

Development of a line-start permanent-magnet synchronous machine

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26-03-1923 to 26-10-2010

“Een Integer Man”

Summary

Electrical machines form part of our everyday life at home and in industry plants. Currently induction machines are the backbone of the industry machine installation as these are robust, reliable and have relatively high efficiency. However as the price of energy increases and stricter efficiency regulations are put into place there is a need for more efficient electrical machines.

The majority of induction machines on Sasol's plants are between 2.2 kW and 22 kW. Of these, 95% machines are connected to pump loads and 2% to fan loads. Thus the majority of the machines operate at a constant speed. Rather than try to improve an induction machine, this project proposes the design for a more efficient LS PMSM that can also be used in the same applications as mentioned above. Although LS PMSMs aren't a new concept, the demand and industry interest in this technology has increased in recent years. Since 2000 the number of research publications with regards to this machine has increased significantly.

The goal of this project is to gain a better understanding of these machines by designing a prototype. The design entitles the stator and rotor. As Sasol provided the funding for the project it was decided to design a three phase, 7.5 kW 525V, four-pole machine. During the design phase several design techniques done by other researchers were incorporated into the prototypes. The design is done with the aid of two FEM software packages namely FEMM and ANSYS Maxwell[®] and verified against calculated values.

The final prototype is tested and compared to the predicted values determined during the design. An industry available LS PMSM from Weg, the WQuattro is also used to compare the results of the prototype. The prototype machine's no-load, full load and locked rotor behaviour is tested as well as the back-emf waveform. From the results gained the machine is validated. The machine did not perform as predicted and further investigation into the reason is needed.

Due to the incorrect wiring of the stator and some other rotor manufacturing issues the prototype cannot be fully validated. However it was found that several of the designed values correlated to the measured values. Further investigation into the under performances as well as more relevant testing and practical manufacturing method is needed.

Keywords: Electrical Machine, Machine Design, LS PMSM, PMSM, FEM, Induction Machine,

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“Our deepest fear is not that we are inadequate. Our deepest fear is that we are powerful beyond measure. It is our light, not our darkness that most frightens us. We ask ourselves, Who am I to be brilliant, gorgeous, talented, fabulous? Actually, who are you *not* to be? You are a child of God. Your playing small does not serve the world. There is nothing enlightened about shrinking so that other people won't feel insecure around you. We are all meant to shine, as children do. We were born to make manifest the glory of God that is within us. It's not just in some of us; it's in everyone. And as we let our own light shine, we unconsciously give other people permission to do the same. As we are liberated from our own fear, our presence automatically liberates others.” – by Marianne Williamson

Declaration

I, *Albert Johan Sorgdrager*, declare that the dissertation is a presentation of my own original work, conducted under the supervision of Dr A.J Grobler.

Whenever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature.

No part of this work has been submitted in the past, or is being submitted, for a degree or examination at any other university or course.

Signed on this 26 day of August 2013, in Stellenbosch.

AJ Sorgdrager

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List of Publications

AJ Sorgdrager and AJ Grobler, "Influence of Magnet Size and Rotor Topology on the Air-gap Flux Density of a Radial Flux PMSM," in IEEE International Conference on Industrial Technology, Cape Town, 2013, 337-343.

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List of Symbols

A	Linear current density	A/m
B	Magnetic flux density	T
b_t	Slot tooth width	m
B_δ	Air gap magnetic flux density	T
D	Electric flux density	C/m ²
D_r	Outer diameter: rotor	m
D_{ri}	Inner diameter: rotor	
D_{si}	Inner diameter: stator	m
D_{so}	Outer diameter: stator	m
D_δ	Air gap diameter	m
E	Electric field strength	V/m
E_0	Back-emf	V
E_m	Main electromotive force	V
F	Force	N.m
f	Frequency	Hz
F_{tan}	Tangential force	N.m
H	Magnetic field strength	A/m
H_{tan}	Tangential magnetic field strength	A/m
h_t	Slot tooth height	m
I	Current	A
J	Current density	A/m ²
k	Current loading	A/m
k_d	Distribution factor	
k_p	Pitch factor	
k_{sq}	Skewing factor	
k_w	Winding factor	
l	Stator stack length	m
L	Inductance	H
m	Number of phases	
N	Number of turns per coil	
η	Efficiency	
P	Power	W
p	Number of pole pairs	
P	Number of poles	
q	Number of Slots per pole phases	
Q_r	Number of rotor slots	
Q_s	Number of stator slots	
r	Radius	m
R_{iron}	Core resistance	Ω
R_r or R_2	Rotor resistance	Ω
R_s or R_1	Stator resistance	Ω



s	Slip	
S	Area	m^2
S_r	Rotor outside area	m^2
S_{sc}	Stator slot conductors area	m^2
S_{ss}	Stator slot area	m^2
S_δ	Air gap cross-section	m^2
T_{asy}	Asynchronous torque developed	N.m
T_c	Torque developed by the rotor cage	N.m
T_d	Torque developed	N.m
T_m	Magnetic braking torque	N.m
T_{rated}	Rated torque	N.m
T_{start}	Starting torque	N.m
V	Voltage	V
V	Volume	m^3
v	Ordinal of harmonic	
X_{rl}	Rotor leakage reactance	Ω
X_{sl}	Stator leakage reactance	Ω
α_{ap}	Pole arch coefficient	
α_{md}	Magnetic depth coefficient	
α_{mt}	Magnetic thickness coefficient	
δ	Air gap length	m
λ	Flux linkage	Wb/turns
λ_{sq}	Skewing leakage factor	
λ_u	Slot leakage factor	
λ_w	End winding leakage factor	
λ_{zz}	Zig-zag leakage factor	
ξ_{se}	Skin effect	
ρ	Resistivity	$\Omega.m$
σ	Air gap shear stresses	N/m^2
σ	Conductivity	S/m
τ_p	pole pitch	m
τ_s	Pole arch width	m
τ_u	Slot pitch	m
τ_v	Phase zone distribution	m
φ	Flux	Wb
χ	Active length to diameter ratio	
ω	Angular velocity/speed	rad/s
ω_e	Angular velocity: electrical	rad/s
ω_r	Angular speed: mechanical rotor	rad/s
ω_s	Angular speed: mechanical stator field	rad/s



Subscripts

Al	Aluminium
bd	Break down
Cu	Copper
d	Direct axis
lam	Lamination
pm	Permanent magnet
q	Quadrature axis
r	Rotor
s	Stator
si	Stator inner
so	Stator outer
ss	Stator slot
tan	Tangential
δ	Air gap

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List of Abbreviations

ac	alternating current
CAD	Computer Aided Design
dc	direct current
DOL	Direct-On-Line
FEM	Finite Element Method
ICFM	Imbedded Circumferential Flux Magnets
ICT	Imbedded Combination Topology
IE1	Standard Efficiency
IE2	High Efficiency
IE3	Premium Efficiency
IE4	Super Premium Efficiency
IEC	International Electrotechnical Committee
IM	Induction Motor
IRFM	Imbedded Radial Flux Magnets
LS PMSM	Line Start Permanent Magnet Synchronous Machine/Motor
LV	Low Voltage
LW	Low Wattage
PM	Permanent Magnets
PMSM	Permanent Magnet Synchronous Machine/Motor
SMM	Surface Mount Magnets
SSMM	Slotted Surface Mount Magnets
SWG	Standard Wire Gauge
VPI	Vacuum Pressure Impregnate