

Abstract

Nowadays, the most currently installed variable speed wind turbines are based on doubly fed induction generator (DFIG). In this thesis, a revision for the objectives and techniques used in the control of DFIG will be presented. A D-Q model for the simulation and the analysis of a double-fed induction generator is developed. A simulation for the stand alone DFIG with inverter controlled by 180° conduction will be considered. A comparison between the simulation and experimental results is performed to verify the output voltage and frequency. In order to improve the performance of the output waveform, the space vector pulse width modulation (SVPWM) technique is used for controlling the stand alone DFIG. A complete study and simulation for the self-excited DFIG using SVPWM will be presented. A grid-connected DFIG for wind-turbine system is also studied to control both active and reactive power under variable speed operation; this includes both sub-synchronous and super-synchronous speeds.

Table of contents

Acknowledgment	i
Abstract	ii
Table of contents	iii
List of figures	vi
List of tables	viii
List of symbols	ix

Chapter 1 Introduction 1

1.1 Wind Energy	1
1.2 Wind Turbine	1
1.2.1 Horizontal Axis Wind Turbines	2
1.2.1.1 Upwind turbine	2
1.2.1.2 Downwind turbine	2
1.2.2 Vertical Axis Wind Turbines	3
1.3 Generators	4
1.3.1 Synchronous generator	4
1.3.1.1 Wound rotor synchronous generator (WRSG)	5
1.3.1.2 Permanent magnet synchronous generator (PMSG)	5
1.3.2 Asynchronous (induction) generator	6
1.3.2.1 Squirrel cage induction generator (SCIG)	6
1.3.2.2 Wound rotor induction generator (WRIG)	7
1.3.3 Different types of generators connected with the wind turbine	9
1.4 Thesis Objective	11
1.5 Scope of the Thesis	11

Chapter 2 D-Q Model of Induction Machine 12

2.1 Introduction	12
2.2 Induction Machine Model	12
2.2.1 Equations	12
2.2.2 Simulation	14
2.2.2.1 Conversion Block	15
2.2.2.2 abc System Block	15
2.2.2.3 D-Q Model Block	16
2.2.3 Results	17
2.2.3.1 Initialization	17
2.2.3.2 Scopes	17

Chapter 3 Stand-Alone Doubly-Fed Induction Generator 19

3.1 Introduction	19
3.2 Machine parameters	19

3.3 Uncontrolled DFIG	19
3.3.1 Simulation	20
3.3.2 Scopes	20
3.3.3 Comment	21
3.4 Controlled DFIG	22
3.4.1 Simulation	23
3.4.1.1 Inverter frequency	23
3.4.1.2 Inverter firing	24
3.4.1.3 Discrete Synchronized 6-Pulse Generator	24
3.4.2 Generator loading characteristic	24
3.4.3 Simulation Results	25
3.4.4 Experimental Verification	26
3.4.4.1 Experimental Setup	26
3.4.4.2 Experimental Results	27
3.4.4.3 Comparison between Simulation and Experimental Results	30

Chapter 4 Space-Vector Controlled Doubly-Fed Induction Generator 31

4.1 Introduction	31
4.2 Space-Vector Controlled DFIG	31
4.2.1 Principle of the SVPWM	31
4.2.2 Simulation	35
4.2.2.1 Discrete SVPWM Generator	36
4.2.2.2 Subsystem 1	36
4.2.3 Simulation Results	37
4.2.3.1 Without Harmonic Elimination	37
4.2.3.2 With 3rd Harmonic Elimination	38
4.2.4 Comment	41
4.3 Space-Vector Controlled DFIG Self-excited	41
4.3.1 Simulation	41
4.3.2 Simulation Results	42

Chapter 5 Grid-Connected Doubly-Fed Induction Generator 44

5.1 Introduction	44
5.2 Control strategy	45
5.3 Simulation	46
5.3.1 Embedded MATLAB function block	47
5.3.2 Grid-side converter firing angle	47
5.3.3 Rotor-side converter firing block	47
5.4 Simulation results	48
5.4.1 Sub-synchronous speed results	48
5.4.2 Super-synchronous speed results	49
5.4.3 Speed variation results	51

Chapter 6 Conclusion 54

Appendix	56
References	62

List of figures

- Figure 1.1** Types of Wind turbine
Figure 1.2 Wound rotor synchronous generator
Figure 1.3 permanent magnet synchronous generator
Figure 1.4 Squirrel cage induction generator
Figure 1.5 Wound rotor induction machine
Figure 1.6 Different types of generators connection
Figure 1.7 Interaction between the rotor speed and the frequency of the rotating magnetic field created in the rotor windings of a doubly-fed induction generator
Figure 1.8 Circuit topologies for two types of generators found in variable-speed wind turbines
- Figure 2.1** Induction machine model
Figure 2.2 Induction machine simulations
Figure 2.3 Conversion block
Figure 2.4 Dynamic model of Induction machine
Figure 2.5 Performance Characteristics
- Figure 3.1** Uncontrolled DFIG
Figure 3.2 Stand-alone uncontrolled DFIG Simulink simulations
Figure 3.3 Stator voltage at different speeds
Figure 3.4 Effect of speed variation at the stator frequency and the stator voltage
Figure 3.5 Controlled DFIG
Figure 3.6 Closed loop Simulink simulation
Figure 3.7 Inverter frequency block
Figure 3.8 Inverter firing block
Figure 3.9 Stator voltages and frequency at different loading
Figure 3.10 Stator and rotor voltages at different speeds
Figure 3.11 Hardware components
Figure 3.12 Stator and rotor voltage
Figure 3.13 Stator and rotor voltage at 1000-rpm
Figure 3.14 Stator and rotor voltage at 1200-rpm
- Figure 4.1** Space-Vector Controlled DFIG
Figure 4.2 Possible switching configurations of a 3-phase inverter
Figure 4.3 Representation of the eight possible switching configurations
Figure 4.4 Closed loop Simulink simulation
Figure 4.5 Subsystem1
Figure 4.6 Stator and rotor voltages at different speeds
Figure 4.7 One cycle of the stator and rotor voltages at steady state
Figure 4.8 Stator and rotor voltages at steady state with filter
Figure 4.9 one cycle of stator and rotor voltages at steady state with filter
Figure 4.10 Space-Vector Controlled DFIG Self-Excited
Figure 4.11 Closed loop Simulink simulation
Figure 4.12 Stator and rotor voltages at different speeds
Figure 4.13 One cycle of the stator and rotor voltages at steady state

Figure 5.1 Grid connected DFIG

Figure 5.2 Power flow of grid-connected DFIG

Figure 5.3 Induction machine IEEE recommended equivalent circuit

Figure 5.4 Grid-connected DFIG simulation

Figure 5.5 Inverter firing signal

Figure 5.6 Stator and rotor power and voltages at 1300-rpm

Figure 5.7 Stator and rotor power and voltages at 1700-rpm

Figure 5.8 Stator and rotor power and voltages

List of tables

Table 1.1 Comparisons between VAWTs and HAWTs

Table 1.2 Different types of generators used in wind turbines

Table 1.3 Comparisons between synchronous and asynchronous generators

Table 3.1 Mutual inductance look-up table

Table 4.1 Space Vector Modulation Inverter States

Table 4.2 Switching Time Table for Each Sector

List of symbols

f_r : Rotor frequency,
 f_s : Stator frequency,
P: Number of poles,
 n_r : Rotor speed,
 n_s : Synchronous rotating field speed (rpm);
S : Slip,
d: Direct axis,
q: Quadrature axis,
s: Stator variable,
r: Rotor variable,
 Φ_{ij} : is the flux linkage ($i = q$ or d and $j = s$ or r),
 v_{qs}, v_{ds} : q and d-axis stator voltages,
 v_{qr}, v_{dr} : q and d-axis rotor voltages,
 F_{mq}, F_{md} : q and d-axis magnetizing flux linkages,
 R_r : Rotor resistance,
 R_s : Stator resistance,
 X_{ls} : Stator leakage reactance,
 X_{lr} : Rotor leakage reactance,
 i_{qs}, i_{ds} : q and d-axis stator currents,
 i_{qr}, i_{dr} : q and d-axis rotor currents,
J: Moment of inertia,
 T_e : Electrical output torque,
 T_L : Load torque,
 ω_e : Stator angular electrical frequency,
 ω_b : Motor angular electrical base frequency, and
 ω_r : Rotor angular electrical speed,
 $T_z = \frac{T_s}{2}$;
 T_s : Sample time;
M: Modulation index;
 P_s : Stator active power –W,
 Q_s : Stator reactive power –VAR,
 V_s : Stator voltage –V,
 I_s : Stator current –A,
 ϕ : Angle between stator voltage and current,
 V_m : Magnetization branch voltage –V,
 I_m : Magnetization branch current –V,
 V_r : Rotor voltage –V,
 I_r : Rotor current –A