

Addendum of 2MW Wind Turbine to A Power with Directly-Driven Permanent Magnet Generation System

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Abstract.

In recent years, wind turbine has become an acceptable alternative energy generation, because of the environmental and economic benefits. Notwithstanding more research works still need to be done to reduce wind turbine installation complexity, enhance profitability and reliability especially in developing countries like Nigeria. This paper presents the modeling and analysis of a 2MW variable-speed directly-driven permanent magnet synchronous generator (PMSG), Wind energy conversion system (WECS). The objective is to optimize the power captured from the wind, ensure optimum efficiency for power generation and reduce system hardware count. The mathematical model for the permanent magnet synchronous wind turbine and its power control algorithms are modified by removing the speed sensors. Further, enhancement was achieved by utilizing wind speed forecasts as the starting speed. A modified Field Orientation Control FOC and voltage orientation control VOC scheme were developed for the system using matlab Simulink CAD application. The Simulation results of the model for various changes in wind speed utilizing average wind speed data of Mmaku in Awgu local government area of Enugu state Nigeria. The developed system ability to 'smoothen' the power, voltage output and operates at the optimum coefficient of performance between the cut in speed of 3m/s and 12m/s without wind sensor is found to be promising.

Key words: wind turbine, variable-speed, permanent magnet, synchronous generator, efficiency

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1.0 Introduction

The African Development Bank (AfDB) estimated Nigeria electricity supply per capita from the national grid to be less than 0.8kwh and below 50% access in 2009 from 151.3kWh /capita and 67% access in 2000. This is against the estimated per capita of 1416.87Kwh and 95% access to public power supply based on country with similarity in terms of education and lifestyle (Olanyande, J.S. & Rogo, 2010). Energy is an essential input for economic growth; the lack of electricity restricts the development of all aspects of a normal modern life style. Nigeria, the most populous Black Country of the world, has experienced hampered economic and industrial growth primarily on account of inadequate and inefficient electricity generation and supply systems.

On the contrary Nigeria is blessed with evenly distributed and abundant renewable energy resources such as waterfalls that can power small hydro dams, an average 10hours daily annual average sun shine period and estimated wind speed of over 3m/s to 17m/s increasing from south to north (above the projected cut in speed of

2.5m/s for most turbines) (Illojeo, 2004). Renewable energy has the advantages that it is abundant, clean, and becoming increasingly economical. Infact, renewable energy sources help in reducing about 70 million metric tons of carbon emissions per year that would have been produced by fossil fuels (U.S. green house gas emissions, 2007)

Most of the wind turbines applied in industry is variable-speed wind turbines. Among various types of variables peed WECSs, three kinds are most widely applied in industry:

(i) Doubly-fed induction generator (DFIG) WECSs with reduced-capacity power converters. (ii) Geared/gearless quirel-cage induction generator (SCIG) WECSs with full-capacity power converters. (iii) Geared/gearless Wound-Rotor Synchronous Generator (WRSG)/ Permanent Magnet Synchronous Generator (PMSG) WECSs with full-capacity power converters (B.Wu Y. L.,2011).

Large scale wind turbines (up to 10MW) seems to attracts more and more research attention, the direct-drive PMSG based WECSs which are very suitable for large scale wind plants have become a "trending topic". The direct-drive wind turbine PMSGs does not have the gear box between the wind turbine and the PMSG rotor shaft, thus avoids the mechanical power losses caused by the gear box. Further more, the removal of the gear box also helps in reducing the cost of the system.

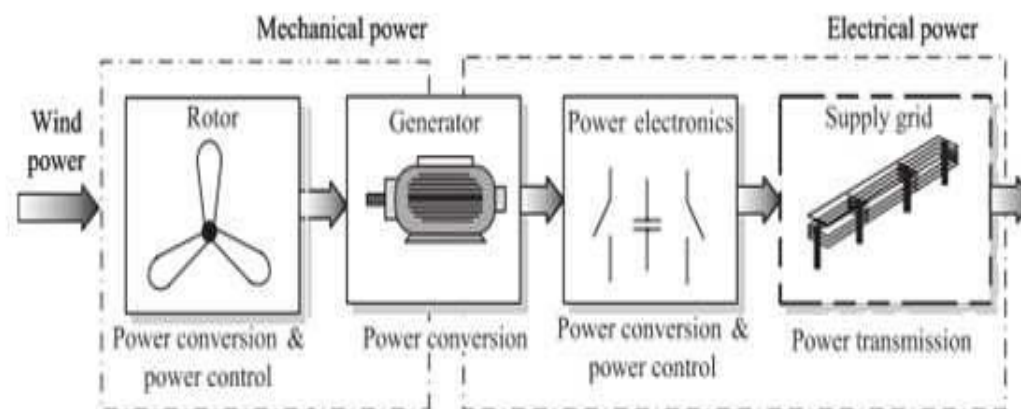


Figure 1.1 System configuration of the direct drive wind

The overall configuration of a direct-drive wind turbine PMSG system is shown in Figure 1.4. From this figure, this system is composed of a wind turbine PMSG, a rectifier, and an inverter. The wind turbine PMSG transforms the mechanical power from the wind into the electrical power, while the rectifier converts the AC power into DC power and controls the speed of the PMSG. The controllable inverter helps in converting the DC power to variable frequency and magnitude AC power. With the voltage oriented control VOC algorithm, the inverter also possesses the ability to control the active and reactive powers injected into the grid.

In control of direct-drive PMSG systems, the information of the rotor position and Speed is needed to implement the advanced control algorithms such as the field oriented control (FOC) and direct torque control (DTC). Conventional methods to acquire the rotor position and speed information are based on an encoder or a transducer mounted on the rotor shaft. However, such electrical speed sensors increase the hardware count, complexity and system cost. In addition, the rotor mounted sensors have to endure the constant oscillations of the rotor shaft, which reduces the reliability of the system. Speed sensor failures cause more than 14% of failures in such WECSs (Bertling,2005). The malfunction of the speed sensor will cause the breakdown of the whole system, which will contribute to considerable losses in power production. Additionally, the repair of the failed components results in increase operational cost.

Furthermore, wind speed measurements as a control variable can make the system un-reliable and can lead to considerable trouble (Hau,2006). Usually, the wind speed is measured on the nacelle roof, and the wind speed upstream is estimated. This method of wind measurement shows a discrepancy of 2 to 3m/s (Hau,2006). The accuracy of these measurement devices is about $\pm 2\%$ and they are very sensitive to the air flow around then

acelle. The time response of the anemometer is also large compared to the electrical system's response. Anemometers generate an electrical signal from a rotating spindle, and then the signal is sent to the controller. Nevertheless, the best representation of the wind speed is the rotor power. In an ideal system the rotor power will be equal to the electric power, thus by measuring the electric power we will be able to determine the wind speed, control the wind turbine and make the system more reliable. Further improvement is possible by utilizing wind speed forecast value as the starting or estimated speed. This will in turn reduce considerably the system iteration time and facilitate fast convergence. Based on the mentioned issues, this work proposes a back EMF based rotor position and modified sensor less control approach.

In this work a models for the permanent magnet synchronous wind turbine are evaluated and modified optimal power control system model is developed with intension to control a variable speed wind turbine to maximize the power extraction from the wind. This work: (i) computes expected maximum power based on metrological forecast of the wind speed, and select most appropriate blade angle or λ (ii) calculates the rotor position based on same (iii) The electric power, Ac voltage (V_{abc}) and current ($I_{a,b,c}$) components of the PMGS is modeled to estimate the wind speed and rotor angle in six iteration cycle per second (6hz.). These two variables are compared with the calculated (reference value) and measured value and discrepancies feedback into the controller until both measurement converges (optimized) without wind speed sensor. (iv) The developed model performance is tested on matlab Simulink for efficiency. Enugu is situated at 6.44° North latitude, 7.49° East longitude and 248 meters elevation above the sea level. (Most complex maps for all cities in the world, 2015). The State occupies much of the high lands of Awgu, Udi and Nsukka Fig 1.5 Area view of coal mine Enugu.



Figure 1.2 Area view of Mmaku hill, Awgu

The hills are 300 to 1,000 metres (3,300ft) above sea level, and are flanked by the rolling low lands of border towns (Egboka, 1985). This offers ideal site for installation of wind turbine due to reduction of in-wind turbulence and higher wind speed at the elevated plains. Therefore, Mmaku in Awgu Local Government Area, Enugu is chosen as test study site in this work.

2.0 Methods:

Synchronous machines are Ac rotating machines that rotate at a speed proportional to the armature current frequency. In this type of machine the magnetic field created by the armature currents rotate at the same speed as that created by the field current on the rotor. Synchronous machines have been used for many

years as generators of large power plants such as turbine generators and hydroelectric generators. These synchronous generators are normally used at constant speed and are connected directly to the electric grid. For variable speed applications permanent magnet synchronous machine (PMSM) are used and are quickly becoming the next-generation variable speed Ac motor drives due to the availability of high-energy permanent magnet materials. The PMSM has widely found its application as a high performance machine drive because of the ripple free torque characteristics and simple control strategies. Compared to induction machine drives, the PMSM has less rotor losses hence, it is potentially more efficient. In addition, the PMSM can achieve higher torque densities than its wound rotor counterpart.

Permanent magnet synchronous machines have lower reactance values than their equivalent rotor wound machines. In addition, PMSM are more power dense than their rotor wounded counter parts and they can provide full rotor flux at all times. Due to these characteristics, permanent magnet synchronous generators (PMSG) have high peak torque capabilities that would be beneficial to a wind turbine system during wind gust. These machine scan also resist repetitive torque pulsations of up to 20% of the rated torque (Bhadra,2005).For EMF and estimation of the rotor position and speed, David (1999), Spurpeon (1998)& Kang (2004)

2.1 Modeling of Control Scheme of WECS

In this session, the mathematical models of the wind turbine and the PMSG is developed and analyzed. These further deepens the understanding of the control modeling for the generator and grid side control system. Modeling is a basic tool for engineering analysis, such as: project optimization, design and control. Wind energy conversion systems are very different in nature from conventional generators, and therefore dynamic studies must be addressed in order to integrate wind power into the power system. Mathematical models utilized for steady-state analysis are extremely simple, while the dynamic models for wind energy conversion systems are not easy to develop. Dynamic modeling is needed for various types of analysis related to system dynamics: stability, control system and optimization.

2.1.1 Wind Turbine Aerodynamic Model

The main components of a direct-drive permanent magnet synchronous generator (PMSG) wind turbine are the wind turbine and the PMSG. The wind turbine captures the power from the wind for the system, and the PMSG transforms the mechanical power into electric power.

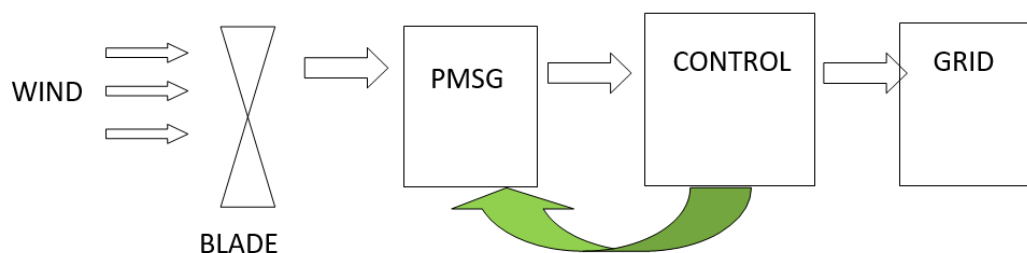


Figure 2.1 WEC Control System Block Representation

In order to investigate the effectiveness so the energy conversion in wind energy conversion systems WECS, first the available energy stored in the wind needs to be determined. The energy in the wind can be treated as the kinetic energy of a large amount of air particles with. A total mass, m , moving at a wind velocity, V_{air} . Assuming that all the air particles are moving at the same speed and direction before impacting the rotor blades of the wind turbine, the potential available (kinetic energy stored) in the wind can be expressed according to the following expression:

$$E = \frac{1}{2} m V_{air}^2 \quad (2.1)$$

Where, E , is the kinetic energy of the moving air particles, and the total mass of the air particles, while, V_{air} , is the velocity of the air particles (wind speed). Since the air particles are moving at a speed, V_{air} , the total mass, M , of the particles for a period of time, t , can be rewritten as follows:

$$\begin{aligned} m &= \rho \times A \times V_{\text{air}} \times t \\ &= \rho \pi r^2 \times V_{\text{air}} \times t \end{aligned} \quad (2.2)$$

Where, ρ , is the air density, and A is the swept area of the wind turbine rotor. Here, r , is the radius of the wind turbine rotor.

3.0 Results and Discussion

In this section the simulation model of the wind turbine is implemented. Fig. 2.1 shows the complete system model diagram in which each block represents a sub-system of the system. There is a mathematical model for each sub system. In the previous section model and power capacity of the wind turbine, the generator, the dc-to-dc converter and dc-to-ac inverter was simulated.

3.1 Wind Turbine Model

The amount of power that a wind turbine can extract from the wind depends on the turbine design. Factors such as the rotor diameter and the wind speed affect the amount of power that a turbine can extract from the wind. The wind turbine was modeled using the mathematical equations shown in session 2. Table 3.1 shows the average recorded wind speed at 180m above sea level used in simulation model and table 3.2 shows the power capacity and parameters of the wind turbine.

3.2 Electrical System Model

The electrical system is formed by the permanent magnet machine, a passive rectifier, a dc-to-dc converter and a voltage source inverter. In the following section the electric machines parameters, the components of the electrical system and the simulation model of the electrical systems is shown. The value of the elements for the dc-to-dc converter and the inverter dc bus side were obtained using the design equations given in session 2.

3.3 Control Simulation Model

The model for the maximum power tracking algorithm and the dc-to-dc controller are shown in Fig. 3.4. The embedded MATLAB function contains the mathematical model that represents the maximum power tracker and developed PMSG control model. The triggered is set at a frequency of 10Hz; therefore running algorithm 6 times per second. Every time the model is run the power is calculated from projected wind speed and the controller reacts to the reference voltage commanded by the maximum power tracker. The generated EMF is compared with calculated and the difference is applied to MPPT in subsequent iteration. The inverter controller has two feedback loops, the generator side loop control the dc side voltage of the PMSG and the grid loop controls the active power injected into grid.

Table 3.2 Parameters and Operating Conditions of the Generator Side Control System (Vestas Wind Systems A/S,2014)

S/N	Technical specifications	Operational data
1	Rated power	2,000kW(50/60Hz)
2	Cut-in wind speed	3m/s
3	Rated wind speed	11.5m/s
4	Cut-out wind speed	20m/s
5	Wind class	IECIIIA
6	Operating temperature range standard turbine	20°Cto40°C
7	Operating temperature range low temperature turbine	-30°Cto40°C
	SOUND POWER	Max107.5dB
1	(Mode 0,10m above ground, hub height 80m, air density1.225kg/m ³)	
	Rotor	
1	Rotor diameter	110m
2	Sweptarea	9,503m ²
3	Airbrake full blade feathering with 3 pitch cylinders	
	Electrical	
1	Frequency	50/60Hz
2	Generator type 4- pole, PMS generator	(50Hz)/
3	Generator type 6-pole,slip rings	60Hz
	Gearbox	
		Type two planetary stages and One helical stage
	Tower	
1	Type	Tubular steel tower
2	Hub heights	95m and125m (50Hz)
		80m and95m (60Hz)
	Blade dimensions	
1	Length	54m
2	Max. Chord	3.9m
	Rated Mechanical Torque	848826Nm
	Rated Rotor Flux Linkage	5.8264(rms)
	Stator Winding Resistance	0.821mΩ
	D axis Synchronous Inductance	1.5731mH
	Q axis Synchronous Inductance	1.5731mH
	Wind Turbine Rotor Radius	34m
	Wind Turbine Optimal Tip Speed Ratio	6.16
	IGBT Modulation Frequency	1.5kHz

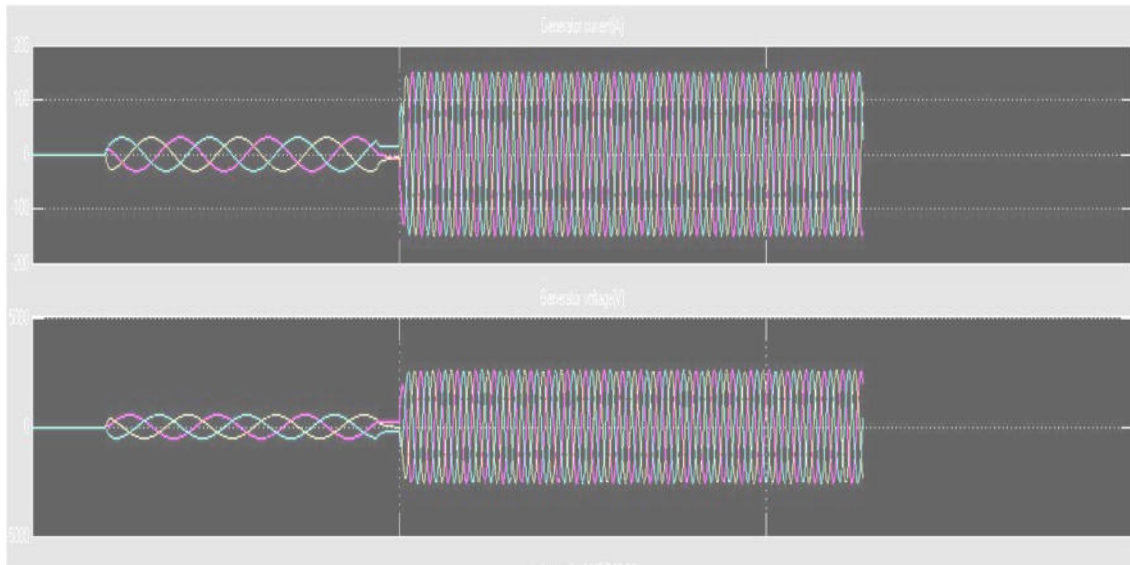


Figure 3.1 Generator current and voltage output waveform

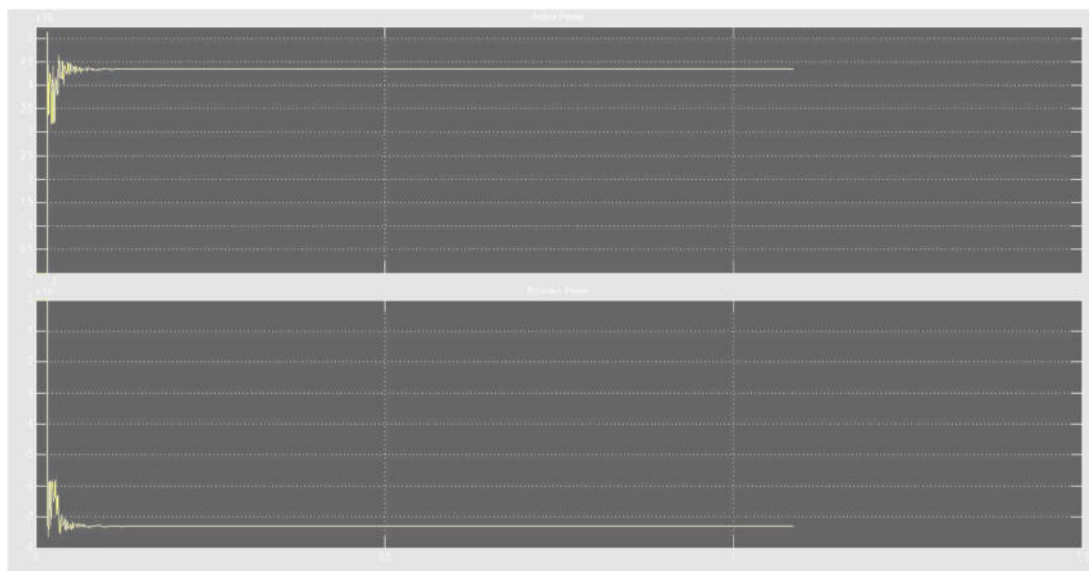


Figure 3.2 Wind speed & power (kw) output wave form

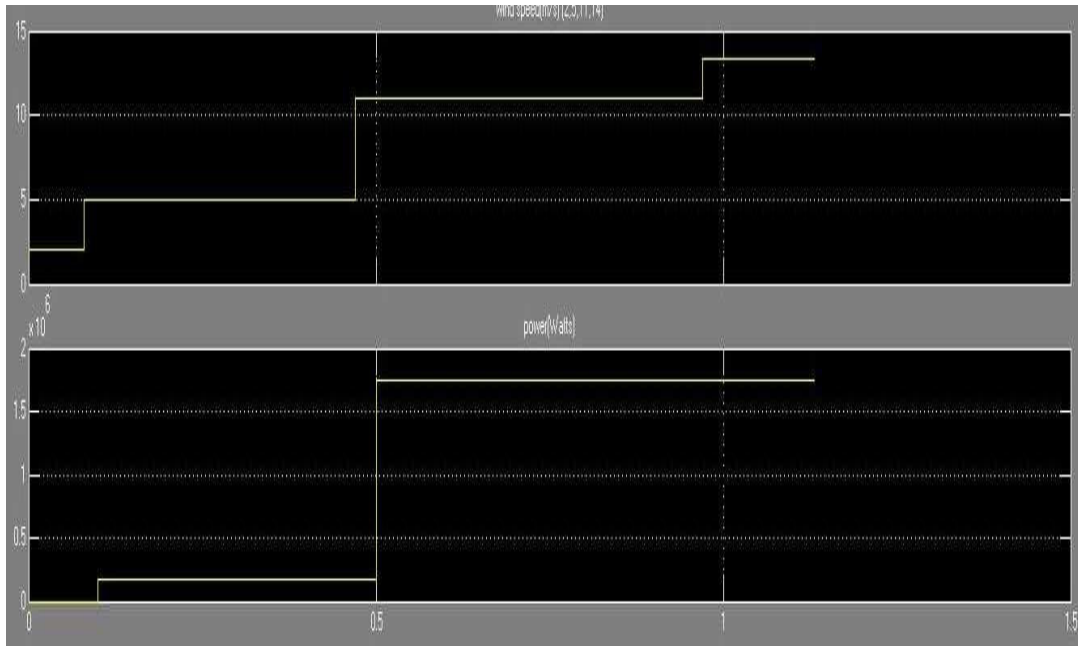


Figure 3.3: Active and output wave form

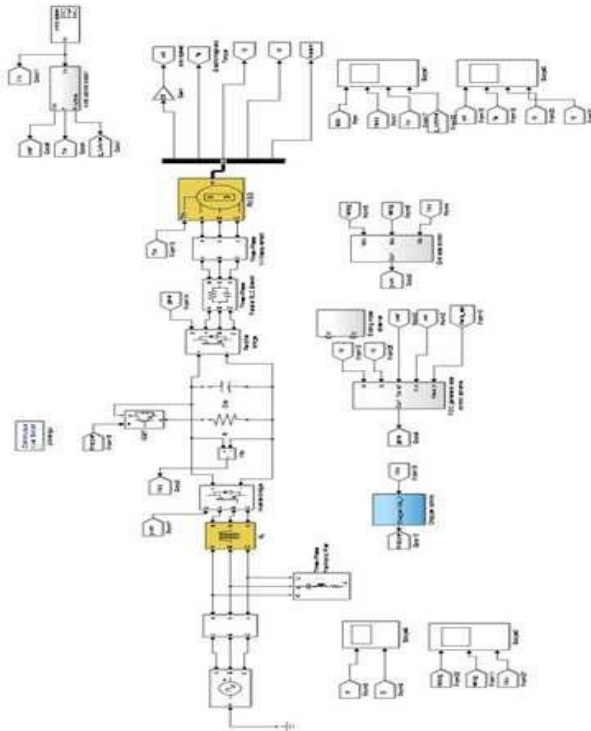


Figure 3.4 .Matlab power system model

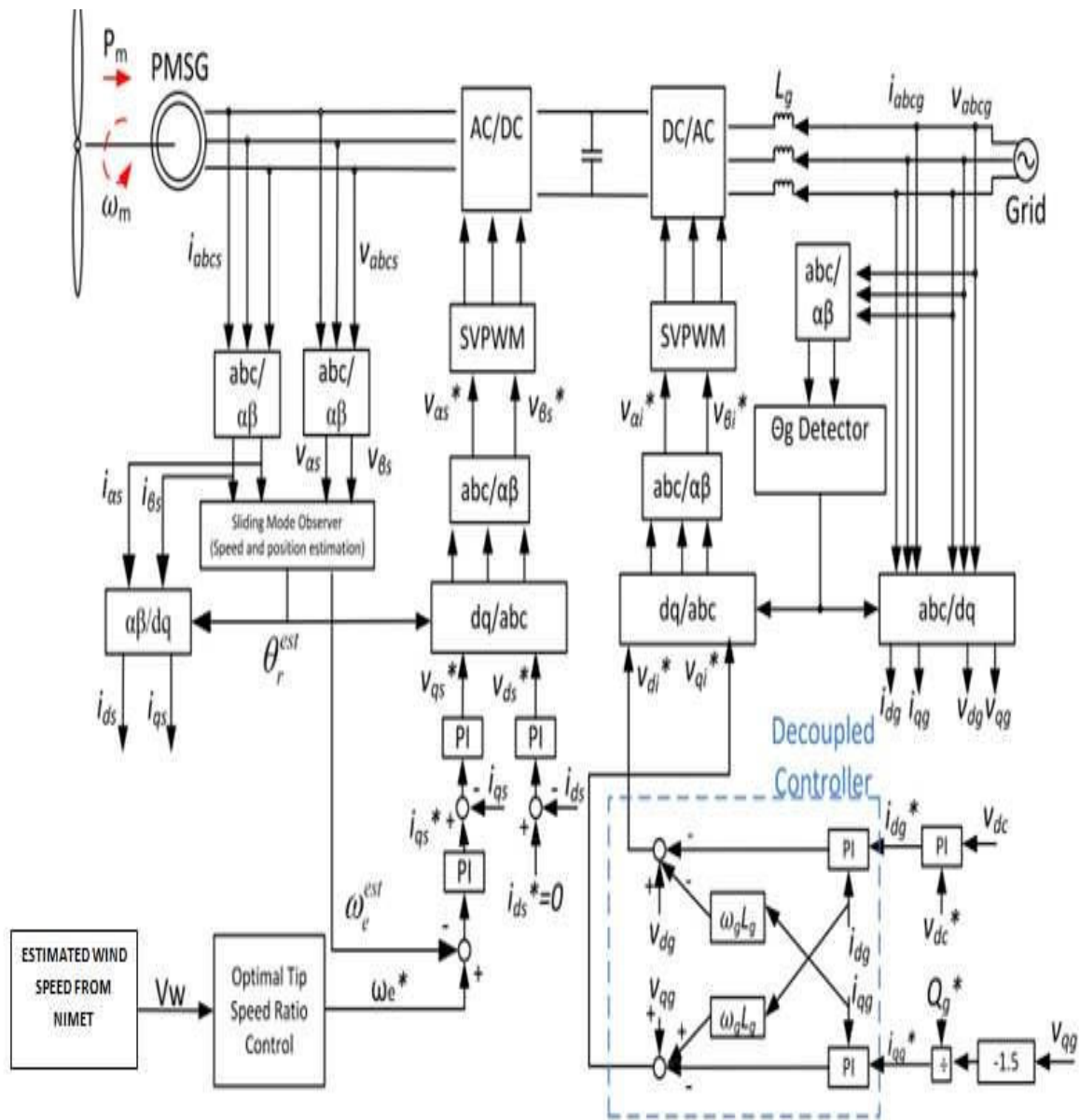


Figure 3.5. Control scheme of the wind turbine generation system including the sliding mode observer

4.0 Conclusions

This work has presented and analyzed modified sensor less control algorithms for the wind turbine PMSG systems. This control methods is further validated by its application by simulation to a case study of 2MW wind turbine PMSG system. A simulation study was performed for generator-side converter control, the MPPT control algorithm and vector control method were applied. The simulation results shows capability of the modified sensor less model to control: the MPPT, PMSG to generate the maximum power at 3m/s to 12m/s typical meteorological wind speeds of Enugu state. We observed high dynamic performance of the vector control method when the wind speed changed, the generator speed which was controlled by the vector control algorithm reacted to the wind speed change very fast. Thus, for the wind turbine PMSG systems that require high dynamic performance and high power capture efficiency, the modified model of FOC and vector control algorithms were proven to be efficient. It also shows good control of VOC algorithm; its capability to control the active power and reactive

power injected into the grid easily with high dynamic performance. Our developed modified sliding mode observer based PMSG rotor position and speed self-sensing control applied to the system also show a lot of superiority. The simulation results indicated that the estimated rotor position and speed correspond to their actual values very well.

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