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Operations of Doubly-Fed Induction Generators Connected To Variable Speed Prime Movers

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Abstract: **The induction generator is controlled by electronic equipments for the optimal energy conversion system operated by the variable speed wind turbines as prime mover can be controlled by the DFIG's rotor parameters. It has been observed that the losses at lower speed of the DFIG systems are higher than those of the VSIG Power generating system 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 almost fixed to the stator voltage. This means that for the VSIG system a lower flux level is used when the wind speeds are relatively low, i.e., the magnetizing losses are minimized.**

1. INTRODUCTION

At present, induction generators are applied in commercial wind turbines having of high power ratings up to 10 MW and above. The behavior of these machines, with sophisticated control via power electronic controllers, can be different than generating units normally used now these days. The research work focuses on:

1. Determination of the 'effective resistance' parameter for the damping of

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disturbance and the variations in the back EMF for the DFIG operations.

2. Influence of the converters losses as function of wind speed of various types of induction generation.
3. Evaluation of the Doubly-Fed Induction Generators system to other similar electrical generating systems.

2. WIND TURBINES CONNECTED DFIG SYSTEMS

The wind velocity deviations can be effectively absorbed by changing the machines (DFIGs) rotor's speed as stated by T. Thiringer and J. Linders in [1], thus power fluctuations which is initiated from the wind energy conversion systems can be minimized. Hence, the electrical power quality generated by the wind conversion systems can be get better with respect to the fixed- speed wind turbine systems. Normally following wind turbine systems have been used for power generation.

1. Asynchronous generator with fixed of the speed wind inflow.
2. Cage-Bar Synchronous generator operated by Fluctuating wind speed.
3. Poly-Pole permanent-magnet synchronous generator (PPPMSG) operated by Fluctuating wind speed.
4. DFIG operated by Fluctuating wind speed.

Description of some of these systems are being presented by L. H. Hansen et al (2001) in [2].

The advantage with the system had been well explained and robust control strategy had been discussed by Pena et al (1997) in [3]. A Doulby-Fed Induction Generator with poly - poles constructions operated with wind turbine generator had been developed by the company Enercon (2004) in [4].

3. VARIABLE SPEED WIND TURBINE OPERATED DFIG SYSTEM

As we know that the electronic power converters of the DFIG and other electronic components and devices contribute a fraction of about 25% of the total power, which is being presented by Kana, C.L., Thamodharan, and M., Wolf, A. (2001) in [5]. Similarly the overall losses of the input in the power electronic converter and other controlling units can be trim down, comparing with the system of electronic converters have to handle the total incoming power. The Figure 1.1 shows a DFIG System. The main DFIG operated Wind Energy converters original manufacturers are, for example, DeWind (2005) in [6], Nordex (2004) in [7] and Vestas (2004) in [8]. Dr. Ranganath Muthu and Dr. S. Ranganathan (2006) in [9] have explained about Intelligent Control systems.

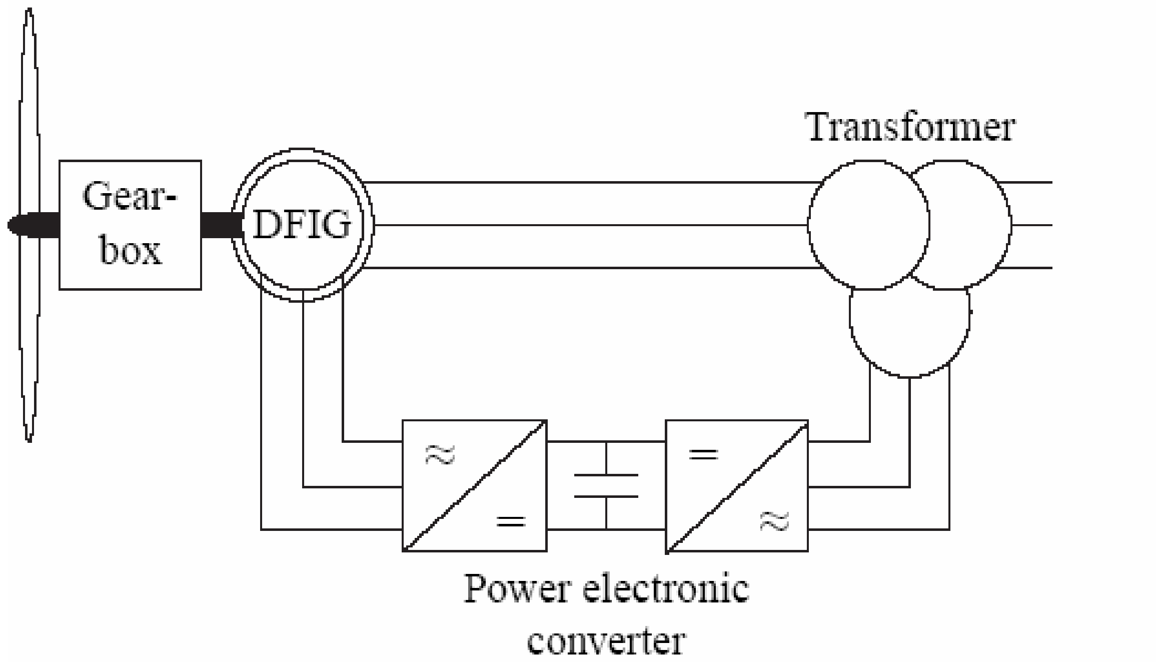

Figure 1.1. Variable-speed wind turbine with a DFIG system

4. DETERMINATION OF EFFICIENCY OF DFIG SYSTEM:

The four power generating systems are included in the research work: The four losses are taken into account they are:

I. Converter losses.
II. Gearbox losses
III. Generator losses and
IV. Aerodynamic losses Induction Generator Losses

- FSIG 1 Generating system FSIG - 1 (Fixed-speed system, having only one induction generator).
- FSIG 2 Generating system FSIG - 2 (Fixed-speed system, having two induction generator or Pole Changing Facility).
- VSIG Power generating system — (Variable-speed induction generator with full-power converter).
- DFIG Power Generating system.

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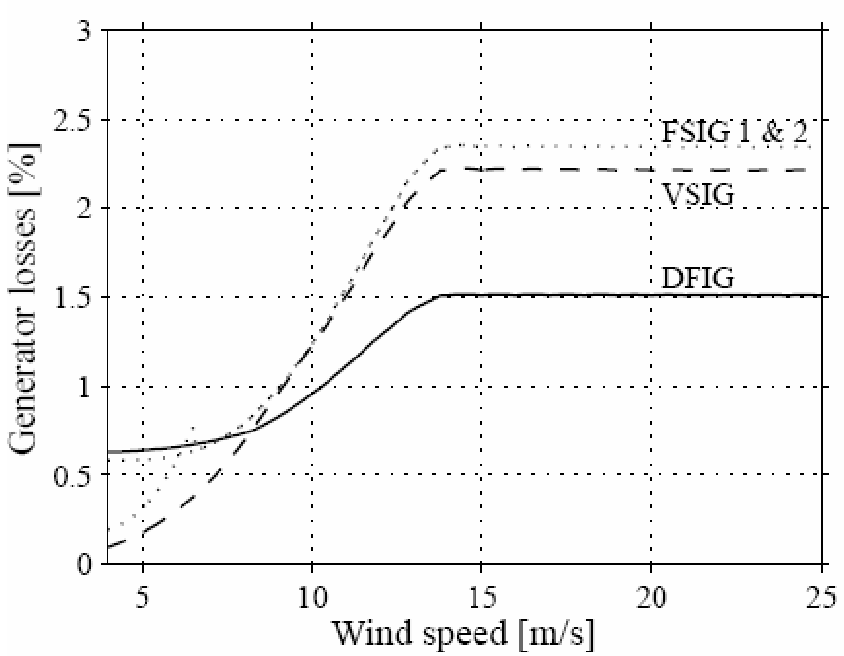

Figure 1.2 comparisons of the DFIG, VSIG and FSIG 1&2 losses.

In Figure 1.2 the induction generator losses of the DFIG system are shown. For the asynchronous generators used in this chapter are operated at three phase, 440 V, 50 Hz and with a rated full load current of 450A. The electrical parameters detail of the 150 kW induction generator has been provided below:

R_s = 0.05 p.u., R_r = 0.02 p.u., R_m = 195 p.u.,

L_{sy} = 0.16 p.u., $L_{r□}$ = 0.06 p.u., L_m = 3.8p.u. and n_p = 3

The stator-to-rotor turns ratio of the DFIG is regulated in such a fashion so that maximum rotor voltage should be not more than 65% of the rated power grid voltage maintaining the safety margin, It has been presented elaborately by M. A. Poller (2003) in [10] and Salman S.K. (2003) in [11]. Dr. Ranganath Muthu and Dr. S. Ranganathan (2006) in [12] have explained about control systems strategies.

5. TOTAL CONVERTER LOSSES OF THE DFIG

In Figure 1.3, an equivalent circuit diagram of the power converter has been developed with the six transistors numbered from T1 to T6, all are equipped with a reverse diode. The asynchronous generators can be connected to a PWM converter. The total converter losses can be divided into (I) the switching losses and (II) the conducting losses.

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The former loss of transistors is due to the (x) turn-on and (y) turn-off losses. For the various diodes the major switching losses consist of turn-off losses.

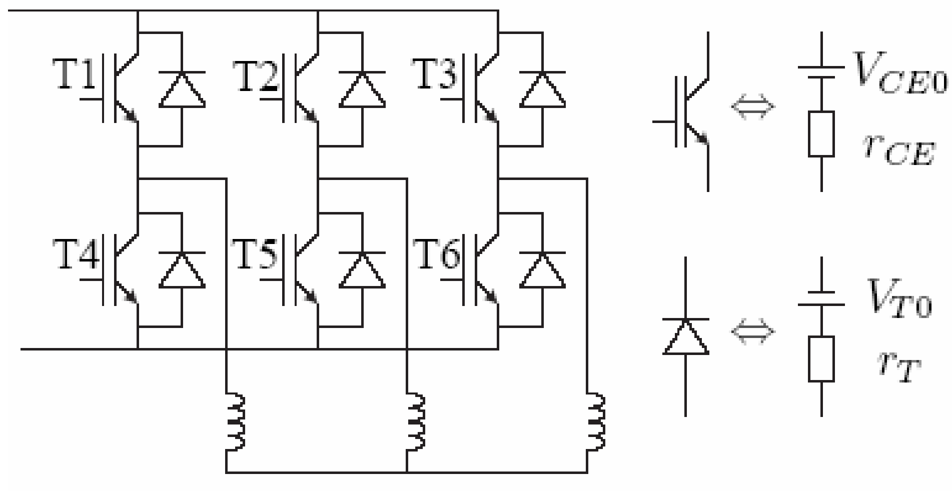

Figure 1.3. Converter Scheme.

All the transistor and connected diodes are having certain constant voltage drops, V_{CEO} and V_{TO}, and a resistance in series, r_{CE} and r_T , that has been made known in the Figure 1.3. Simplified expressions of the transistors and diodes conducting losses, are (with a third harmonic voltage injection) as follows:

$$P_{C,T} = [V_{CEO}\, I_{rms}\, \sqrt{2} / \pi] + [V_{CEO}\, I_{rms}\, m_i \cos(\square) / \sqrt{6}] + [r_{CE}\, I^2_{rms} / 2]$$

$$+ [r_{CE}\, I^2_{rms}\, m_i / \sqrt{3} \cos(\square)\, 6\, \pi] - [4\, r_{CE}\, I^2_{rms}\, m_i \cos(\square) / 45\pi \sqrt{3}]$$

(

1.1) $P_{C,D} = [V_{TO}\, I_{rms}\, \sqrt{2} / \pi] - [V_{TO}\, I_{rms}\, m_i \cos(\square) / \sqrt{6}] + [r_T\, I^2_{rms} / 2]$

$$- [r_T\, I^2_{rms}\, m_i / \sqrt{3} \cos(\square)\, 6\, \pi] + [4\, r_T\, I^2_{rms}\, m_i \cos(\square) / 45\pi \sqrt{3}] \quad (1.2)$$

Here the investigations are based on Semikron (2004 and 2004a) in [13] and [14] (shown in the Table 1.1 for actual values), $r_{IGBT} = r_{CE} \approx r_T$ and $V_{IGBT} = V_{CEO} \approx V_{TO}$. Hence, it is possible to reduce the loss of the six connected transistor and the diodes. The conduction losses can, can be written as follows:

$$P_C = [P_{C,T} + P_{C,D}] = [V_{IGBT.}\; 2 \sqrt{2}/ \pi]\, I_{rms} + r_{IGBT}\, I^2_{rms}] \quad (1.3)$$

The switching losses of all six transistor the connected inverse diode can be expressed as:

$$P_{S,T} = (E_{on} + E_{off}) (2 \sqrt{2}/ \pi) (I_{rms} / I_{C,nom})\, f_{sw} \approx [V_{sw,T}\, 2 \sqrt{2}/ \pi]\, I_{rms} \quad (1.4)$$

$$P_{S,D} = E_{rr} (2 \sqrt{2}/ \pi) (I_{rms} / I_{C,nom})\, f_{sw} \approx [V_{sw,D}\; 2 \sqrt{2}/\pi]\, I_{rms} \quad (1.5)$$

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Where E_{on} is the turn-on and E_{off} represents the turn-off energy

The losses r for the transistor, and E_{rr} represents the reverse recovery energy for the diode and the nominal current through the transistor has been represented by $I_{C,nom}$. In the equations stated above, two voltage drops, the $V_{sw,T}$ and the $V_{sw,D}$, have been introduced). The ratios $(E_{on} + E_{off})/ I_{C,nom}$ and $E_{rr} / I_{C,nom}$ are found to be unchanged for all the valves shown in the Table 1.1. The switching frequency used in this research work is 5 kHz. Moreover, since the products r_{CE} $I_{C,nom}$ and r_T $I_{C,nom}$ are constant and equal to each other, it is possible to find out the control value of the resistance, r_{IGBT1},1 A. and $I_{C,nom}$ = 1 A. The resistance of a specific valve $r_{IGBT} = r_{IGBT1, 1A} / I_{C,nom}$, can be find out, where $I_{C,nom}$ equals the value of the supposed current of the valve. In this research work, $I_{C,nom}$ has been provided as two and I_{max} rms value is the maximum RMS value of the current in the control valve.

TABLE 1.1: Converter Data (IGBT and Inverse Diode).

Nominal current	$I_{C,nom}$	300A	650A	1000A	1500A
Operating dc-link voltage	V_{CEO}	1.05 V	1.05 V	1.05 V	1.05 V
Operating dc-link voltage	V_{CC}	650V	650V	650V	650V
Lead resistance (IGBT)	r_{CE}	3 m□	1.8 m□	1.2 m□	0.9 m□
Turn-on and turn-off energy (IGBT)	$E_{on} + E_{off}$	295 mJ	570 mJ	860 mJ	1100 mJ
Turn-on and turn-off energy (IGBT)	V_{TO}	1.15 V	1.15 V	1.15 V	0.95 V
Lead resistance (diode)	r_T	2.5 mΩ	1.6 mΩ	1.1 mΩ	0.9 mΩ
Reverse recovery energy (diode)	E_{rr}	45mJ	85mJ	125mJ	168 mJ

Using the stated values provided in the Table 1.1, it is possible to determine the drops in the voltage of $V_{sw,T}$ = 2.3 V and $V_{sw,D}$ = 0.4 V, presuming of a switching frequency of 5 kHz and $r_{IGBT1,\ 1A}$= 1.8 Ω. When determining $V_{sw,T}$, $V_{sw,D}$, and r_{IGBT1},1 A. Table 1.1 shows the average value of the electrical parameters of the IGBT and Inverse Diode. The total losses of the 3 transistor of the IGBT converters become as follows:

$$P_{loss} = 3[P_C + P_{S,T} + P_{S,D}]$$

$$= 3[(V_{IGBT} + V_{sw,T} + V_{sw,D})\, I_{rms}\, 2\, \sqrt{2}/\pi + r_{IGBT}\, I^2_{rms}] \quad (1.6)$$

The losses of the back-to-back converter can be determined as

$$P_{loss,converter} = [P_{loss,GSC} + P_{loss,MSC}] \quad (1.7)$$

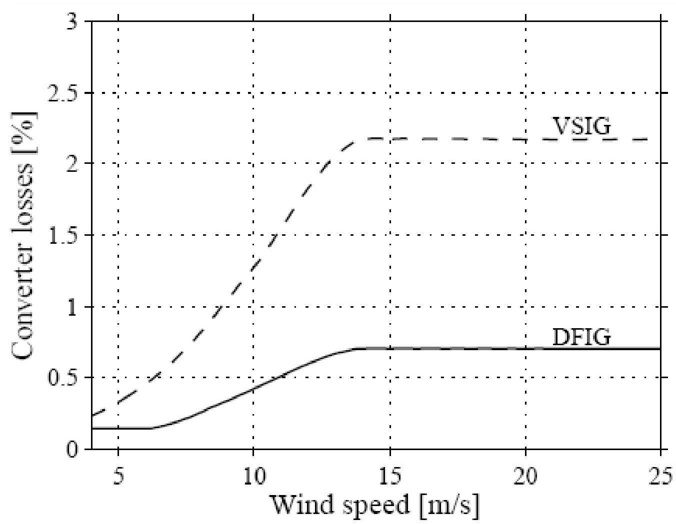

Figure 1.4: The total converter losses

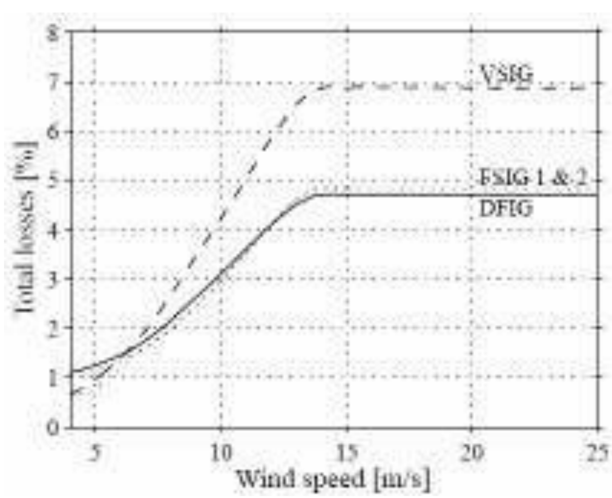

Figure 1.5 Total power Losses of DFIG, FSIG and VSIG.

The total converter losses in terms of the percentage are shown in the Figure 1.4 and the total losses (mechanical, aero-dynamic, induction generator, IGBT converter) are shown in Figure 1.5. Figure 1.4 shows the Percentage Converter losses of DFIG and VSIG.

6. CONCLUSION

The rationale of this chapter is to examine the Energy Losses and energy efficiency of the various types of the DFIG systems This study can be very useful to other types of wind turbines connected to the grid with various electrical systems. Steady-state performances are carried out. Comparison of the performances of the various types of the DFIG systems and analyzes and the power losses of other systems with induction generators has been evaluated.

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