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A Review of Control Techniques Future Trends in Wind Energy Turbine Systems with Doubly Fed Induction Generators (DFIG)

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Abstract

Wind energy is currently widely regarded as one of the most favorable green clean sources of energy. Several wind turbine principles with various generator architectures have been evolved to exchange the available wind energy into electric power. The DFIG partial Variable-Speed Wind Turbine (VSWT) system is most proper for wind turbine energy because of its numerous benefits over Fixed-Speed Wind Turbines (FSWT). This paper introduces a comparative review of the different wind turbine conversion energy and a valuable summary of the recent work in the literature on different Wind Energy Conversion Systems (WECS) of a DFIG modeling, Maximum Power Point (MPP), and the latest control system for operation. On the other side, comparisons and discussions between different wind turbines have been presented in the current study to be beneficial for research studies.

Keywords: MPP, Pitch control, WECS, DFIG, VSWTS

1. Introduction

Environmental pollution has been an increasing concern in people's daily lives in recent years. Therefore, the possibility of energy trouble has prompted academics to explore modern methods for producing clean and green energy technologies. Moreover, renewable energy use in wind power generation rapidly grows as a significant source of electricity used to replace harmful and depleting fossil fuels. According to the most recent World Wind Energy Association (WWEA) global statistics, 840.9GW of total wind energy capacity was installed globally by the end of 2022 [1,2].

A wind turbine alters the energy of the winds into mechanical rotational energy that can be utilized to a power generator, as depicted in Figure 1. The essential components of a WEC system are wind turbines that capture the wind power using aerodynamically made blades and change it into mechanical rotating energy, a gearbox, an electrical generator, a power converter with a control system, and an electrical transformer for the electrical grid connection [3].

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2. Wind Turbine Generators: Overview

Based on the rotor speed control criterion, two main wind turbine configurations are available on the global market: Fixed Speed (FSWT); and wind turbines with Variable Speed (VSWT). The FSWT wind turbine systems have an uncomplicated structure without a power Voltage Source Converter (VSC) interface and limited speed ranges in comparison to the wind turbine variable-speed system can be categorized into semi-variable and fully variable speeds according to synchronous speed. Moreover, variable-speed generators are used with a full-power or partial-power converter power electronic interface. The most significant advantage of utilizing the (VSWTs) is that it provides (MPP) at every variable wind speed with decreased stress of the mechanical and reduction of fluctuations in the power supply. These structures can be classified based on operating speeds, wind turbine power electronics converter designs, and the mechanism for limiting aerodynamic power.

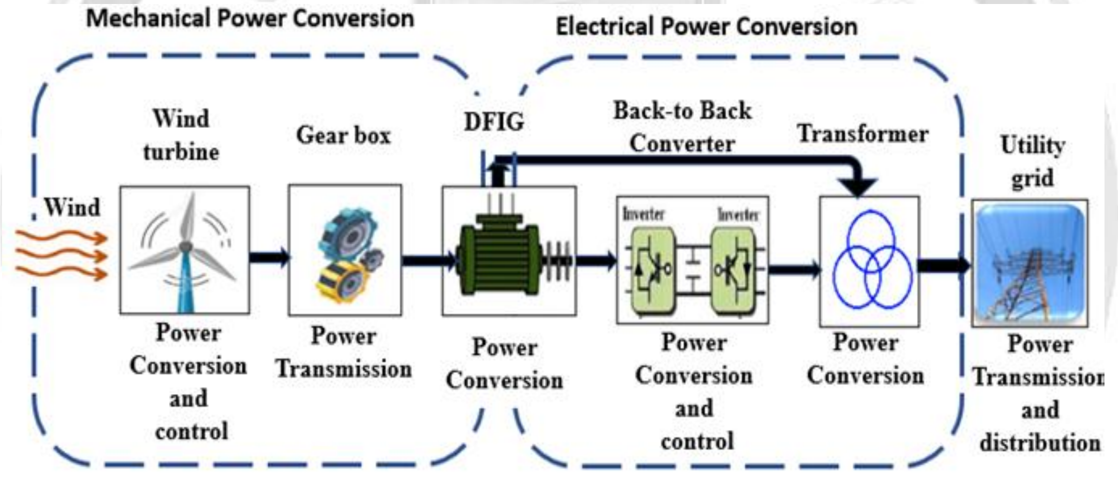

Figure 1: A scheme of wind turbine conversion into electrical power using the (DFIG).

2.1 Type 1: FSWT Strategies

A fixed-speed system turbine (FSWTs) runs at a fixed angular speed without a power converter link. The first and oldest model ("Danish" conception) was developed for WECS in the 1980s. The structure of this approach is commonly referred to FSWTs system since, during various wind speeds, the generator changes by just over one percent 1% of the synchronous speed [4]. This wind turbine generator concept is based on an asynchronous rotor generator depicted in Figure 2. The stator of a wind generator is directly connected through a soft starter to the infinite bus with a transformer device, and the wind turbine drives the rotor part. The rotor speed principle is specified by the generator (number of the pole) and a gearbox. The drawback of this technique of the WECS is that it cannot achieve maximum wind energy tracking according to changes in the wind [5].

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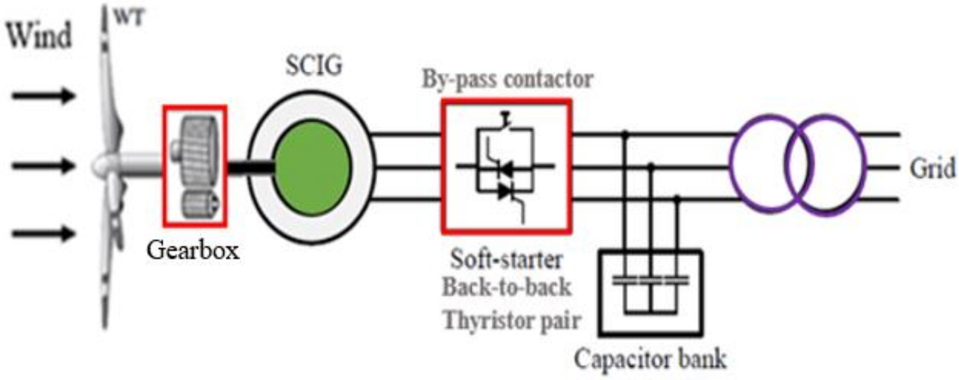

Figure 2: Schematic of asynchronous induction generator system.

2.2 Type 2: Partial-Variable Speed Dynamic Rotor Resistance

The concept of a wind turbine Wound Rotor Induction Generator (WRIG), variable-slip, or dynamic rotor resistance is the same as (SCIG) shown in Figure 3. The winding of the stator has been joined to the electrical network through a soft starter, and wound rotor windings are linked to the converter-controlled external resistor via brushes and slip rings. An electronic control system through a 3-phase H-bridge diode rectifier and a chopper circuit using a transistor bipolar insulated gate can be used to adjust the equivalent resistance in the system. This enables it to operate at a variable speed of 10% over the synchronous speed range. The configuration is frequently known as Optislip WT [6]. The drawback of variable-slip or dynamic rotor resistance is limited and is associated with the rotor ohmic losses being increased by the external rotor resistances leading to less system efficiency. The higher initial cost than the Type 1 WECS. This type requires more servicing.

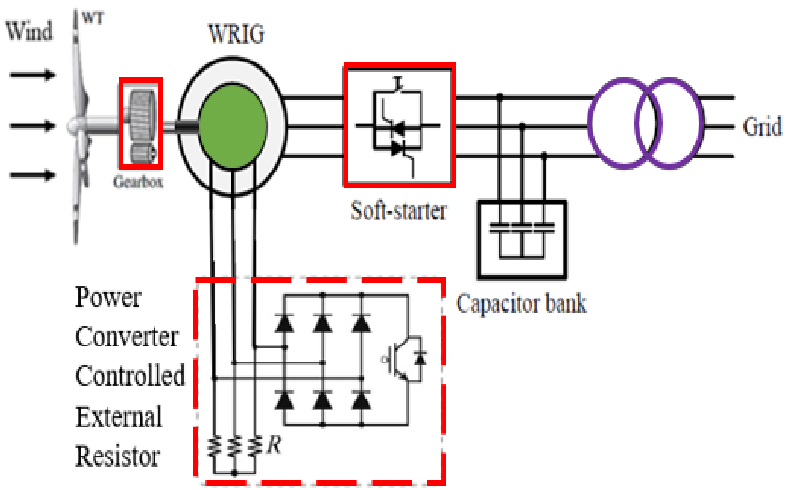

Figure 3: Schematic of a partial-variable speed dynamic rotor resistance (WRIG).

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2.3 Type 3: Partial-variable speed WECS of (DFIG)

Figure 4 illustrates a typical (DFIG) wind turbine configuration. It is one of the essential trend generators for (WEC) systems and is utilized for semi-variable-speed techniques. The windings of the DFIG's stator are directly joined to the electrical network, and the windings of the wound rotor are connected via a bi-directional power converter to the infinite bus. The DFIG's speed range is roughly about ∓ 30% of the synchronous speed [7].

In addition, many reasons to utilize a DFIG due to the lower inverter rating electronic equipment with a minimal percentage of the overall power (25%-30%). The drawback of DFIG is the requirement to use a wound rotor induction machine, and three slip-ring requires maintenance and cost. To overcome the disadvantages of the slip-rings in DFIG, the elimination of slip-rings and brushes reduces losses and needs fewer services [8]. There are many brushless (BDFIG) configurations available as follows:

- Cascaded (CDFIG).
- Single-Frame Cascaded (SF-CDFIG).
- Brushless Doubly-Fed Reluctance Generator (BDFIRG).

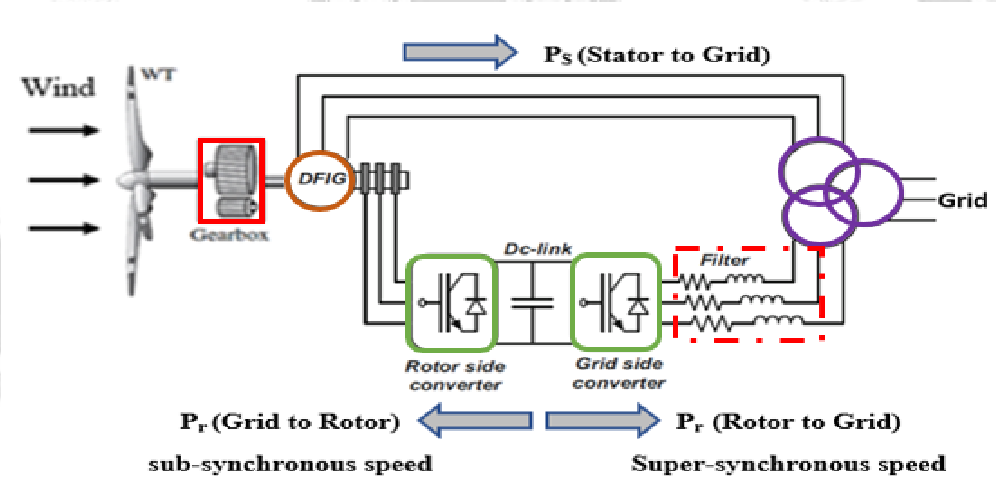

Figure 4: Schematic of DFIG- WEC system.

2.4 Type 4: Full-Variable speed WECS of (PMSG)

A Generator of the type Permanent Magnet Synchronous (PMSG) is a self-excitation. Because PMSG's rotor is energized by permanent magnets and does not need a power source to be excited, and the slip-rings can be omitted, maintenance costs will be reduced. It uses the Back-To-Back (BTB) configuration, with (100%) full-scale of the power converter thus, power between the generator and power network goes through bi-directional converters shown in Figure 5. The drawback of this type ٤ is the requirement a full-scale (BTB) converter must be rated for 100% of the generator power, cost, and complexity increase in comparison to the partial scale concept, higher power losses in the converter, and require a system for cooling since the materials of permanent magnetic are affected by heat and can lose their magnetic characteristics if exposed to very hot [9].

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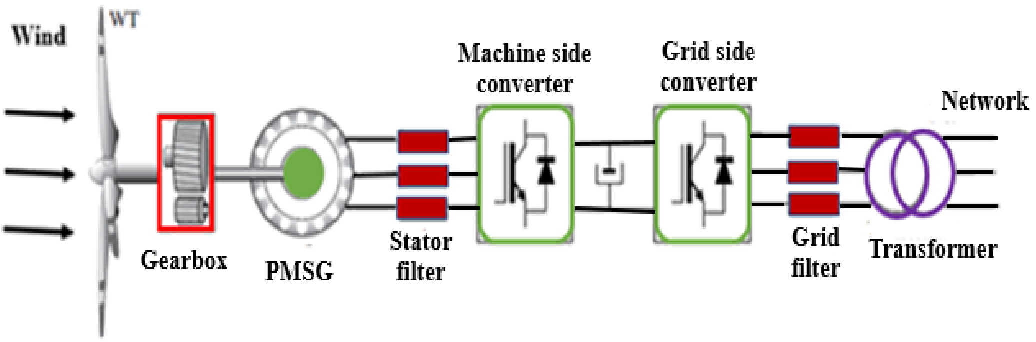

Figure 5: Schematic of a full-scale bi-directional converter for (PMSG).

Figure 6 describes the overview kinds of wind power generation systems. Furthermore, Table 1 summarizes the main types of wind turbine generator classifications to the types of generators, power voltage converters, speed range, soft-starter, gearbox, aerodynamic power control, active power control, and reactive power compensation requirement.

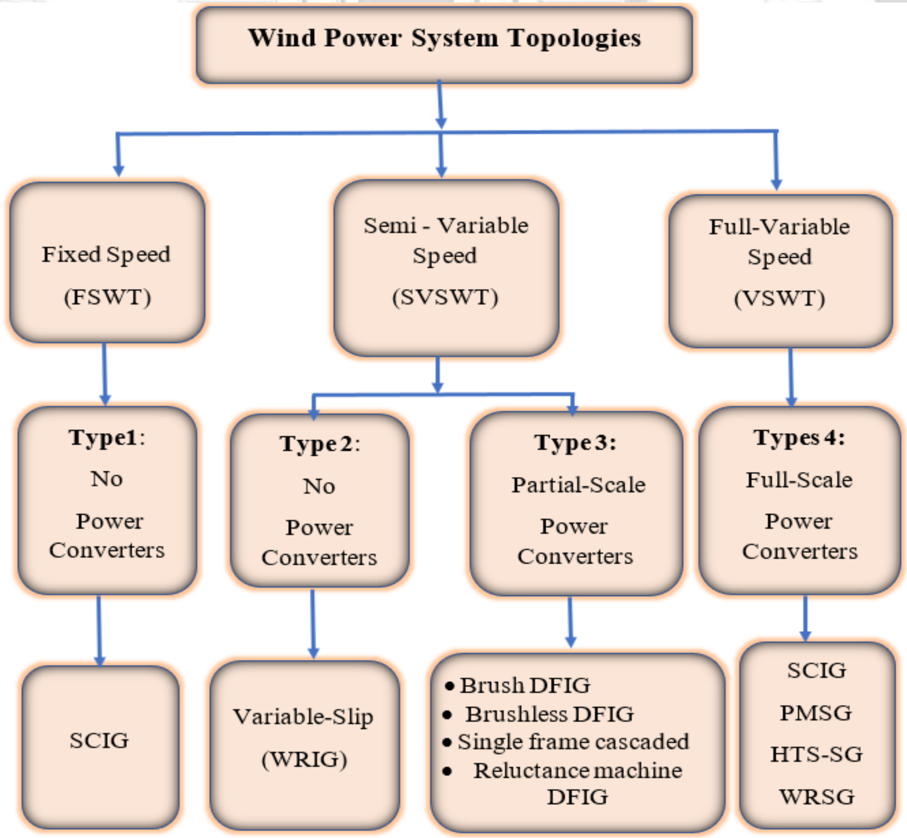

Figure 6: Overview of kinds of wind power generation systems.

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Table 1: The main differences between the four types of WECS configurations.

Types of Wind Turbine generators (WTGs)				
Wind Turbine Technology	Fixed Speed	Semi-Variable Speed		Full-variable speed
Wind generator kinds	SCIG	variable rotor resistance WRIG	DFIG	PMSG
Types of generators	Type 1	Type 2	Type 3	Type 4
Power converters	No	Partial	Partial	Full
Speed range	<1% of rated	<10% of rated	∓ 30% of the rated	Full, 100% of rated
Soft starter	Yes	Yes	No	No
Gearbox	Yes	Yes	Yes	Optimal
Aerodynamic power control	• Pitch • Stall • Active stall	Pitch	Pitch	Pitch
Grid side reactive power compensator	Yes	Yes	No	No
Active power control and MPPT	N/A	Limited	Yes	Yes
Short circuit (Fault active)	No	No	No/Yes	Yes
Efficiency rating	Low	Low / reduced	Good	Good

3. Wind Turbine System Operation Zone

The power curve shows three major distinct winds. The cut-in region is the lowest possible wind speed will a turbine begins to generate electrical energy. In addition, a rated power region is the wind speed applied at the blade that will generate the maximum power. Subsequently, a cut-out region is the speed of the turbine that should be turned off system to protect the equipment. The typical power can be classified among four operation zones according to the speed of wind value as shown in Figure 7.

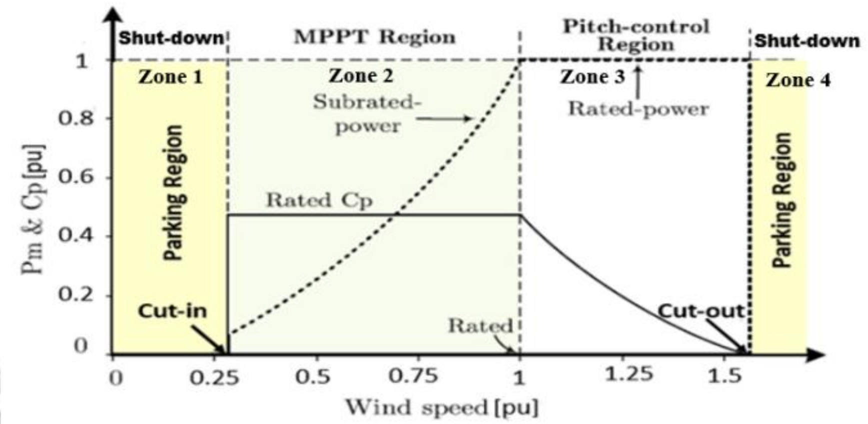

Figure 7: The typical wind turbine operating regions.

In zones 1 and 4 (parking control): ($v_w < v_w^{cutin}$ *or* $v_w > v_w^{cut\ out}$), a braking system is activated to park the wind turbine and the pitch angle is set to its peak value.

In zone 2 (MPPT control): ($v_w^{cutin} \leq v_w \leq v_w^{rated}$), the MPPT control regions when the speed of the wind is more than the cut-in value but minimal than the rated value (i.e., pitch angle $\beta = 0$) [10].

In zone 3 (pitch control): ($v_w^{rated} < v_w \leq v_w^{cut\ out}$), the system controls the pitch angle in such a way the power remains fixed at rated-power [11].

4. Aerodynamic Modeling of WECs

At a given wind speed v_w, the power of the mechanical captured from a wind turbine can be calculated by Eq. (1) [12].

$$P_m = C_p P_{air} = \frac{1}{2}\rho_{air}\pi R^2 v_w^3\ C_p(\lambda,\beta) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where: ρ denotes air density in (kg/m^3), which varies with atmospheric pressure and air temperature (e.g., $\rho_{air} = 1.225\,Kg/m^3$ and a temperature of 15C degrees at sea level), R blade radius in meter square, v_w speed of the wind (m/s), and C_p power coefficient. The power coefficient is affected by tip speed of the ratio and blade pitch angle $C_p(\lambda,\beta)$.

Eq. (2) shows that the tip speed ratio can be described as the speed at the tip of the blade to the wind velocity it can be written [13]:

$$\lambda = \frac{speed\ of\ a\ blad\ tip}{wind\ speed} = \frac{R\Omega_m}{v_w} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Thus,

$$v_w = \frac{R\,\Omega_m}{\lambda} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where Ω_m denotes the wind turbine's rotational speed in (rad/sec) [14]. For a specific rotor running at $\lambda = \lambda_{opt.}$, and $C_p = C_{p(max.)}$. Thus, the expression for optimum mechanical power can be written as:

$$P_{m-opt.} = \frac{1}{2}\rho_{air}\pi R^5 \frac{C_{p(max.)}}{\lambda_{opt.}^3}\Omega_m^3 = K_{p-opt}\Omega_m^3 \quad \ldots\ldots\ldots\ldots\ldots (4)$$

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Vol.31, No.7.| 2023

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

The formula for the wind turbine's optimum mechanical torque can be obtained using Eqs. (4) and (5) as a function of Ω_m^2.

$$T_{m-opt.} = \frac{1}{2}\rho_{air}\pi R^5 \frac{C_{p(max.)}}{\lambda_{opt.}^3}\Omega_m^2 = K_{p-opt}\Omega_m^2 \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Albert Betz, a pioneer of German wind power, established the theoretical Betz limit, proving that a wind turbine cannot capture more than 59.3% of the kinetic energy from an air stream into mechanical energy. The maximum power coefficient equal to Cp = 0.48 is obtained from Figure 8, a tip speed ratio of optimal equal to $\lambda_{opt.} = 8.1$.

For VSWT, one expression commonly used and easy to adapt to the power coefficient estimated for different turbines is as follows [15], [16].

$$C_p(\lambda, \beta) = a_1\left(\frac{a_2}{\lambda_i} - a_3\beta - a_4\right)\left(e^{\left(\frac{a_5}{\lambda_i}\right)}\right) + a_6\lambda \ \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.0035}{\beta^3 + 1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

The coefficient of Eq. (7) from a_1 to a_6 are given:

$a_1 = 0.5, \quad a_2 = 119, \ a_3 = 0.4, \ a_4 = 5, \ a_5 = -21, \quad a_6 = 0.0098$

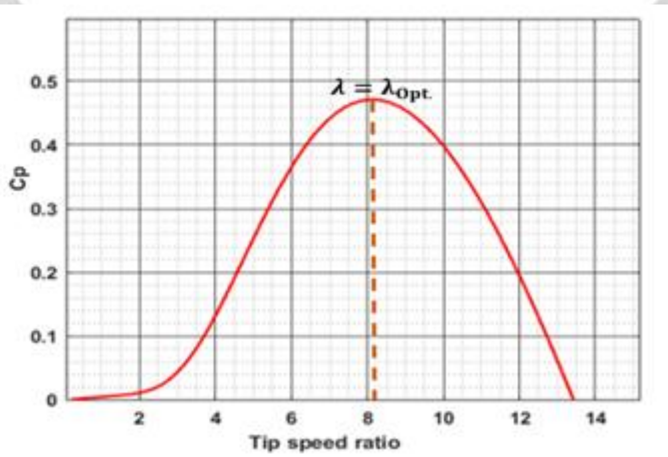

Figure 8: A typical characteristic C_p versus λ (fixed-pitch turbine β ≡ 0)

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5. dq Modelling of DFIG

The use of Park's conversion to the DFIG's 3-phase equivalent allows the dynamic voltages and fluxes equations to be written using a d-q reference frame [17].

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d\Psi_{ds}}{dt} - \omega_s \Psi_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d\Psi_{qs}}{dt} + \omega_s \Psi_{ds} \end{cases} \quad \ldots\ldots (9)$$

$$\begin{cases} v_{dr} = R_r i_{dr} + \frac{d\Psi_{dr}}{dt} - \omega_r \Psi_{qr} \\ v_{qr} = R_r i_{qr} + \frac{d\Psi_{qr}}{dt} + \omega_r \Psi_{dr} \end{cases} \quad \ldots\ldots (10)$$

$$\omega_r = \omega_s - \omega_{m.} \quad \ldots\ldots (11)$$

With:

$$\omega_m = P_p \Omega_m \quad \ldots\ldots (12)$$

The assumption is that power losses in (stator &rotor) windings are small. The (stator & rotor) equation of the real power and reactive power is defined as follows [18], [19].

$$P_s = \frac{3}{2}[v_{ds} i_{ds} + v_{qs} i_{qs}] \quad \ldots\ldots (13)$$

$$Q_s = \frac{3}{2}[v_{qs} i_{ds} - v_{ds} i_{qs}] \quad \ldots\ldots (14)$$

$$P_r = \frac{3}{2}[v_{dr} i_{dr} + v_{qr} i_{qr}] \quad \ldots\ldots (15)$$

$$Q_r = \frac{3}{2}[v_{qr} i_{dr} - v_{dr} i_{qr}] \quad \ldots\ldots (16)$$

The relationship between mechanical and electromagnetic torque is provided equation:

$$T_{em} - T_m = f\Omega_m + J\frac{d\Omega_m}{dt} \quad \ldots\ldots (17)$$

$$T_{em} = P_p \frac{3L_m}{2L_s}(\Psi_{ds} i_{qr} - \Psi_{qs} i_{dr}) \ldots\ldots (18)$$

Where $v_{ds}, v_{qs}, v_{dr}, and\ v_{qr}$ denotes the d,q axis components of stator voltage and rotor voltage; $i_{ds}, i_{qs}, i_{dr}, and\ i_{qr}$ denotes the stator current, and rotor current components d,q axis respectively; while $\Psi_{ds}, \Psi_{qs}, \Psi_{dr}, and\ \Psi_{qr}$ represents the stator, and rotor flux vector of d,q-axis components; R_s, R_r are the winding resistances per phase of the stator and rotor; J the moment of total inertia and f total friction factor constant (DFIG & turbine) respectively; T_{em}, T_m electromagnetic of the generator torque and mechanical of a machine torque respectively; P_p pole pairs number of the generator; ω_s synchronous angular velocity of the stator windings (rad/sec); and ω_r angular velocity of the rotor windings in (rad/sec) [20].

6. Controlling Operation Techniques for DFIG

Control strategies of the WECS operation innovation focused on cost reduction, power quality enhancement, reduced Total Harmonic Distortion (THD), and system simplification to overcome the unexpected nature of wind variation [21]. The bidirectional power converters linked between the rotor side circuit is called the rotor side converter RSC, and the grid is called the grid side converter GSC, typically rated about (25%–30%) of the design rating depicted in Figure 9. The GSC is utilized to keep the DC voltage bus constant at its desired value. Moreover, the RSC are controlling the DFIG electromagnetic generator torque and rotor flux [22].

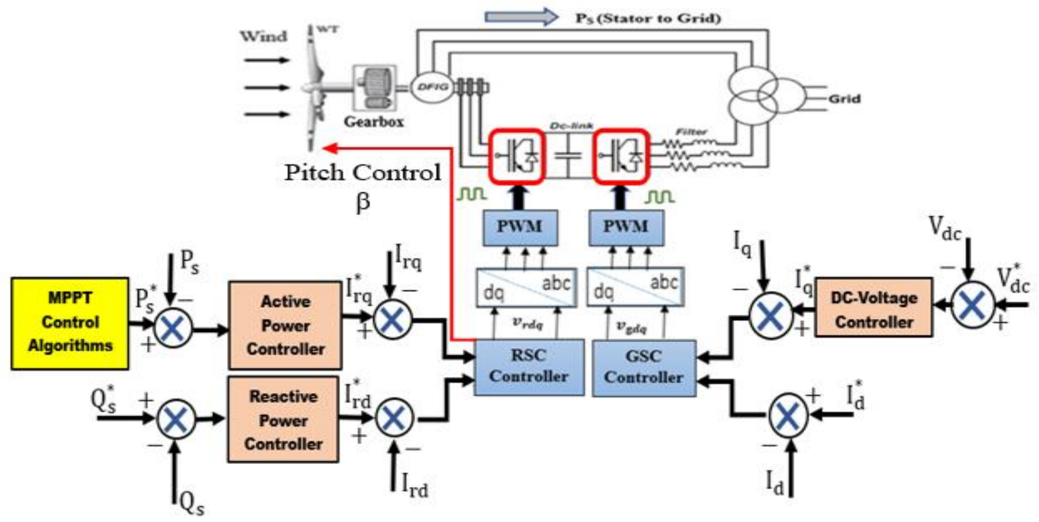

Figure 9: Propose control structure for DFIG-based WECS.

6.1 Control Safety of Modern Wind Turbines

Wind energy turbines may theoretically generate more power than the designer data sheet values if the speed of the wind is greater than the rated value. Therefore, to limit the speed of the wind turbine when the speed is exceeded, the mechanical output power of the turbine must be controlled to not over speed the rated value [23]. Modern WECS can be safely managed in three several methods of aerodynamic power regulation: stall, pitch, and active stall control.

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6.1.1 Stall-Control Wind Turbines (Passive)

The blades of the rotor shaft are bound to the hub at a fixed angle. When the speed of the wind is more than a specific limit, the turbulence formed on the rotor blade's surface leads to the airfoils losing lift force, thus reducing the air energy captured by the wind. The advantages of this technique are that it is less expensive and more reliable because it doesn't require any sensors, electronic controllers, or actuators [24]. The disadvantage of this control method is the high stress of the mechanical caused by wind gusts. Stall (passive control) is commonly utilized in medium and small-scale power wind turbines.

6.1.2 Pitch-regulated Wind Turbine (active)

A pitching regulator is commonly utilized today. When the wind speed is higher than the rated, the computer transmits an electrical control signal to the actuator (motor or hydraulic) that moves the rotor blades along the direction longitudinal axis reducing the blade's angle of attack turn “out of wind". The benefits of regulator pitch angle are improved efficiency of power control, enhanced start-up, and adjustment of power emergency stop [25].

6.1.3 Active Stall or Combi Stall Control

A more advanced technique than passive stall control uses adaptive rotor blades. Thus, also possible to modify the angle of attack toward the stall to limit the aerodynamic power. The blades are turned "into the wind" in this technique to create a stalling mechanism. This technology is utilized to fine-tune the wind turbine level of fixed-speed turbines at high wind speeds. If the speed of the wind exceeds the limited rate, the computer automatically shuts off the WECS to protect the turbine.

6.2 Overview of MPPT Algorithms

In recent years, several papers review different algorithms and techniques contributing to tracking the (MPP) to the WECs for different variable speeds. The algorithms are categorized according to the measurement of direct electrical power P_{ele}control (DPC), indirect mechanical power P_{wind} control (IPC), and hybrid to capture the extracted maximum power MPPT from WECS. These structures can be classified based on operating speeds and wind turbine power converter structures [26], as shown in Figure 10.

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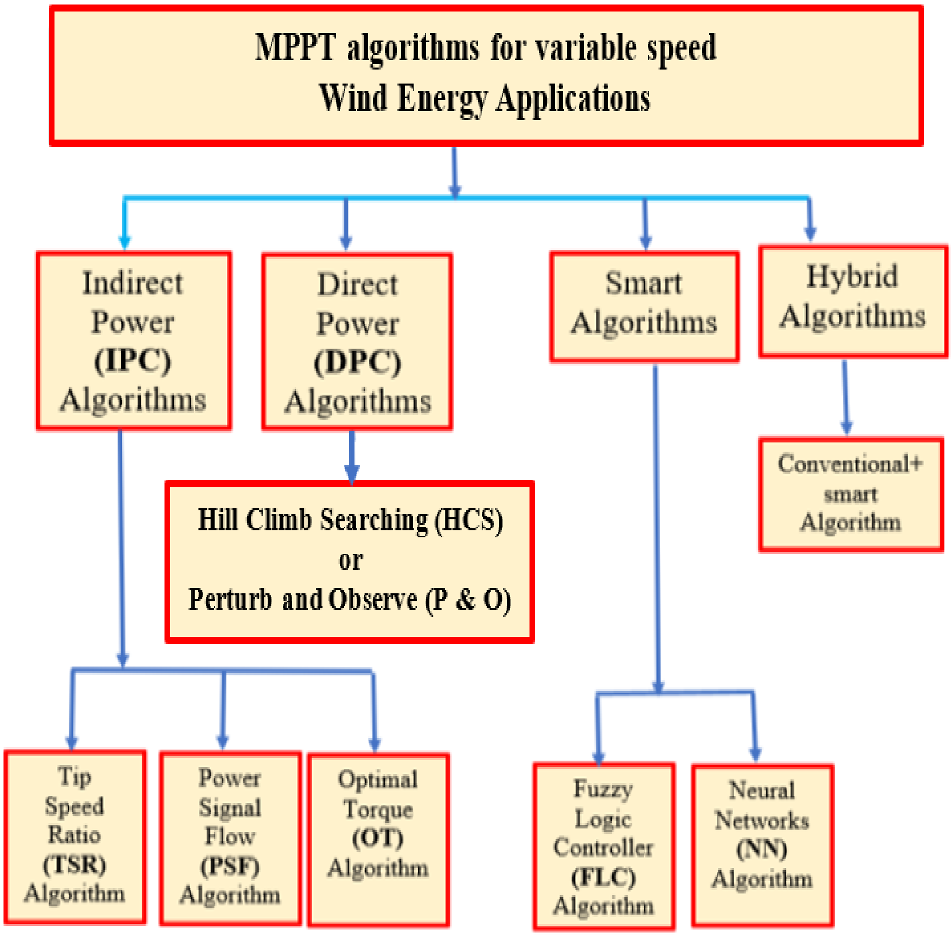

Figure 10: Overview of MPPT algorithms for variable speed applications.

Figure 11 depicts the maximum power that can be captured in Zone 2, which is located between the (Vcut-in and Vrated). In indirect mechanical power (IPC), sensors like anemometers are utilized in MPPT strategies to measure the speed of the wind. MPPT strategies many algorithms utilized to control for WECS like conventional or modified Tip Speed of Ratio (TSR), Feedback of the Power Signal as known (PSF), and Optimal Torque (OT) algorithms consist of sensors of speed based on capture (MPP) approaches, but direct electrical power (DPC), MPPT techniques that don't require wind speed sensors are (P&O) Perturbed and Observed or the Hill Climb Searching (HCS) algorithms. To overcome the drawbacks of the classical methods, there are different hybrid techniques for capturing maximum energy from WECS. There are various hybrid algorithms available that use intelligent algorithms like Neural Networks (NN), also Fuzzy Logic Controllers (FLC) to extract the maximal power of WECS [27].

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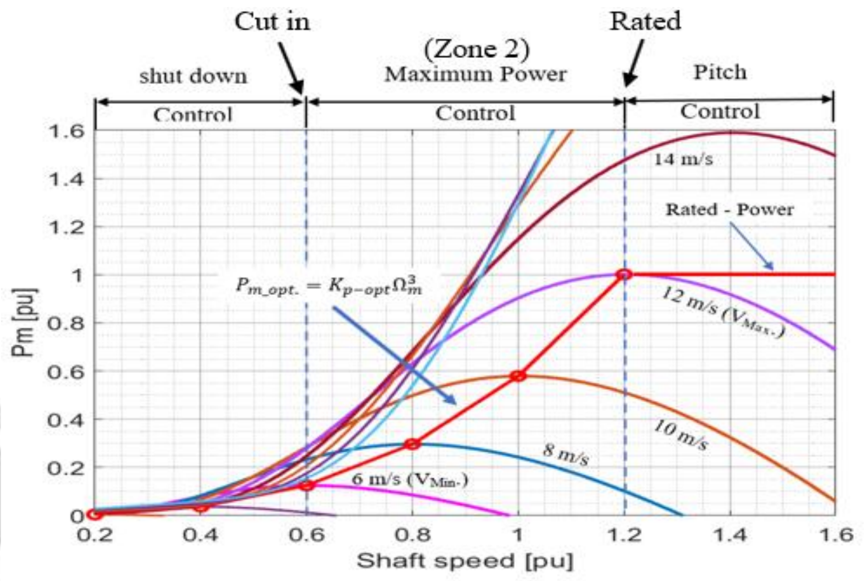

Figure 11: MPPT curve with different wind speeds.

6.2.1 The TSR Algorithm

In this technique, the TSR algorithm based on mechanical sensors employs many anemometers that surround the WT to measure wind speed. The tachometers or absolute position encoders are used for measuring generator speed. On the other technique, an appropriate reference of rotor speed ($\Omega_{ref.}$) is obtained by estimating the rotor of the speed shaft (Ω_m) and the wind is the result. The TSR strategy has many benefits, including immediate response and efficiency, but the drawback is increased servicing and initial cost. Moreover, the system parameters must be given.

6.2.2 PSF Algorithm

This approach generates lookup tables for the optimum power ($P_{opt.}$) using simulations or experimental setups for each wind turbine. The angular speed (Ω_m) of the wind generator is measured using the optimal power characteristics with estimated output power and compared to the actual output power value. The outcome of the error can be used for controlling a power converter [28]. The advantages of this technique are low-cost and robustness. The disadvantage is the difficulty of extracting the MPP for wind turbines due to large inertia at very lower wind.

6.2.3 OT Algorithm

The OT MPPT algorithm's strategy for controlling the torque of the existing generator by utilizing optimal torque characteristics for different wind speeds. This approach has the advantages of increased efficiency, ease, and excellent tracking speed. The drawbacks are the dependence on environmental variables and the need to know the wind turbine's characteristics [29].

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6.2.4 Conventional and Modification P&O Algorithm

The conventional (P&O) method technique includes the position of the MPPT using a mathematical optimization strategy in the target when the slope reaches zero for the (P, ω) characteristics. The main benefits of this method are it has no need for the use of sensors like an anemometer, and it also does not require knowledge of the WT characteristics. The drawback of this technique bigger step sizes cause oscillation close to the MPP, but reducing step sizes will cause more convergence time and a lower response. Moreover, this approach is unsuitable for high-inertia wind turbines because it is difficult to achieve MPP when wind speed fluctuates rapidly. In addition, modified (P&O) algorithms, which utilize varying, and adapt step sizes, are improvements to the conventional P&O that the maximum tracking technique [30]. In addition, modified adaptable step-size algorithms have been developed to increase the qualification and accuracy of the classical P&O strategy. Figure 12 represents the conventional P&O flowchart proposed system. Figure 13 demonstrates how this method works.

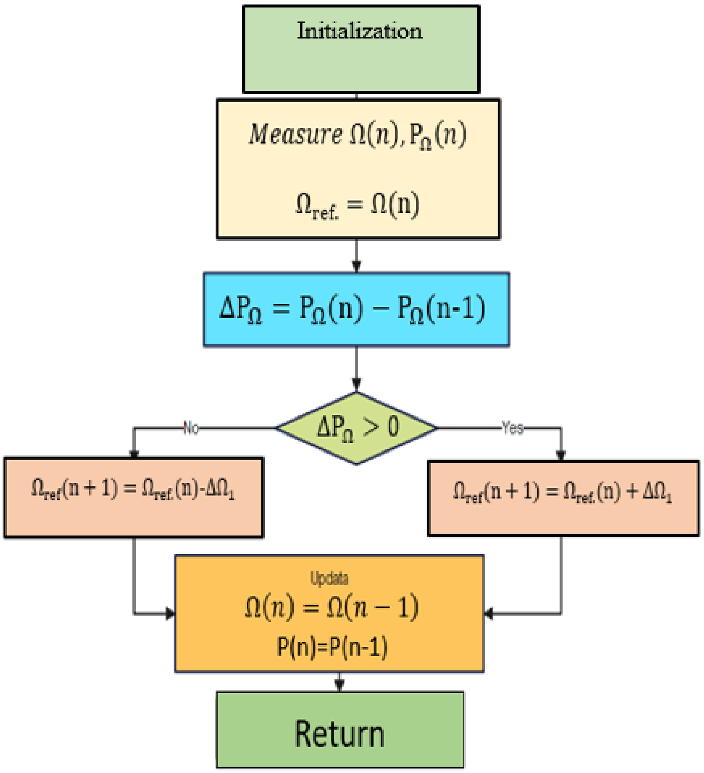

Figure 12: The flowchart of conventional P&O algorithm.

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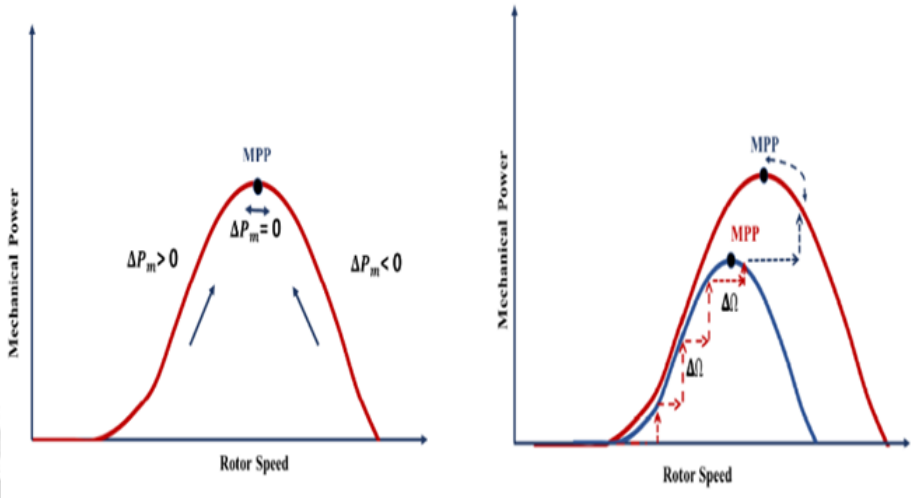

Figure 13: The conventional P&O MPPT technique operation concept.

6.3 Smart MPPT Algorithms

Recently, among users of a variety (MPPT) algorithms that employ intelligent controllers, such as the Fuzzy Logic Controller (FLC), improves the system's fineness and minimizes the loss of bi-directional converters. Artificial Neural Networks (ANN) are currently utilized to solve complicated practical troubles at various wind speeds. additionally, other soft computing (MPPT) techniques are used. In addition, (MPPT) algorithms based on optimization techniques, like the Cuckoo Search (CS) algorithm, modified the Genetic Algorithm, Teaching Learning Based (TLB), and algorithm of the Grey Wolf (GW), are used in combination with classical (MPPT) algorithms to increase the efficiency and overcome the limitations of classic strategies of the (MPP) algorithms.

6.3.1 Fuzzy Logic Controller

The (MPPT) technique uses Fuzzy logic control (FLCs) to overcome the problem of oscillations around the power peak point. The ability of the controller's variables to change quickly in response to fluctuations in the system dynamics is what characterizes this technology. Consequently, there is no need for wind energy conversion WECS to be modeled mathematically. This method's overall system performance is good even under fluctuating conditions in wind speed [31].

6.3.2 Algorithm Artificial Neural Network

The intelligence of an Artificial Neural Network (ANN) is constructed from three parts layers: the first layer is the input, the median represented hidden layers, and the third layer represents the output, with node number modifications based on designer decisions, as depicted in Figure 14. The variables like the terminal input voltage, speed of the wind, torque, and the output given are used as reference variables like the power output or the rotor speed a reference to drive the electronic power converter circuit. The designated layer weights determine how the point of operation and the global point will correspond [32].

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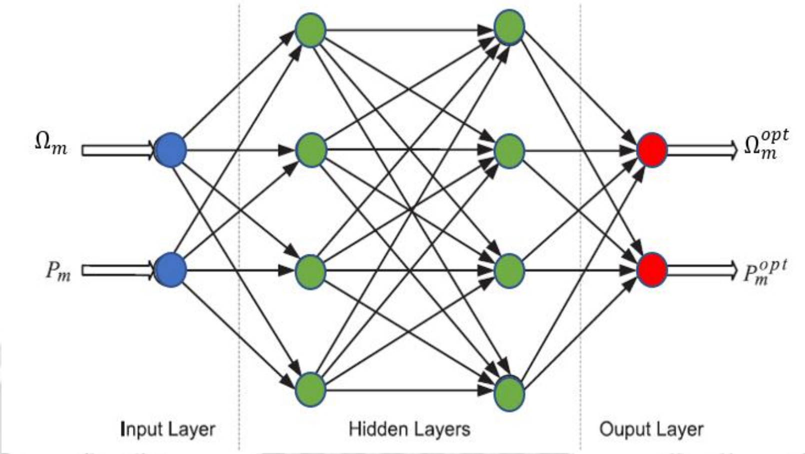

Figure 14: ANN diagram used for estimation of optimal WECS.

6.4 Hybrid Algorithms for MPPT

The concept of hybrid MPP strategies is based on combining two or more features of various MPP algorithms to overcome limits of restrictedly MPPT techniques and improve WECS performance [33].

7. Conclusions

The paper reviews recent different controller trends and control system strategies used in DFIG-based WECS. The main benefit of the (DFIG) is that (25%-30%) of the produced power passes through the partial-scale power converter as compared with other (VSWTs) like (SCIG), and (PMSG) are required a full-range bi-directional converter to operate. Therefore, the overall losses and costs are reduced. The equation model of the turbine and the electrical generator of a DFIG is initially set introduced. In this work, the majority of the important MPPT characteristics are described and summarized with different algorithms commonly used.

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مراجعة لتقنيات التحكم المستقبلية الاكثر شيوعا في أنظمة توربينات طاقة الرياح باستخدام المولدات الحثية ذات التغذية المزدوجة

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الخلاصة

تعتبر طاقة الرياح حاليا واحدة من أكثر مصادر الطاقة الخضراء النظيفة الملاءمة على نطاق واسع في العالم. تم تطوير العديد من مبادئ توربينات الرياح بستخدام المولدات المختلفة لتحويل طاقة الرياح المتاحة إلى طاقة كهربائية. يعد نظام المولد الحثي ذي التغذية المزدوجة DFIG لتوربينات الرياح ذات السرعة المتغيرة نسبيا (VSWT) هو الأكثر ملاءمة لطاقة توربينات الرياح بسبب فوائده العديدة مقارنة بتوربينات الرياح ذات السرعة الثابتة نسبيا (FSWT). تقدم هذه الورقة مراجعة و مقارنة عن طاقة توربينات الرياح المختلفة وملخصًا قيمًا للعمل الأخير المتعلقة بأنظمة طاقة الرياح المختلفة (WECS) لنمذجة DFIG وأقصى نقطة طاقة MPP وأحدث نظام تحكم للتشغيل. ومن ناحية أخرى تم في الدراسة الحالية تقديم مقارنات ومناقشات بين توربينات الرياح المختلفة لتكون مفيدة للدراسات البحثية.

الكلمات الدالة: أقصى نقطة طاقة MPP , إعادة ضبط السيطرة, أنظمة تحويل طاقة الرياح WECS , المولد الحثي ذي التغذية المزدوجة DFIG , توربينات الرياح ذات السرعة المتغيرة نسبيا (VSWT).

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