INTERNATIONAL JOURNAL OF TECHNOLOGY ENHANCEMENTS AND EMERGING ENGINEERING RESEARCH, VOL 3, ISSUE 04
ISSN 2347-4289

Increasing Wind Turbine Efficiency Using Doubly-Fed Induction Generator

Eng.Sameh Karem Saeed, Dr.Salah-Aldin Kamal, Dr.Mohammad Kamal Alshaer

Assistant professor, Dept. of Electrical Power Eng., Azhar University, Cairo, Egypt
PG Student, Dept. of Electrical Power Eng., Helwan University, Cairo, Egypt
Email: sameh-karem@hotmail.fr

ABSTRACT: we will discuss in this paper how the Doubly-Fed Induction Generator (DFIG) Increases The energy efficiency of the wind turbine compared with other types of generator such as Fixed Speed or Variable Speed Induction Generator (FSIG , VSIG). This investigation Based a practical tests and data from wind turbines in Zaafrana wind power plant at Suez Gulf Area in Egypt and also based on some expression from References and Data sheets from manufacturer all will be mentioned Later .at first we shall explain the wind energy theory and the Wind Turbine combination this will be useful to illustrate the advantage of using DFIG in wind turbine system. also we will discuss the wind energy in the area of Suez Gulf area Zaafrana power Plant.

Keywords: Wind tubine efficiency, Doubly-Fed Induction Generator, Variable speed Indution generator, Converter

1 INTRODUCTION

WIND turbines produce electrical Energy by the power of the wind to run an electrical generator. when the wind go over the blades, the wind produce a lift and generate an turning force. The shaft is beeing turned by the rotating blades which goes into a gearbox So The rotational speed increases to be suitable for the generator, also the generator convert the rotational energy into electrical energy. figure 1 illustrate the wind turbine combination The power output goes to a step up transformer, which increase the output voltage from transformer from 690V To 33KV to be suitable for the power collection system of the grid.

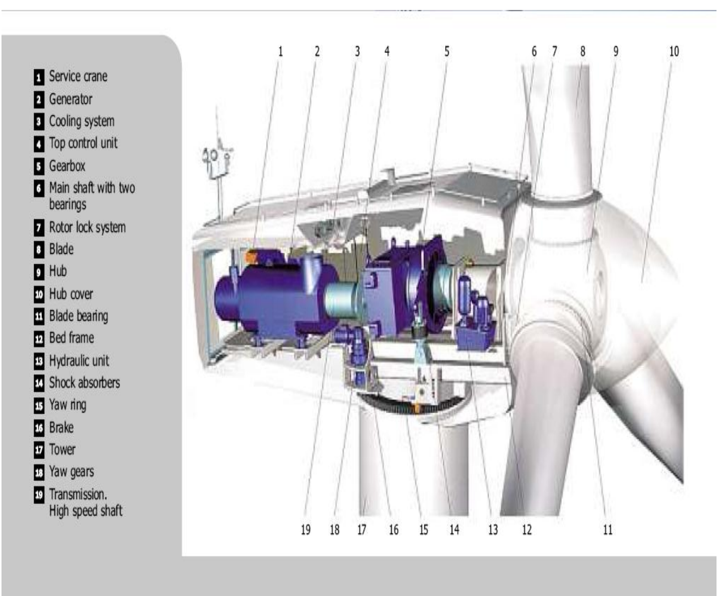

Figure 1 *Gamesa wind Turbine*

About Zaafrana wind Farm Egypt have excellent wind system particularly in the Suez Gulf area where the wind speed average almost 11 m/sec , See fig.(2)

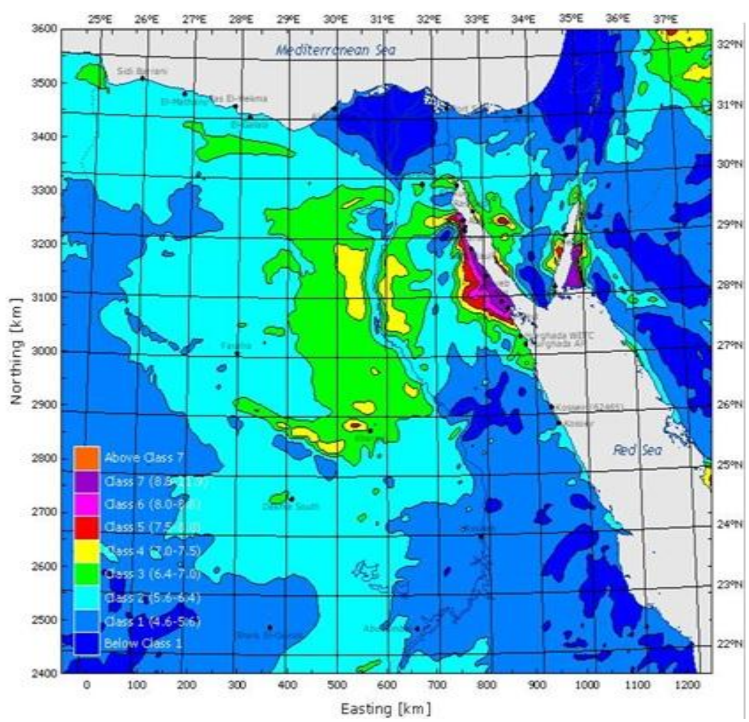

Figure 2 *Wind Atlas of Egypt*

Our site Zaafrana wind farm (which has the turbines of concern) consist of 8 particular wind farms as shown in fig.(3).

ISSN 2347-4289

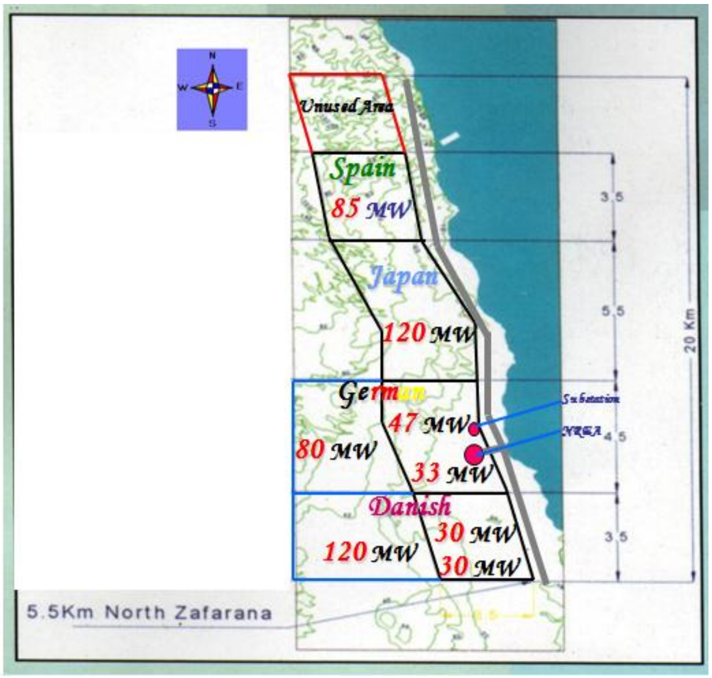

Figure 3 *Site layout for Zaafrana wind farms*

Site data: Total Number of Turbines : 700 Wind turbines - Total Installed Capacity : 545 MW - Total Produced Energy :1152450 MWh - Capacity Factor : 32.69 % - Performance Availability : 97.7 % - Average Measured W.S : 8.2 m/s - FUEL SAVED : 252357 TON - CO2 EMMISION : 633848 TON

2 BACKGROUND OF WIND TURBINES TYPES

In order to illustrate our investigation we must at first discuss wind turbines types

2.1 Fixed-speed wind turbine with an induction generator (FSIG)

This type of turbine used in old wind turbine since 1999 in Nordex Wind turbines in Hurgada wind farm and redeveloped to another types will be disscused later.

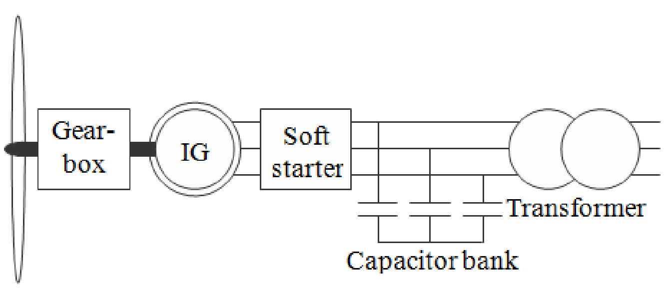

Figure 4 *Fixed-speed wind turbine*

This type of wind turbines have simple Electrical system consisting of a rotor turning a low speed shaft, a gearbox, a high speed shaft and an induction generator. From the electrical system point of view they are considered as large fan drives with torque applied to the low-speed shaft from the wind power. For the fixed-speed wind turbine the induction generator is directly connected to the electrical grid [3].

2.2 Variable-speed wind turbine with an induction generator (VSIG)

The Variable-speed wind turbine consists of a wind turbine connected with a converter connected to generator's stator. The gearbox ratio is designed so that maximum rotor speed corresponds to rated speed of the generator. Sometimes the Generator made with multiple poles which reveals that there is no need for a gearbox, Since this “full-power” converter/generator system is commonly used for other applications, one advantage with this system is its well-developed and durable control [3].

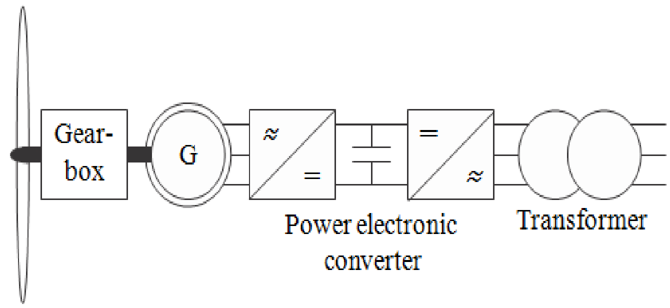

Figure 5 *Variable speed induction generator*

2.3 Variable-speed wind turbine with a doubly-fed induction generator (DFIG)

This system is the finally developed turbines and used in Zaafrana last wind farm in Gamesa Spanish wind turbine. the turbine consists of a wind turbine with doubly-fed induction generator. in This system the generator's stator is connected directly to the grid while the rotor is connected to a converter by the slip rings. This system have lately become commonly used as generators for variable-speed wind turbines. The main advantages of this sytem is that the power electronic converter has to handle only a fraction (20–30%) of the total power.

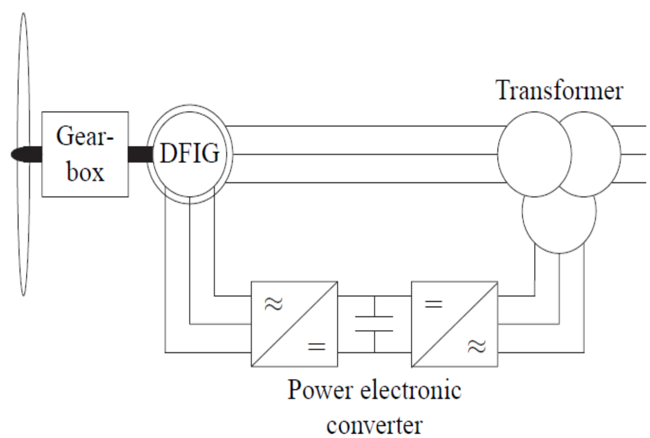

Figure 6 *Variable-speed wind turbine with a doubly-fed induction generator*

So the losses in the power electronic converter can be reduced, compared to a system where the converter has to handle the total power. Also, the cost of the converter wiil be lower. There exists a variant of the DFIG method that uses controllable external rotor resistances (compare to slip power recovery). Some of the drawbacks of this method are that energy is unnecessary dissipated in the external rotor resistances and that it is not possible to control the reactive power [4] [5].

3 Wind turbines Effieciency

We shall investigate how using DFIG used in Gamesa wind turbine increases the efficiency of the wind turbine with mitigating the two mean losses:

1- Induction Generator Losses.
2- Converter Losses.

Compared with the other types of turbine Vestas and Nordex which used The VSIG & FSIG. in order to be a fair comparison we will assume in this paper is that the average shaft torque of all wind turbines should be the same. also the rated power 2MW.

3.1 Induction Generator Losses

we will use the equivalent circuit of the induction generator to calculate the losses of the induction generator, with inclusion of magnetizing losses.

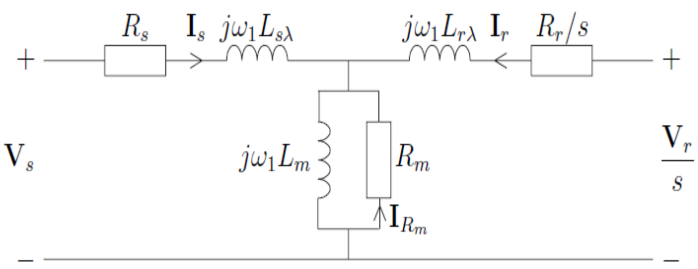

Figure 7 *DFIG Equivalent circuit*

Neglecting the voltage drop across the slip rings. Moreover, the stator-to-rotor turns ratio for the DFIG is adjusted so that maximum rotor voltage is 75% of the rated grid voltage. This is done in order to have safety margin, in other hand a dynamic reserve to handle, for instance, a wind gust. Observe that instead of using a varying turns ratio, the same effect can also be obtained by using different rated voltages on the rotor and stator [1].

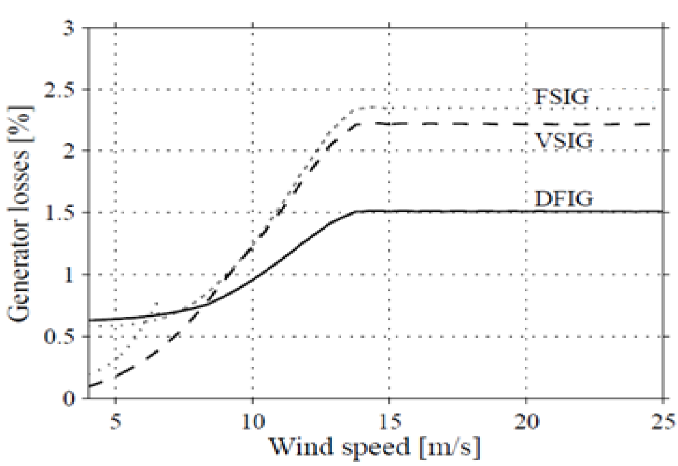

Figure 8 *Induction generator losses. The losses are given in percent of maximum shaft power.*

It can be noted in Figure(8) that the losses of the DFIG are higher than those of the VSIG for low wind speeds. The reason for this is that the flux level of the VSIG system has been optimized from an efficiency point of view while for the DFIG system the flux level is used for low wind speeds, So, the magnetizing losses are reduced. For the Induction Generators used in this paper operated at 690 V 50 Hz and with a rated current of 1900 A and 390 A, respectively, the following parameters are used:

From turbines Data sheets

2-MW power: Rs = 0.01 p.u., Rr = 0.009 p.u., Rm = 198 p.u., Lsλ = 0.18 p.u.,

Lrλ = 0.07 p.u., Lm = 4.4 p.u. and np = 2

0.4-MW power: Rs = 0.04 p.u., Rr = 0.01 p.u., Rm = 192 p.u., Lsλ = 0.12 p.u.,

Lrλ = 0.04 p.u., Lm = 3.7 p.u. and np =3.

3.2 Converter Losses

a pulse-width modulated (PWM) converter used in to feed the Induction Generator with a variable voltage and frequency source.

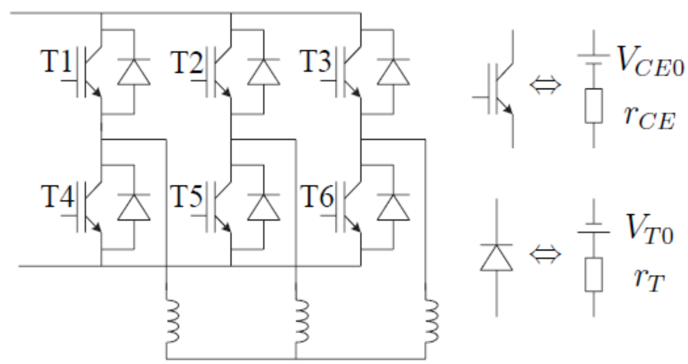

Figure 9 *Converter scheme*

From the converter scheme (Figure(9)) every transistor from T1 to T6, is connected in parallel with a reverse diode. A PWM circuit switches the transistors to on and off states. The duty cycle of the transistor and the diode determines whether the transistor or a diode is conducting in a transistor leg. the converter Losses can be divided into two sources of losses switching losses and conducting losses:

3.2.1 The switching losses

There are Losses Due to the transistors are the turning-on and turning-off losses. For the diode the switching losses mainly consist of turn-off losses [6], as reverse-recovery energy. The turn-on and turn-off losses for the transistor and the reverse-recovery energy loss for a diode can be found from data sheets of the converter. there are Simplified expressions of the transistor's and diode's conducting losses [2].

Equation 1

$$P_{c,T} = \frac{V_{CE0} I_{rms}\sqrt{2}}{\pi} + \frac{I_{rms} V_{CE0} m_i \cos(\emptyset)}{\sqrt{6}} + \frac{r_{CE} I_{rms}^2}{2} + \frac{r_{CE} I_{rms}^2 m_i}{\sqrt{3}\cos(\emptyset) 6\pi} - \frac{4 r_{CE} I_{rms}^2 m_i \cos(\emptyset)}{45\pi\sqrt{3}}$$

Equation 2

$$P_{c,D} = \frac{V_{T0} I_{rms}\sqrt{2}}{\pi} - \frac{I_{rms} V_{T0} m_i \cos(\emptyset)}{\sqrt{6}} + \frac{r_T I_{rms}^2}{2} - \frac{r_T I_{rms}^2 m_i}{\sqrt{3}\cos(\emptyset) 6\pi} + \frac{4 r_T I_{rms}^2 m_i \cos(\emptyset)}{45\pi\sqrt{3}}$$

I_{rms} : the root mean square (RMS) value of the current to the grid or the generator,
φ : the phase shift between the voltage and the current,
m_i : the modulation index.

Table 1 Converter Characteristic Data (IGBT and Inverse Diode).

Nominal current	$I_{C,nom}$	500 A	1200 A	1800 A	2400 A
Operating dc-link voltage	V_{CC}	1200 V	1200 V	1200 V	1200 V
	V_{CEO}	1.0 V	1.0 V	1.0 V	1.0 V
Lead resistance (IGBT)	r_{CE}	3 mΩ	1.5 mΩ	1 mΩ	0.8 mΩ
Turn-on and turn-off energy (IGBT)	$E_{on} + E_{off}$	288 mJ	575 mJ	863 mJ	1150 mJ
	V_{TO}	1.1 V	1.1 V	1.1 V	1.1 V
Lead resistance (diode)	r_T	2.6 mΩ	1.5 mΩ	1.0 mΩ	0.8 mΩ
Reverse recovery energy (diode)	E_{rr}	43 mJ	86 mJ	128 mJ	171 mJ

The values in this paper, which are based on References will Be mentioned later,

$r_{IGBT} = r_{CE} \approx r_T$ and $V_{IGBT} = V_{CEO} \approx V_{TO}$.

Hence, it is possible to reduce the loss model of the transistor and the diode to the same model.

3.2.1 The conducting losses

The conducting Losses is a result of the current pass through the diodes and transistors and where they can be modeled as constant voltage drops, V_{CE0} and V_{T0} , and a resistance in series, r_{CE} and r_T , see Figure(9) We can approximate The conduction losses expression which mentioned above as

Equation 3

$$P_c = P_{c,T} + P_{c,D} = V_{IGBT}\frac{2\sqrt{2}}{\pi} I_{rms} + r_{IGBT} I_{rms}^2$$

This implies that the switching losses from the transistor and the diode can be expressed as :

Equation 4

$$P_{s,T} = (E_{on} + E_{off})\frac{2\sqrt{2}}{\pi}\frac{I_{rms}}{I_{C,nom}} f_{sw} \approx V_{sw,T}\frac{2\sqrt{2}}{\pi} I_{rms}$$

Equation 5

$$P_{s,D} = E_{rr}\frac{2\sqrt{2}}{\pi}\frac{I_{rms}}{I_{C,nom}} f_{sw} \approx V_{sw,D}\frac{2\sqrt{2}}{\pi} I_{rms}$$

E_{ON} : Turn-on energy losses , EOff : Turn-off energy losses for transistor

Err : the reverse recovery energy for the diode

$I_{C,nom}$: is the nominal current through the transistor

$V_{sw,T}$: is the voltage drop across the transistor , $V_{sw,D}$: is the voltage drop across the Diode.

Practically the ratios ((Eon + Eoff)/Ic,nom) , (Err/Ic,nom) is constant for all the converter valves with the data in table. we will take the switching Frequency in this paper 5kHZ , using the average of the valves values in the table we can calculate the voltage Drops $V_{sw,T} = 2.5$ V, $V_{sw,D} = 0.38$V, using the values on the table, so we find the value of $r_{IGBT} = 1.76\ \Omega$. from equations 3,4,5 we can express the total losses from the three transistor legs of the converter become

$$P_{loss} = 3(P_c + P_{s,T} + P_{s,D}) = 3\left((V_{IGBT} + V_{sw,T} + V_{sw,D})\frac{2\sqrt{2}}{\pi} I_{rms} + r_{IGBT} I_{rms}^2\right)$$

In the DFIGs when The back-to-back converter used it considered as two converters which are connected together: the machine-side converter (MSC) and the grid-side converter (GSC). So, we can calculate the losses of the back-to-back converter as Ploss,converter = Ploss,GSC + Ploss,MSC. The total converter losses are now presented as a function of wind speed in Figure(10)

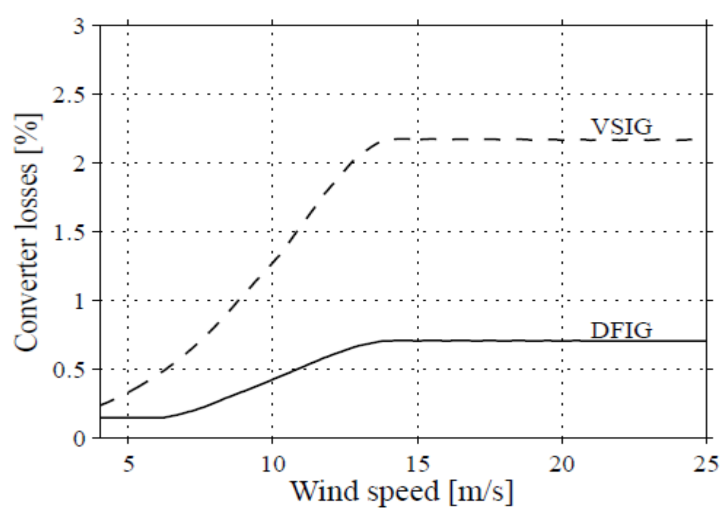

Figure 10 *Converter losses. The losses are given in percent of maximum shaft power. DFIG is solid and VSIG is dashed reference [6] .*

ISSN 2347-4289

From the figure we conclude that the converter losses in the DFIG system of Gamesa wind turbine have been reduced compared with the full power converter in the old turbines VSIG in vestas and nordex turbine types in Zaafrana projects.

3.2 Total Electrical Losses

The total losses (generator, converter) are presented in Figure From figure (11) it can be noted that the DFIG system and the two-speed system (FSIG 2) has roughly the same total losses while the full-power converter system has higher total losses.

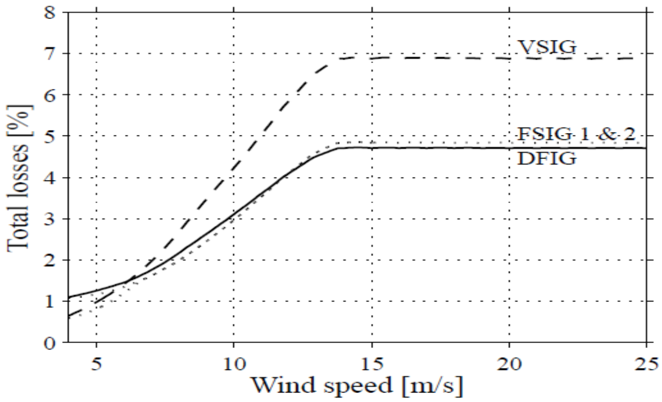

Figure 11 *Total losses The losses are given in percent of maximum shaft power.*

4 SOME PRACTICAL LOSSES MITIGATION METHODS

4.1 What happened to the energy production when the manufacturer of the turbines reduces Converter's Size:

In practical the wind turbine can't reach the full speed range with DFIG system if the converter is smaller than the rated power of the turbine. So, for low wind speeds the smaller coverter means more wind turbines in the site will operate at a non-ideal speed. in our wind farm Zaafrana the average wind speed is 10.5 m/s and the wind speed range from 5 m/s to 20 m/s, we often produce power from DFIG turbines (Gamesa) at range from 8 m/s to 13 m/s. The designers of Gamesa wind turbine take this points in consideration to be adaptable to produce power at suitable wind speed ranges and also the Less cost from economic criteria. We will show some curves from references to illustrate this point

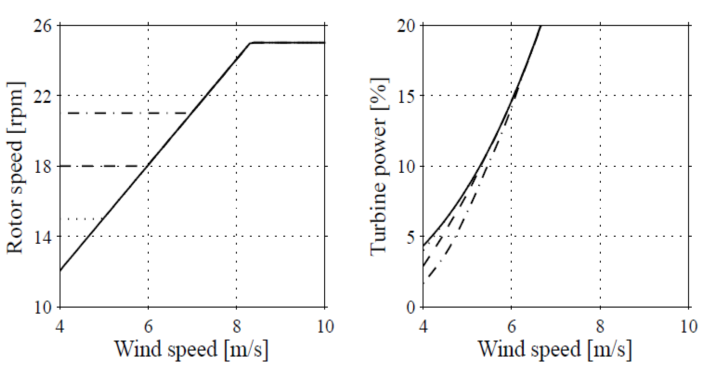

Figure 12

Fig.(12) *illustrates the impact of having a smaller converter and thus a smaller rotor-speed range, i.e., the wind power losses become higher.*

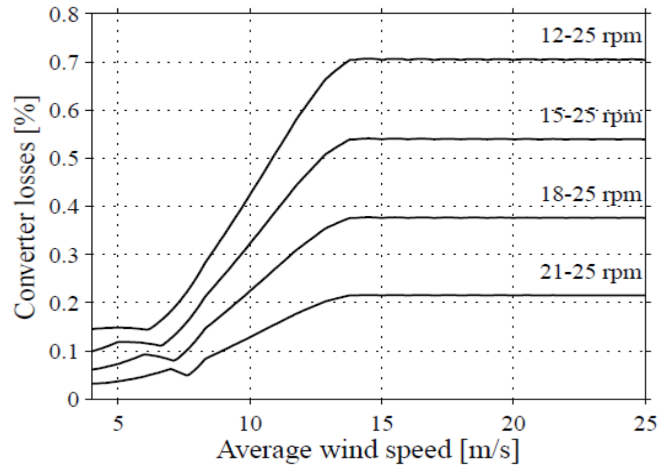

Figure 13 *Converter losses and average wind speed*

In Fig.(13) the converter losses are presented for different designs of the rotor-speed range, i.e., a smaller rotor-speed range implies smaller ratings of the converter. So, we realize that the converter losses are lower for smaller rotor-speed ranges (or smaller converter ratings). the stator-to-rotor turns ratio must be designed according to desired variable-speed range in order to minimize the converter losses.

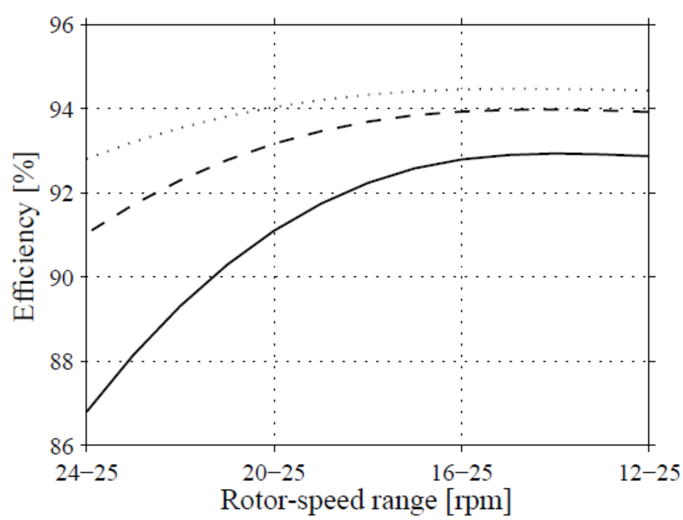

Figure 14 *Efficiency and rotor-speed range*

In Fig.(14) the energy efficiency of the DFIG for different rotor-speed ranges (or converter sizes) can be seen. It can be seen in the figure that the gain in energy increases with the rotor-speed range (converter size), while the converter losses of the DFIG system increase with the rotor-speed range (converter size) note: wind speeds of 5.4 m/s (solid), 6.8 m/s (dashed) and 8.2 m/s (dotted). It can be seen in the figure, as expected, that the rotor-speed range is of greater importance for a low average wind-speed compared to a high average wind speed. in our wind farm the location of the project provide a high average wind speed and moderate range. So it help the designer of Gamesa to balancing between the power captured and the converter losses to produce a high efficiency turbine as much as possible.

ISSN 2347-4289

4.1 Best way to Reduce of Magnetizing Losses of DFIG

there are at least two ways of lowering the magnetizing losses, i.e., this can be done by:

1. short-circuiting the stator of the induction generator at low wind speeds, and trans- mitting all the turbine power through the converter. This set-up is referred to as the short-circuited DFIG.
2. having the stator Δ-connected at high wind speeds and Y-connected at low wind speeds.

The break-even point of the total losses or the rated values of the equipment determines the switch-over point for the doubly-fed generators, i.e., the Y-Δ coupling or the synchronization of the stator voltage to the grid.

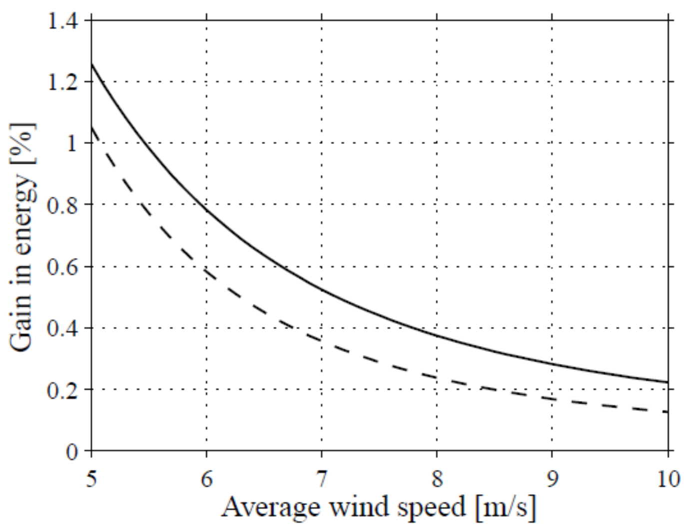

Figure 15 *Average wind speed vs energy %*

In Fig.(15) the energy gain using the two methods are presented. It can be seen in the figure that the solid line represent Y-Δ-connected DFIG system produces approximately 0.2 percentage units more energy than the short-circuited DFIG system represented by Dashed line, at least for low average wind speeds.The designer of the Gamesa DFIG turbine approve and use the Y-Δ-connected system Because it performs better than the short-circuited system.

5 COMPARISON BETWEEN DFIG AND OTHER TYPES (RESULTS AND DISCUSSION)

The base assumption made here is that all wind turbine systems have the same average maximum shaft torque as well as the same mean upper rotor speed.

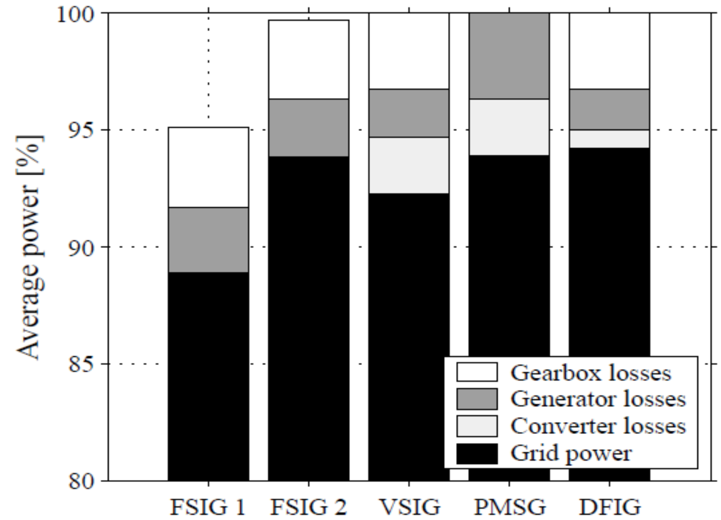

Figure 16

In Fig.(16) the produced grid power together with the various loss components for a wind speed average of 6 m/s are presented for the various systems. The systems are the DFIG system, the full variable-speed system (VSIG), one-speed system (FSIG 1), two-speed system (FSIG 2), and, a variable-speed system equipped with a permanent magnet synchronous generator (PMSG). (FSIG 1) has the disadvantage of poor wind power efficiency. However, with the two-speed system (FSIG 2) the aerodynamic efficiency is improved and close to the variable speed systems (VSIG, PMSG and DFIG).

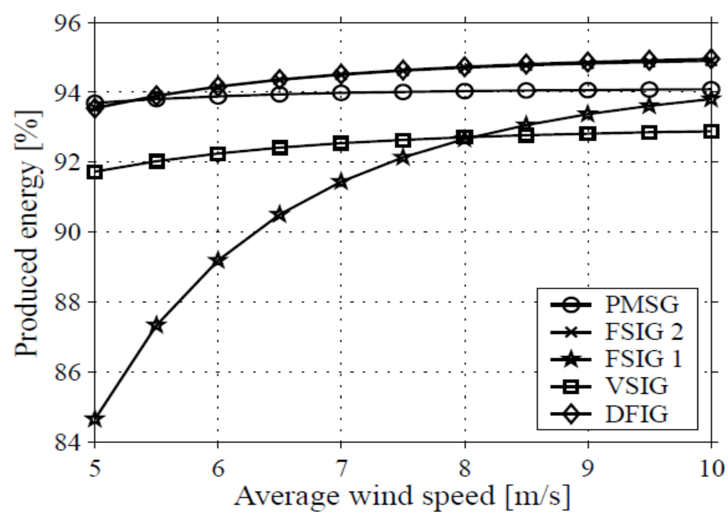

Figure 17 *Produced energy at average wind speeds*

In Fig.(17) the produced energy of the different systems, for various average wind speeds, are presented. In the last figure, the DFIG is runnig with a speed range ranging from to 12 rpm to 25 rpm.

6 COCLUSION

In the Last comparison it can be seen that the turbine use DFIG system produced 60% more energy compared to the turbine use fixed-speed system. Further, it was found in this paper that there is a possibility to gain a few percentage units (approximately 2%) in energy using the DFIG system in the

ISSN 2347-4289

turbine compared to the full variable-speed system. This can be compared to a gain of 20% for the DFIG system compared to the variable-speed system.we focus in this paper on the electrical energy efficiency of the DFIG-system in relation to other systems but there are mechanical efficiency which take in the over wind turbine efficiency. However, wind power must be accounted for when fixed-speed and variable-speed turbines are compared. To reduce the number of debts, only the average wind speed has been used and the effect of turbulence has not been treated. It is important to point out is that when comparing the DFIG system to the full variable system, the turbulence intensity, regardless of value plays an unimportant role since the torque and speed control of the turbines are in principle the same. (The rotor-speed range of the DFIG system is assumed to be almost the same as for the full-variable speed system). Another problem when discussing the effect of the turbulence intensity is that the selection of torque, speed and pitch control affect the result.Also, among other factors, the time delay between generator switchings for the fixed-speed systems, start and stop, Δ-Y-reconnections for the DFIG-systems must be known, to perform a detailed energy capture calculation.

References

[1] “Analysis, modeling and control of doubly-fed induction generators for wind turbines,” Chalmers University of Technology, G¨oteborg, Sweden, Licentiate Thesis 464L.

[2] H. Akagi and H. Sato, “Control and performance of a doubly-fed induction machine intended for a flywheel energy storage system,”.

[3] "Wind energy generation : modelling and control" / Olimpo Anaya-Lara.

[4] Ledesma, P. & Usaola, J. (2005). Doubly fed induction generator model for transient stability analysis.

[5] P. Mutschler and R. Hoffmann, “Comparison of wind turbines regarding their energy generation,”.

[6] K. Thorborg, Power Electronics – in Theory and Practice.