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Sensorless Speed Estimation of Permanent Magnet Synchronous Generator for Wind Energy Conversion System

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ABSTRACT

In this paper comparative study of Flux estimation method and model reference adaptive system speed observers in permanent magnet synchronous generatoris done.The mechanical sensors equipped wind turbine generator measure the speed and rotor position which increases the size, price and reduces the reliability of the wind system. In this paper, sensor-less control is applied to permanent magnet synchronous generator which increases the reliability of the system. The mathematical model was established for the sensor-less Field oriented control of Permanent Magnet Synchronous Generator, which estimates the speed. The speed is determined by the methods flux estimation and model reference adaptive system. Comparative studies of both the methods control were done. Simulation studies validate the results. The simulation is done in Mat LAB/ Simulink.

Index Terms**:** Permanent Magnet Synchronous Generator (PMSG), Field Oriented Control (FOC), Flux Estimation, Model Reference Adaptive System (MRAS), estimated speed, optimum speed.

I. INTRODUCTION

Wind Energy Conversion System

In recent times, there has been a transfer to renewable energy resources (the wind, solar, biomass, hybrid, etc.) due to increasing awareness about global warming caused by the emission of carbon from conventional energy resources. So wind power has been an alternate to fossil fuels, which doesn't produce any flue gasses. According to World Wind Energy Association, the wind energy capacity has expanded to 370 GW by February 2015 and has reached around 4% of worldwide electricity usage [1].

Permanent Magnet Synchronous Generator is widely used in WECS as it has minimum inertia when connected to power converter gearbox can be eliminated, fast response, high power density, and high efficiency [11]. When compared to Induction Generators PMSG is smaller, easy to control and more efficient. PMSG can operate at variable speeds so that maximum power could extract even when it is rotating at small or medium speeds [1]. The accurate position and speed estimation of the generator are required for high performance of field oriented control. Conventionally position of the rotor is determined by a encoder, which may damage and effect reliability. Sensor causes drawbacks like requiring maintenance, complexity, increased cost, size and gross errors due to which system will be unstable. Therefore sensor-less control methods are developed for the control of the generator for estimating the speed and position by the measurement of voltage and current of the generator.Several techniques are present for sensor-less control [2].

In Digital phase-locked loop for sensor-less vector control controls the frequency of output signal by a control signal that is proportional to the change in the output signal and the input signal. This technique

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doesn't work well when a machine runs at low speeds [4]. In Robust Extended Kalman Filter, though the gross error of estimation is low but complex calculations were involved which are time-consuming and tough [8]. In High-Frequency signal injection method, though it is valid at low and zero speeds but requires an additional carrier signal, which results in unnecessary losses thereby causing distortion of current and torque of the generator. [7].

This paper studies the performance of two types of sensor-less control of PMSG based WECS, the Flux estimation method and Model Reference Adaptive System. The performance of the both the algorithm is observed through comparison. Simulation is carried out using MATLAB. A comparison based on settling time of speed, estimation of speed is shown. The outcome of both the methods are observed through the simulation.

II. WIND TURBINE MODEL

The turbine converts wind energy into mechanical torque. The mechanical torque can be obtained from mechanical power. The mathematical equation of wind turbine is given below

The out power of the wind turbine is given by

$$P_m = 0.5\,\rho\,\pi\,R^2\,V_W^3\,C_p(\lambda,\beta) \tag{1}$$

Where, P_m is a mechanical power of the wind turbine in watts, C_p is the power coefficient, ñ is the density of air in kg/m^3, V_m is the wind speed in m/sec. R is the blade radius in meters,â is the pitch angle, ë is the tip speed ratio.

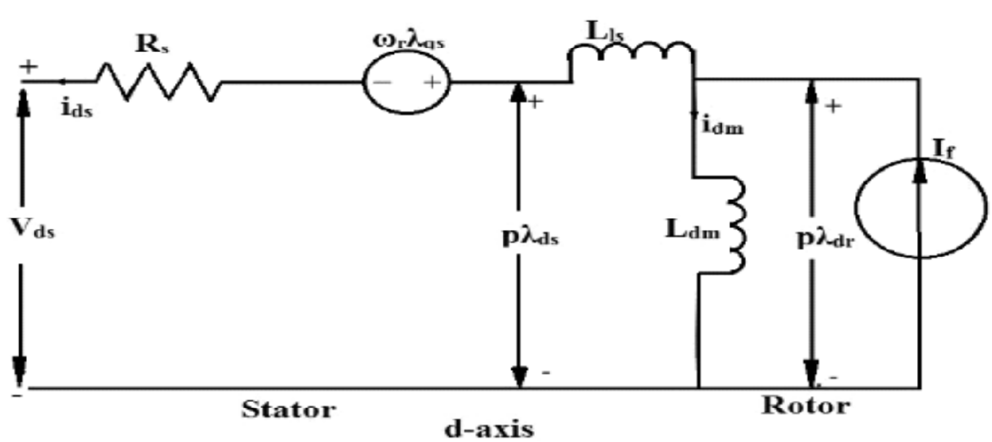
General equation to model coefficient of performance C_p is given by

$$C_p(\lambda,\beta) = C_1\left[\frac{C_2}{C_3} - C_3\beta - C_4\right]e^{\frac{C5}{\lambda_i}} + C_6\lambda \tag{2}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 \quad +1} \tag{3}$$

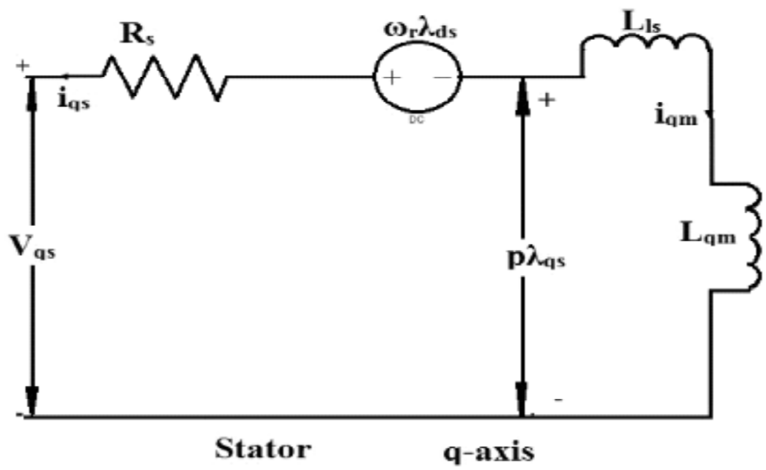
III. MODELING OF PMSG

The mathematical model of PMSG was derived from stator and rotor equations in the d-q reference frame. The d-axis and q-axis circuits of PMSG are as shown below:



(a)

Figure 1(a): d-axis Equivalent circuit of PMSG



(b)

Figure 1(b): q-axis Equivalent circuit of PMSG

Voltage equations of d-q axis are given below:

$$V_{ds} = -R_s i_{ds} - \omega_r \lambda_{qs} + p\lambda_{ds} \tag{4}$$

$$V_{qs} = -R_s\, i_{qs} + \omega_r \lambda_{ds} + p\lambda_{qs} \tag{5}$$

Where V_{ds} and V_{qs} are the stator d and q axis voltages, i_{ds} and i_{qs} are the stator d and q axis currents R_s denotes stator resistance, λ_{ds} and λ_{qs} are the stator d and q axis inductances, ù$_r$ is rotor speed.

Electromagnetic torque developed is given by expression:

$$T_s = \frac{3}{2} p\,(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}) \tag{6}$$

Where T_e is electromagnetic torque and p is no of pole pairs.

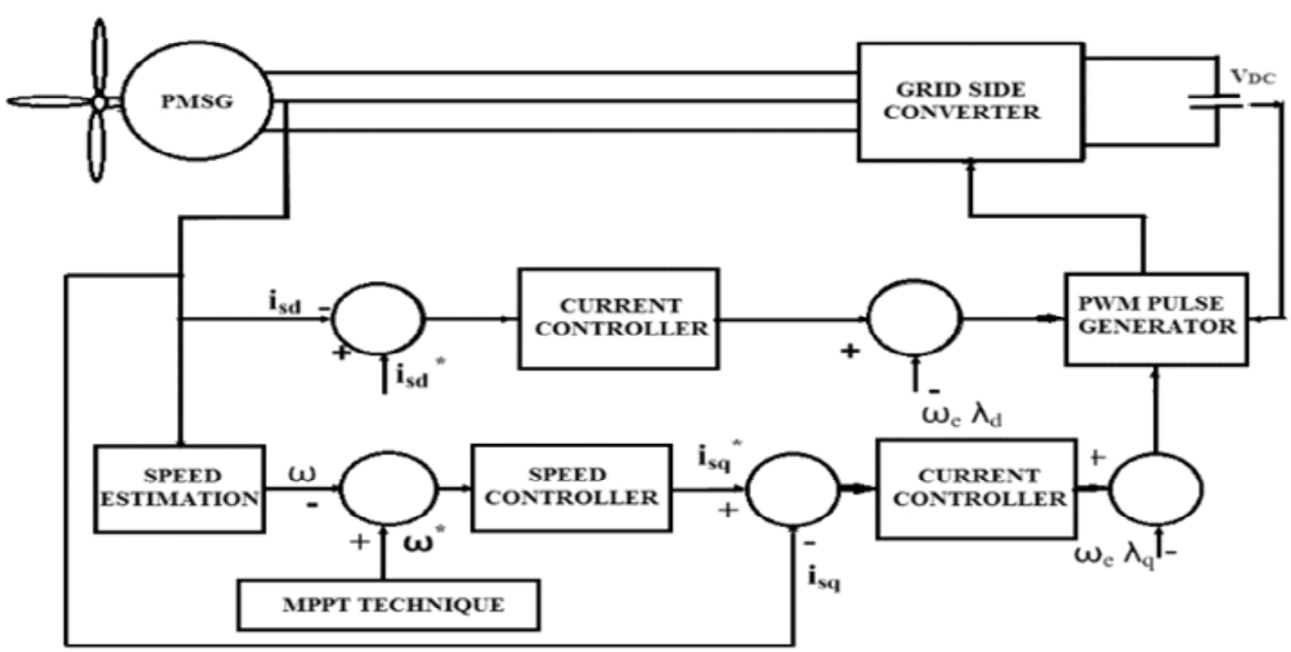


Figure 2: Sensor-less vector control of PMSG based wind turbine

II. BLOCK DIAGRAM

Field oriented control (FOC) is one of the most popular control techniques as it enables PMSG to execute high-performance level. The FOC algorithm block diagram is shown in the Fig 2.The algorithm regulates the generator speed. The algorithm is performed in two control loops, speed and current control loop.Torque is a function of i_d and i_q current components, torque can be controlled indirectly by making i_d component to zero and controlling i_q component. Torque angle is kept at right angle. In this paper, MPPT with PI controller is used. The input to the controller is the error between the estimated speed and the optimum speed from MPPT.

III. FLUX ESTIMATION METHOD

This method is used for estimating rotor position using flux linkage equations. Initial position of rotor was estimated from the flux linkages using stator currents and inductances. This estimation method involves five steps. In the first step stator flux linkages are estimated, in the next step from estimated flux stator current is estimated, and from estimated current and the predicted position in the last step position was corrected. In the next step flux linkage is updated and from the updated flux position is predicted.

Step 1: Estimation of Stator Flux Linkages

In this step, stator flux is estimated by integrating the difference between the stator voltage and the voltage drop, rectangular rule is used.

Stator flux linkages are obtained as

$$\lambda_{qs}(t) = T_s[V_{qs}(t-1) - R_s i_{qs}(t)] + \lambda_{qs}(t-1) \tag{7}$$

$$\lambda_{ds}(t) = T_s[V_{ds}(t-1) - R_s i_{ds}(t)] + \lambda_{ds}(t-1) \tag{8}$$

Where T is sampling time and t is the sampling number, i_{qs} and i_{ds} are obtained by transforming measured three-phase current components to two phase stationary reference frame current components. Drift problem arises in the flux values due to integration, to avoid it estimated flux is updated in step four which uses corrected rotor position and measured current. These updated fluxes are used for estimation of fluxes in the next sampling period.

Step 2: Stator Current Estimation

In this step stator current is estimated using estimated flux in the previous step and predicted rotor position.

Stator current estimation equations are obtained as

$$i_{ds} = \frac{L\lambda_{ds}(t) - L\lambda_m \cos(\theta_{rp}(t))}{L^2} \tag{9}$$

$$i_{qs} = \frac{L\lambda_{qs}(t) - L\lambda_m \sin(\theta_{rp}(t))}{L^2} \tag{10}$$

Step 3: Position Correction

In this step predicted position is corrected using the difference between actual and estimated stator currents.

Error in stator currents are calculated as below

$$\Delta i_{qs}(t) = i_{qs}(t) - i_{qs}(t) \tag{11}$$

$$\Delta i_{ds}(t) = i_{ds}(t) - i_{ds}(t) \tag{12}$$

Rotor position is corrected using following equation

$$\theta_r(t) = \theta_p(t) + \Delta\theta(t) \tag{13}$$

Where $\Delta\theta$ is calculated by error current,

$$\Delta\theta = \frac{-L_q \Delta i_q}{\lambda_m} \tag{14}$$

θ_r is corrected rotor angle, θ_p is predicted rotor angle.

Step 4: Flux Linkage Updating

In this step, estimated flux is updated using corrected rotor position and stator currents. Updated flux equations are as below

$$\lambda_{ds}(t) = L\, i_{ds} + \lambda_m \cos(\theta_r(t)) \tag{15}$$

$$\lambda_{qs}(t) = L\, i_{qs} + \lambda_m \sin(\theta_r(t)) \tag{16}$$

These updated fluxes are used to estimate flux in next sampling period in step1.

Step 5: Position Prediction

Considering that position varies with time as a second-order polynomial, position can predict as

$$\theta_{rp} = At^2 + Bt + C \tag{17}$$

Where A, B, C are constants.

Using three estimating sampling periods second order polynomial equation is solved.

Solving the above equation,

$$\theta_r(t+1) = 9AT_s^2 + 3BT_s + C \tag{18}$$

IV. MRAS ESTIMATOR

In this estimation method, the rotor speed is estimated using stator flux equations. MRAS has two models, one act as a reference model which depends only on stator currents to find the stator flux, other acts as an adaptive model which considers the rotor speed as an adjustable variable. The outputs of both the models compared in the adaptive mechanism, which consists of a PI controller to compensate error between those two models. Block diagram of MRAS is shown in the below figure 3.

The Stator flux equations are given below,

$$\lambda_{sd} = L_{sd}\, i_{sd} + \lambda_m \tag{19}$$

$$\lambda_{sq} = L_{sq}\, i_{sq} \tag{20}$$

$$\lambda^*{}_{sd} = \int \left(V_{sd} + \omega_{est} L_{sq} i_{sq} - R_s i_{sd}\right) dt \tag{21}$$

$$\lambda^*_{sq} = \int \left(V_{sq} - \omega_{est} L_{sq} i_{sd} - R_s i_{sq} + \lambda_m\right) dt \tag{22}$$

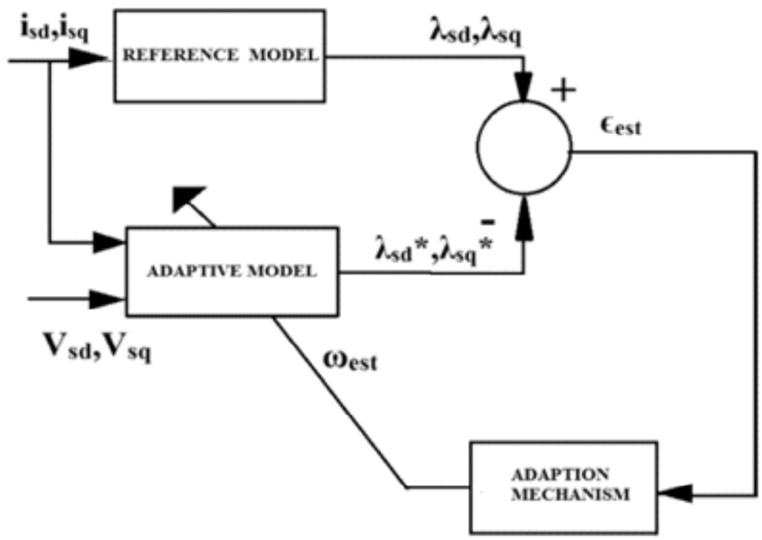


Figure 3: MRAS speed estimator

Estimated rotor speed is

$$\omega_{est} = \left(K_p + \frac{K_i}{s} \right) \left(\lambda_{sd}^* \ \lambda_{sq} - \lambda_{sq}^* \ \lambda_{sd} \right) \tag{23}$$

Where K_p and K_i are PI controller parameters.

V. RESULTS DISCUSSION

A steady state simulation has been done for flux estimation and Model Reference Adaptive System for a wind speed of 10 m/sec. PMSG output voltage for a base wind speed of 10m/sec shown in the Fig: 5.The electromagnetic torque of PMSG varies as indicated in the Fig: 6. Fig 7: displays the actual speed (rad/sec) of PMSG when wind speed is 10m/sec. Simulation results for flux estimation and MRAS method are shown in the fig: 8. According to the simulation results with the flux linkage shows settling time of 0.5 sec

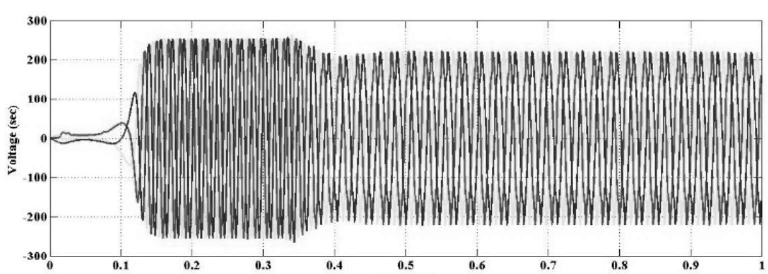


Figure 4: PMSG output voltage

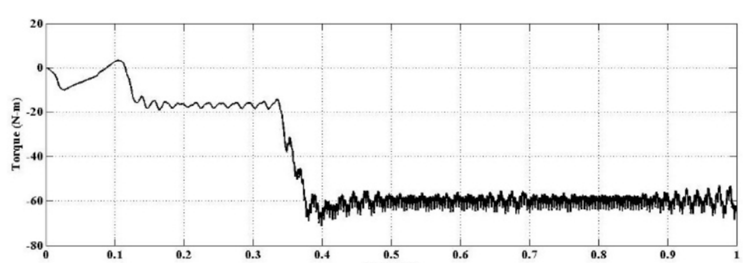


Figure 5: Electromagnetic Torque of PMSG

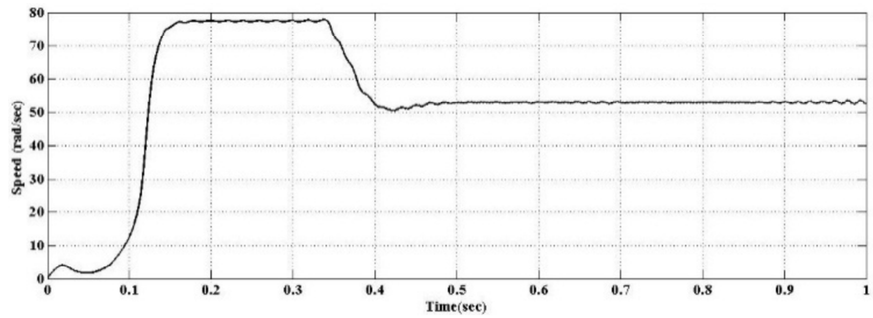


Figure 6: Actual speed of PMSG

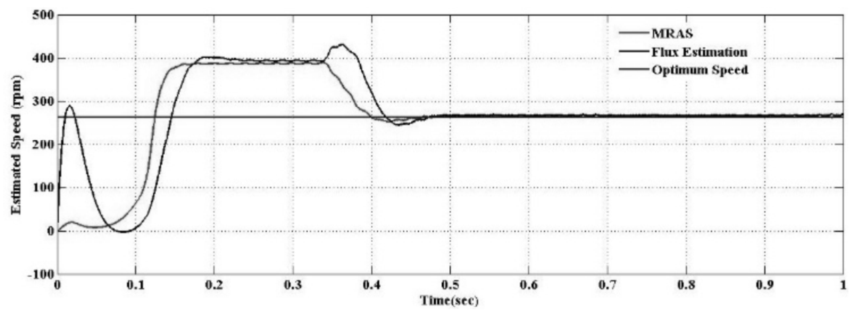


Figure 7: Comparison of speed estimation methods

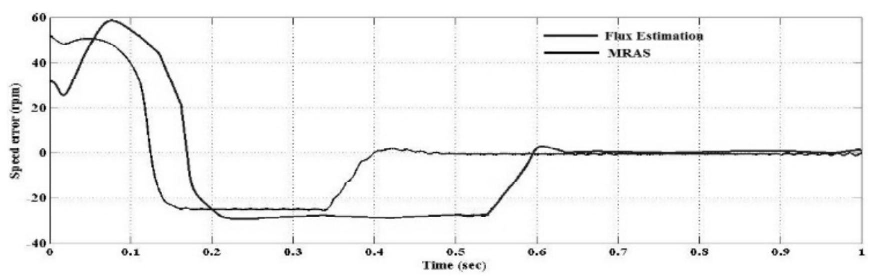


Figure 8: Speed error

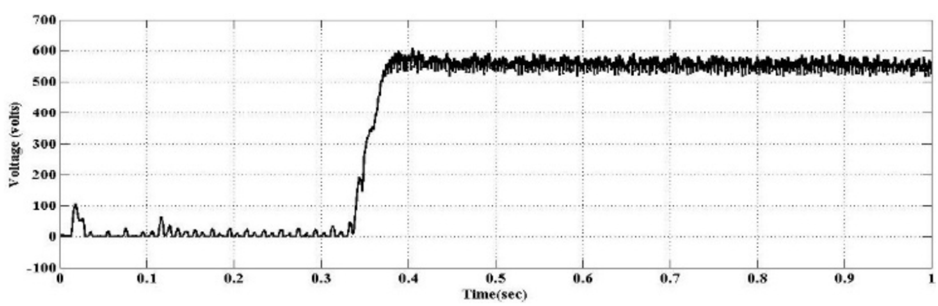


Figure 9: DC link voltage

whereas the MRAS estimated speed settles with optimum speed in 0.4sec. It has been observed that the performance of the MRAS method estimated speed follows the optimum speed.

Comparison of Various Estimation Methods:

Table 1
Comparison of various estimation methods

Method	*Settling time(sec)*	*Speed error settling time (sec)*
Flux Linkage Estimation Method	0.5	0.6
MRAS	0.4	0.4

The speed error graphs for the two systems are depicted in the fig: 9. the error reduced to zero at 0.4 sec for the MRAS and nearly 0.6 sec for the flux linkage method. Fig: 10 show the DC link voltage remains constant. The effectiveness of the MRAS method is observed with the simulation results.

VI. CONCLUSION

In this paper sensor-less field oriented control is used for WECS using PMSG. Speed observers were done with the flux linkage and MRAS method. Even though the calculation of flux estimation method is simple and less dependent on machine parameters, the response time is more due to the problem in the integration It is. observed that estimated speed is with good accuracy with optimum speed in MRAS method and the speed error also considerably reduced with this method. The simulation results have confirmed that the MRAS control strategy gives better performance for estimating the speed of PMSG.

VII. APPENDIX

PMSG: stator resistance per phase is 0.425 ohms, armature inductance is 0.008H, torque -70 Nm, no of poles 5, speed 500rpm. Wind Turbine: wind speed 10 m/sec, pitch angle 0 degree.

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