ARAB ACADEMY FOR SCIENCE, TECHNOLOGY AND MARITIME TRANSPORT

College of Engineering and Technology- Cairo

Power Management of Open Winding PM Synchronous Generator for Unbalanced Voltage Condition

by

Eng. Ashraf Saeed Huessin El-Bardawil

A Thesis submitted in partial fulfillment for the requirements for the degree of **Master in Electrical Engineering**

Prof. Dr. Yasser Gaber Dessouky
Supervisor

Prof. Dr. Samir Yousef Marzouk
Supervisor

Assoc. Prof. Mona Fouad Moussa
Supervisor

Prof. Dr. Samir Mohamed EL- Makkawy
Examiner

Prof. Dr. Essam Eddin M. Rashad
Examiner

Cairo

2016

ACKNOWLEDGEMENTS

First of all, thanks to **ALLAH** for aiding, guiding and giving me power to accomplish this work.

I would like to express my deepest thanks, gratitude and sincere appreciation to ***Prof. Dr. Yasser Gaber****, Professor of Electrical and control Engineering, Arab Academy for Science and Technology for his meticulous guidance, continuous encouragement, generous help, and real support throughout the conduct of the work reported in this thesis. Without his wonderful, repeated, and nonstop efforts this thesis would have not been accomplished. A special debt of gratitude and cordial appreciation is to him.*

My sincere thanks and gratitude are expressed to ***Dr. Mona Fouad Moussa****, Assistance professor of Electrical Power & Control Engineering, Arab Academy for Science and Technology for her supervision, guidance, scientific help, and constructive criticism.*

I am deeply indebted to ***Prof. Dr. Samir Yousef Marzouk,*** *Professor of Basic and applied science, Arab Academy for Science and Technology, for his generous help. His scientific guidance is highly appreciated.*

Finally, I find it my pleasant and necessary duty to thank my wife, and my son who gave me solid-moral encouragement, continuous help and warm support throughout the years of research reported in this thesis. Also, my personal thanks are extended to my whole family especially ***Uncle: Ali Hassan EL-Bardawil*** *who helped me to make this work. I also would like to dedicate this thesis to my mother who passed away.*

Ashraf Saeed

2016

ABSTRACT

Wind energy is currently the fastest growing electricity source worldwide. Since wind generators have to compete with other energy sources, their cost efficiency is effective. In this thesis, a system utilizing an open-winding Permanent Magnet Synchronous Generator (PMSG) is studied for wind energy generation. The proposed system controls generated power using an auxiliary voltage source inverter. The volt ampere (VA) rating of the auxiliary inverter is only a fraction of the system rated power. An adjusted control system, which consists of two main parts, the first is implemented to control the generator power and the second is control the active and the reactive power injected into the grid. Balanced and unbalanced voltage effects are studied for the wind generation model. Theoretical and experimental results are demonstrated which verify the validity of the proposed system to achieve the power management requirements for balanced and unbalanced voltage condition of the grid. The proposed system is designed and simulated utilizing MATLAB /Simulink software.

List of Content

Acknowledgements ii
Abstract iii
Table of Contents iv
List of Figures...vii
List of Tables ix
List of Abbereviations... x
List of Numencleature.. xii
List of Publication xiv
Chapter 1: INTRODUCTION 2
1.1. Review... 2
1.2. Renewable energy source 2
1.2.1 Biomass Energy 2
1.2.2 Tidal Energy 3
1.2.3 Wave Energy 3
1.2.4 Geothermal Energy 4
1.2.5 Hydro-electric Energy 5
1.2.6 Solar Thermal Technologies and Photovoltaic 6
1.2.7 Wind Energy 7
1.3 Wind energy in Egypt 9
1.4 Wind Energy Conversion Systems Configurations 10
1.5 Fixed-Speed WECS.. 11
1.6 Variable-Speed Induction Generator WECS 12
1.6.1 Wound-Rotor Induction Generator with External Rotor Resistance 13
1.6.2 Doubly-Fed Induction Generator Wind Turbine 13
1.6.3 Squirrel-cage Induction Generator Wind Energy Systems with Full-Capacity Power Converters 14
1.6.4 Variable-Speed Synchronous Generator Wind Turbines 14
1.7. Grid connection.. 17
1.7.1 AC Connection Scheme 17
1.7.2 DC Connection Scheme 18
1.7.3. Grid connection requirement in Egypt 18
1.8. Power management control... 20

Chapter 2: Literature Review 24
2.1.1 General overview of voltage sags in power systems 24
2.1.2 General overview of open winding PMSG 25
2.1.3 Static synchronous series compensator 26
Chapter 3: Modelling of a Permanent Magnet Synchronous Generator based Wind Energy Conversion System 29
3.1 Wind Energy Conversion System Overview 29
3.2 Wind Turbine Model 30
3.3 Generator Model 31
3.4 AC-DC Conversion Unit 34
3.5 DC-AC Conversion Unit 37
3.6 PMSG WECS Control 39
3.6.1 Grid side converter 40
Chapter 4: Theory of operation of the proposed system 47
4.1HistoricalBackground 47
4.2 Theory of operation of the proposed system 49
4.3 Simulation results 52
4.3.1 PMSG model 53
4.3.2 Series compensator with open-winding PMSG 55
4.3.3 PMSG with Grid side inverter control 57
4.3.4 Series compensated open-winding PMSG generator connected to balanced grid 60
4.3.5 Series compensated open-winding PMSG generator connected to unbalanced grid 64
Chapter 5: Design and Implementation of the Experimental Test 68
5.1 System Topology 68
5.1.1 Three phase inverter 69
5.1.2 Uncontrolled three phase rectifier 71
5.1.3 The Digital Signal Processor DSP 72
5.2 Simulation diagram 73
5.3 Experimental result 74
5.4 Valdation Experimental result with simulation 75
5.5 Simulation Result 76
Chapter 6: Conclusion and Future Work 80
6.1 Conclusion 80
6.2 Future Work 80

References..81
Appendix A..

List of Figures

Figure1.1: Wave Energy Levels in kW/m Crest Length Courtesy of the European Ocean Energy Association. 4
Figure1.2: Formation of horizontal-axis wind turbine. 8
Figure1.3: Vertical axis turbine. 9
Figure1.4: Wind energy in Egypt. 10
Figure1.5: Wind energy conversion systems configurations. 11
Figure1.6: Fixed speed WECS using a soft starter. 12
Figure1.7: Variable speed WECS using a WRIG. 13
Figure1.8: Configuration of the DFIG. 14
Figure1.9: VSI WECS using a SCIG. 14
Figure1.10: 2-level based WECS using back-to-back converters 15
Figure1.11: 3-level SG based WECS using NPC converters. 15
Figure1.12: WECS with PWM current source converters. 16
Figure1.13: Single channel boost converter. 16
Figure1.14: A 3-level boost converter. 16
Figure1.15: A 2-channel boost converter. 17
Figure 3.1: PMSG wind energy conversion system. 30
Figure 3.2: The synchronous machine: (a) co-ordinate system and (b) idealized machine. 32
Figure 3.3: Mathmatical model of PMSG 34
Figure 3.4: Open winding PMSG 34
Figure 3.5: Machine side converter: (a) voltage-source PWM rectifier and (b) diode rectifier with boost. 35
Figure 3.6: Three-phase full-wave bridge rectifier waveforms: (a) 3-phase voltage (b) line voltageVs, and output voltage, Vdc, (c) load current Idc, (d) diode $D1$current$Id1$, (e) diode $D4$ current, $Id4$, and (f) supply current ia. 36
Figure 3.7: Grid-connected inverter in a WECS. 37
Figure 3.8: Sinusoidal pulse-width modulation (SPWM). 38
Figure 3.9: Proposed series compensated diode rectifier open-winding. 40
Figure 3.10: General structure for stationary reference frame control strategy. 41
Figure 3.11: PLL (a) block diagram and (b) coordinate system. 42
Figure 3.12: Simplified diagram and phasor diagram and PF. 43
Figure 3.13: Control diagram of GSC. 45
Figure 4.1: PMSG WECS employing rectifier and dc-dc boost converter. 47
Figure 4.2: PMSG cascade driving wind turbine. 48
Figure 4.3: (a) Proposed series compensated diode rectifier open-winding, (b) Control method of overall system. 50
Figure 4.4: Series compensation equivalent circuit. 50
Figure 4.5: Phasor diagram of operating principle of proposed system employing salient synchronous generator. 51
Figure 4.6: (a) Model of PMSG, (b) Subsystem of DQ PMSG. 53
Figure 4.7: Relationship between $Vabc$ three phase voltage and time, under no voltage test. 54
Figure 4.8: Relationship between time and: (a) Va & Ia with Resistive load, (b) Va & Ia with Inductive load, (c) Va & Ia with RL Load. 55

Figure 4.9: PMSG with series compensator..56
Figure 4.10: Relationship between time and (a) generator current Ia , (b) Compensator voltage Vsc, (c) active generator power Pgen, (d) Vrect rectification voltage. 57
Figure 4.11: (a) PMSG with Grid side inverter control, (b) Subsystem of the balanced grid...........58
Figure 4.12: Relationship between time and: (a) $Pgrid$& $Qgrid$ (b) Id & Iq and (c) $Vrectifier$..59
Figure 4.13: Series compensated open-winding PMSG generator connected to balanced grid........60
Figure 4.14: Relationship between time and: (a) The generator power (Pgen), (b) the compensator voltage (Vsc), (c) Direct current (Id), (d) Quadratic current (Iq), (e) Active & Reactive power injected to the grid and (f) Generator current all for step change in (Pgen). 61
Figure 4.15: Relationship between time and: (a) The generator power (Pgen), (b) the compensator voltage (Vsc), (c) Direct current (Id), (d) Quadratic current (Iq) and (e) Active & Reactive power injected to the grid all for step change in the compensation voltage. 62
Figure 4.16: Relationship between time and: (a) the compensator voltage (Vsc), (b) The generator power (Pgen), (c) Active & Reactive power injected to the grid and (d) Generator current all for step change in the speed. 63
Figure 4.17: (a) Series compensated open-winding PMSG generator connected to unbalanced grid, (b) Subsystem of unbalanced grid..64
Figure 4.18: Relationship between time and**:** (a) Active & Reactive power of the grid in unbalanced voltage value, (b) Id, Iq current component during the unbalanced voltage value.........................65
Figure 4.19: Relationship between time and: (a) Active & Reactive power of the grid in unbalanced voltage phase, (b) Id, Iq current component during the unbalanced voltage phase. 65
Figure 5.1: Schematic diagram of experimental work. 68
Figure 5.2: (a) Overall rig (open winding generator, grid side converter) Photograph picture, (b) DC/AC Converter with DSP. 69
Figure 5.3: Six pulse three phase inverter: (a) Schematic diagram of inverter, (b) Photographic picture. 70
Figure 5.4: Power supply for driving circuit: (a) Schematic diagram, (b) Photographic picture......71
Figure 5.5: Uncontrolled three phase rectifier Photographic picture. 71
Figure 5.6: Photographic picture of DSP TMS320F2812. 72
Figure 5.7: Signal conditioning for analog input to DSP. 73
Figure 5.8: Simulation digram of DSP. 73
Figure 5.9: Generator side: (a) The fundamental component of the compensator voltage versus the phase ‘A’ of generator voltage (b) The generator voltage and current of phase ‘A’. 74
Figure 5.10: DC Side: rectified voltage ($\boldsymbol{Vdc}$). 74
Figure 5.11: Grid side control: (a) the fundamental component of the grid inverter voltage versus the phase ‘A’ of grid voltage. (b) The grid voltage and current of phase ‘A’..................................75
Figure 5.12: Simulation system with open loop control. 76
Figure 5.13: Generator side: (a) shows the fundamental component of the compensator voltage versus the phase ‘A’ of generator voltage, (b) shows the generator voltage and current of phase (‘A’ *40).. 76
Figure 5.14: DC Side: rectified voltage ($\boldsymbol{Vdc}$). 77
Figure 5.15: Grid side control: The grid voltage and current of (phase ‘A’ * 20).. 77

List of Tables

Table 1.1: Minimum time periods....20
Table 1.2: Maximum level of harmonic voltage distortion....20
Table 4.1: Generator parameter for test 53
Table 4.2: Simulation result 66
Table 5.1: Comparison between experimental test results and simulation results 78

List of Abbreviations

A/D	**Analogue to Digital**
CVVF	**Constant volt variable frequency**
D/A	**Digital to Analogue**
DFIGs	**Doubly fed induction generators**
DG	**Distributed generation**
DSP	**Digital Signal Processor**
GSC	**Grid side converter**
GB	**Gear box**
HAWT	**Horizontal-Axis Wind Turbines**
HCC	**Half-controlled-converters**
HEVs	**Hybrid electric vehicles**
HVDC	**High voltage direct current**
I/O	**Input-Output**
LVRT	**Low voltage right through problem**
MERC	**Magnetic energy recovery**
MPPT	**Maximum power point tracking**
NPC	**Neutral point clamped**
NREA	**New and Renewable Energy Authority**
NRSE	**Renewable Sources of Energy**
ORB	**Optimum relationship-based**
PCC	**Point of common coupling**
PID	**Proportional Integral Differential**
PLLs	**Phase-lock loops**
PM	**Permanent magnet**
PMSG	**Permanent Magnet Synchronous Generator**
PWM	**Pulse Width Modulation**
RSC	**Rotor-side converter**
RES	**Renewable energy source**
SCIG	**Squirrel-cage induction generator**

SSSC	**Static synchronous series compensator**
SHE	**Selective Harmonic Elimination**
SGs	**Synchronous generators**
WECS	**Wind energy conversion system**
WPS	**Wind power system**
WRIG	**Wound rotor induction generators**
WRSGs	**Wound-rotor synchronous generators**
THD	**Total harmonic distortion**
TSR	**Tip speed ratio**
UPQC	**Unified power quality conditioner**
VA	**Volt ampere**
VAWT	**Vertical-Axis Wind Turbines**
VOC	**Voltage oriented control**
VSC	**Voltage source converter**
VSI	**Voltage source inverter**
VSR	**Voltage source rectifier**
WEC	**World Energy Council**
WRIGs	**Wound-rotor induction generators**
WT	**Wind turbines**

LIST OF NUMENCLEATURE

i_d, i_q	**d-and q-axis components of stator currents.**
R_a	**Generator resistance**
J	**Rotor and shaft moment of inertia.**
L_d, L_d	**d-and q-axis inductances.**
$\frac{d}{dt}$	**Differential operator.**
P	**Number of pole pairs.**
v_d, v_d	***d-and q-axis components of stator voltages.***
ρ	**Wind density**
A	**Blades swept area**
V	**Wind speed**
C_p	**power coefficient**
λ	**Tip speed ratio**
β	**pitch blade angle**
$[c_1 \ldots\ldots c_9]$	**Characteristic constants for each wind turbine**
v_{abcg}	**Three phase stator voltages**
i_{abcg}	**Three phase stator currents**
φ_{abc}	**Three phase stator flux**
R_a	**Resistance of the three phase stator winding**
φ_f	**The amplitude of the flux linkages established by the permanent magnet**
l_{aa}, l_{bb}, l_{cc}	**Self-inductances of phase abc**
$l_{ab} = l_{ba}$	**Mutual inductance between phase a and b**
$l_{bc} = l_{cb}$	**Mutual inductance between phase b and c**
$l_{ac} = l_{ca}$	**Mutual inductance between phase *a* and *c***
ω_e	**Electrical angular frequency**
ω_r	**Rotor mechanical angular frequency**
T_e	**Electromechanical torque**
T_L	**Load torque**
ω_s	**Supply voltage angular frequency**
V_{PH}	**RMS value of the phase voltage**
f	**Supply frequency**
V_{LL}	**Rms value line-to-line voltage.**
m_a	**Modulation index**
$\hat{V}_m$	**Amplitude of the modulating signals**
$\hat{V}_c$	**Amplitude of the carrier signals**
P_{grid}	**Active power**
φ_{grid}	**Grid power factor angle**

Q_{grid}	**Reactive power**
Q^{*}_{grid}	**Reference for the reactive power**
v_{di}	**Decoupled controller in the d-axes**
v_{qi}	**Decoupled controller in the q-axes**
L_{1k}	**Leakage inductance**
I_a	**Armature current**
V_g	**Generator output volt**

List of Publication

- Ashraf El- Bardawil, Mona Fouad Moussa, Yasser Gaber Dessouky, Samir Yousef Marzouk , "Power Management of Open Winding PM Synchronous Generator for Unbalanced Voltage Condition", Journal of Power Electronics (JPE), Korean Institute of Power Electronics (KIPE), ISSN 0.8, 2016.