ANALYSIS AND DESIGN OF PERMANENT MAGNET GENERATORS AND DOUBLY FED INDUCTION GENERATORS FOR RENEWABLE ENERGY APPLICATIONS

VAKIL GAURANG INDRAVADAN

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

VAKIL GAURANG INDRAVADAN

Department of Electrical Engineering

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CERTIFICATE

This is to certify that the thesis entitled, "**Analysis and Design of Permanent Magnet Generators and Doubly Fed Induction Generators for Renewable Energy Applications**" being submitted by **Mr. VAKIL GAURANG INDRAVADAN** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Vakil Gaurang Indravadan has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained herein have not been submitted to any other University or Institute for the award of any degree.

Date:

Prof. K. R. Rajagopal

Department of Electrical Engineering

Indian Institute of Technology Delhi

Hauz Khas, New Delhi – 110016, India

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ABSTRACT

The research described in this thesis primarily focuses on the analysis and design of variable speed generators used in wind power applications. Different market segments have emerged for the small power stand alone and grid connected renewable energy applications. For the design of variable speed wind generators, five applications and their power ratings are targeted, viz. 2.2kW and 5kW for standalone small scale village electrification, 7.5kW and 10kW for standalone or grid connected application used for rural electrification or residential loads and 15kW for irrigation and/or farm electrification.

There are numerous rotor topologies when it comes to permanent magnet brushless machines (PMBM). A detailed comparison is carried out for different rotor topologies having various PM configurations of PMBM in terms of generated voltage (back-EMF in case of motoring operation), cogging torque, static torque profile with one phase excited with the dc supply which eventually gives the average torque and ripple torque for various load angles (i.e. the angle between the rotor polar axis and stator polar axis).

To determine the effect of different design parameters on the permanent magnet generator (PMG) performance, a detailed parametric analysis is carried out. The analysis feeds in as an input to the process of optimization, as it provides the understanding as to which parameter is required to be varied or to be discarded and in what way, to enhance the generator performance. An analytical set of design equations for designing each – high speed and direct drive PMG, and high speed doubly fed induction generator (DFIG) specifically for low power applications was developed.

Novel reduced single tooth model to represent magnetic circuit for integral slot and fractional slot stator configuration is developed and evaluated against the results obtained from the finite element analysis (FEA). A generic winding arrangement algorithm is developed to generate a double layered short pitched distributed or concentrated winding layout for various integral slot or fractional slot configurations that are considered.

An unconstrained design space is considered and hence, a custom genetic algorithm with an adaptive ranging is developed and verified to span a significantly large design space for design optimization of direct drive PMG. With an objective to include restriction on mechanical resonances at the design stage, a detailed structural FEA was carried out, on the direct drive PMG to determine the free mode frequencies so as to avoid them.

While considering the PMG, it is important to consider the condition monitoring of the permanent magnet (PM). Being the most vulnerable component of the generator, PM gets affected by both temperature and excitation. Comprehensive signatures for condition monitoring of PM were developed, that would help detect local, partial and complete PM demagnetization. The developed signatures also help to distinguish PM demagnetization fault from the inter-turn fault. By knowing the PM state of health, it is possible to operate a faulty generator (with partially, locally or completely demagnetized PM) at a lower output rating (or with different control scheme), without demagnetizing the PM any further and hence, prolonging the generator life.

A parallel tooth configuration is selected for the rotor of DFIG. For the rotor, as the height of the slot increases, the slot area increases but slot width decreases, therefore, even though there is sufficient area, the conductors may not fit in the slot because the width is too small. To overcome this problem, a generic algorithm is developed to precisely arrange the conductors in the slot and determine the slot fill factor. It sets the limit to the maximum fill factor that can be considered for the design of the generator. A similar algorithm is also applied to the stator design. With this understanding, design optimization of the DFIG is carried out using the custom GA based design optimization process for different stator and rotor slot combinations and different stator to rotor turns ratios along with the conventional set of design variables.

Using the established understanding, a comprehensive computer aided design (CAD) package is proposed and developed using the extended design variables and GA based optimization process is used to design PMGs and DFIGs for wind power applications in the power range of 2kW to 15kW which covers the major applications discussed earlier. Specific designs are generated utilizing the developed CAD program for high speed and direct drive PMG, and high speed DFIG that meet the specific market driven power ratings and are characterized in detail.

This thesis eventually gives a comprehensive solution for designing a high performance PMG and DFIG. Important parameters of these generators to be considered for the design are dealt in detail with supportive information obtained from the analysis supplemented by the FEA results. Hence, this work provides the insight into the design process of PMG and DFIG, and provides optimization methodologies to develop compact and high performance generators.

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LIST OF SYMBOLS

$\emptyset_g$	Airgap Flux (Wb)
$\emptyset_l$	Leakage Flux (Wb)
$\emptyset_r$	Remenance Flux (Wb)
B	Magnetic Flux Density (T)
B_g	Airgap Flux Density (T)
H	Magnetic Field Intensity (A/m)
H_c	Coercive Field Strength (A/m)
H_{ci}	Intrinsic Coercivity (A/m)
μ	Relative Permeability of the Material
μ_0	Absolute Permeability
μ_m	Relative Permeability of the Magnet
μ_r	Magnet Recoil Permeability
V_{ls}	Stator Terminal/Line Voltage (V)
V_{lr}	Rotor Terminal/Line Voltage (V)
V_{phs}	Stator Phase Voltage (V)

V_{phr} Rotor Phase Voltage (V)

V_{gs} Stator Generated No-Load Voltage (V)

V_{gr} Rotor Generated No-Load Voltage (V)

V_{dc} DC Link Voltage (V)

I_{ls} Stator Line Current (A)

I_{lr} Rotor Line Current (A)

I_{phs} Stator Phase Current (A)

I_{phr} Rotor Phase Current (A)

P_o Rated Output Power (W)

P_{max} Maximum Output Power (W)

P_i Input Power (W)

N_s/N_r Stator to Rotor Turns Ratio for Doubly Fed Induction Generator

N_s Number of Stator Slots

N_r Number of Rotor Slots

D_{os} Stator Outer Diameter (m)

D_{is} Stator Bore Diameter (m)

L_{stack} Stack Length (Axial Length of the Machine) (m)

L_i Effective Iron Length (m)

l_g Length of the Airgap (m)

D_{or} Rotor Outer Diameter (m)

D_{rm} Rotor Magnet Inner Diameter (m)

D_{sh} Shaft Diameter (m)

τ_{ps} Stator Pole Pitch (m)

τ_s Stator Slot Pitch (m)

τ_r Rotor Slot Pitch (m)

τ_{pr} Rotor Pole Pitch (m)

α_m Magnet Pole Arc (rad or deg)

k_c Carter's Coefficient

k_{ws} Stator Winding Factor

k_{wr} Rotor Winding Factor

k_s Stator Slot Fill Factor

k_r Rotor Slot Fill Factor

K_e Back EMF Constant

K_t Torque Constant

B_{cs}	Stator Back Iron Flux Density (T)
B_{cr}	Rotor Back Iron Flux Density (T)
B_{ts}	Stator Tooth Flux Density (T)
B_{tr}	Rotor Tooth Flux Density (T)
t_{ws}	Stator Tooth Width (m)
t_{wr}	Rotor Tooth Width (m)
b_{0s}	Stator Slot Opening (m)
b_{1s}	Stator Slot Lower Width (m)
b_{2s}	Stator Slot Top Width (m)
H_{0s}	Stator Tooth Shoe Height (m)
H_{1s}	Stator Tooth Wedge Height (m)
H_s	Total Stator Slot Height (m)
h_s	Stator Slot Height (m)
h_{rs}	Stator Back Iron (m)
b_{0r}	Rotor Slot Opening (m)
b_{1r}	Rotor Slot Lower Width (m)
b_{2r}	Rotor Slot Top Width (m)

H_{0r}	Rotor Tooth Shoe Height (m)
H_{1r}	Rotor Tooth Wedge Height (m)
H_r	Total Rotor Slot Height (m)
h_r	Rotor Slot Height (m)
h_{rr}	Rotor Back Iron (m)
α_{ss}	Stator Slot Fraction at the Surface
α_{bs}	Stator Slot Fraction at the Slot Back End
α_{sr}	Rotor Slot Fraction at the Surface
α_{br}	Rotor Slot Fraction at the Slot Back End
α_{ts}	Stator Tooth Shoe Height to Stator Slot Wedge Height Ratio
α_{tr}	Rotor Tooth Shoe Height to Stator Slot Wedge Height Ratio
A_{ss}	Stator Slot Area (m^2)
A_{sr}	Rotor Slot Area (m^2)
P	Number of Poles
p	Number of Pole Pairs
a	Number of Parallel Paths
n_{phs}	Number of Conductors per Phase of Stator Winding

n_s	Number of Conductors per Slot of Stator Winding
n_{ss}	Number of Strands in Stator Winding
n_{phr}	Number of Conductors per Phase of Rotor Winding
n_r	Number of Conductors per Slot of Rotor Winding
n_{rs}	Number of Strands in Rotor Winding
q_s	Slots per Pole per Phase for Stator
q_r	Slots per Pole per Phase for Rotor
D_{cs}	Diameter of Stator Conductor (m)
D_{cr}	Diameter of Rotor Conductor (m)
R_L	External Load Resistance (Ω)
R_{ph}	Phase Resistance (Ω)
L_{ph}	Phase Inductance (H)
η	Efficiency of the Machine (Motor/Generator)
N	Speed (RPM)
ω	Angular Speed (rad/s)
f	Frequency (Hz)
ψ	Magnetic Flux Linkage (Wb)

ψ_{pm}	Magnet Flux Linkage (Wb)
ψ_s	Stator Flux Linkage (Wb)
ac	Specific Electric Loading (AT)
J_s	Stator Current Density (A/mm^2)
J_r	Rotor Current Density (A/mm^2)
J	Rotor Moment of Inertia (kg.m^2)
l_{mc}	Length of the Magnet (m)
N_p	Number of Turns per Pole
N_{ph}	Number of Turns per Phase
N_{sp}	Number of Slots per Phase
R_{phs}	Stator Phase Resistance (Ω)
R_{phr}	Rotor Phase Resistance (Ω)
L_{phs}	Stator Phase Inductance (H)
P_{rs}	Stator Copper Losses (W)
P_{rr}	Rotor Copper Losses (W)
P_{cls}	Stator Iron Losses (W)
P_{cls}	Rotor Iron Losses (W)

P_{fw}	Mechanical Power Losses (Friction and Windage) (W)
P_{ltotal}	Total Power Losses (W)
p_{Fe}	Specific Core Losses (W/kg)
m	Number of Phases
T	Rated Output Torque (Nm)
T_{av}	Average Output Torque (Nm)
T_{max}	Maximum Output Torque (Nm)
W_C	Magnetic Coenergy (Ws)
W_F	Magnetic Field Energy (Ws)
σ	Electrical Conductivity (S/m)
ρ	Density of Material (kg/m^3)
δ	Load Angle (deg)
$cos\varphi$	Power Factor
L_d	Direct Axis Inductance (H)
L_q	Quadrature Axis Inductance (H)
s_{max}	Maximum slip for DFIG
P_{ag}	Generator Airgap Power (W)

P_s	Generator Stator Power (W)
P_m	Mechanical Power delivered by the turbine to the generator (W)
P_r	Generator Rotor Power (delivered to or from) (W)
ω_s	Speed of the stator magnetic field (rad/s)
ω_r	Speed of the rotor magnetic field (rad/s)
ω_m	Mechanical speed of the rotor (rad/s)
s	Operating slip
A	Magnetic Vector Potential
A_x	Magnetic Vector Potential along x-axis
A_y	Magnetic Vector Potential along y-axis
A_z	Magnetic Vector Potential along z-axis
θ_e	Electrical Angular Position (rad or deg)
θ	Mechanical Angular Position (rad or deg)
ψ	Flux linkage with the winding (Wb)
B_{rd}	Radial component of the flux density (normal to the ling l_g) (T)
$B_{\theta e}$	Azimuthal component of the flux density (tangential to the line l_g) (T)
B_r	Magnetic Remenance (Maximum Flux Density of the Magnet) (T)

B_m	Operating Magnet Flux Density (T)
H_c	Coercive Force (Maximum Coercive Force of the Magnet) (A/m)
H_{ci}	Intrinsic Magnetic Coercivity (A/m)
H_m	Operating Magnet Coercive Force (A/m)
BH_{max}	Maximum BH Product (MGOe)
n_{seg}	Number of segments used for adaptive ranging GA based design optimization process
B_{maxr}	Allowable maximum flux density in the rotor back iron (T)
B_{tmaxr}	Allowable maximum flux density in the rotor teeth (T)
k_{st} / k_{stack}	Stacking factor
α_{cp}	Stator coil span angle (rad or deg)
α_{cpr}	Rotor coil span angle (rad or deg)
$cos\varphi_s$	Stator rated power factor
$cos\varphi_r$	Rotor rated power factor
L2L	Line to line voltage (V) (used in graphs of generated voltage)
k_{ml}	Magnet internal leakage
P_C	Permeance coefficient

LIST OF ABBREVIATIONS

kW	Kilo watt
MW	Mega watt
PV	Photovoltaic
AWEA	American Wind Energy Association
IG	Induction Generator
SG	Synchronous Generator
SEIG	Self-Excited Induction Generator
SCIG	Squirrel-Cage Induction Generator
DFIG	Doubly-Fed Induction Generator
PMG	Permanent Magnet Generator
RG	Reluctance Generator
PM	Permanent Magnet
AlNiCo	Aluminum Nickel Cobalt
Sm-Co	Samarium Cobalt Alloy
Nd-Fe-B	Neodymium Iron Boron Alloy

PMBM	Permanent Magnet Brushless Machine
PM BLDC	Permanent Magnet Brushless DC Machine
PMSM	Permanent Magnet Synchronous Machine
PM BLAC	Permanent Magnet Brushless AC Machine
VVVF	Variable Voltage Variable Frequency
CVCF	Constant Voltage Constant Frequency
VSC	Voltage Source Converter
RSC	Rotor Side Converter
GSC	Grid Side Converter
EMF	Electro Motive Force
MMF	Magneto Motive Force
THD	Total Harmonic Distortion
EPFM	Exterior Penalty Function Method
ALMM	Augmented Lagrangian Multiplier Method
IALMM	Improved Algorithm Augmented Lagrangian Multiplier Method
NFMZ	Not Full Magnetized Zones
3D	Three Dimensional

2D	Two Dimensional
1D	One Dimensional
LEF	Leading Edge Fault
TEF	Trailing Edge Fault
MF	Motoring Fault
GF	Generating Fault
LD	Local Demagnetization
AD	Asymmetric Demagnetization
SD	Symmetric Demagnetization
MCM	Magnetic Circuit Model
FEM	Finite Element Method
FE	Finite Element
FEA	Finite Element Analysis
BEM	Boundary Element Method
FDM	Finite Difference Method
MM	Moments Method
NRM	Newton-Raphson Method

RE	Renewable Energy
CAD	Computer Aided Design
kW	Kilo Watt
VAR	Volt Ampere Reactive Power
THD	Total Harmonic Distortion
UPF	Unity Power Factor
PF	Power Factor