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Modelling of Permanent Magnet Axial Flux Synchronous Machine and Its Application to the Wind Energy Conversion

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Abstract: This paper presents the Modeling and Simulation of Axial Flux Permanent Magnet Synchronous Machine for Single and Double Stator configurations. It proposes the AFPMSM to be used in Wind Energy Conversion System as the replacement of conventional induction generator. The MPPT technique is incorporated to extract the maximum power and the comparison of output powers with and without MPPT is presented.
Keywords: Axial flux permanent magnet synchronous machine, modeling, TSAFPMSM, MPPT, MATLAB

I. Introduction

Based on the direction of air gap flux, the energy conversion rotating electric machines are broadly classified into Radial flux machines and Axial flux machines. Off-course the operating principle is same, but the construction is different in both the machines. In Radial flux machine conductors are parallel to the shaft and air gap flux is perpendicular to shaft axis whereas in axial flux machine the arrangement is just opposite.

In 1821, Faraday invented a primitive disc motor which was in the form of an Axial Flux Machine(RFM). However, since 1837, when Davenport claimed the first patent for a RFM, it became the accepted configuration for electrical machines. Since 1980 the applicability of axial flux machines to low-speed, direct-drive electrical drive applications has been found [i].

In Axial flux machine rotor has disc shape and stator of ring structured. The active part to produce the torque is the radial length from stator inner radius to the outer radius and it is dependent on flux density in the stator and rotor yokes. It is independent of number of poles. Because of the having higher pole number it is attractive for the applications of low speed and high torque.

The adoption of Axial Flux permanent magnet synchronous Machines in Wind Energy Conversion Systems exploits the advantages: The gear box of single stage is enough so that the cost and weight of the system reduce [ii]. Further, it decreases the friction and wind age losses and hence the system efficiency increases. And also the power output gets enhanced twice for the same turbine rotor diameter with the use of twin stator axial flux permanent magnet synchronous machine.

II. Modeling of Axial Flux Permanent Magnet Synchronous Machine (AFPMSM)

A) Single Air Gap AFPMSM:

The single air gap flux permanent magnet synchronous machine consists of one stator and one rotor. The equations which describe the performance of permanent magnet synchronous machine are independent of magnetic flux. The system equations of an axial flux permanent magnet synchronous machine in matrix form are given below.

$$\begin{bmatrix}[V_s]\\ [V_r]\end{bmatrix} = \begin{bmatrix}[R_s] & 0\\ 0 & [R_r]\end{bmatrix}\begin{bmatrix}[I_s]\\ [I_r]\end{bmatrix} + p\begin{bmatrix}[L_s] & [L_{sr}]\\ [L_{rs}] & [L_r]\end{bmatrix}\begin{bmatrix}[I_s]\\ [I_r]\end{bmatrix} \quad \ldots..(1)$$

The above equations are expressed in a simplified way as

$$[V] = [R][I] + p[L][I] \ldots\ldots \ldots..(2)$$

The generalized d-q axes models are used for analyses of machines. The voltage equations of single air gap flux permanent magnet synchronous machine are

$$\left.\begin{aligned} V_{ds} &= R_d i_{ds} + L_d p i_{ds} - \omega_r \lambda_{qs} \\ V_{qs} &= R_q i_{qs} + p\lambda_{qs} + \omega_r \lambda_{ds}\end{aligned}\right\} \ldots\ldots (3)$$

Where

$$\left.\begin{aligned} \lambda_{qs} &= L_q i_{qs} \\ \lambda_{ds} &= L_d i_{ds} + \lambda_{af}\end{aligned}\right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where p represents the differential operator

Equation (2) can be represented in StateVariable form as

$$\frac{d}{dt}[I] = [L]^{-1}[V] - [L]^{-1}[R][I] \quad \ldots\ldots\ldots (5)$$

The above equation can be solved in MATLAB using Runge-Kutta method to obtain d-q currents of both stator and rotor currents.

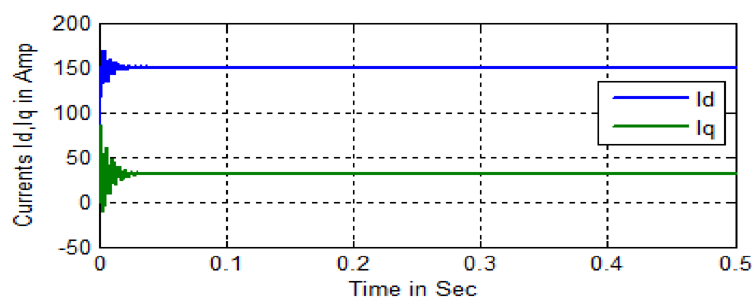

Fig.1. Stator currents of AFPMSM

The electromagnetic torque obtained by

$$T_e = \frac{3}{2}\frac{p}{2}[(L_d - L_s)i_{ds}i_{qs} + \lambda_r i_{qs}] \ldots\ldots.. (6)$$

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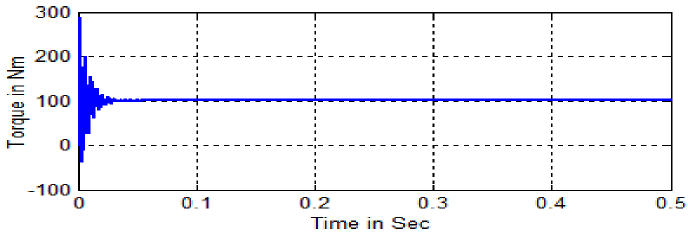

Fig.2. Steady state torque of AFPMSM

B) Twin Stator (Two Air-gap) AFPMSM:

This machine consists of single rotor sandwiched between two stators. The equations of voltage and flux linkage equations of twin rotor AFPMSM d-q axis model in synchronously rotating reference frame are given below.

$$\left.\begin{aligned} V_{ds1} &= R_{s1} i_{ds1} + L_{s1} p i_{ds1} - \omega_r \lambda_{qs1} \\ V_{qs1} &= R_{s1} i_{qs1} + p\lambda_{qs1} + \omega_r \lambda_{ds1} \\ V_{ds2} &= R_{s2} i_{ds2} + L_{s2} p i_{ds2} - \omega_r \lambda_{qs2} \\ V_{qs2} &= R_{s2} i_{qs2} + p\lambda_{qs2} + \omega_r \lambda_{ds2} \end{aligned}\right\} \text{..... (7)}$$

$$\left.\begin{aligned} \lambda_{ds1} &= L_{d1} i_{ds1} + \lambda_{af1} \\ \lambda_{qs1} &= L_{q1} i_{qs1} \\ \lambda_{ds2} &= L_{d2} i_{ds2} + \lambda_{af2} \\ \lambda_{qs2} &= L_{q2} i_{qs2} \end{aligned}\right\} \text{...... (8)}$$

The above equations are represented in matrix form as

$$[V_{dqs1s2r}] = [R][I_{dqs1s2r}] + p[L][I_{dqs1s1r}] \quad \text{.... (9)}$$

To obtain the d-q axis currents of stator and rotor, equation (9) must be represented in the state variable form and simulate in the environment of MATLAB. The simulation results are shown below.

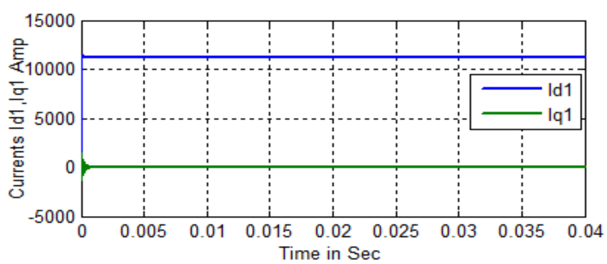

Fig.3. Stator1 d, q currents of double air gap PMSM

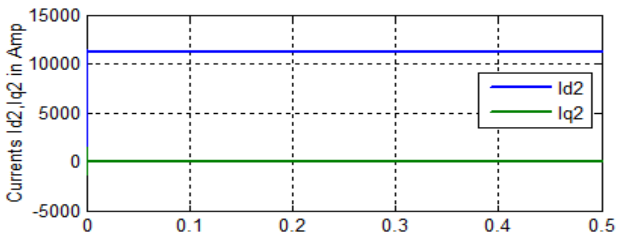

Fig.4. Stator2 d, q currents of double air gap PMSM

The electromagnetic torque of Twin stator axial flux permanent magnet synchronous machine is given by

$$T_e = \frac{3}{2}\frac{p}{2}\left[(L_d - L_q)(i_{qs1} i_{ds1} + i_{qs2} i_{ds2}) + \lambda_{af}(i_{qs1} + i_{qs2})\right]$$

…………………… (10)

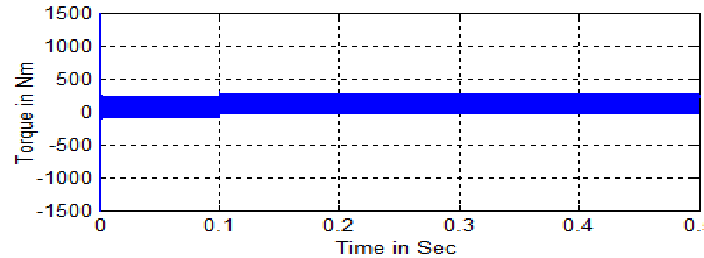

Fig.5.Steady state torque of Double air gap PMSM

Therefore the twin stator axial flux machine is designed and torque corresponding to the rotors is obtained and the torque is found to be doubled than with single stator. And this analysis lets to investigate on the possibility of replacing the conventional generator in the VSWECS with the medium speed TRAFIG so as to reduce the gear box ratio and enhance the power output in "wind energy conversion systems".

III. Application of AFPMSM in Wind Energy Conversion System

For wind energy conversion system applications, the use of Axial Flux Machines is an attractive alternative due to their compactness and lightness. These machines are directly connected to the wind turbine without the gear box. The axial flux machines are applicable for low speed and high torque electric drive. Twin stator axial flux permanent magnet synchronous machine has one rotor with two stator core.

A) System Modeling:

Figure 6 illustrates the proposed configuration of Wind Energy System. This system consists of a wind turbine coupled with a Twin Rotor Axial Flux Permanent Magnet Synchronous Generator (TSAFPMSG). A diode rectifier is used to convert AC produced by the wind generator into DC. The DC-DC boost converter processes this DC before it is fed to an inverter. A Maximum Power Point Tracking (MPPT) is also incorporated in the system. The MPPT controller continuously reads the voltage and current of the wind generator.

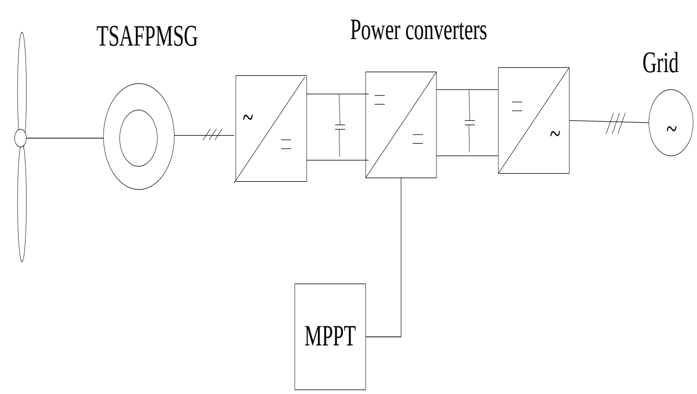

Fig.6. Block diagram of proposed work

The output power of Wind Generator is given by the following equation

$P_m = \frac{1}{2}\rho A V^3 C_p(\lambda, \beta)$ ……… (11)

Where $\lambda = \frac{R\omega}{v}$

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$$C_p(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} + 0.068\lambda$$

…… (12)

And $\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}$ ………(13)

The motion equation of Wind turbine is given below.

$$T_m - T_e - B\omega = J\frac{d\omega}{dt}$$ …… (14)

Where Pm- mechanical output power of wind turbine(W) , ρ-density of air (kg/m3), A-turbine swept area(m2), v - wind speed(m/sec) , R - turbine radius (m) , $C_p(\lambda,\beta)$ power coefficient of wind turbine , ω- turbine angular velocity (rad/sec) , β- blade pitch angle(deg), λ-tip speed ratio the rotor blade tip speed to wind speed , Tm -shaft mechanical torque , Te -electromagnetic torque ,F – combined viscous friction of rotor and load and J is combined inertia of rotor and load.

B) Maximum Power Point Tracking (MPPT):

The figure 7 shows the Simulink model of MPPT. The Diode Rectifier output voltage, current and the system speed are measured in order to track the maximum power for wind energy system. The reference torque is compared in accordance with the speed. The output signal is compared with current signal in order to produce the pulses.

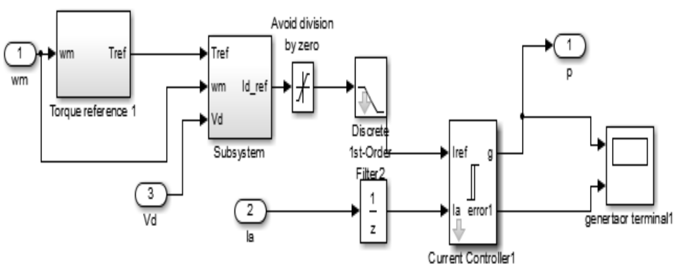

Fig .7. Simulink Diagram of MPPT

IV. Results and Analysis

The following figure shows the Simulink model of proposed Wind Energy Conversion System with MPPT controller.

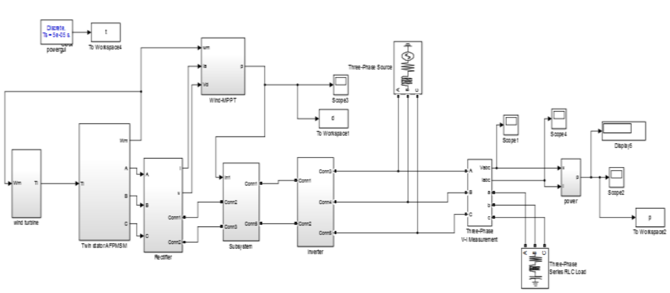

Fig .8.Simulink diagram of proposed work

The power outputs from the proposed system with and without implementation of MMPT for fixed wind speed are observed in the figures 11 and 12. The wave forms for torque and output power for variable wind speed are shown in figures 13 and 14 respectively.

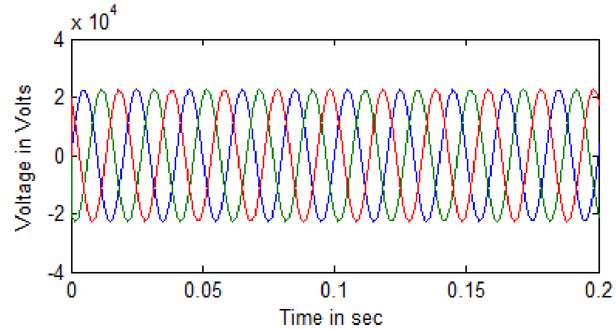

Fig.9. Voltage of WECS

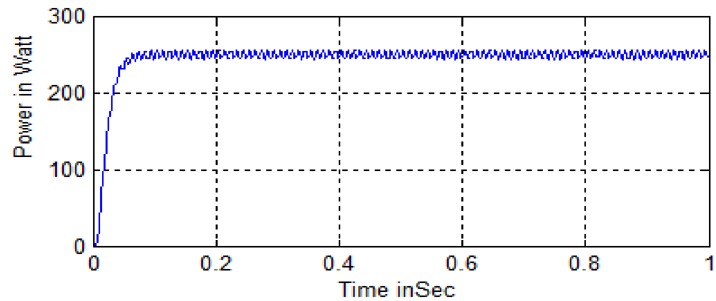

Fig.10. Power of AFPMSM

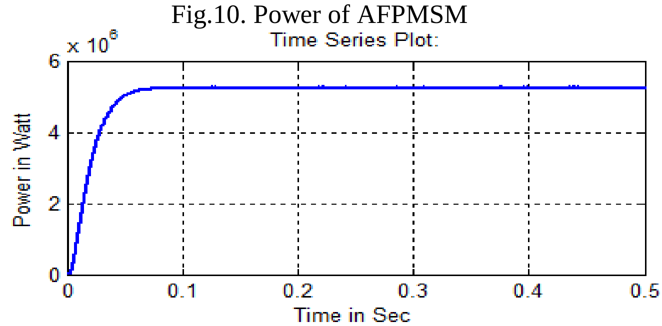

Fig.11. Power of WECS without MPPT

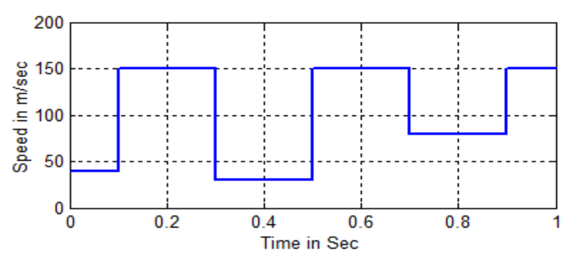

Fig. 12.Variable speed of wind energy conversion

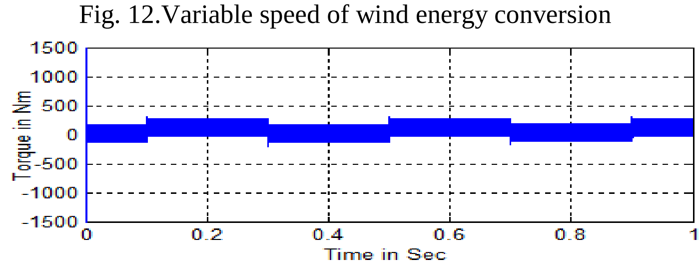

Fig.13.Torque of Double air gap PMSM for different wind speeds

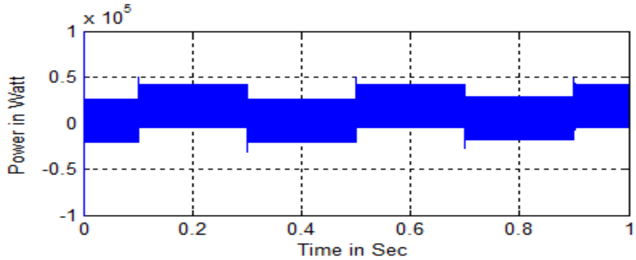

Fig.14.Power of double sir gap PMSM at different wind speeds

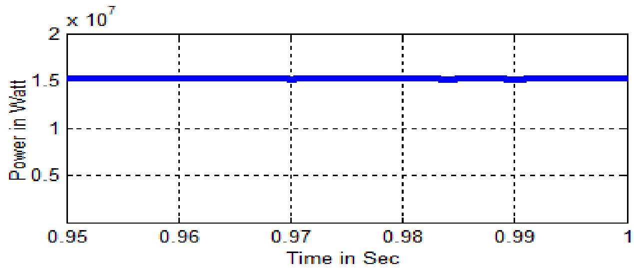

Fig. 15.Power of WECS with MPPT

V. Conclusion

The Axial Flux Permanent Magnet Synchronous Machine is mathematically modeled for Single and Double Stators. The Power and Torque levels are found to be doubled with two stators. The TSAFSM is used for Wind Energy Conversion System being MPPT technique has been implemented for extracting the maximum power. The output power is compared with and without MPPT controllers. As the power output becomes twice with Double Stator system, it is useful avoiding complexities associated with increase of turbine blade length and size.

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