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Maximizing Wind Power Creation of DIFG-Based Wind Turbines at Low Wind Speed Operation

Amy Heider[1] and Nancy Knechtel[2]
[1]PG Scholar, [2]Assistant Professor, Department of Electronics, University of Nigeria.

ABSTRACT: *This paper introduces an improved strategy to increase the power production of wind turbines equipped with doubly fed induction generators (DFIGs) at low wind speed operation. The performance of DFIG-based wind turbines at low wind speeds, close to the cut in speed, is investigated. A modified control to extend the concept of maximum wind power tracking to cover the low wind speed region is implemented. The associated effects of the expanding technique are examined. Reasonable value for the dc link voltage is investigated. A comprehensive time-domain model for the wind turbine with DFIG and the decoupled dq controller are implemented using Matlab/Simulink software. Simulation results are included to ensure the validity and feasibility of the proposed modification for low wind speed operation.*

I. INTRODUCTION

The doubly fed induction generator (DFIG) speed. At low wind speeds, the efficiency of the DFIG becomes the common option for MW-class wind turbines. Different wind generation schemes, such as variable-speed wind turbines with full-size converters, fixed-speed wind turbines, and DFIG-based wind turbines, have been compared in [1, 2]. These comparisons concluded that the DFIG system is superior because of higher energy output, lower rating of converters, and better utilization of a generator compared to the mentioned wind generation schemes. Although the wind power generation by the DFIG-based wind turbines is more efficient compared to different wind generation systems, it has constraints that must be fulfilled to gain such results. The maximum aerodynamic power can be captured, but the DFIG may not provide the maximum expected active power generation. The lack of DFIG production is, in most cases, more significant at the boundaries of the operating wind speed range. This work focuses on the performance of DFIG-based wind turbines in the vicinity of cut in wind system compared to that of cage rotor induction generator with full-size interfacing converters is lower. The reasons for this kind of deficiency can be summarized in the following points:

- Magnetization losses during low wind speeds have not been treated.
- The converters' dc link voltage is not sufficient to produce the required rotor voltage at low speeds.
- The generator operation is not optimized. i.e., the reactive power flow is not optimized to reduce the total losses.

Concerning the magnetization losses at low wind speeds, two ways to lower the magnetizing losses of DFIGs were presented in [2]. The first one is a stator short-circuited DFIG and the other is a Y- stator- connected DFIG. Both techniques require a comprehensive modification in the DFIG stator circuit. The efficiency gain of using these methods is approximately 0.2-1.3%. A comparison between the two schemes showed that the Y-Connected DFIG scheme performs better than the short-circuited DFIG [2].

In a trial to overcome the consequence of the restricted dc link voltage, tackling the effect of the dc link voltage constraint was addressed in [5, 6]. Different suggestions for the gear box ratio, the stator/rotor turns ratio, and converter ratings were presented. The objective was to optimize the selection of these parameters in order to minimize the system losses. A slightly increase in the efficiency of DFIG systems at low wind speeds are offered by the modifications introduced in these articles. It is worth mentioning that these studies, [5, 6], were devoted mainly to enhance the efficiency of the DFIG systems by parameters' modification that must be done during the design process. In other words, modifying the gear box ratio or the stator/rotor turns ratio is not an easy task to be implemented in on-service wind turbines.

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One of the dominant features of the DFIG is the reactive power control. Fulfilling the reactive power demand or the power factor requirement is typically accompanied by increased losses due to the flow of the reactive current component in the generator windings and converter switches. The losses caused by the flow of the reactive current affect the system's efficiency at low wind speeds, but their effect is more significant at higher wind speeds. Hence, the flow management of the reactive current in DFIG circuit is out of scope in this study.

This paper considers enhancing the DFIG performance at the low margin of the wind speed range by proposing control modifications based on expanding the concept of maximum wind power capturing to lower wind speeds. Firstly, the relationship which governs the rotational speed with the incident wind speed has been modified to increase the power capturing from lower wind speeds. Secondly, the nominal voltage of the dc link is chosen to fulfill the higher rotor voltage requirement of the expanded slip. To evaluate the feasibility and effectiveness of the proposed control modifications on the DFIG performance, comparative simulation results are presented. The paper is organized as follows: Section II describes the probability distribution function of low wind speeds. Section III discusses the DFIG operation at low wind speeds. The expansion of the DFIG slip to increase the wind power capturing is explained in Section IV, and finally conclusions are drawn in Section V.

II. DISTRIBUTION FUNCTION OF LOW WIND SPEEDS

Although the aerodynamic power at low wind speeds is less than that at high wind speeds, the probability distribution function for most sites indicates that the low wind speeds (close to cut in speed) probability has significantly higher values compared to high wind speed (around the turbine's rated speed) probability. The probability distribution of wind speed is typically described by Rayleigh function [7], which is defined mathematically as follows:

$$f(W) = \frac{\pi \cdot W}{2 \cdot \overline{W}^2} \exp\left[-\frac{\pi}{4} \left(\frac{W}{\overline{W}} \right)^2 \right] \qquad (1)$$

Where *f(W)* represents the Rayleigh probability density function for a given wind speed *W*, and W represents the mean value for the wind speed. Figure 1 shows a sketch of wind speed distribution for a site by Rayleigh probability density function, with a mean wind speed of 7 m/s. Typically, for such a site, wind turbines are selected to have a rated wind speed of 10-11 m/s.

Given a probability density function, the annual electrical energy production, ε, can be estimated by equation (2).

Where:

ci : cut in wind speed.

co : cut out wind speed.

Paer : the aerodynamic power extracted from the turbines' blades.

η : the system efficiency starting from gear box up to the PCC for each wind speed.

According to (2), a small percentage increase in the efficiency, η, at low wind speeds may be translated to hundreds of kilowatt-hours.

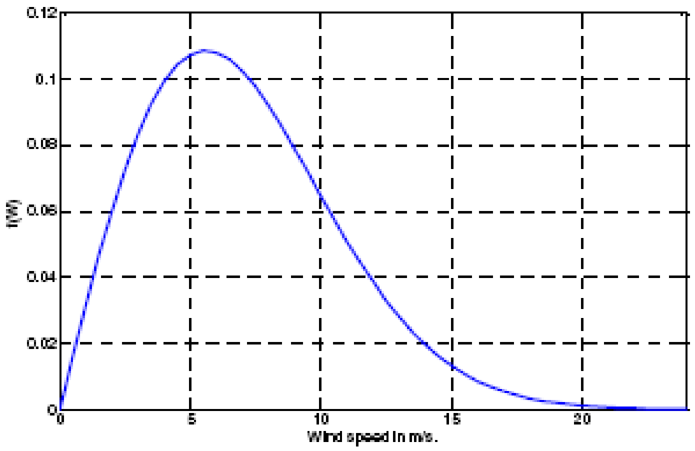

Fig.1. Rayleigh probability density function at 7m/s mean wind speed

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DFIG OPERATION AT LOW WIND SPEEDS

The DFIG generation system is experiencing increased losses and suboptimum performance at low wind speeds. The next subsections will go through some details about the causes of this inefficient situation.

A. Magnetization Losses

Generally, for induction generators interfaced by full-size converters, the flux is controlled to achieve optimum efficiency. At low wind speeds, the generator is not fully loaded. Utilizing the fact that the converter is acting as a buffer between the grid voltage and the machine terminals, it is easy to reduce the flux level by controlling the converter switches resulting in lower magnetization losses. On the contrary, the DFIG stator is directly connected to the grid and consequently the generator flux is almost fixed and controlled by the grid voltage. Therefore, reducing the flux at low wind speeds is not a straight forward task in DFIG operation.

Flux reduction is mainly tackled by reducing the stator voltage at low wind speed operation. Major modifications in the stator circuit either by short-circuiting or inserting a Y-Δ switch were suggested. More details about the techniques used to minimize the magnetization were discussed in [2].

B. DC Link Voltage Restriction

The aerodynamic wind power, Paer, obtained from the wind is:

$$P_{aer} = \frac{1}{2}\rho \cdot \pi \cdot R^2 \cdot W_{eq}^3 \cdot C_p(\beta,\lambda) \qquad (3)$$

Where:

ρ : air density (kg/m3).

R : blade length (m).

Weq : equivalent wind speed (m/s)

Cp(β,λ): the power coefficient of wind turbines; Β : blades' pitch angle (deg.)

Λ : the tip speed ratio (R. ωwtr / Weq).

ωwtr : the rotational speed of the wind turbine shaft (rpm).

The tip speed ratio, λ, should be set at its optimum value to maximize the power coefficient. Hence, the rotational speed of the wind turbine shaft should be adjusted carefully according to the incident wind speed. Changing the rotor speed (sliding the rotor speed back and forth around the synchronous speed) requires higher voltages at the rotor slip rings. At synchronous speed, the induced voltage at the rotor circuit is almost zero; consequently minimum voltage requirement can be stipulated at the rotor terminals. The trend of rotor voltage variation according to speed variation is shown in Figure 2.

Ideally to get the maximum wind power capturing even at the cut in speed, the lower rotational speed limit should be extended to the ideal lower limit. In a response, higher rotor voltage is required, as indicated by the point K in Fig. 2.

The typical tracking of the rotor voltage according to the incident wind speed is shown in Fig. 3, where the rotor voltage requirement at low wind speed is the highest compared to that required for the rest of the wind speed range. The maximum affordable voltage at the rotor terminals has to yield to the dclink voltage according the following relation [8]:

$$1.634 \cdot V_{r-LL} \leq V_{DC} \qquad (4)$$

Where: *Vr-LL*: line-to-line rms of the fundamental rotor voltage (V).

VDC: dc link nominal voltage (V).

Moreover, the actual design should give certain voltage margin to allow full controllability over the currents injected to the rotor from the converter. Therefore, the maximum voltage at the rotor terminals is constrained as follows:

$$1.634 \cdot V_{r-LL} \leq V_{DC} - V_{marg} \qquad (5)$$

Where: *Vmarg:* a margin of voltage to ensure appropriate controllability.

The voltage required at rotor terminals for low wind speeds may not be afforded by the rotor-side converter due to dc link voltage constraint described in (5). The effect of that constraint is illustrated in Fig. 4. As shown in Fig. 4, the dc link constraint limits the rotor voltage to a reduced value less than the desired one. Instead of keeping the variable-speed concept, the fixed- speed operation extends to cover wider range of low wind

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speeds. In due course, the region of maximum wind power capturing is shrunk. So, the efficiency of DFIG at low wind speeds becomes poorer. In order to have a safety margin for wind gust conditions, the rated speed is selected to be close to the synchronous speed. The slip range is commonly from 0.3 to -0.2; i.e., the rotor speed is varied from 0.7 to 1.2 times the synchronous speed. For wind speeds beyond the rated, the rotational speed is kept at its rated (1.2 times the synchronous speed) by the action of the pitch control, as indicated by the point R in Fig.2.

The lower rotational speed limit (0.7 times the synchronous speed) which is designed in DFIG control can not guarantee maximum power capturing in the vicinity of the cut in speed, represented in the point L.

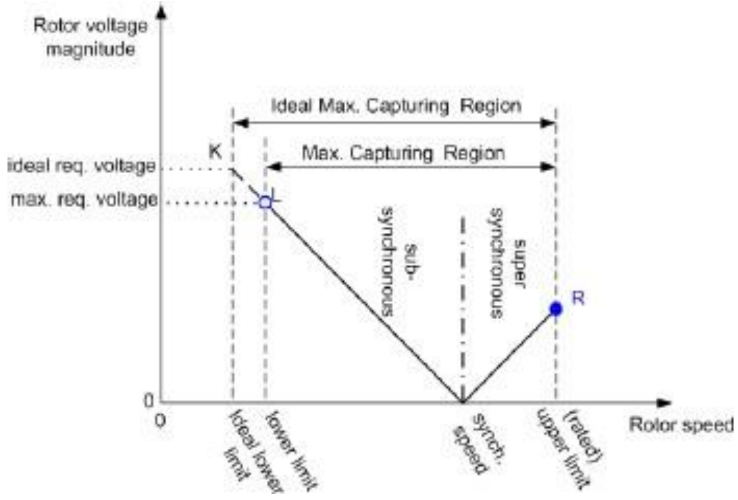

Fig.2.Rotor voltage enforced according to rotor speed deviation around the synchronous speed.

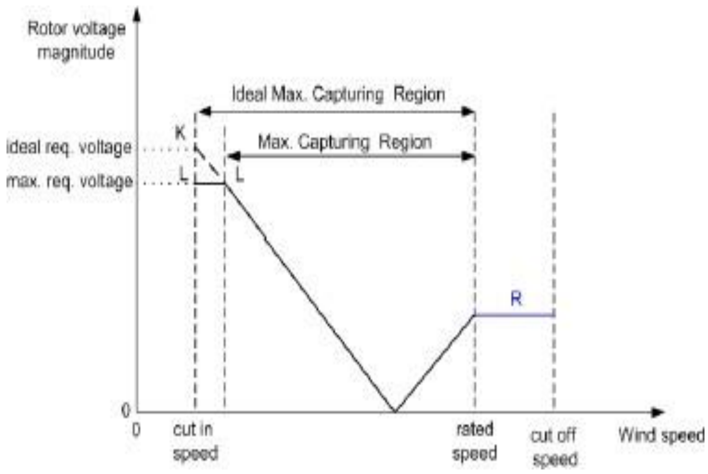

Fig. 3. Rotor voltage variation according to different incident wind speeds.

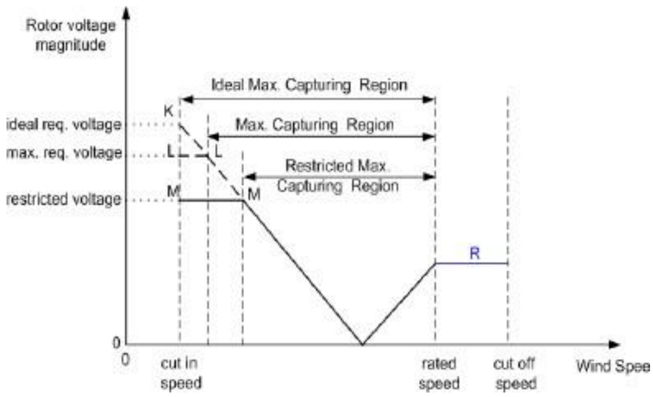

Fig. 4. Effect of dc link voltage limitation on the DFIG performance at low wind speed range.

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Reforming this kind of deficiency was carried out by assuming major adaptations in the wind turbine design [5, 6]. In a trial to set the synchronous speed in the middle of the rotor speed range, it was suggested in these articles, [5, 6], that gear box ratio can be tuned to reduce the rotor voltage required at low wind speed. Another suggestion claiming the change of the rotor/stator winding turns ratio to reduce the rotor voltage requirement was also presented in [5, 6].Further, the effect of the converters' rating on the efficiency of DFIG-based wind turbines was investigated. It is quite clear that the slightly enhanced efficiency obtained in [5, 6] is not comparable to such major adaptations required in the wind turbine.

III. PROPOSED STRATEGY TO ENHANCE DFIG PERFORMANCE AT LOW WIND SPEED OPERATION

This section considers the improvement of DFIG performance at low wind speed region by expanding the DFIG slip and avoiding the associated limitations. The parameters of the DFIG under study are shown in the appendix.

A. Selection of the dc Link Voltage Level

In the DFIG configuration under study, shown in Fig. 5, the grid side converter is connected to the grid via RL filter. The dc link voltage has to ensure the voltage level required to extract the grid (stator) voltage level (Vs).

$$V_{DC} \geq 1.634 \cdot V_s$$

$V_s = 690$ V.

Then

$V_{DC} \geq 1127.46$ V.

Since the turns' ratio between the rotor and the stator windings is less than unity, the dc voltage level is typically chosen according to the voltage that should be forced by the grid side converter. Hence, responding to the constraint in (6), 1200V has been set as a nominal value for the dc link voltage. An appropriate value for the dc link capacitance shown in the DFIG data (in the appendix) has been selected.

B. Extended Slip Approach for Low Wind Speed Operation

The variable speed operation at low wind speed is ceased at low wind speed operation. The generator is basically working at constant rotational speed and consequently its ability to capture maximum wind power is not available. The objective of this section is to extend the operation of variable speed concept for low wind speed region to maximize the capturing ability of the DFIG system.

Figure 6 illustrates the modification applied to the DFIG control to extend the variable speed operation concept to the low wind speed region. Basically, the maximum power point tracking (MPPT) of wind turbines depends on optimal tracking control which governs the rotational speed and the power in an optimum manner [9]. Conventionally, the optimal tracking is no longer working below the speed of 0.7 pu of the synchronous speed, slip=0.3, as shown in Fig. 6. The rotational speed is kept at 0.7 pu regardless of the incident wind power at this region (W<6.5m/s). The reasons for this attitude can be summarized as follows:

- An increased rotor voltage is demanded for slip expansion.
- The rotor core loss is increasing since the slip frequency is going up.
- Avoiding high ramp rate of the power generated at the cut in speed.
- The power gain is not worthy.

The modification proposed in this paper is to extend the slip margin from 0.3 to 0.4, as depicted in Fig. 6, i.e., the lower

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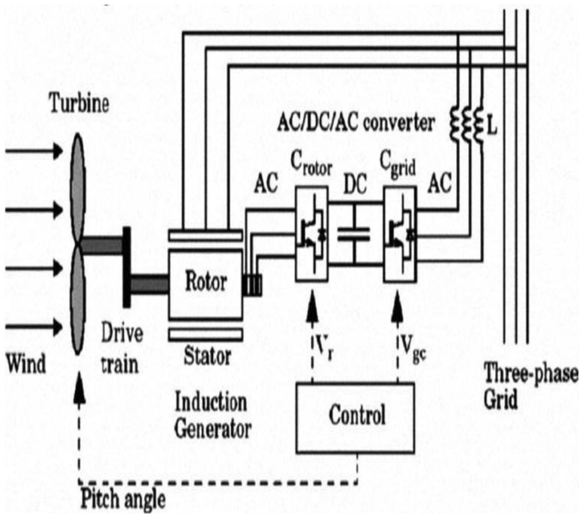

Fig. 5. Wind turbine and the doubly fed induction generator system

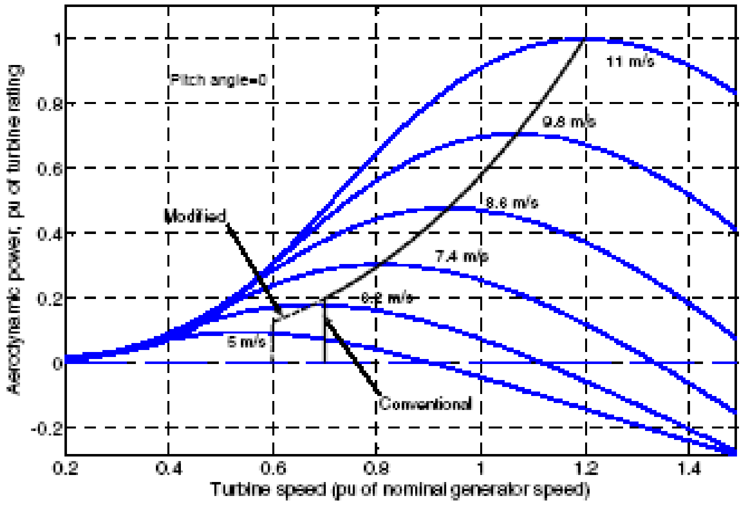

Fig. 6. Expanding the slip range for optimum operation at low wind speed.

Rotational speed limit becomes 0.6 pu. This extension is positively affecting the power produced from wind speeds below 6.5 m/s. Moreover, it gives an opportunity for the wind turbine to work at lower cut in wind speeds below 4.5m/s. A comparison between the modified and conventional principle of operation is illustrated in Fig. 7. Since low wind speeds are characterized by high probability, a significant annual energy gain from this modification is expected. Based on (2), the annual energy captured by the expandable slip modification, introduced in this paper, is increased by 6.49% of its original value. The power generated by the expanded slip concept also considers an optimized reactive current flow.
The power handling through the converters is not a concern since it is too small. Therefore, this modification can be applied to different converters ratings (0.3-0.5pu).

Since the power at low wind speeds is generally small compared to that at rated wind speed operation, the effect of higher ramp rate close to the cut in can be ignored. The rotor voltage is increased with expanding the speed range of operation since the slip is increased. Figure 8 depicts the rotor voltage increase caused by the suggested modification. Although, the rotor voltage is higher with the suggested modification, the rotor-side converter can ensure the new required voltage levels with the higher dc link voltage level of 1200V. Moreover the rotor voltage due to the suggested modification is still below the rotor voltage rating, 0.5pu=345V, i.e., it does not cause voltage stress on rotor circuit winding.

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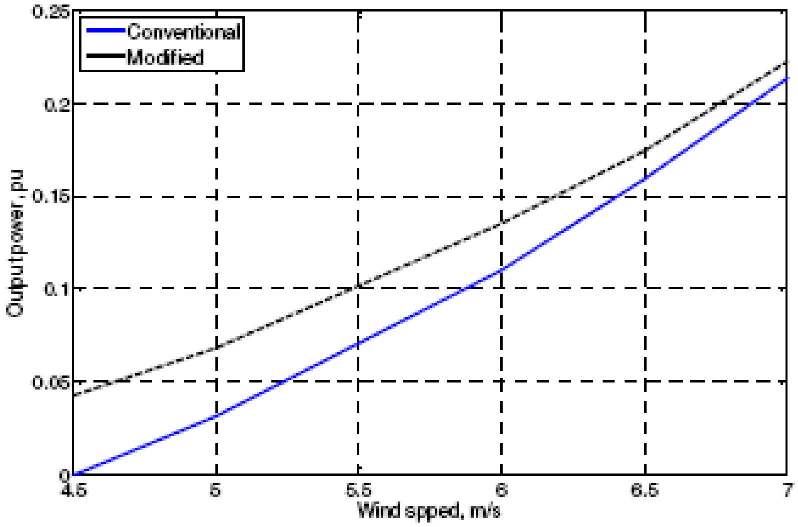

Fig. 7. Magnified view of power generated at low wind speed using two modes of operation.

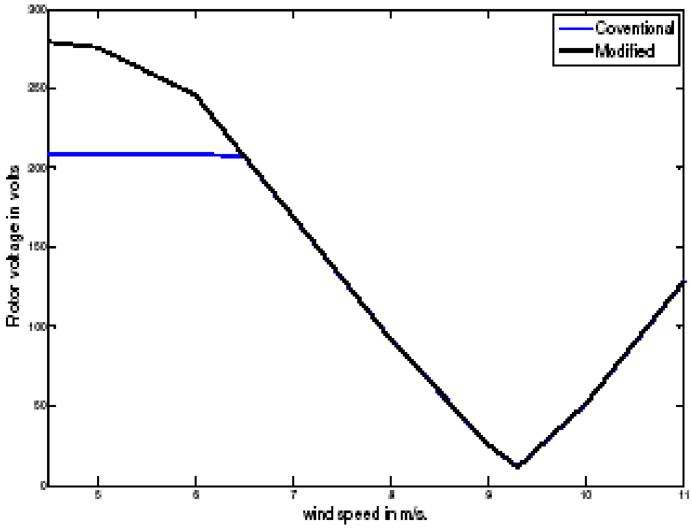

Fig. 8. Rotor voltage for different modes of operation

In regard to the implementation of the proposed control modification, the slip expansion is excuted by modifying the look up table of the power/speed tracking curve. The DFIG contol scheme is shown in Fig. 9 and the power/speed tracking curve is indicated by the shaded block. Matlab/Simulink environment is employed to represent the wind turbine, induction machine, and the control scheme.

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