# Evaluation of Speed Control of Permanent Magnet Synchronous Motor (PMSM) in Wind Turbine Environment

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**Abstract**— This paper proposes to simulate the characteristics of wind turbine using Permanent Magnet Synchronous Motor (PMSM). Which includes some of the aspects of wind turbine such as torque-speed curve, closed-loop control, and simulate entire characteristics of a wind turbine considering closed-loop vector control. The closed-loop control simulation of PMSM is implemented to replicate the steady-state and dynamic characteristics of wind turbine. Subsequently, the results of steady-state and dynamic characteristics are closely matched with theoretical curve. This indicates that close loop control of PMSM is an excellent method for simulating the characteristics of wind turbine. Considering this a wind turbine emulation system using a PMSM is designed, simulated, and analyzed. In this simulation study, simulation model is prepared considering one of the existing wind farms. Here, the torque-controlled method using field orientation technique for PMSM is used which achieves the Maximum Torque per Ampere (MTA) and Flux-weakening Control (FC) for PMSM. The simulation results show that PMSM with proposed technique can achieve maximum torque efficiency and reduce energy consumption. This drive includes components such as a PWM operated three-phase Insulated Gate Bipolar Transistor (IGBT) inverter and a closed loop current PI-controller. The simulation results show the effectiveness of the proposed technique during different types of load variations of the wind turbine. The comparative analysis of the proposed technique proves that it emulates the static and dynamic characteristics of the wind turbine closely with the actual results.

**Keywords:** — Wind Turbine, PMSM, SVPWM, FOC, MTPA, PI Controller

## 1. INTRODUCTION

Windmill is considered as one of the best renewable energy sources to cater the demand of the consumers. Compared to day time availability of the solar plant, it provides electricity round the clock. Moreover, it is virtually pollution free and save the fossil fuel. Wind energy has gained widespread recognition and development as an environmentally friendly, socially advantageous, and economically competitive means of electricity generation for various applications. Today, wind energy as a pollution-free renewable source has attracted a lot of attention. The nonlinear and stochastic behavior of wind causes to be great challenges for the accuracy of power system It serves below mentioned advantages such as.[1],[2]

- Wind energy conversion system (WECS) produces the electrical energy by transforming the incoming air stream.

This system has two basic steps.

- First step is the mechanical power which comesfrom the wind turbine blades.
- The second step is the electrical power whichproduces by the generator.
- The wind energy market has grown with roughly30% per year
- For a wind turbine, the wind power shown in equation[1]

$$P_{wind} = \frac{1}{2}\rho A V_W^3 \qquad (1)$$

Nowadays, the wind turbines are designed which improves the efficiency and reduces the costs of wind power setup [3]. In WT systems, the electrical and mechanical parts behave globally as a nonlinear system where electromechanical parameter variations are a well-recognized problem. Additionally, WTs are expected to operate under a wide range of wind speeds, which makes the control design more difficult.[4] Overcome these drawbacks, aerodynamic torque control is another method of controlling a wind turbine. This involves adjusting the blade pitch and/or rotor speed to change the torque applied to the generator. The main goal of torque control is to maintain a constant rotational speed of the turbine, which maximizes power output. There are several ways to achieve torque control in wind turbines, including:

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There are several ways to achieve torque control in wind turbines, including:

- Blade Pitch Control
- Rotor Speed Control
- Aerodynamic Add–Ons[5][6]

The blades of a rotor were headed to turn when fluid flows through the rotor. A bluff body creates a pressure difference around the rotor. The internal stream tube in gas turbines, blowers, and air compressors was used to create the pressure difference. In day-to-day applications, fans, wind turbines, and water turbines utilize the thrust incited from the pressure distribution.[15]

Other types of motors that could potentially be used for wind turbine emulation include induction motors, synchronous reluctance motors, and switched reluctance motors. These motors have their own advantages and disadvantages, such as lower cost and greater ruggedness, but may not have the same level of efficiency or controllability as PMSM motors. [7],[8],[9],[10],[11].

The PMSM are receiving increased attention in the recent years because of their high efficiency, large torque to volume ratio, and reliable operation So far, some control strategies namely the volts/Hertz control, Field Oriented Control (FOC) and Direct Torque Control (DTC) have been used for speed regulation of PMSM.[7].

A complete wind energy conversion system (WECS) in a similar way like an actual wind turbine by generating torque similar to the aerodynamic torque at a given wind speed. PMSM (Permanent Magnet Synchronous Motor) has reliable and simple structure. Its torque and speed characteristics are better than those of DC motors and asynchronous motors. So in this paper, PMSM is proposed to simulate wind turbine characteristics and realize the complete steady-state and dynamic characteristics simulation, which provide a novel method for simulating wind turbine characteristics.[8],[9].

Vector controlled drives were initially proposed for induction motor drives but recently they have also been investigated in different motor types like the PMSMs. Naturally, the FOC and the DTC have some structural and behavioural differences. Unlike the FOC, the DTC does not require any current regulator, complex coordinate transformation, not needed many parameters, etc. However, DTC presents some disadvantages like control difficulties at low speed and high current and torque ripples.[4]

Other types of motors that could potentially be used for wind turbine emulation include induction motors, synchronous reluctance motors, and switched reluctance motors. These motors have their own advantages and disadvantages, such as lower cost and greater ruggedness, but may not have the same level of efficiency or controllability as PMSM motors. Ultimately, the choice of motor will depend on the specific requirements of the application and the trade-offs between performance, cost, and complexity.[7]–[11].

Overcome these drawbacks, different nonlinear control techniques have been followed, such as, for instance, gain scheduling PI controller and neural networks-based control. As is well known, to achieve the goal of power efficiency maximization, the turbine tip speed ratio should be maintained at its optimum value despite of wind variations. For such purposes, different control strategies can be implemented, such 3 as direct torque control and field-oriented control (FOC).[10]

The FOC technique provides a decoupling of the flux and torque similar to that of a DC motor, where the control strategy is to guide the park plan to cancel a component of the flux to obtain a simplified expression of torque for better control.[11] In a wind turbine, the [Maximum torque per ampere] MTPA control is used to maintain the optimum power output by adjusting the rotor speed and torque to match the wind speed and load conditions. This is done by regulating the stator current and angle based on feedback from sensors such as wind speed, rotor speed, and generator voltage. The main role of [MTPA] control is to ensure that the (Permanent magnet synchronous motors) PMSM operates at the highest possible efficiency by maintaining a constant power output while minimizing the current drawn from the grid. This is achieved by controlling the motor's stator current and angle in such a way that it delivers maximum torque for every ampere of current drawn. By controlling the stator current and angle, MTPA control ensures that the PMSM operates in a safe and stable manner, even under varying wind conditions [17],[18],[19].

The main role of MTPA control in wind turbine in PMSM motor speed and torque control. MTPA (Maximum Torque per Ampere) control is an important control strategy used in Permanent Magnet Synchronous Motors (PMSM) in wind turbines to regulate motor speed and torque. The system is represented in simulation to check the static and dynamic behaviour of the wind mill site without installation work. To control the speed of the PMSM, the control system uses a closed-loop control algorithm, such as a proportional-integral (PI) controller or a more advanced control algorithm, such as field-oriented control (FOC). The speed control system can also include features to regulate the speed of the PMSM under different wind conditions, such as gusts or changes in wind direction. In this system is emulation based and that emulation is represented in simulation. This emulates simulate the dynamic and static behaviour of the real wind turbine without the need of natural wind resources and actual wind turbines.[8]

## 2. Modelling parameters

### 2.1. Wind turbine

In order to implement the proposed scheme in real time application, one of the real time model of the wind turbine is considered. This simulation model has been prepared and its analysis has been carried out in MATLAB environment keeping sampling frequency of 1 kHz considering rated frequency of 50 Hz fundamental.

### 2.1.1. Layout of WTEC

The shown in fig.1 In WECS, electrical energy is generated from wind employing a wind turbine and an electric generator. The wind turbine is coupled to the prime mover either directly or by a gear box setup. The prime mover is coupled to the shaft of the generator's rotor, whereas the stator is linked either to standalone loads or the utility grid by an appropriate power electronic interface. This setup converts mechanical energy to magnetic energy and later to electrical energy for the utility grid.

Basically, a single speed Slip Ring Induction Generators, similar to the generator used in 1.5 MW & 2.1 MW with SFS turbines. Stator is connected to grid circuit, similar to any other induction generator. Rotor windings are also connected to grid, but through an AC-DC-AC converter circuit. The rotor side converter is called as machine side converter (MSC) and the grid side converter is called as line side converter (LSC). Rotor circuit electronics capacity would be around 30 % of the turbine ratings. As both stator and rotor are connected to grid, hence the name Doubly Fed Induction generators (DFIG).

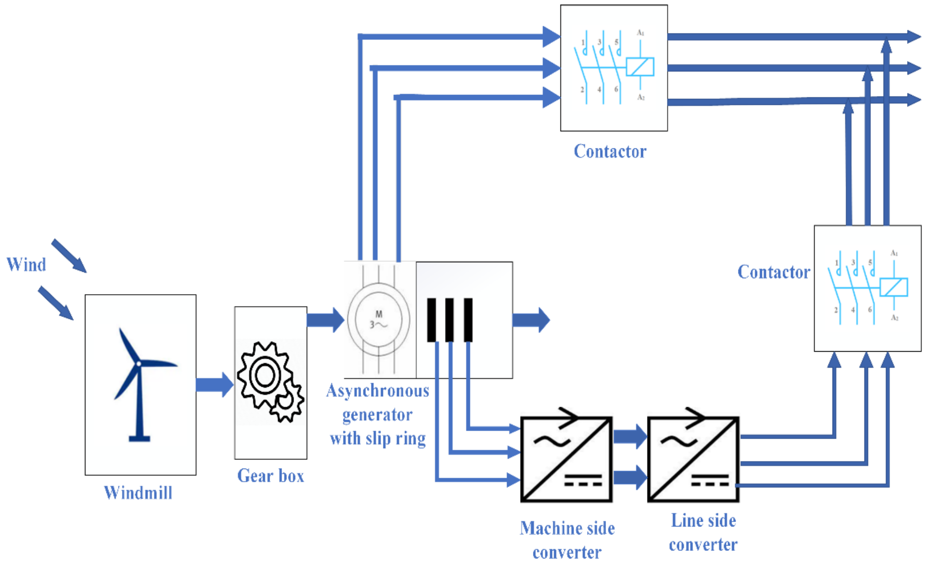


Figure 1 Conceptual diagram for wind turbine energy conversion

The growing demand for electricity from wind power refers to the increasing need for electrical power generated by wind turbine. The growing demand for electricity from wind power is driven by several factors. Firstly, wind energy is a clean and renewable source of electricity that does not produce greenhouse gas emissions or air pollution, making it an attractive option for governments and utilities seeking to reduce their carbon footprint and meet climate change targets.

One can ignore the important role of renewable energy which is obtained from natural resources like sunlight, wind, rain, and geothermal heat.

Environmental concerns in energy generation from the conventional sources make fast development of renewable energy sources (RES), like wind, solar, fuel cell, etc.

### 2.1.2. Mathematical Modelling of Wind Turbine.

The wind turbine is the crucial mover of the WECS. Thus, the modelling of wind power is vital in studying and improving WECS. The mechanical output power of the wind turbine is given by Eq. (1) [13]

$$\mathrm{P_m} = \frac{1}{2}\rho \mathrm{A C_{P(\lambda\,,\,\beta)} V_w^3} \tag{1}$$

Where, ρ is the air density in (Kg/m3), R is the radius of the rotor's swept area in (m), Cp is the power coefficient and $V_w$ is the wind speed in (m/s). The power coefficient is defined as the ratio of the turbine mechanical power to the power available by the wind. This coefficient is a function of TSR (λ) and the pitch angle of the blades (β) in ( ◦). The TSR is the ratio of the blade tip-speed divided by the wind speed as illustrated in Eq. (2)

$$\lambda = \frac{\omega_{\mathrm{m}} \mathrm{R}}{\mathrm{V_w}} \tag{2}$$

Where, $w_t$ is the rotor angular speed in (rad/s). The aerodynamic mechanical torque of the wind turbine is given by Eq. (3)

$$\mathrm{T_m} = \frac{1}{2}\frac{\rho\pi \mathrm{R}^3 \mathrm{C_p}(\lambda,\beta)\mathrm{V_w^3}}{\lambda} \tag{3}$$

As pointed in, the power coefficient, Cp (λ, β), is a non-linear function of the tip speed ratio, λ, and the blade pitch angle, β. The Cp (λ, β) curve is specific characteristics of each wind turbine design and can be derived from a field test of the turbine. An empirical equation is normally used to model the Cp, λ and β surface, based on the turbine characteristics, as illustrated in Eq. (4)

$$C_P(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-\frac{C_5}{\lambda_i}} + C_6\lambda \tag{4}$$

Where the parameters C1–C6 are constants and λi is given by Eq. (5)

$$\frac{1}{\lambda_{\mathrm{i}}} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{5}$$

From the wind turbine power and torque in Eqs. (1) and (3), it can be noticed that the inputs are the wind speed, the blades pitch angle and the rotor speed and the output is the aerodynamic torque.

The characteristics of x (Rotor speed Rad/sec) versus y (Torque N-m) is shown in fig.3. It is to be noted that when the wind speed increase, the torque and speed of the PMSM motor increase illustrated in Fig. 1.

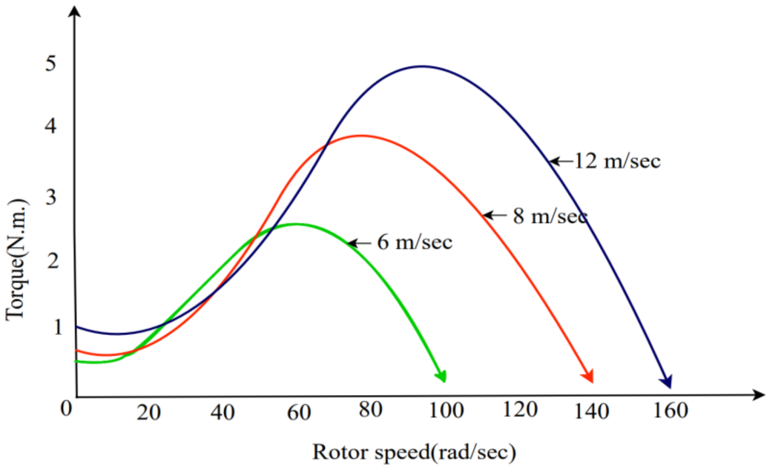


Figure 2 Torque speed characteristic of wind turbine simulation using PMSM[13]

Within the first set of test, at each wind speed, the resistive load on the PM generator changes from no load to full load to draw the torque-speed characteristic of the emulated turbine and verified against the real wind turbine torque-speed characteristic which is generated from the system simulation on MATLAB/Simulink. The exact wind turbine torque-speed characteristic and the torque-speed characteristic of the WTE system implemented using PMSM is shown in Fig. 2.

### 2.2. Permanent Magnet Synchronous Motor (PMSM):

#### 2.2.1. Working Principle of PMSM

When the three-phase stator winding is energized from 3 phase supply, a rotating magnetic field is set up in the air gap. The Permanent Magnet Synchronous Motor (PMSM) is a rotating electrical machine where the stator is a classic three-phase stator like that of an induction motor and the rotor has surface mounted permanent magnets.

**Advantages of PMSM:**

High torque/inertia ratio.

High power density.

Reliability and easy maintenance

Fast torque response.

Extensive speed, the range including constant-torque and constant-power regions.

#### 2.2.2. Mathematical modelling of PMSM:[20]

Mathematical model to control of speed, current, and torque of a PMSM drive is prepared in MATLAB.

A speed control method for a PMSM drive that provides a high-performance vector control and scalar control.

The mathematical model of the PMSM drive is established using a 3-phase configuration along d-q axes.

**3 Phase To 2 Phase Transformation:**

When a 3-phase system (called a-b-c frame of reference) of current or voltage or flux linkage is transformed into an equivalent two-phase system (called d-q reference frame) by means of a transformation relationship known as parks transformation.

**Park's transformation**

(a, b, c) → (d, q) (the Park's transformation)

The abc to dq0 block uses a Park transformation to transform a three-phase (ABC) signal to a dq0 rotating reference frame. The angular position of the rotating frame is given by the input $Wt$, in rad.

**Inverse Park transformation**

(d, q) → (α, β) (the Inverse Park transformation)

Inverse Park Transform block computes the inverse Park transformation of the orthogonal direct and quadrature axes components in the rotating *dq* reference frame. You can configure the block to align either the *d*- or *q*-axis with the *α*-axis at time *t* = 0.

**Voltage (abc to qdo) Park Transformation:**

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{6}$$

a, b, c) → (d, q) (the Park's transformation)

The abc to dq0 block uses a Park transformation to transform a three-phase (ABC) signal to a dq0 rotating reference frame. The angular position of the rotating frame is given by the input $Wt$, in rad

**Now, Modeling Of Current $i_d$ and $i_q$ Through Equation:**

$$\frac{\mathrm{di_d}}{\mathrm{dt}} = \frac{1}{\mathrm{L_d}}\left(\mathrm{v_d} + \mathrm{L_q}\omega_e \mathrm{i_q} - \mathrm{R_s i_d}\right) \tag{7}$$

$$\frac{\mathrm{di_q}}{\mathrm{dt}} = \frac{1}{\mathrm{L_q}}\left(\mathrm{v_q} - \mathrm{R_s i_q} - \mathrm{L_d}\omega_e \mathrm{i_d} - \emptyset_m \omega_e\right) \tag{8}$$

The $i_q$ and $i_d$ currents for a PMSM are similar to $i_q$ and $i_d$ for a salient-pole wound field synchronous machine (WFSM). $i_q$ and $i_d$ are phasor components of the armature current. The $i_q$ component is in phase with the generated armature voltage and produces a magnetic flux that is centered on the space between the permanent-magnet field poles.

**Now, Modeling Of Torque ($T_e$) Through Equation:**

$$\mathrm{T_e} = \frac{\mathrm{P}}{2}\left(\frac{3}{2}\right)\left(\left(\mathrm{L_d} - \mathrm{L_q}\right)\mathrm{i_d i_q} + \emptyset_m \mathrm{i_q}\right) \tag{9}$$

The mechanical torque $T_e$ of the PMSM using the torque equation in the *d*-*q* rotor reference frame.

Where,

- *p* is the number of pole pairs of the PMSM.
- $\phi_m$ is the flux linkage of the permanent magnet.
- $L_d$ and $L_q$ are the *d*- and *q*-axis inductances of the PMSM.
- $i_d$ and $i_q$ are the *d*- and *q*-axis currents of the PMSM.

**Now, Modeling of Speed ($W_m$) Through Equation:**

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(T_m - T_L - b\omega_m\right) \qquad (10)$$

## 3. Proposed technique

Shown in fig.3 the general control scheme of the designed PMSM-based WTE system. A three-phase thyristor bridge rectifier is connected to the grid to provide DC voltage for a three-phase IGBT voltage source inverter. The inverter feeds three-phase power to the motor through space vector pulse width modulation SVPWM. The motor phase currents are controlled such that for all speeds less or equal to the rotor speed, the d-axis current is maintained zero and the q-axis current is maintained at the value that is sufficient to issue the commanded torque. For speeds higher than the rated speed, field weakening is achieved by permitting sufficient amount of the d-axis current to weaken the rotor magnet flux as desired. In both cases, the machine flux and the developed torque are separately controlled and decoupled from each other. MTPA (Maximum torque per ampere) will take the reference speed from the wind turbine and compare it with the speed of the PMSM motor and MTPA will generate a reference current and compare that current with PMSM actual current. Which is the major merit of field orientation that resembles the characteristics of a separately excited DC motor.

### 3.1. Flow chart

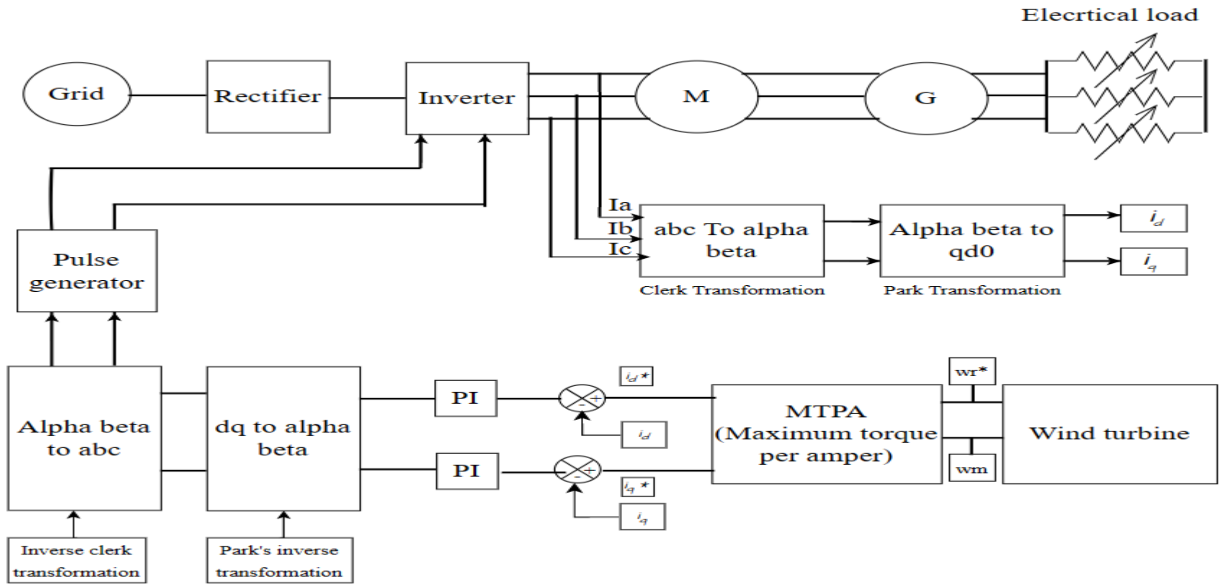


Figure 3 Proposed technique

### 3.2. The PMSM is torque-controlled using field orientation technique.

Vector control is actually control of phase and amplitude for a motor stator voltage or current vector at the same time. The motor torque will depend on the stator current space vector $i_s = i_d + ji_q$. When the permanent magnet flux and the direct excitation, cross-axis inductance is confirmed. In other words, control id and iq that can control the motor torque.[21]

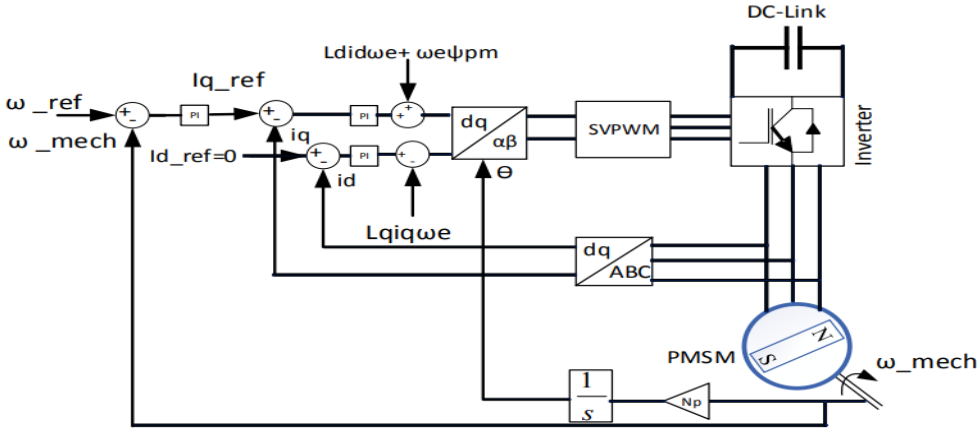


**Figure 4 Vector control of PMSM [3]**

Permanent magnet rotor according to the location of the different permanent magnet synchronous motor can be divided into: the surface and inside buried. The tile-shaped magnet was generally and in the outer surface of the rotor iron core in the surface permanent magnet synchronous motor (SPMSM).

By the formula (11) can know, the current is a linear time-invariant systems. When $\omega$ constant through the coordinate transformation, particularly $\omega$fs is constant and iq proportional to the electromagnetic torque. By controlling the torque current component $i_q$ to complete the linear motor electromagnetic torque control to obtain high performance.

$$T_e = \gamma \times \omega_{fs} \times i_q \tag{11}$$

Surface permanent magnet synchronous motor (SPMSM). This important feature of the motor is that straight axis and cross axis for the main inductance is equal ($L_d = L_q$). And within the interior permanent magnet synchronous motor (IPMSM) of the permanent magnets in the rotor inside the stator magnet in vitro surface and inner circle core made of ferromagnetic material between the pole shoes can protect the permanent magnets. This important feature of permanent magnet motor is direct, cross-axis of the main inductance is not equal to ($L_d \neq L_q$). For surface-type PMSM, as ($L_d = L_q$), this style incorporated into the electromagnetic torque equation. Torque equation can be obtained equation (11) that only related to the electromagnetic torque and the q axis current $i_q$. So let $i_d = 0$, through control the $i_q$, you can achieve maximum torque control in the surface type PMSM vector control.[21]

### 3.3. Maximum Torque per Ampere (MTPA)

The maximum torque per ampere (MTPA) control strategy maximizes the torque for a unit stator current and enhances the inverter utilization. The torque production equation (9). The torque production is the function of flux linkages ($\gamma$), d axes inductance ($L_d$ ), q axes inductance ($L_q$), d axes current ($i_d$), q axes current ($i_q$) and load or torque angle ($\delta$). Different combination of current id and $i_q$ produces the torque.

MTPA is the maximum torque produced in this and compare the current. The torque angle for a given stator $i_s$ current magnitude is derived in reference as,

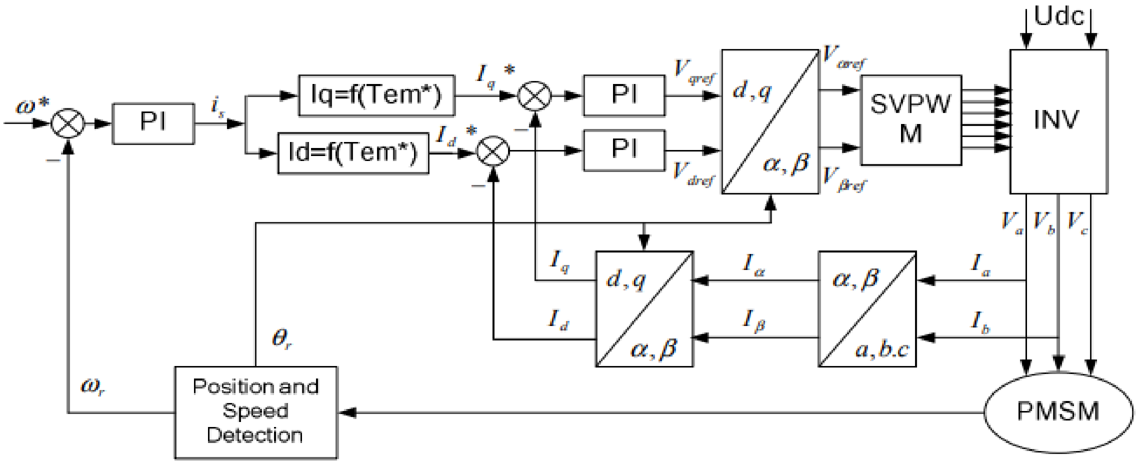


**Figure 5 Salient-pole PMSM MTPA control system diagram.**

When the PM flux linkage varies due to magnet temperature variation, the variation of PM flux linkage is not reflected to the developed MTPA LUT and this results in undesired q-axis current command selection from the MTPA and eventually in undesired torque development. Figure 6 shows the MTPA trajectory of SPMSM.

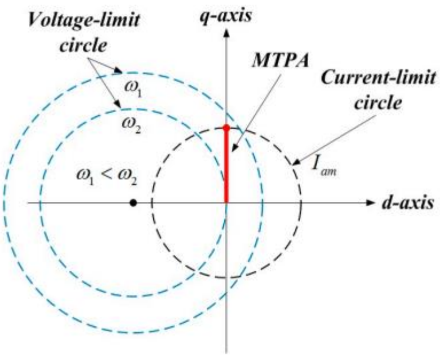


**Figure 6 MTPA curve of SPMSM**

The MTPA control methods for PMSMs have been proposed in the MTPA control is implemented with two stabilizing loops to correct the stator voltage amplitude and phase by controlling the reactive power. The fast dynamic response and the high efficiency can be achieved[22]

The maximum torque-per-ampere (MTPA) control method provides a maximum torque/current ratio, hence increasing the efficiency of the PMSM drive.[23]

The torque angle for a given stator $i_s$ current magnitude is derived in reference [24] as,

Electromagnetic torque $T_m$ ,

$$T_m = \frac{3P}{4}[\gamma_{af} i_s sin\delta + \frac{1}{2}\left(L_d - L_q\right) i_s^2 \sin 2\delta] \tag{11}$$

Electromagnetic torque in normalize unit system,

$$T_{Mn=i_{sn}[\sin\delta+\frac{1}{2}(L_{dn}-L_{qn})\ i_{s\,\sin 2\delta]}^{2}} \tag{12}$$

The base torque defined as,

$$T_{b=\frac{3P}{4}\gamma_{af}I_b} \tag{13}$$

Torque per unit stator current is given as,

$$T_{Mn=[\sin\delta+\frac{1}{2}(L_{dn-L_{qn}})i_{sn}\sin\delta]} \tag{14}$$

Maximum of stator current $i_s$ is found by differentiating it with respect to δ and equating it to zero to obtain the condition for torque angle as,

$$\delta = \cos -1\,[-\frac{1}{4(L_{dn}-L_{qn})i_{sn}} + \sqrt{\left(\frac{1}{4_{a1}i_{sn}}\right)^2} + \frac{1}{2} \tag{15}$$

### 3.4. Flux-weakening control for PMSM

The voltage equation of a PMSM can be expressed as:

$$\mathrm{u} = \sqrt{\left(L_d i_q\right)^2} + (L_{di_q} + \varphi_f)^2 \tag{16}$$

Where, u is the stator voltage, ω is the electrical angular velocity, ρ is the salient-pole rate of the motor. As can be seen from (10), the motor speed is proportional to the terminal voltage of PMSM, so when the motor reached rated speed, in order to further improve the speed, while maintaining the motor terminal voltage constant, only by regulating $i_d$, $i_q$which is so-called flux-weakening control, usually through increasing the direct-axis demagnetization current to achieve.

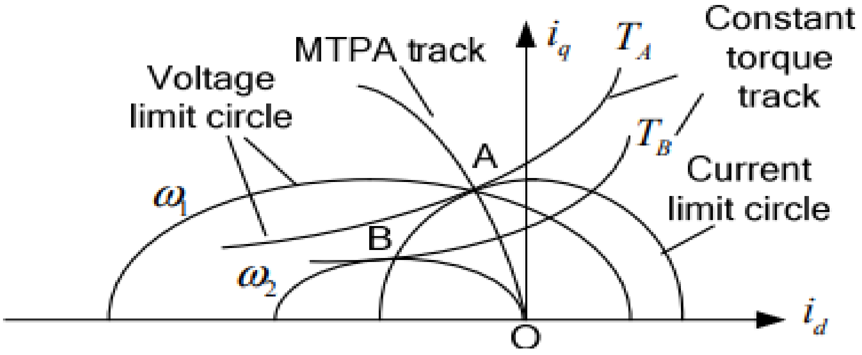


**Figure 7 Stator current vector track.[25]**

The flux-weakening speed control for PMSM can be illustrated by the stator current vector trajectory as shown in Fig.4. First, the motor run along with OA, the MTPA curve. When the motor voltage and current reached the limit, the time the speed ω1 corresponding to the turning speed when the motor reach maximum torque TA.

To further increase speed to ω2, while making maximum use of inverter capacity, it is need to control the current vector to run along the current limit circle, i.e. counter-clockwise down along the AB segment. As can be seen from the diagram, when the current vector run from point A to point B, the direct-axis demagnetization current component increases, at the same time , the motor output torque smaller, i.e. constant power operation.[25]

## 4. Result and discussion

### (1) Dynamic behaviour

**The Sudden change of load at constant wind speed**

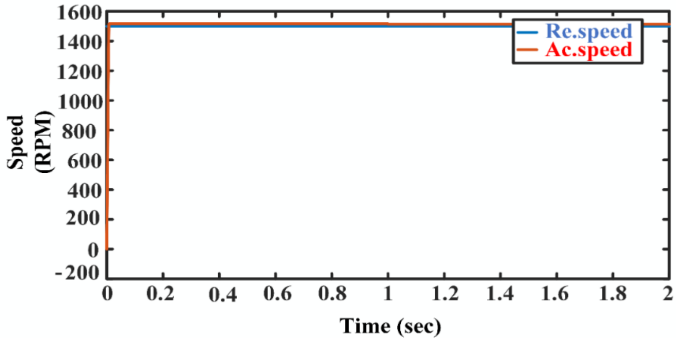


**Fig. 8. WTE dynamic behavior under load change at constant wind speed of (a) comparison between actual speed and reference speed**

In this Fig. 8 shows the maintain a constant speed using an MTPA controller, the controller needs to be maintained at a constant frequency and voltage in the motor

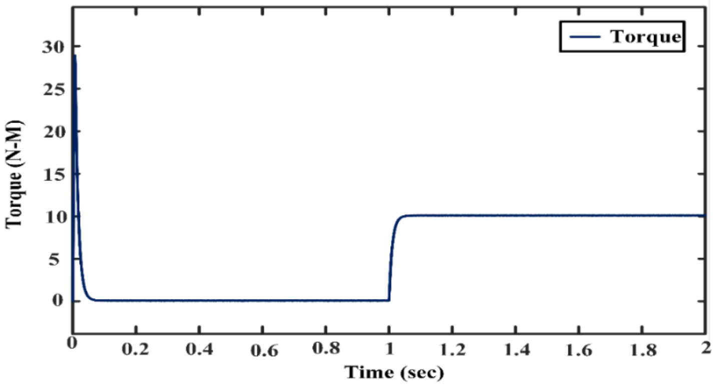


**Fig. 9. WTE dynamic behaviour under load change at constant wind speed of (b) The Sudden change of load**

Shows Fig.9 in the time is on x-axis and torque on the y-axis there will be a change in the load but the speed of the motor will not change and the torque will also be constant.

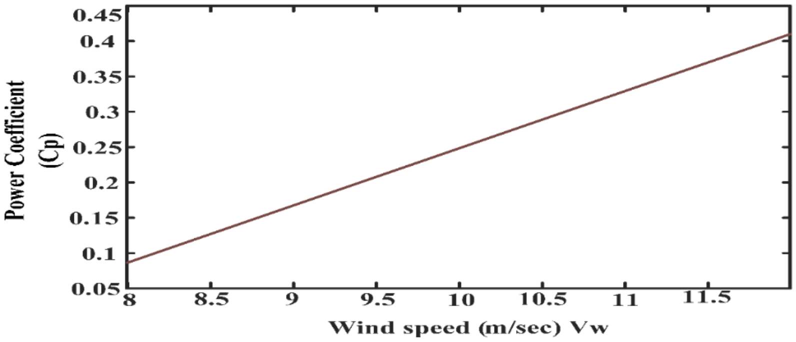


**Fig. 10 Wind turbine characteristic at wind speeds 8 and 12 m/s**

Fig. 10 shows in the wind speed is x-axis and the cp on y-axis, wind speed increases by increasing the Cp (power coefficient).

The maintain a constant speed using an MTPA controller, the controller needs to be configured to maintain a constant frequency and voltage in the motor. This can be achieved using a closed loop feedback control system that measures the motor's speed
and adjusts the frequency and voltage according.

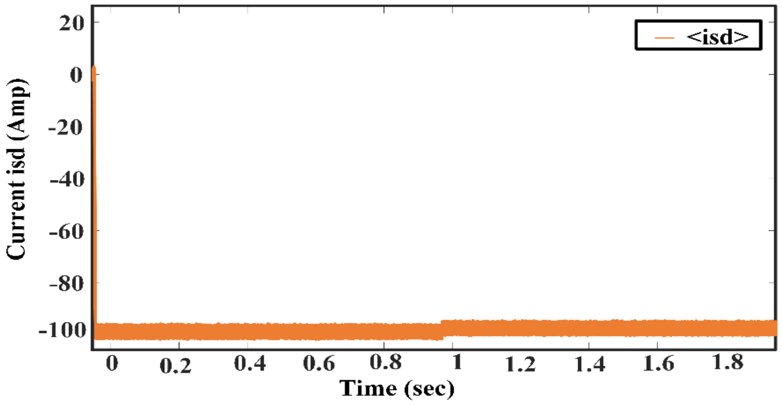


**Fig. 11. Direct axis stator current (isd) of PMSM**

In this Fig. 11 shows a negative value of id current reduces the required iq current by adding reluctance torque.

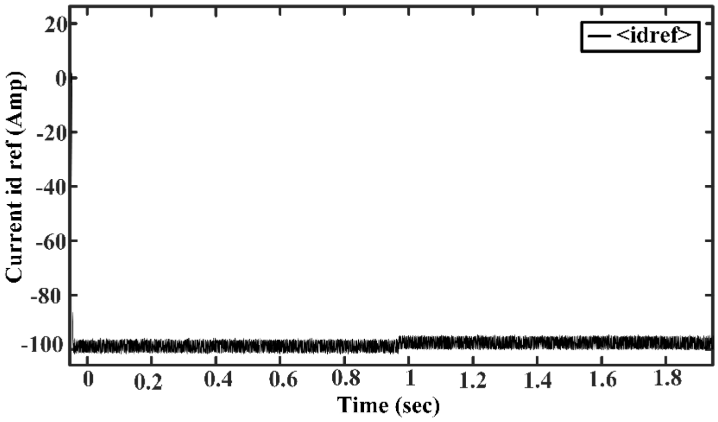


**Fig. 12. Direct axis Ref. current (id)**

In this Fig. 11 shows on the other hand, the d-axis current reference (id) is typically set to zero or a

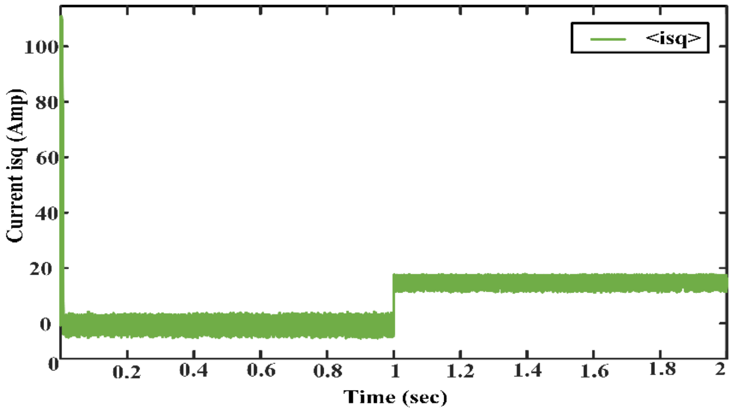


**Fig. 13. Quadrature axis stator current (isq) of PMSM**

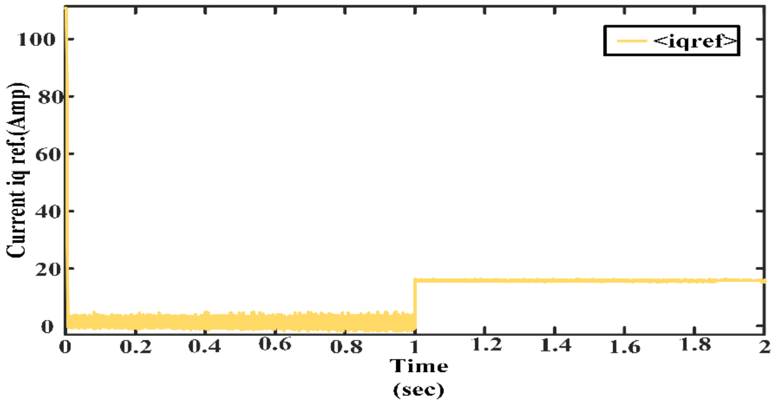


Fig. 14. Quadrature axis Ref. current (iq)

Fig.12 and Fig .14 in MTPA control, the *id* and *iq* currents are adjusted to maximize the torque produced by the motor while keeping the total stator current within a predetermined limit.

**Sudden change wind speed at constant load**

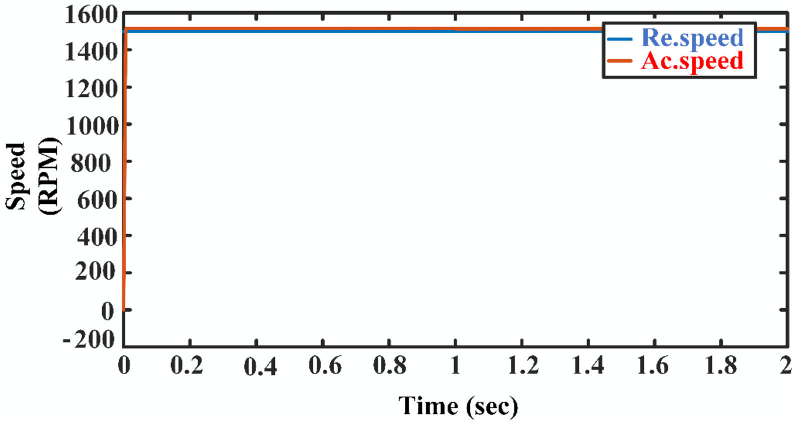


Fig. 15. Sudden change wind speed

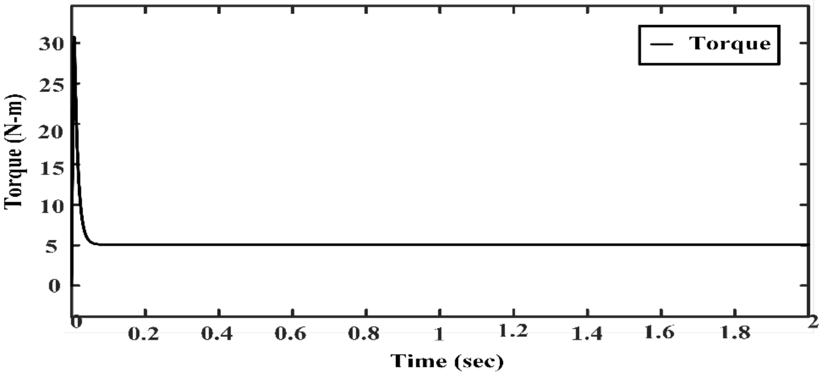


Fig. 16. Sudden change wind speed at constant load

Shows Fig. 15 the even if the wind speed changes, the output of the motor will not change and shows Fig. 16 the torque of the motor will not change because the FOC is used to control the speed and through the MTPA.

## 5. Comparative Analysis

In order to analyse the performance of proposed technique a comparative evaluation has been carried out with reported methodology [19]

**Table 1 Comparative results of Torque Ripples**

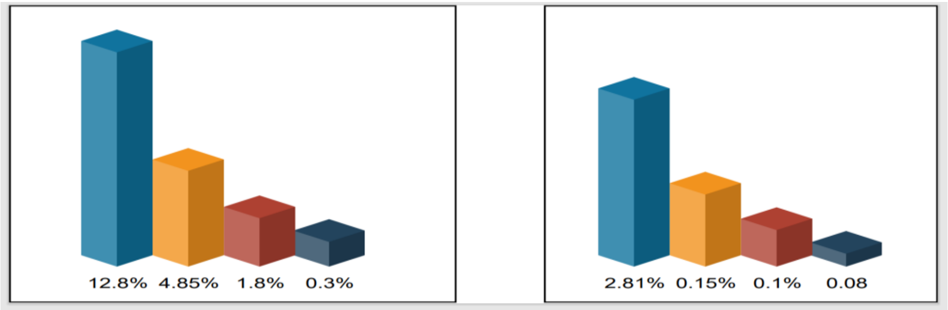
| Field Oriented Control | Developed Torque | Torque Ripple Factor (%) |
|---|---|---|
| FOC with BLDC Drive | 2.2-2.6 Nm | 50 |
| FOC with PMSM Drive | 2 Nm | 5 |

Table 2. Comparison of FOC and DTC w.r.t a PMSM [20]

**Table 2 Comparison of FOC and DTC w.r.t a PMSM[26]**

| | Field-Oriented Control | Direct Torque Control |
|---|---|---|
| Dynamic response for torque | Slower | Faster |
| | Steady-state behaviour for torque,<br>stator flux and currents<br>Lower ripple and distortion | Higher ripple and distortion |
| Parameter sensitivity | Decoupling depends on $L^d$ $_q$ | Sensitive to stator resistance (Rs) |
| Controllers | Linear PI regulators for Stator currents | Hysteresis controllers for Torque and Stator flux |
| Switching Frequency | Constant | Variable |
| Implementation Complexity | High complexity, Coordinate transformation necessary | Medium complexity, No coordinate transformation |

### 5.1. Performance analysis of proposed methodology.



DTC

FOC

Fig. 16. Steady-state performance index [21]

## 7. Conclusion

This paper presents the PMSM is used to simulate the aerodynamic behaviour of a wind turbine rotor. The system tracks the torque command issued from a wind turbine block under a sudden change in the applied load to the motor, sudden change in wind speed, and under stochastic wind speed variation. The system precision in emulating the torque-speed characteristics of the target turbine is also verified. The system dynamic behaviour is tested under different cases. These cases include a sudden change in load under constant wind speed, sudden change in wind speed, and finally system performance.

To maintain a constant speed using an MTPA controller and flux weakening control for PMSM, the controller needs to be configured to maintain a constant frequency and voltage in the motor. This can be achieved using a closed-loop feedback control system that measures the motor's speed and adjusts the frequency and voltage accordingly. The conclude that the PMSM is the best option to this emulates simulate the wind turbine characteristics to be used in the research and development of the wind energy conversion systems

# References

[1] L. Yang, S. Yan, Z. Chen, and W. Liu, “A Novel Wind Turbine Simulator for Wind Energy Conversion Systems Using an Pemanent magnet synchronous motor,” pp. 2156–2158, 2013.

[2] “Electricity_sector_in_India @ en.wikipedia.org.” [Online]. Available: https://en.wikipedia.org/wiki/Electricity_sector_in_India

[3] Z. M. Hailemariam, R. Leidhold, and G. T. Tesfamariam, “Real-Time Speed Control of a PMSM for Wind Turbine Application,” *IEEE PES/IAS PowerAfrica Conf. Power Econ. Energy Innov. Africa, PowerAfrica 2019*, pp. 396–401, 2019, doi: 10.1109/PowerAfrica.2019.8928919.

[4] F. Korkmaz, I. Topaloğlu, M. F. Çakir, and R. Gürbüz, “Comparative performance evaluation of FOC and DTC controlled PMSM drives,” *Int. Conf. Power Eng. Energy Electr. Drives*, no. May, pp. 705–708, 2013, doi: 10.1109/PowerEng.2013.6635696.

[5] J. Oest, R. Sørensen, L. C. Lars, and E. Lund, “Structural optimization with fatigue and ultimate limit constraints of jacket structures for large offshore wind turbines,” *Struct. Multidiscip. Optim.*, vol. 55, no. 3, pp. 779–793, 2017, doi: 10.1007/s00158-016-1527-x.

[6] F. Famoso, S. Brusca, D. D’Urso, A. Galvagno, and F. Chiacchio, “A novel hybrid model for the estimation of energy conversion in a wind farm combining wake effects and stochastic dependability,” *Appl. Energy*, vol. 280, no. July, p. 115967, 2020, doi: 10.1016/j.apenergy.2020.115967.

[7] J. Zhao and B. K. Bose, “Neural-network-based waveform processing and delayless filtering in power electronics and AC drives,” *IEEE Trans. Ind. Electron.*, vol. 51, no. 5, pp. 981–991, 2004, doi: 10.1109/TIE.2004.834949.

[8] M. P. Kazmierkowski, “Electric motor drives: Modeling, analysis and control, R. Krishan, Prentice-Hall, Upper Saddle River, NJ, 2001, xxviii + 626 pp. ISBN 0-13-0910147,” *Int. J. Robust Nonlinear Control*, vol. 14, no. 8, pp. 767–769, 2004, doi: 10.1002/rnc.811.

[9] J. . 4. Kirtley, “Electric Machines: Analysis and Design Applying MATLAB,” 2001.

[10] M. . 5. Rahman, “Permanent Magnet Synchronous and Brushless DC Motor Drives,” 2012.

[11] B. . 3. Bose, “Modern Power Electronics and AC Drives,” 2001.

[12] X. del T. Garcia, B. Zigmund, A. A. Terlizzi, R. Pavlanin, and L. Salvatore, “Comparison between

FOC and DTC Strategies for Permanent Magnet Synchronous Motors," *Adv. Electr. Electron. Eng.*, vol. 5, no. 1, pp. 76–81, 2006.

[13] M. E. Abdallah, O. M. Arafa, A. Shaltot, and G. A. Abdel, "Wind turbine emulation using permanent magnet synchronous motor," *J. Electr. Syst. Inf. Technol.*, vol. 5, no. 2, pp. 121–134, 2018, doi: 10.1016/j.jesit.2018.03.005.

[14] E. Engineering, "WIND TURBINE SIMULATOR USING PMSM Xu Ke , Hu Minqiang , Yan RongYan W Du R ω v," pp. 732–737, 2007.

[15] M. L. Corradini, G. Ippoliti, and G. Orlando, "Robust control of variable-speed wind turbines based on an aerodynamic torque observer," *IEEE Trans. Control Syst. Technol.*, vol. 21, no. 4, pp. 1199–1206, 2013, doi: 10.1109/TCST.2013.2257777.

[16] M. Abassi, A. Khlaief, O. Saadaoui, A. Chaari, and M. Boussak, "Performance analysis of FOC and DTC for PMSM drives using SVPWM technique," *16th Int. Conf. Sci. Tech. Autom. Control Comput. Eng. STA 2015*, pp. 228–233, 2016, doi: 10.1109/STA.2015.7505167.

[17] "MTPA book.pdf."

[18] M. M. Chowdhury, M. E. Haque, S. Saha, M. A. Mahmud, A. Gargoom, and A. M. T. Oo, "An Enhanced Control Scheme for an IPM Synchronous Generator Based Wind Turbine With MTPA Trajectory and Maximum Power Extraction," *IEEE Trans. Energy Convers.*, vol. 33, no. 2, pp. 556–566, 2018, doi: 10.1109/TEC.2017.2769126.

[19] Z. Zhang, Y. Zhao, W. Qiao, and L. Qu, "A Discrete-Time Direct Torque Control for Direct-Drive PMSG-Based Wind Energy Conversion Systems," *IEEE Trans. Ind. Appl.*, vol. 51, no. 4, pp. 3504–3514, 2015, doi: 10.1109/TIA.2015.2413760.

[20] F. Amin, E. Bin Sulaiman, W. M. Utomo, and H. A. Soomro, "Modelling and Simulation of Field Oriented Control based Permanent Magnet Synchronous Motor Drive System," vol. 6, no. 2, pp. 387–395, 2017, doi: 10.11591/ijeecs.v6.i2.pp387-395.

[21] M. P. Magnet, S. Motor, and V. Control, ")ic," pp. 539–542, 2010.

[22] K. Lee and Y. Han, "Maximum Torque per Ampere (MTPA) Control for Scalar v/f Controlled SPMSM Drives," *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC*, vol. 2020-March, pp. 2429–2433, 2020, doi: 10.1109/APEC39645.2020.9124498.

[23] A. Engineering, H. Lei, and I. Control, "Universal MTPA Control for Permanent Magnet Synchronous Motor Drives," vol. 3, no. 1, 2017.

[24] R. Krishnan, *Permanent magnet synchronous and brushless DC motor drives.* 2017.

[25] Z. Chen, "Maximum Torque Per Ampere and Flux-weakening Control for PMSM Based on Curve Fitting," vol. 4, no. 3, pp. 3–7.

[26] X. del T. Garcia, B. Zigmund, A. A. Terlizzi, R. Pavlanin, and L. Salvatore, "Comparison between FOC and DTC Strategies for Permanent Magnet Synchronous Motors," *Advances in Electrical and Electronic Engineering*, vol. 5, no. 1. pp. 76–81, 2006.

[27] M. A. W. Begh and Hans-Georg Herzog, "Comparison of Field Oriented Control and Direct Torque Control for PMSM," *World Academy of Science, Engineering and Technology*, vol. 21, no. April. pp. 209–304, 2019.

[28] H. Hadla and F. Santos, "'Performance Comparison of Field-oriented Control, Direct Torque Control, and Model-predictive Control for SynRMs,'" *Chinese J. Electr. Eng.*, vol. 8, pp. 24–37, 2022.