Enhancement of Grid Connected Variable Speed Direct-Drive PMSG-Based Wind Energy Conversion System (WECS) through integration of Flywheel Energy Storage System (FESS)

By

Ahmed Mohamed Abd El-Baset El-Komy

A Thesis submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
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Title of Thesis:

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Key Words:
Wind Energy Conversion Systems, Flywheel Energy Storage Systems, Maximum Power Point Tracking, Active and Reactive Power Control, Low Voltage Ride-Through Capability

Summary:

This thesis presents a study of improving grid connected wind energy conversion systems through the integration with flywheel energy storage systems. The study has shown the effectiveness of flywheel system to control the grid active and reactive power simultaneously, while extracting the maximum power from the wind generator considering a variable wind speed profile. Also, the study has proved the ability of the flywheel system to enhance the low voltage ride-through capabilities of the wind generator. MATLAB / SIMULINK models have been conducted showing the different integration topologies between the wind and flywheel systems. Finally, the study presents recommendations for the convenient integration topology based on the performance required from the integrated system.

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LIST OF SYMBOLS AND ABBREVIATIONS

- **List of Abbreviations**

APS	Active Power Stabilization
BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage
CPC-S	Conditioning Power Control System
DD-WECS	Direct Drive Wind Energy Conversion System
DFIG	Doubly Fed Induction Generator
DOD	Depth of Discharge
DTC	Direct Torque Control
DVR	Dynamic Voltage Restorer
EEHC	Egyptian Electrical Holding Company
ESS	Energy Storage System
FACTS	Flexible AC Transmission Systems
FBESS	Flow Battery Energy Storage System
FC	Frequency Control
FESS	Flywheel Energy Storage System
FOC	Field Oriented Control
FRT	Fault Ride-Through
GSC	Grid Side Converter
HCS	Hill Climb Searching
IDFOC	Indirect Field Oriented Control
IM	Induction Machine
IPP	Independent Power Producer

LVRT	Low Voltage Ride-Through
MMC	Modular Multilevel Converters
MPPT	Maximum Power Point Tracking
MSC	Machine Side Converter
MTPA	Maximum Torque per Ampere
NREA	New and Renewable Energy Authority
OTC	Optimal Torque Control
PCC	Point of Common Coupling
PHS	Pumped Hydro Storage
PLL	Phase Locked Loop
PMSG	Permanent Magnet Synchronous Generator
PMSM	Permanent Magnet Synchronous Machine
PPA	Power Purchase Agreement
PSF	Power Signal Feedback
PSO	Power System Operator
PWM	Pulse Width Modulation
RSC	Rotor Side Converter
SCE	Supreme Council for Energy
SCESS	Super Capacitor Energy Storage System
SCIG	Squirrel Cage Induction Generator
SDBR	Series Dynamic Braking Resistor
SMES	Super Magnetic Energy Storage System
SOC	State of Charge
SPWM	Sinusoidal Pulse Width Modulation
STATCOM	Static Compensator
SVC	Static VAR Compensator
SVM	Space Vector Modulation

TCSR	Thyristor Controlled Series Reactor
TSO	Transmission System Operator
TSR	Tip Speed Ratio
TSRC	Tip Speed Ratio Control
UPF	Unity Power Factor
VAR	Volt Ampere Reactive
VC	Voltage Control
VRM	Variable Reluctance Machine
VSC	Voltage Source Converter
VSWG	Variable Speed Wind Generator
WPP	Wind Power Plant
WRIG	Wound Rotor Induction Generator
WWEA	World Wind Energy Association

- **List of Symbols**

A	: The area covered by rotor blades, m^2
C	: The DC link capacitor, F
C_p	: The power conversion coefficient
D_f	: The Damping Coefficient of the Flywheel Rotor, N.m/rad/sec
D_r	: The damping coefficient of the generator, Nm/(rad/sec)
D_t	: The damping coefficient of the wind turbine rotor, Nm/(rad/sec)
E_C	: The Energy Stored in capacitor, Joules
E_f	: The Energy Stored in flywheel, Joules
E_L	: The Energy Stored in inductor, Joules
e_m	: The Energy stored per unit mass, MJ / kg
E_s	: The Grid voltage amplitude, V
e_v	: The Energy stored per unit volume, MJ / m^3
i_{dg}	: The *d*-axis component of the GSC current, A
i_{ds}	: The *d*-axis component of the stator current, A
i_{qg}	: The *q*-axis component of the GSC current, A
i_{qs}	: The *q*-axis component of the stator current, A
J_f	: The flywheel inertia, kg/m^2
J_r	: The generator inertia, kg/m^2
J_t	: The wind turbine inertia, kg/m^2
k	: The shaft stiffness, N/rad
K	: The Flywheel Shape Factor
L_{df}	: The *d*-axis component of the filter inductance, H
L_{ds}	: The *d*-axis component of the stator inductance, H
L_f	: The filter inductance, H
L_{qf}	: The *q*-axis component of the filter inductance, H

L_{qs} : The *q*-axis component of the stator inductance, H

L_s : The stator inductance, H

p : The pair poles

P_g : The grid active power, W

P_s : The PMSG active power, W

P_t : The extracted mechanical power from the wind, W

Q_g : The reactive power output to the grid, VAR

Q_s : The PMSG reactive power, VAR

R : The radius of the wind turbine rotor, m

R_f : The filter resistance, Ω

R_s : The stator resistance, Ω

T_e : The generator electromagnetic torque torque, Nm

Te_{fw} : The electromagnetic torque of flywheel generator rotor , N.m

T_t : The wind turbine torque, Nm

V_{dc} : The dc-link voltage, V

V_{dg} : The *d*-axis component of the GSC output voltage, V

V_{ds} : The *d*-axis component of the terminal stator voltage, V

V_{qg} : The *q*-axis component of the GSC output voltage, V

V_{qs} : The *q*-axis component of the terminal stator voltage, V

V_{wind} : The wind speed, m/s

β : The pitch angle of the rotor blades, deg

θ_g : The angular position of the grid voltage, rad

θ_r : The rotational angle of the generator rotor, rad

θt : The rotational angle of the wind turbine rotor, rad

λ : The tip speed ratio

ρ : The air density, Kg/m^3

ρ_f : The Flywheel Material Density, kg / m^3

σ : The Material Tensile Strength, MPa

ψ_{ds} : The *d*-axis component of the stator flux linkage, Wb

ψ_f : The permanent magnet flux, Wb

ψ_{qs} : The *q*-axis component of the stator flux linkage,Wb

ω : The angular frequency of the grid voltage, rad/sec

ω_{fw} : The angular frequency of the grid voltage, rad/sec

ω_r : The rotational angular speed of the generator, rad/sec

ω_t : The angular speed of wind turbine rotor, rad/sec

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