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Wind Power Plant Modeling for the Conditions of Grid-Connected Mode: the Review

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***Abstract*— The load demand to the power grid, as well as the interest in clean and low-cost energy resources, lead to the high integration of wind power plants into the power system grid. There are grid code standards that are set for the design and integration of these wind power plants. These codes often look at the design operation of the wind power plant in islanded mode, where possible analysis of the most sensitive power system quantities such as voltage, frequency, reactive power, etcetera is done. Therefore, attention needs to be paid to the application of these codes to keep the design and integration of wind power plants well standardized as much as possible. The purpose of this research is to review and discuss the literature and theory about the design of the wind turbine generators, model the wind power plant, and integrate it into the power system grid while adhering to the grid code requirements.**

Keywords— Integration, Point of Common Coupling (PoCC), Renewable Power Plant (RPP), South African Renewable Grid Code Standards (SAREGCS), Wind Power Plant (WPP), Wind Turbine, Wind Turbine Generator Unit (WTGU), Wind Turbine Power Coefficient (Cp).

I. INTRODUCTION

It is believed that the traditional energy resources of power will vanish in the next coming years. This will lead to a complete escape from the traditional resources of power to renewable resources. Wind energy has been leading. This is proven by the recorded data obtained from the worldwide gigawatt (GW) installation [1], whose data shows that the world estimated installed total capacity of wind power was 592 GW in 2018.

One of the wind power plants (WPPs) benefits is that they are located close to the customer. WPPs can be operated in two modes, such as the grid-connected and standalone (islanded) mode, depending on grid stability requirements. In grid-connected mode, WPPs contribute additional power when the load demand has increased. In islanded mode, they serve as an emergency supply for individual loads when the power supplied by the grid is insufficient. There are additional services for the conditions of a grid-connected mode, such as frequency and voltage adjustments, harmonic compensation, power backup, network stability, additional reserve, and clearing of load peaks [2].

One of the requirements in power system operation is to keep the power grid supply stable. There are control techniques used on the mechanical side of the traditional generating stations to ensure the stability of the system in the conditions of power system disturbances. However, their operation is limited when severe disturbances like sudden increase or decrease in load demand occur in the system. In the case of an increase in load demand, additional power sources like WPPs play a significant role.

A lot of research work has been done relevant to the integration of wind power plants (WPPs) into the power grid. However, research that considers the WPPs in an islanded mode of operation is rare. In addition, some of the published work makes use of a single wind turbine generator unit (WTGU) and assumes it is a complete WPP, as is supposed to consider the modeling of multiple WTGs to accommodate WPP dynamics at large. Lastly, for scholarly benefits, it is rare to find research work covering theory about how WTGs work in line with the modeling, as is it significant to cover in-depth modeling parameters. To mention a few studies, [3] did a study of the wind power plant integration into a weak distribution network. Their wind power plant model consists of a 6 MW single wind turbine generator (WTG) model made large enough to represent a reasonable megawatt capacity of a wind power plant. A 9 MW single WTG for the integration into the grid through the static synchronous compensator (STATCOM) is modeled in [4]. Their results show that the wind power plant cannot stay connected to the grid without the use of STATCOM.

It is understood that the computation of each component consumes time. In a wind power plant area, the wind speed is not the same. This means that the power produced by each wind turbine generator differs from one another. However, because the turbines are many in a wind power plant, the dynamic behavior from an individual wind turbine is canceled by the other. That being said, the results obtained in [4] may not be true. The same applies to [3], their model may not bring enough validation of their study. Additionally, none of these models were first run standalone for grid compliance tests, as the grid codes require. This violates the design requirements of the wind power plants for grid integration as mentioned in [5].

While the study primarily looks at the modeling of a wind power plant (WPP) for the conditions of grid-connected mode, adhering to the grid code requirements, it is divided into three parts, namely Part 1, Part 2, and Part 3. This part presents the literature and theory about the design and specifications of WTGs. Part 2 focuses on the modeling of a complete wind power plant (WPP). Most importantly for industrial benefits, the grid compliance test is done for the WPP in an islanded mode of operation, to ensure the minimum grid code requirements before the integration. Part 3 presents the integration of WPP into the grid, where the contribution of WPP for voltage stability improvement is evaluated.

II. THE OVERVIEW OF WIND POWER PLANTS

The wind power plant (WPP) is defined as a group of wind turbine generator units (WTGUs) installed in the same area for power generation. These WTGUs are the primary components of energy production in a WPP and are coupled through various circuits as shown in Fig. 1 [6].

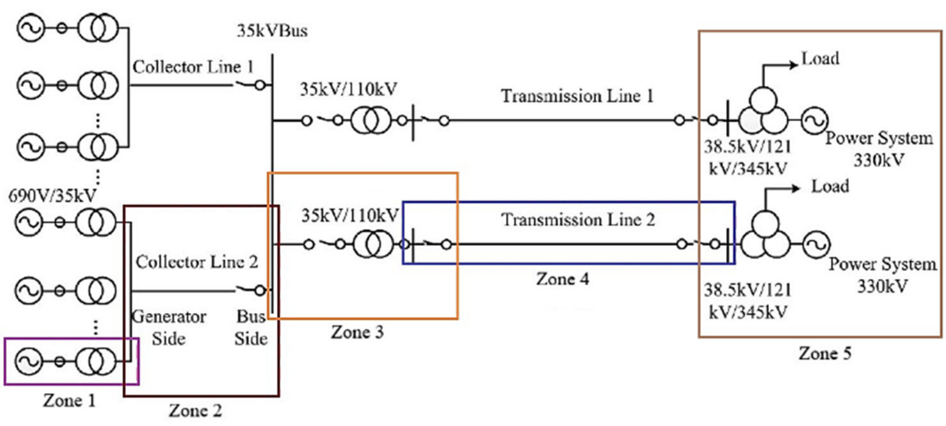

Fig. 1. The wind power plant shows various circuits from wind turbine generator units to the medium voltage to high voltage step-up transformers

Five zones are indicated in this figure as follows: Zone 1 is the WTGU. Zone 2 is the collector feeder. It connects more than one WTGUs to a high voltage step-up transformer located in Zone 3. Zone 4 shows the transmission line system connecting the WPP to the power system grid. The transformer symbols shown in the figure represent substations. These substations contain switchgear and protective devices [6].

Standards are set to specify the requirements for WPPs based on their categories. According to the South African Renewable Grid Code (SAREGC) standards, renewable power plants (RPP) are divided into five categories as listed in Table I [7]. Each RPP category has a specified minimum volt-ampere (VA) capacity which it must produce, and the voltage level to be operated at. Voltage is one of the significant parameters to look at for the design and integration of WPPs for synchronization with the power system grid, to ensure grid compliance.

TABLE I. RENEWABLE POWER PLANT CATEGORIES ACCORDING TO THE SOUTH AFRICAN GRID CODE STANDARDS

Category	**Minimum size**	**Maximum size**	**Connection level**
	(kVA)	***(kVA)***	
A1	0	13.8	LV
A2	13.8	100	LV
A3	100	1 000	LV
B	0	20 000	MV
C	>20 000	-	MV/HV

Each generating unit in a WPP consists of a low-voltage (LV)-to-medium voltage (MV) step-up transformer whose location depends on the design of the WTGU [8]. For example, in Fig. 2, a single WTGU is shown with its transformer. This transformer is called the wind turbine generator substation unit (WTGSU) and is located in the nacelle. The MV circuit breaker (CB) shown at the bottom of the WTGU is used for protection purpose switching. Some WTGUs consist of WTGSUs located outside the tower.

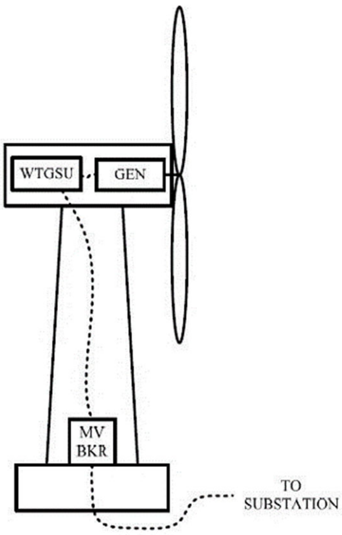

Fig. 2. Wind turbine generator unit showing the wind turbine generator substation unit located in the nacelle. The WTGU consist of a medium voltage (MV) circuit breaker

Fig. 3 shows an example of these types of WTGUs, with an LV circuit breaker between the generator and the WTGSU [8].

Wind power plants consist of different types of wind turbine generator units. However, in this paper, the focus is put on the variable wind turbine generators (VWTGs). In addition, the electrical generator considered in this paper is a squirrel cage induction generator (SCIG) for its simplicity, affordability as well as the availability of its parameters.

Various components are involved in completing up a wind power plant, and therefore, a theoretical framework is done in this paper, pertinent to the components that make up a complete WPP.

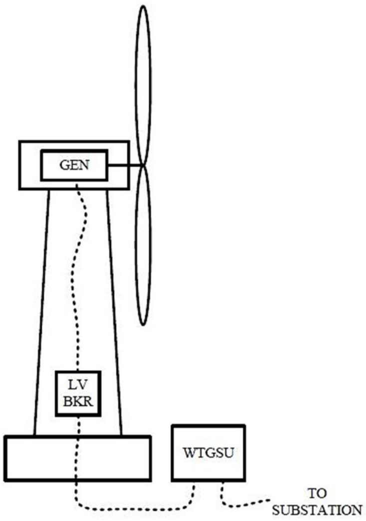

Fig. 3. Wind turbine generator unit showing the wind turbine generator substation unit located at the bottom or outside of the WTGU. The WTGU consists of a low voltage (LV) circuit breaker

A. *Wind turbine generators*

Wind turbine generators are classified into two main groups based on the wind turbine (WT) shaft orientation. These groups are horizontal and vertical shaft wind turbines. The horizontal shaft wind turbine has turbine blades connected to one end of the rotor as shown in Fig. 4. In the case of a vertical shaft, blades connect in two points as shown in Fig. 5 [9].

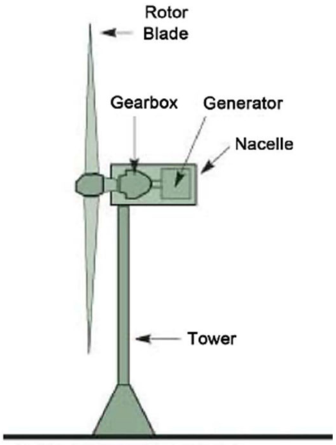

Fig. 4. Horizontal shaft wind turbine generator

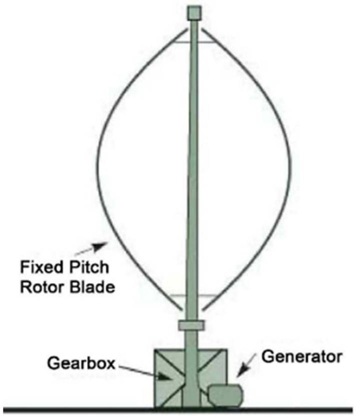

Fig. 5. Vertical shaft wind turbine generator

Also, a subdivision exists within the groups of wind turbines based on the configuration and number of blades. This paper focuses on the three-blade horizontal shaft configuration turbine technology, due to its greater dynamic strength as the result of aerodynamics whose loading is fairly uniform. In addition to the advantages of a three-blade horizontal shaft, the configuration is a smooth operation.

B. *Variable-speed wind turbine generators*

Variable-speed wind turbine generators (VSWTGs) can capture high energy from the wind. The nature of wind causes difficulties in controlling the wind turbine generators (WTGs). The aim of the modern design of the new wind turbine generator technologies is to achieve high-efficiency generator wind turbine systems with smooth output power [10]. As the result, most literature focuses on the design of wind turbine generator controllers. This makes aerodynamics a significant topic, as they are a major key to the wind turbine generator drive.

Since the three-blade variable wind turbine generator is more popular, its structure and major components are provided. Fig. 6 shows the horizontal shaft variable-speed wind speed turbine generator [11].

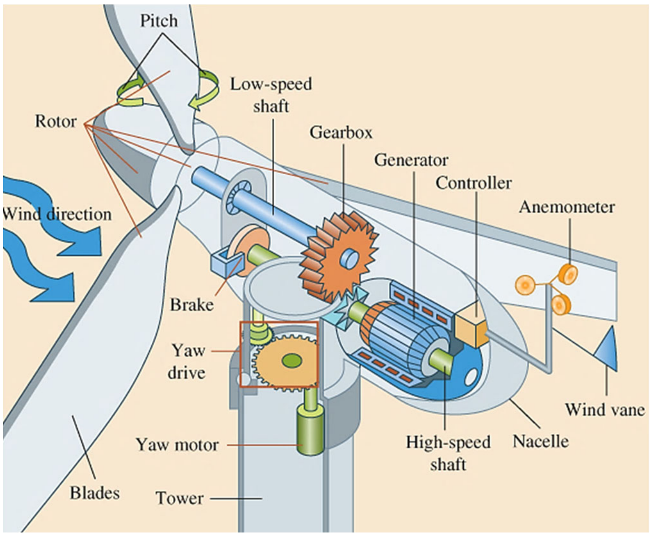

Fig. 6. Horizontal shaft variable-speed wind turbine generator

The energy produced by wind turbines follows the characteristics of the input wind, for instance, if wind fluctuates, the output power will fluctuate too, posing poor power quality. To obtain high-quality energy from wind turbine generators, high-level control strategies are implemented [12]. These control strategies are based on speed control and the pitch-angle adjustment of the wind turbine. When the wind speed is high, the control will adjust the turbine blades to change the angle at which they are being attacked by the wind, to reduce the effectiveness of the wind velocity to the turbine.

C. *The aerodynamics of wind turbines*

Wind turbine generators are designed to capture power from wind, convert it to mechanical power and transfer it to the electrical generators to produce electrical power. There are mathematical equations involved in this process, and their significance makes it a need to be reviewed.

1) Extraction of mechanical power from wind

The moving wind contains kinetic energy whose expression is written as [13]

$$k_e = \frac{1}{2} m {v_w}^2 \tag{1}$$

where m is the mass in kilogram (kg) of the air column.

This air column is given by the expression

$$m = \rho A v_w t \tag{2}$$

In expression (2), ρ, A, v_w and t is the density of air in kilograms per cubic meter (kg/m^3), the area swept by the turbine blades in square meters (m^2), the velocity of the wind in meters per second (m/s), and time in seconds (s). The area swept by the turbine blades is given by the expression

$$A = \pi \left(\frac{D}{2}\right)^2 = \pi (R)^2 \tag{3}$$

where D is the diameter made by the circular movement of the turbines in meters (m). π (Pi) is constant and R is the radius equivalent to the length (in meters) of the turbine blade.

When expression (3) is substituted in expression (2), the resultant expression becomes

$$m = \rho \pi (R)^2 v_w t \tag{4}$$

When expression (4) is substituted in expression (1), expression Power is the rate at which work is done. This definition can be represented mathematically by the expression where P_W is the power in watts (W) produced by the moving air column.

Substituting expression (5) into (6) gives the expression

$$k_e = \frac{1}{2} \rho \pi (R)^2 {v_w}^3 t \tag{5}$$

Power is the rate at which work is done. This definition can be represented mathematically by the expression

$$P_W = \frac{k_e}{t} \tag{6}$$

where P_W is the power in watts (W) produced by the moving air column.

Substituting expression (5) into (6) gives the expression

$$P_W = \frac{1}{2t} \left(\rho \pi (R)^2 {v_w}^3 t\right) \tag{7}$$

$$P_W = \frac{1}{2} \left(\rho \pi (R)^2 {v_w}^3\right) \tag{8}$$

The wind turbine is coupled to the electrical generator through its low-speed shaft. This is the electrical generator that converts mechanical power to electrical power.

However, not all the power produced by the moving wind is converted to electrical power, there is a certain amount of power lost due to wind turbine efficiency, referred to as turbine power coefficient with the symbol C_p.

2) Wind turbine power coefficient C_p

C_p is sometimes called the wind energy utilization coefficient. Theoretically, the electrical power extracted by the wind turbine is 59% of that of the power from the wind. This is according to Betz and it is called the Betz Limit.

Practically this limit varies between 40% up to 48% [13], [14]. The wind energy utilization coefficient is ideally made up of two efficiencies, namely turbine efficiency (η_t) and mechanical efficiency or gearbox efficiency (η_m).

The product of these variables can be used to express C_p as

$$C_p = \eta_t \eta_m = \eta \tag{9}$$

Efficiency is generally defined as the percentage ratio of the output power over the input power, and this can be mathematically represented by the expression…

$$\eta = \frac{P_O}{P_I} (100) \tag{10}$$

where P_O and P_I is the output and input power. With relation to the wind turbine generator unit, expression (10) is re-written as

$$C_p = \frac{P_{WT}}{P_W} (100) \tag{11}$$

where P_{WT} and P_W is the mechanical power produced by the wind turbine from the moving air column and the power of the moving air column [15]. From expression (11), the wind turbine power can be derived by making the wind turbine mechanical power the subject of the equation. Therefore,

$$P_{WT} = C_p P_W \tag{12}$$

is the expression.

The energy utilization coefficient depends on the design of the wind turbine and the angle at which the wind attacks the turbine blades. From Betz principle, it can be concluded that the equation for the power extracted by the turbine from the wind is written as

$$P_{WT} = \frac{1}{2} \rho \pi C_p (R)^2 {v_w}^3 \tag{13}$$

It is a finding from the existing literature that wind fluctuation influences the power output of the generator. The electric generator coupled to the wind turbine shaft, therefore, adopts the changing rotational speed of the turbine. This causes a disaster on both the mechanical part of the wind turbine and the power system to which the wind turbine generator system is connected. To overcome this issue, special control algorithms are introduced. The most effective control technique used in variable-speed wind turbine generators is pitch angle control.

3) Pitch angle control

The pitch control allows the wind turbine blades to rotate around their alignment allowing a change of angle with regards to the wind speed. This system allows the continuous production of the rated output constant power from the wind turbine even when the actual wind speed is above the rated speed of the wind turbine [14], [16]. The adjustment of a pitch angle also limits the turbine performance within a certain range even in strong winds.

The main purposes of the control can be summarized as [17], [18]

- Optimization of the output power when wind speed falls less than the rated.
- Maintaining the rotor power at design limits.

- Avoiding wind turbine mechanical failures.
- To ensure the rated output power even at multiple ranges of wind speed.

Fig. 7 shows the pitch angle adjustment effects in a variable-speed wind turbine generator.

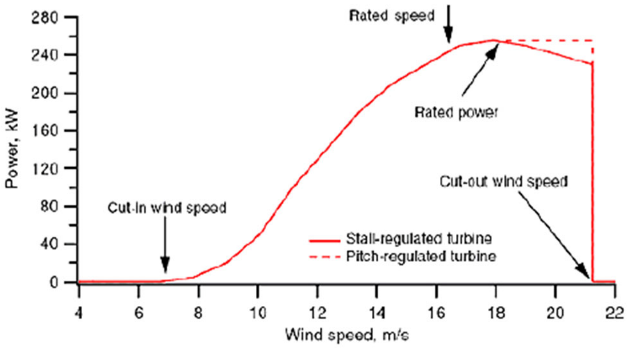

Fig. 7. Power versus wind speed for a variable-wind speed turbine with a pitch angle and stall control technique

The output power of the wind turbine generator system is controlled using the turbine blade adjustments. Practically, C_p is in a function of β (beta) and λ (lambda). β is the pitch angle in degrees (°) and λ is the ratio of the wind speed to the angular rotational speed of the rotor given by the expression

$$\lambda = \frac{v_w}{\omega_r} \tag{14}$$

where v_w and ω_r is the velocity of the wind at the tip of the turbine blade in meters per second (m/s) and the rotational speed of the turbine rotor in radians per second (rad/sec). The pitch angle control techniques for variable-speed wind turbine generators lead to different expressions of C_p.

The development of different approximations of power coefficient for various types of wind turbines is not necessary because there is just a small difference between C_p versus λ curves for wind turbines [16], [19]. The C_p equations may be different on the design, but the operation of variable-speed wind turbines is slightly similar. Found from [20] and [21] are C_p expressions,

$$C_p = 0.5\,(\lambda - 0.022\beta^2 - 5.6)e^{-0.17\lambda} \tag{15}$$

$$C_p = 0.3\,(\lambda - 0.0604\beta^2 - 3.5)e^{-0.155\lambda} \tag{16}$$

whose operating characteristic curves are slightly the same.

There are two modes in which the pitch angle control technique works, namely the hydraulic and the mechanical or motor mode. In a mechanical or motor mode controller, a gear is fixed on the rotor. This gear drives the gear located in the nacelle, leading to a changing pitch angle. In most cases for this design, the angle changes very often between the angle of 10° and 20°.

This change makes only several gear teeth work with load, which causes the need for the replacement of the gear because of its teeth [12], [17].

In hydraulic mode, the control works with three cylinders to drive the connections to cause changes in the pitch angle. This type of mechanism has a good influence on the rotor mode because of its larger torque even for large-scale wind turbine generators. For hydraulic mechanism control, the pitch angle can be adjusted until 3°, and as the result, maximum power can be captured [12], [17]. Fig. 8 shows a C_p versus the λ curve for different pitch angle adjustments.

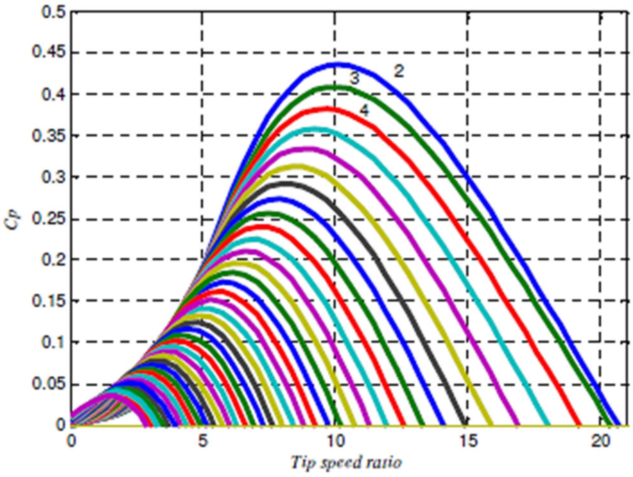

Fig. 8. Power coefficient versus tip speed ratio curve for different pitch angles

A pitch angle controller needs error input signals to generate a pitch set point. There are three ways in which this can be done as listed below:

- The pitch angle versus wind speed curves ideally assists in obtaining the pitch angle reference. For this method, the effective wind speed cannot be accurately measured, because it is unreliable, therefore unacceptable.
- The error signal from the power generated is sent to the pitch angle controller to produce a reference pitch angle.
- An error exists between the generator speed and its set point. This error is sent to the controller to produce a reference value for the pitch angle. This method is one of the most popular because of its accuracy.

4) *Gearbox*

The turbine is made up of three blades (about 80 m long), made from very light and resistive material. The way turbine blades are made, making it easier for wind turbine generators to produce energy even with the very light winds of about 3 m/s. For stronger winds of about 25 m/s, the blades are placed further apart and immediately stop spinning, for security reasons.

Blades are attached to the turbine through the rotor, which is coupled to the low-speed shaft. The rotor of the turbine is said to be a low-speed shaft because it spins at the same speed as the blades, between 7 RPM and 12 RPM. To produce electrical energy, it is necessary to increase the turning speed of the low-speed shaft to a higher speed, required for a generator to produce the rated output power. Therefore, the gearbox increases the turning speed of the shaft, depending on the ratio of the gearbox. This rotational speed is transferred to a high-speed shaft of the generator, which rotates at 700 RPM to 1 200 RPM [13], [17].

A lot of theory revolves around the turbine generator. It is also important to review the theory about the conversion of mechanical power to electrical power. Therefore, Section D of this paper is a review of the electrical side of a wind turbine generator unit (WTGU).

D. Wind turbine generator unit electrical generation

There are different types of electric generators used for wind turbine generator units. For this paper, an induction generator is preferred, for its simplicity.

1) Induction generator

An induction generator is simply an induction motor driven beyond its synchronous speed by a prime mover to produce electrical energy. The operating principle can be understood at its best by first looking at the basic operation of the induction motor. Fig. 9 [22] shows the induction motor.

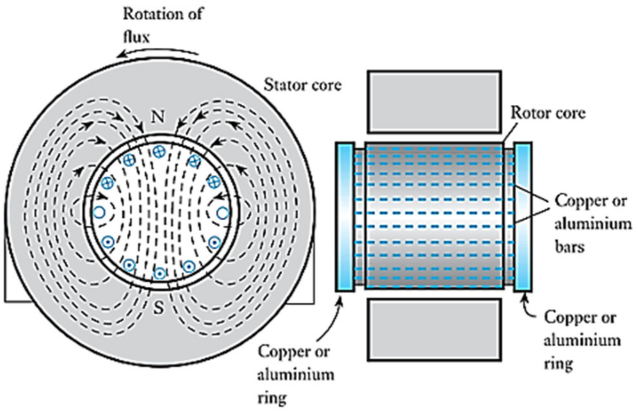

Fig. 9. Induction motor with a cage rotor

The stator winding of an induction motor is the same as that of a synchronous motor. If the stator of the motor is supplied with a three-phase alternating current, the reactive power will flow on the stator windings inducing a rotating magnetic field around the stator at a speed known as synchronous speed [22].

Fig. 10 is a combination of plots on how the induction motor and generator performance with speed variation [23].

Induction motors must draw lagging current, usually at -36.86989° (power factor angle). This current is a two-part current, real, and reactive. The reactive (imaginary) part of this current is called the magnetizing or exciting current. In the case of an induction motor operating in generator mode, this current is supplied by the synchronous generators of the system to which the induction generator is connected.

One of the benefits of using a squirrel-cage induction generator (SCIG)for a wind turbine generator (WTG) is that a SCIG is fairly simple [24],

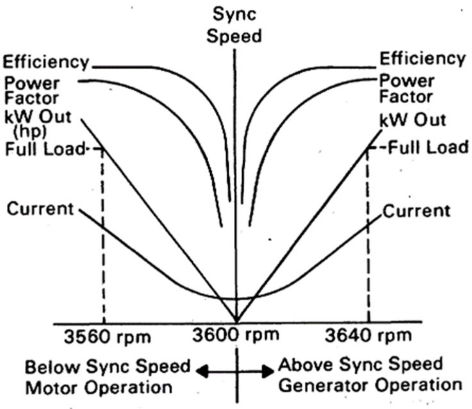

Fig. 10. The induction motor and generator performance based on the speed

Also, the voltage and frequency of the induction generator depend upon that of the system to which it is connected [25]. This means that an induction generator cannot restore power for a de-energized power system network, therefore as a standalone generator, it requires exciting circuits. This tends to be the main disadvantage of an induction generator operating standalone. It is due to its mechanical strength characteristic, the ability to run at high speeds, decrease in station sustained short-circuit risk, low cost, and the interest in renewable energy sources that an induction generator is chosen as a distributed generator [26].

2) Induction generator excitation circuit

The induction generator produces a frequency slightly lower than the frequency of the load if it is not connected to the external system. So, the frequency generated is also slightly lower than the one which would correspond to the rotational speed.

The terminal voltage is directly proportional to the capacitance. Therefore, if the capacitance is not sufficient, the generator terminal voltage will never build up. That is why an appropriate size of the capacitor bank is needed to supply enough reactive power. Fig. 11 shows the single line representation of a capacitor self-excited induction generator [26].

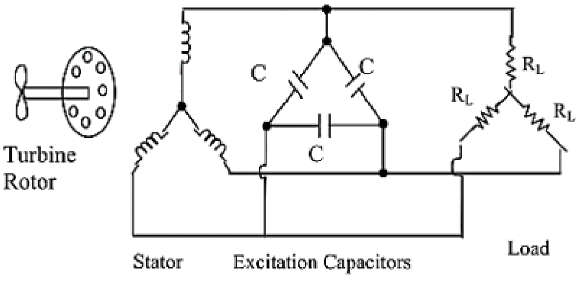

Fig. 11. Self-excited induction generator connected to a purely resistive load

When the capacitors are connected in a star configuration, each capacitor takes the voltage and reactive power of $1/\sqrt{3}$ and 1/3 times that of the delta-connected capacitors. For the same reactive power, large capacitance is required in the star connection. This increases the size of the capacitor bank unit, which increases the cost, so the connection of the capacitor bank is mostly preferred in the delta (mesh) connection for economic reasons [26], [27].

The amount of excitation current required is the same amount of current required to sustain the rotating magnetic field, which has got nothing to do with the loading of the generator. An induction generator requires a fixed excitation for its operation, and the required reactive (exciting) power is given by the expression

$$Q_E = \sqrt{3} V_T I_{NL} \tag{17}$$

where Q_E is the exciting reactive power in kVars, V_T the rated generator's stator terminal voltage in volts, $\mathrm{I_{NL}}$the no-load current in amperes [23].

Driving mechanically a standalone induction machine on its shaft induces the residual magnetic field on the squirrel cage rotor bars (windings). This magnetic field induces emf in the stator windings at a frequency proportional to the speed of the rotor. The emf formed in the stator windings is applied to the capacitors through the stator terminals, causing the flow of the reactive current on the stator windings of the generator, finally establishing the magnetizing flux. Under this principle, the induction machine can operate as a generator even if it is stand-alone [28].

III. CONCLUSIONS

The key focus of this paper is to provide the wind power plant (WPP) modeling for the conditions of the grid-connected mode of operation. The literature is reviewed in this part, on the discovered work about wind turbine generator (WTG) design and operation. The theoretical framework about wind turbine generators (WTGs) and their major components are covered. The aerodynamics of wind turbines are also re-examined. The power coefficient characteristic curve is selected for modeling the WTGs used for WPP that will be modeled in Part 2 where the overall wind power plant modeling, as well as the grid code compliance test will be done. Part 3 will cover the operation of the wind power plant under the conditions of grid-connected mode for voltage stability improvement.

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