverter is obtained with three inverters etc. Although inverters are usually combined for the purpose of achieving increased voltage or current ratings, the quality of the waveform is improved as well[5].

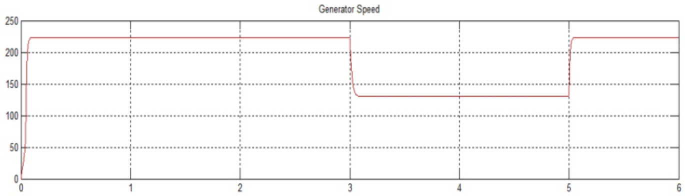
V. SIMULATION RESULT

The proposed technique is applied to the 5.7 kW wind turbine system described in the Appendix, simulated using MATLAB/Simulink. It is assumed that the wind speed starts at 12m/s, is changed to 7 m/s after 3 s and increased again to 12 m/s at t=5 s as shown in Fig. 7(a). It is noticed from Fig. 7(b) that at starting it takes about 0.2 s to reach its rated speed according to the turbine starting characteristics. This wind regime is chosen to test the proposed control technique and the proposed reduced switches converter in cases of increasing and decreasing wind speed. In Fig. 7(a) the wind speed is decreased to 7 m/s after 3 s. It is noticed that the generator speed falls from its rated speed of 230 to 270 RPM that corresponds to the new wind speed, as shown in Fig. 7(b). Then MPPT takes over and produces a generator torque that matches the aerodynamic torque to keep the turbine operating at its optimal condition as shown in Fig. 7(c).

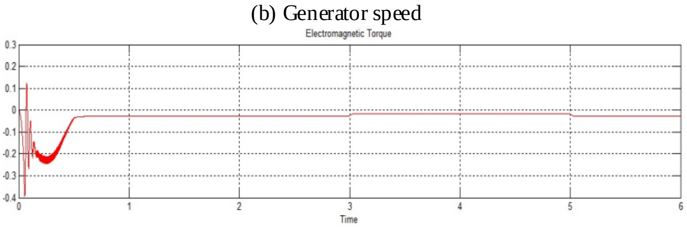
A. *With the variable wind speed:*



(a)



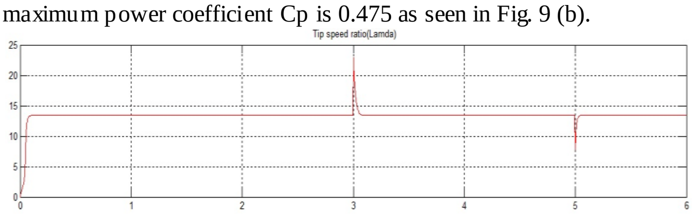
(b) Generator speed



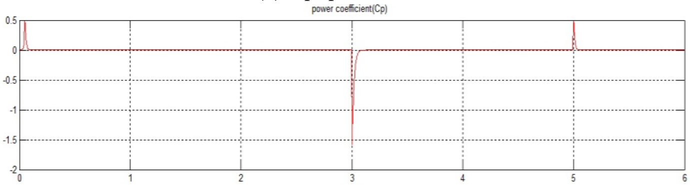
(c) Electromagnetic Torque

Fig. 8 Wind speed (a), Generator Speed (b) and Electromagnetic Torque(c)

The tip speed ratio is kept constant at 7.1 as seen in Fig.9 (a). It means that the controller of MPPT is effective at different wind speeds and it changes according to step changes in wind speed. The maximum power coefficient Cp is 0.475 as seen in Fig. 9 (b).



(a) Tip speed ratio



(b) Power coefficient

Fig. 9 Tip Speed Ratio (a), Power co-efficient (b)

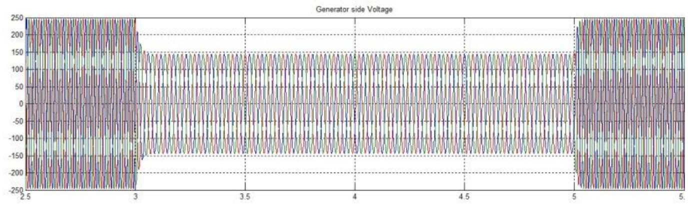


Fig. 10 Output Voltage of Generator

The grid phase voltage and current for phases A, B and C are shown in Fig. 9 It is clear that the current delivered to the grid is 1800 out of phase with respect to the voltage, that is the power delivered to the grid is negative as per the sign convention used and that the reactive power delivered to the grid is zero.

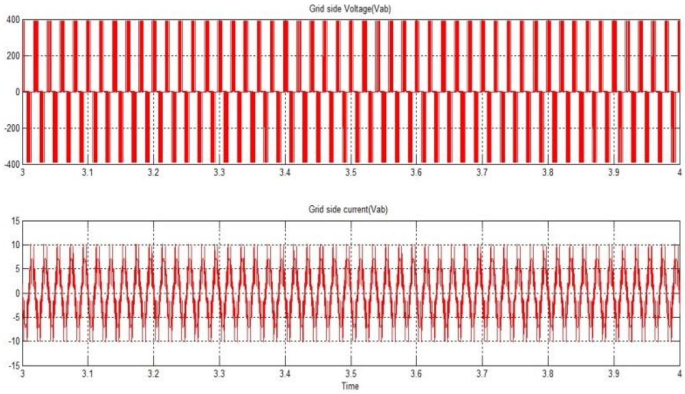
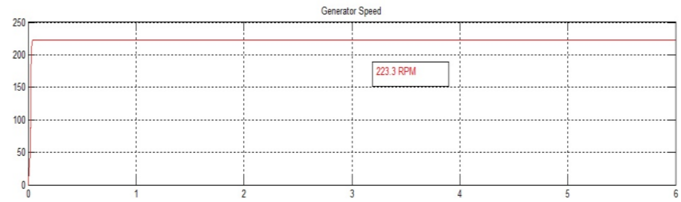


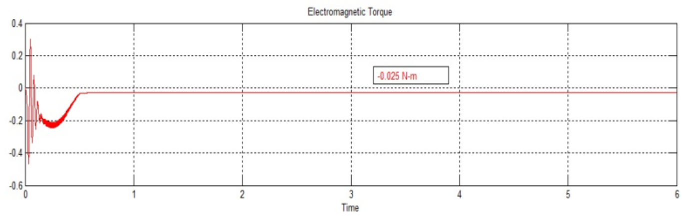
Fig. 11 Grid Side Voltage and Current

B. Simulation result with the fixed wind speed:

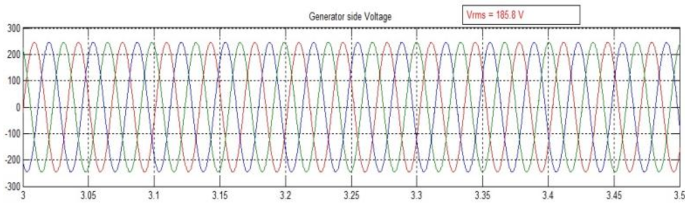
1. At Wind speed 12m/s:



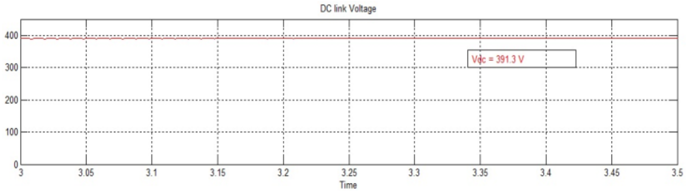
(a) Generator speed



(b) Electromagnetic Torque



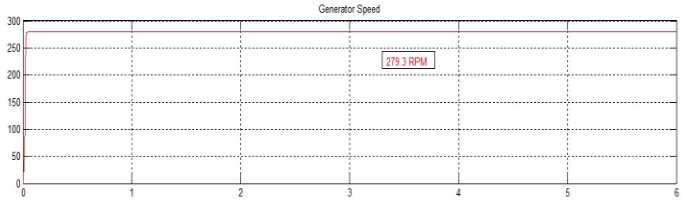
(c) Output voltage of Generator



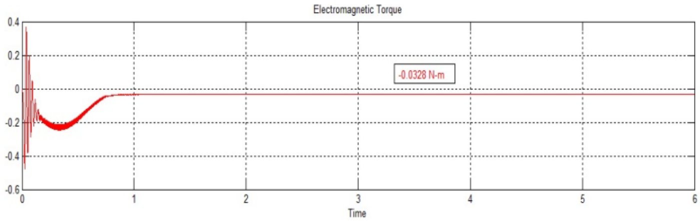
(d) DC link Voltage

Fig. 12 simulation of fixed wind speed at 12m/s (a) Generator Speed, (b) Electromagnetic Torque, (c) Generator voltage and (d) DC link voltage.

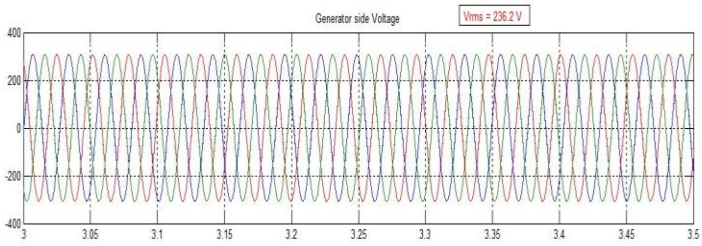
2. At Wind speed 15m/s:



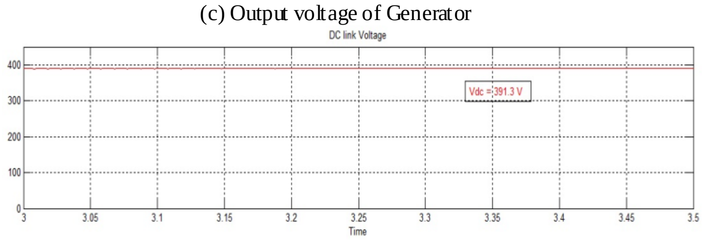
(a) Generator speed



(b) Electromagnetic Torque



(c) Output voltage of Generator



(d) DC link Voltage

Fig. 13 simulation of fixed wind speed at 15m/s (a) Generator Speed, (b) Electromagnetic Torque, (c) Generator voltage and (d) DC link voltage.

Table 1 Observation Result

Wind	Wind Speed (M/S)	Generator Speed(Rpm)	Generator Voltage (V)	Dc Link Voltage (V)
Variable	12-7-12	230	190.1	391.9
Fixed	12	223.3	185.8	391.9
	15	279.3	236.2	391.9

VI. CONCLUSION

This paper carried out a study on principle of PMSG based wind turbine. A wind turbine can keep continuous operation during fixed wind speed & variable wind speed. In this paper shown that the whenever the wind speed varies, change in the generator speed and also change in the generator output voltage.

APPENDIX

Simulation Parameters

5.7 KW Wind Turbine Parameters

Rotor diameter: 5 m
Rotor rated speed: 270 r.p.m
Cut-in wind speed: 2.5 m/s
Rated wind speed: 10 m/s
C_{pmax} : 0.475
Rated frequency: 36 Hz:
Rated speed: 270 r.p.m
Ld = Lq: 14.04 mH
Magnetic flux: 0.76 Wb
Rs: 1.5Ω
Pole pairs: 8
Inertia: 0.138kg.m2

Capacitors for DC Link:

C=2000 µf

Grid Parameters:

Phase voltage (RMS): 220 V
Frequency: 50 Hz

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