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Maximum Power Point Tracking Wind Turbine Based on FOC Control of Variable Speed Axial Flux Permanent Magnet Synchronous Generator

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Abstract **—**This paper presents an revolutionary design of a low- speed, direct-force axial flux permanent magnet generator (AFPMSG) for a wind turbine energy technology machine that is evolved the use of mathematical and analytical techniques, dynamic version of the axial flux generator evolved using Simulink / MATLAB. A maximum strength factor tracking (MPPT)-based totally FOC manipulate approach is used to acquire maximum strength from the variable wind velocity. The simulation effects display the right performance of the developed dynamic model of the AFPMSG, manage approach and electricity era system.

Index Terms : Axial Flux permanent Magnet synchronous machines, Dynamic version, MPPT

I. INTRODUCTION

Axial Flux everlasting Magnet (AFPM) synchronous machines were developing in recognition and have acquired an growing quantity of attention in direct drive wind energy software [1-3]. relies upon at the flux glide inside the air gap, the electromechanical strength conversion machines are labeled as Radial and Axial Flux Machines. The working principle concerned with both the machines is alike but varies in its structure. The AFPMSG turned into designed with a single rotor, a double-sided air hole, and stators. The isotropic rotor is located between tooth of the double-sided stators as shown in Fig. 1The stator lower back yokes are attached to the lateral case covers of the motor. The lateral case covers are made with rolled steel material. The stator enamel are individually fixed to the stator disk.The fan-fashioned magnets of the rotor are hooked up in holes of the rotor disk with out the back yokes. parent 2 suggests the shape of the AFPMSG [1-4].discern 2 suggests that the magnets are established on both aspects of the disc rotor in order that the flux of a pole travels through both magnets related to the pole. the principle additives of a direct-pressure permanent magnet synchronous generator wind turbine are the wind turbine and the AFPMSG**.**

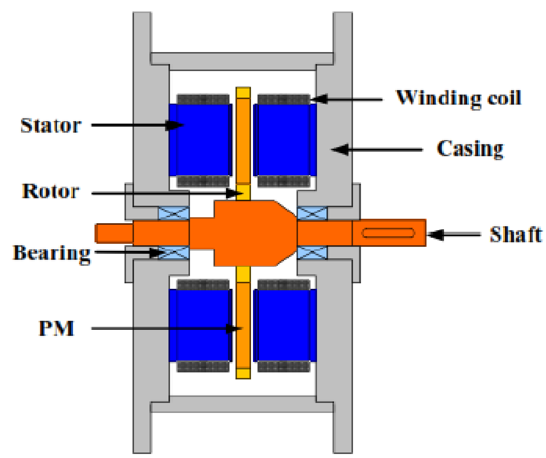

Figure.1. Cross section views of the AFPMSG

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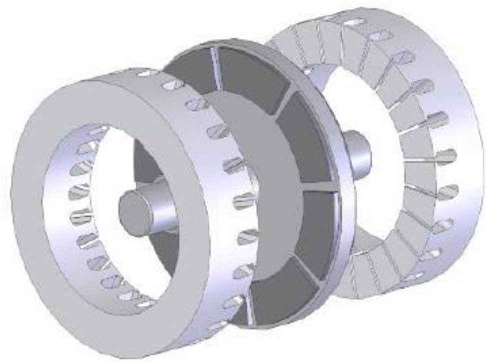

Figure.2.Magnetic circuit parts of an AFPMSG with one rotor-two-stators.

The wind turbine captures the energy from the wind for the machine, and the AFPMSG transforms the mechanical energy into electric electricity. in this paper, the ideas of the electrical electricity technology could be delivered, and the mathematical models of the wind turbine and the AFPMSG may be advanced and analyzed. those will further help in knowledge the manipulate algorithms for the system as the subsequent.

II.MODELING OF WIND TURBINES

In order to investigate the effectiveness of the power conversion in wind electricity conversion device, first the available power saved inside the wind desires to be determined. The wind turbine model is referred to as the aerodynamic version extracts energy from the wind inside the shape of kinetic energy after which converts it into mechanical electricity that is fed to the generator thru a shaft. The aerodynamic strength is given via to the following expression [7]:

$$P_m = \frac{1}{2} C_p(\lambda)\rho A U_w^3 \quad (1)$$

We shall use a generic equation of C_p as proposed by [8]. The equation is expressed below as:

$$C_p(\lambda,\theta) = 0.22\left(\frac{116}{\lambda_i} - 0.4\theta - 5\right) e^{-\frac{12.5}{\lambda_i}} + 0.0068\lambda_i \quad (2)$$

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

The relationship between of Coefficient of power and Tip-speed ratio is given below. The relationship between the tip-speed ratio λ and the rotor angular speed ω_m rads^{-1} is given as:

$$\omega_m = \frac{\lambda U_w}{R} \quad (4)$$

The relationship between the mechanical torque T_m and the mechanical power P_m is given by the equation below:

$$T_m = \frac{P_m}{\omega_m} \quad (5)$$

By subsisting P_m from (1) and ω_m from (4) into (5), the mechanical torque T_m is given as:

$$T_m = \frac{1}{2} C_t \rho A R U_w^2 \quad (6)$$

Where $C_t$is the torque coefficient and is given below as:

$$C_t = \frac{C_p}{\lambda} \quad (7)$$

parent 3 shows the connection between the Coefficient of energy (Cp) as opposed to Tip-velocity ratio (lambda). The Simulik version of the wind turbine primarily based on equations (1) to (7), is finished with the advanced mechanical torque equation, is illustrated in Fig. (4).

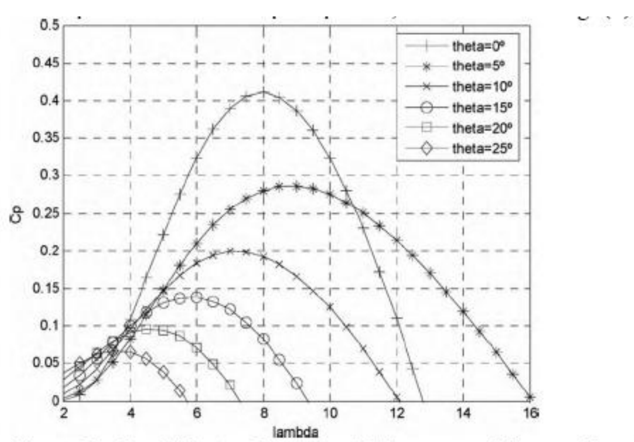

Figure.3. Coefficient of power (Cp) versus Tip-speed ratio (lambda)

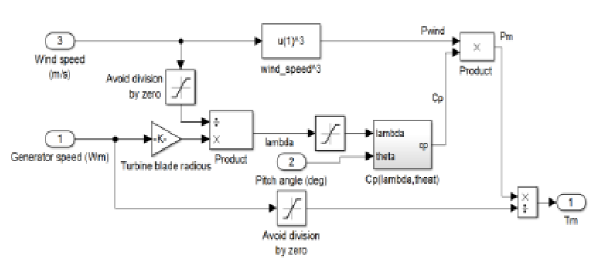

Figure.4. Wind turbine Simulink model.

III. MODELING OF PERMANENT MAGNET SYNCHRONOUS MACHINES

Everlasting magnet synchronous machines/mills (PMSMs/AFPMSGs) play key role in direct-force wind electricity technology systems for reworking the mechanical strength into electrical strength. A rigorous mathematical modeling of the AFPMSG is the prerequisite for the layout of the system manipulate algorithms as well as the evaluation of the consistent-nation and dynamic traits of wind strength conversion systems. The mathematical version of an AFPMSG in both the abc three-phase stationary reference body and dq synchronously rotating reference body might be developed, and the power and torque analysis of AFPMSGs might be given as properly.

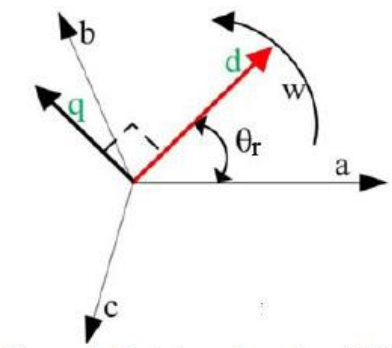

Figure.5. Park transform for AFPMSG generators.

3-1 Modeling of a AFPMSG within the herbal three-segment desk bound reference frame earlier than growing the mathematical version of the AFPMSG,

several crucial assumptions need to be made:

(1) The damping impact in the magnets and inside the rotor, are negligible;

(2) The magnetic saturation results are neglected;

(3) The eddy modern-day and hysteresis losses are disregarded;

(4) The again electromotive pressure (EMF) caused in the stator windings are sinusoidal;

(5) for simplicity, all the equations of AFPMSMs are expressed in motor (client/load) notation, this is, bad cutting-edge might be triumphing whilst the model refers to a generator. terrible current method that on the high quality polarity of the terminal of a tool the modern is out of that terminal. figure 5 indicates the Park transform for a three-section AFPMSG generators. The fixed abcaxes denote the course of the MMFs (fa,fband fc) of the a, b and c section windings, which might be triggered by the point various 3-phase AC currents in those stat or section windings. The flux caused by the permanent magnet is within the direction of the d-axis constant at the rotor. right here, the d-q-axes are rotating at the equal angular pace of the PMs and rotor. alsoθr, denotes the perspective between the d-axis and the desk bound a-axis.

The state space relationship of the terminal voltages of the AFPMSG to the phase currents and the phase flux linkages due to the PMs and stator currents can be written as follows [9]:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} . \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \end{bmatrix} \quad (8)$$

Where, vas, v_{bs}, and v_{cs} are the instantaneous a, b, and c three- phase stator voltages, andi_{as}, i_{bs}, and i_{cs} are the instantaneous three-phase stator currents. Here, Rs is the stator winding resistance per phase, and again, λ_{as}, λbs, and λ_{cs} are the instantaneous flux linkages induced by the three-phase AC currents and the PMs, which can be expressed in expanded form as follows [9]:

$$\begin{bmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} . \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} \lambda_r \cos(\theta_r) \\ \lambda_r \cos(\theta_r - \frac{2\pi}{3}) \\ \lambda_r \cos(\theta_r + \frac{2\pi}{3}) \end{bmatrix} (9)$$

where, Laa, L_{bb}, and L_{cc}, are the self-inductances of the a, b, and c three-phases, and, Lab, L_{ac}, Lba, Lbc, Lca and L_{cb} are the mutual inductances between these phases, while, λr, is the rotor flux linkage caused by the permanent magnet. The self-inductances and mutual inductances are all functions of θ_r. Thus, all of the inductances are time varying parameters.

3-2 Modeling of the AFPMSG inside the dq-axes synchronously rotating reference body

The dq0 Park's transformation is a mathematical transformation which ambitions to simplify the evaluation of synchronous equipment models, and was first delivered by way of R. H.Park in 1929 [10]. within the 3-section structures like PMSMs, the segment portions which include stator voltages, stator currents, and flux linkages, are time varying quantities. by using making use of Park's transformation, which is in essence the projection of the segment portions onto a rotating two axes reference body, the AC portions are transformed to DC quantities which are impartial of time. The abcto

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dq0 transformation may be expressed in matrix shape as follows:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta_r) & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r + \frac{2\pi}{3}) \\ -\sin(\theta_r) & -\sin(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r + \frac{2\pi}{3}) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} (10)$$

The inverse Park's transformation is:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta_r) & -\sin(\theta_r) & \frac{\sqrt{2}}{2} \\ \cos(\theta_r - \frac{2\pi}{3}) & -\sin\left(\theta_r - \frac{2\pi}{3}\right) & \frac{\sqrt{2}}{2} \\ \cos(\theta_r + \frac{2\pi}{3}) & -\sin(\theta_r + \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \end{bmatrix} (11)$$

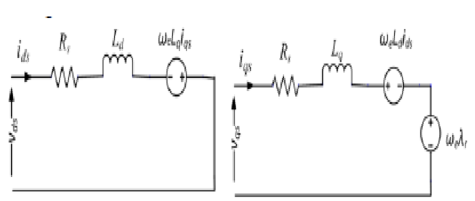

Figure.6. The *dq*-axes equivalent circuits of a AFPMSG in (consumer/load) notation

In expressions (10) and (11), and can represent the stator voltages, stator currents or flux linkages of the AC machines, respectively. Considering that underbalanced conditions, v_0=0, the voltage function of the AFPMSG in the *dq*-axes reference frame can be expressed as follows[9]:

$$v_{ds} = R_s i_{ds} + L_d \frac{di_{ds}}{dt} - \omega_e L_q i_{qs} (12)$$

$$v_{qs} = R_s i_{qs} + L_q \frac{di_{qs}}{dt} + \omega_e L_d i_{ds} + \omega_e \lambda_r (13)$$

Where, vds and v_{qs}, are the instantaneous stator voltages in the *dq*-axes reference frame, andi_{ds} and i_{qs}, are the instantaneous stator currents in the *dq*-axes reference frame. Here, Ld and L_q, are the *d*-axis and *q*-axis inductances, and ω_e is the electrical angular speed of the rotor, while, λ_r , is the peak/maximum phase flux linkage due to the rotor-mounted PMs. According to expressions (12) and (13), the equivalent circuits of the AFPMSG in the *dq-axes* reference frame can be drawn as shown in Figure 6:

Simulik model of the AFPMSG based on equations (10) to (21), is completed with the developed electromagnetic torque equation, are illustrated in Fig. 7:

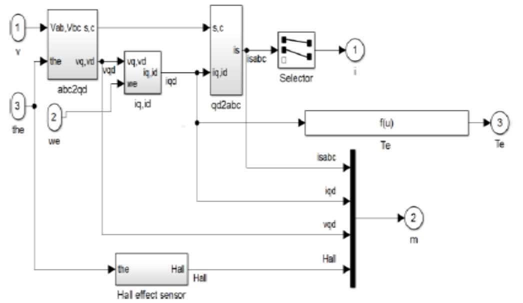

Figure.7. Dynamic model of the considered AFPMSG.

3-3power and torque evaluation of a AFPMSG

In line with assumptions, the electric energy input can be expressed inside the abc reference body as follows:

$$P_{abc} = v_{as} i_{as} + v_{bs} i_{bs} + v_{cs} i_{cs} (14)$$

Or in the *dq*-axes reference frame as follows:

$$P_{dq} = \frac{3}{2}(v_{ds} i_{ds} + v_{qs} i_{qs}) \qquad (15)$$

As part of the input strength, inside the motoring mode, the active electricity is the power this is transformed to mechanical electricity by way of the system, which may be expressed as follows:

$$P_{em} = \frac{3}{2}(e_d i_{ds} + e_q i_{qs}) \qquad (16)$$

where, $e_d = -\omega_e L_q i_{qs} = -\omega_e \lambda_q$ (17)

and $e_q = \omega_e L_d i_{ds} + \omega_e \lambda_r = \omega_e \lambda_d$ (18)

Here, e_d ande_q , are the back EMFs in the *dq*-axes reference frame, and λ_d and λ_q are the *dq*-axes flux linkages. Substituting expressions (17) and (18) into (16), the active power can be re- expressed as follows:

where, p is the number of poles in the machine.

$$P_{em} = \frac{3}{2}\omega_e(\lambda_d i_{qs} - \lambda_q i_{ds}) \qquad (19)$$

Hence, the electromagnetic torque developed by a AFPMSG be deduced as follows:

$$T_e = \frac{P_{em}}{\omega_e/\frac{p}{2}} = \frac{3}{2}\left(\frac{p}{2}\right)(\lambda_d i_{qs} - \lambda_q i_{ds}) \qquad (20)$$

$$\text{Or} T_e = \frac{3}{2}\left(\frac{p}{2}\right)(\lambda_r i_{qs} + (L_d - L_q) i_{qs} i_{ds}) (21)$$

IV. MANAGE OF GENERATOR-ASPECT CONVERTER

In wind turbine AFPMSG structures, three device variables want to be strictly managed [11]:

(1) The most desirable strength generated through the AFPMSG at unique wind speed tiers;

(2) The lively and reactive strength injected into the grid;

(3) The DC bus voltage of the back to back converter. determine eight shows a right away-drive wind turbine AFPMSG fed by a again-to- returned converter. in this system, the generator-facet converter regulates the speed of the AFPMSG to implement the MPPT manipulate. in the meantime, the grid-related converter controls the energetic and reactive strength injected into the grid.

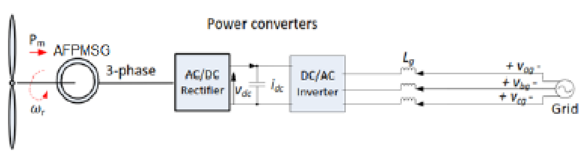

Figure.8. Direct-drive AFPMSG system

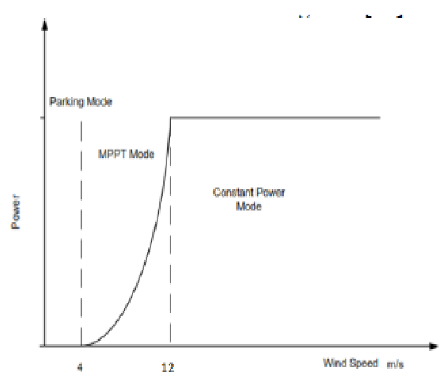

Figure.9. Wind turbine power-speed characteristic for the specific wind turbine

4-1most electricity point tracking manipulate

Direct-power AFPMSGs have the capability to work in a extensive velocity range. consistent with the depth of the wind, the wind turbine generators need to be controlled to operate in three exclusive modes as shown in discern 9 [11]:

1.Parking Mode: when the wind speed is decrease than the reduce-in pace that is 4m/sec in this machine, the wind turbine will now not rotate but stay in parking fame due to the fact that the electric power generated through the AFPMSG device is inadequate to catch up on the internal strength losses in this gadget. therefore, the wind turbine is saved in parking mode by a mechanical brake;

2.MPPT mode: whilst the wind pace is greater than the reduce-in pace, the wind turbine machine starts off evolved to paintings and generate electric strength. due to the fact the wind speed is in fantastically low range in the MPPT mode, the strength captured by way of the wind turbine is under its rated value, the MPPT manage wishes to be applied to make sure a maximum efficiency of strength seizes. The MPPT mode ends while the wind pace is extra than the rated wind pace, 12 m/sec, for this situation-have a look at system.

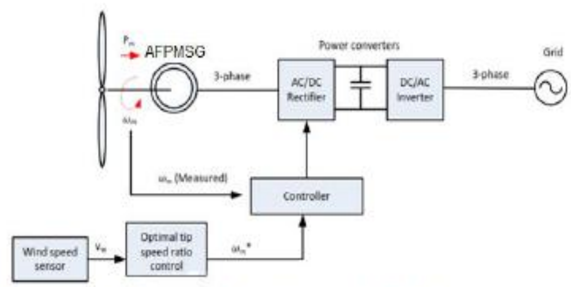

Figure.10. Tip speed ratio control scheme

3.consistent power location: whilst the wind pace becomes more than the rated fee, the energy generated with the aid of the device will be larger than its rated energy if the MPPT manage remains carried out. this will increase the electrical pressure at the AFPMSG and the energy processing gadgets, and might similarly damage them. therefore, the blade angle of the wind turbine blades desires to be well controlled inside the strong wind range to maintain the machine working within its rated output condition. As its name implies, this is consistent electricity place. As proven in equation (1), to control the captured mechanical energy, Pm, at given wind speed, Uw , the best controllable term is the energy coefficient, Cp (λ). The strength coefficient characteristic is shown in discern three. As may be seen in this parent, extraordinary strength coefficient curves correspond to one of a kind blade angles. For every case, there's an top-quality tip velocity ratio, λ, which contributes to a peak power coefficient fee which, in turn, leads to a maximum power capture, Pm . inside the MPPT operation mode, the pitch perspective is commonly kept at zero degree. In order to reap the height energy coefficient cost inside the 0-degree pitch attitude curve in parent 3, the end speed ratio needs to be managed at the choicest fee. From expression (1), the manipulate of the top pace ratio is clearly the manipulate of the rotor velocity of the AFPMSG. A simplified scheme of tip velocity ratio control is shown in figure 10. From this determine, the wind pace facts is sensed by means of a sensor and despatched to a microcontroller, from which the reference pace of the AFPMSG can be calculated in step with the top of the line tip pace ratio. therefore, the generator pace will attain its reference value in the static country, and then the MPPT manipulate is completed.

4-2 field orientated manipulate of the AFPMSG

The FOC technique changed into pioneered by F.Blaschke in Seventies [12].The FOC approach has been and is still a widespread issue in AFPMSGs control. in the FOC technique, the dq-axes are rotating at the rotor electric angular velocity with the d-axis aligned with the rotor flux path. accordingly, the flux producing present day component,ids , and the torque generating modern aspect, iqs,are along the d-axis and q-axis, respectively. accordingly, the dq-axes currents can be controlled independently by two closed loop controls within the FOC approach. The FOC approach, despite the fact that its implementation requires huge computational attempt together with PI manipulate and coordinate modifications, it possesses the following deserves:

(1) speedy velocity and torque reaction;

(2) top notch low speed overall performance; and

(3) low cutting-edge and torque ripples. For the software of direct-force AFPMSG systems, the AFPMSGs are at once pushed by the wind turbine without a gearbox, because of this that their operation speeds are continually in a surprisingly low variety. furthermore, the torque ripples of the direct-drive AFPMSGs have to be managed at a low level to decrease the mechanical stresses at the wind turbine. On the premise of the evaluation above, the FOC method turned into found to be more appropriate for the direct- force AFPMSG structures. For a floor, hooked up PM system (SPM) that's implemented within the case study gadget, the d-axis and q-axis inductances are same. thus, the torque expression equation (21) can be simplified and rewritten as follows:

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\lambda_r i_{qs} (22)$$

for you to achieve the maximum torque consistent with ampere, the d-axis current is about at 0. as a result, there may be a linear dating between the electromagnetic torque and the q-axis current, such that the electromagnetic torque may be easily controlled by way of regulating the q-axis modern. The phasor diagram for the FOC technique is proven in figure 11, and the control scheme of the generator-side converter is shown in determine 12.

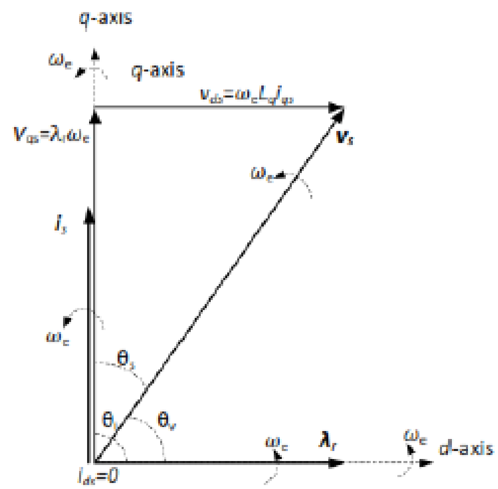

Figure.11. Phasor diagram of the FOC

As stated in advance, the FOC method coupled to the most excellent tip velocity ratio based totally MPPT manage method is implemented here because the control algorithm for the generator-side strength converter. In parent 12, there are 3 comments loops in the manage machine which can be:

(1) the velocity control loop,

(2) the d-axis modern manage loop, and

(3) the q-axis contemporary control loop. inside the pace loop, at each sampling time, the actual velocity of the generator sensed via an encoder established at the shaft of the rotor is as compared to its reference cost, which in turn is generated by the most excellent tip pace ratio manage, after which the mistake is sent to a PI controller so that it will output the reference q-axis current, meanwhile, the reference d-axis current, is constantly set at 0.

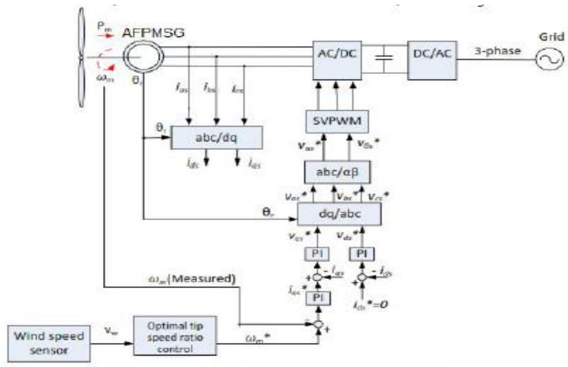

Figure.12. Generator-side control scheme

To collect the comments present day alerts, 3-segment stator currents are sensed and transformed into the dq-axes reference frame in line with Park's transformation. The reference stator voltages are then being done through PI controllers in the dq-axes contemporary control loops. here, the space vector pulse width modulation (SVPWM) method is carried out as the modulation strategy in this machine, as it generates much less harmonic distortion inside the output stator voltages/currents and offers

4-3 Simulation outcomes and analysis

Simulation studies have been achieved in MATLAB-Simulink to validate the chosen case-take a look at gadget. The parameters of the case-study wind turbine and the related AFPMSG are shown in table 1. determine 13 indicates the manage gadget diagram of the FOC approach built in Simulink.

Table.1. Electromechanical data of the considered AFPMSG.

Generator Type	AFPMSG
Rated Mechanical Power	600 W
Rated Rotor Speed	450 r/min
Rated Frequency	50 (Hz)
Number of phases	3
Number of Pole Pairs	8
Rated votage	300 v
Rated Mechanical Torque	8 Nm
Stator Winding Resistance	3.5 ohm
d axis Synchronous Inductance	8 mH
q axis Synchronous Inductance	8 mH
Wind Turbine Rotor Radius	3 m
IGBT Modulation Frequency	3 kHz

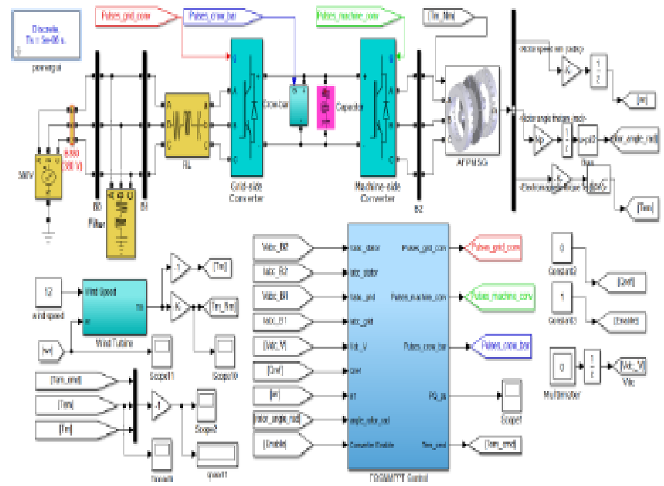

Figure.13. Control diagram of the system

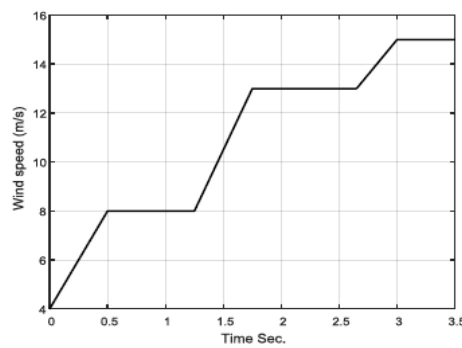

Figure.14. Wind speed input

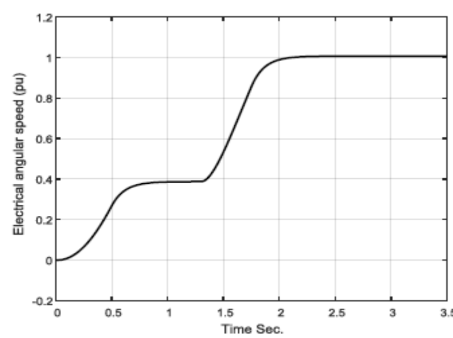

Figure.15. electrical angular speed of the AFPMSG in p.u.

Simulation results of the proposed system are proven in Figures 14 through 20.determine 14 indicates the wind speed input for the device. As can be visible in this figure, from0-1.3s, the wind speed increases from (cut-in velocity) to and then is maintained regular at till 1.3s. on this wind velocity range, we will check out the overall performance of the proposed MPPT manipulate approach. From 1.3-2.6s, the wind velocity will increase from to (rated wind speed). on this wind pace variety, the overall performance of the machine in its rated situation may be evaluated. After that, the wind speed keeps to boom to which exceeds its rated wind speed. as a

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result, the constant strength manage algorithm to address the high wind velocity can be investigated. shown in determine 15 is the actual rotor speed in p.u. Figure16 indicates the corresponding three-phase stator currents in p.u. The d-axis and q-axis currents are shown in figure 17and determine 18, respectively. in the meantime, parent 19 indicates the electromagnetic torque developed by the generator. the electric energy developed via the generator is proven in figure 20.

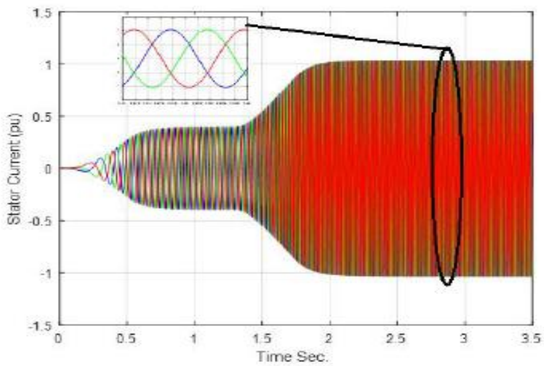

Figure.16. Three-phase stator currents in p.u

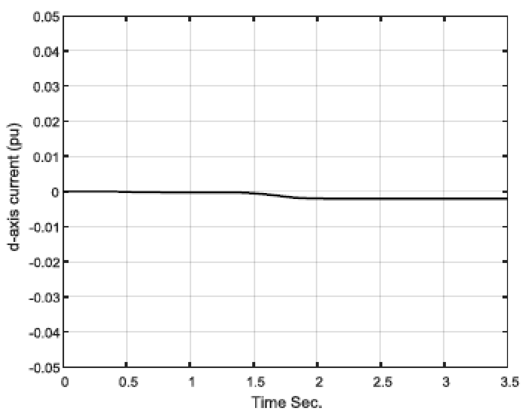

Figure.17.*d*-axis current in p.u.

As may be seen inside the simulation effects, in line with special wind speed tiers, the machine performance has specific characteristics great described as follows:

(1) From 0-1.3s: the wind velocity begins to boom from the cut-in speed (4m/sec), which means that the generated electric electricity is sufficient to compensate for the internal energy intake losses. for this reason, the wind turbine starts to rotate and the AFPMSG starts to generate electrical electricity. As proven in Figures 15 through 20, with the boom of the wind speed, the stator currents, electromagnetic torque, and the generated electrical electricity are step by step elevated.

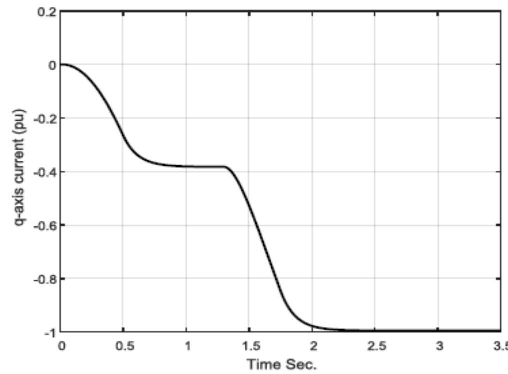

Figure.18.*q*-axis current of the inp.u.

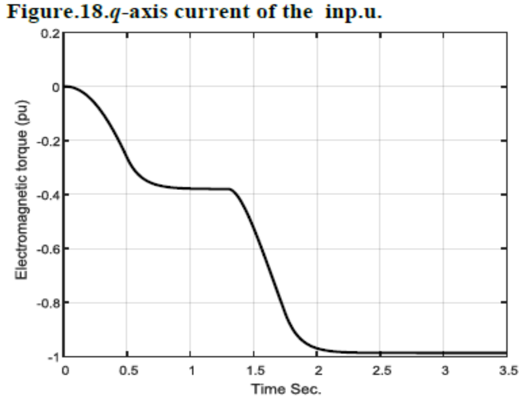

Figure.19. Electromagnetic torque in p.u.

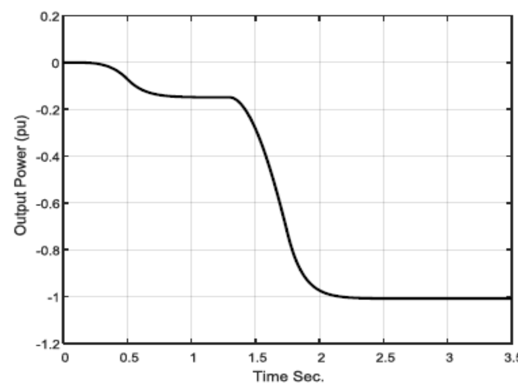

Figure.20. Electrical power generated in p.u.

As can be visible in determine 17, the d-axis contemporary is managed to be zero, which contributes to a linear relationship between the q-axis cutting-edge and the electromagnetic torque. From zero.5s, the wind speed reaches and forestalls growing, quickly after that the gadget comes to the consistent kingdom. (2) From 1.3-2.6s: starting from 1.3s, the wind speed increases from 8m/s to 12m/s ,that's the rated wind speed of the gadget. From 2.6-3.5s: the wind velocity maintains increasing and exceeds the rated price. as a way to restrict the energy input to save you the electrical and mechanical stress on the gadget, the steady strength manipulate changed into carried out on this wind velocity range. that is, the mechanical energy input of the system is saved at 1p.u. and the generator speed is managed at its rated fee in preference to increasing with the wind speed.

V. CONCLUSION

The paper proposes an AFPMSG -primarily based variable pace wind energy conversion device with a simple MPPT manipulate method primarily based at the understanding of the wind turbine characteristics. based totally on the simulation consequences and the analysis above, most advantageous energy is generated through the AFPMSG wind turbine system at exceptional wind velocity degrees. the chosen manipulate algorithms carried out in the control system of the generator-aspect converter are subsequently demonstrated. The manage gadget became able to maximize the power extracted from the wind as pondered from the energy coefficients received all through the simulation scenarios considered.

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