

Nonlinear Deadbeat-Direct Torque and Flux Control for Highly Saturated Synchronous Reluctance Machines in Automotive Traction Applications

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In Gedenken an Leo.

Abstract

This research extends prior research by presenting nonlinear deadbeat-direct torque and flux control (DB-DTFC) for highly saturated synchronous reluctance machines. Main objective is the improvement of the controls performance for automotive traction applications.

Flux linkage including harmonics is observed with a Gopinath observer and precisely closed-loop controlled with high bandwidth by applying DB-DTFC. Nonlinear DB-DTFC is developed by incorporating saturation and cross-saturation directly into the differential torque equation. Flux linkage-based loss models for machine and inverter are evaluated experimentally. Loss model-based flux magnitude is calculated in real-time and overall drive losses of SynRMs are minimized each single switching period. The excellent flux weakening capabilities of SynRMs combined with the direct control of flux applying DB-DTFC lead to a measured efficiency improvement of 1.4% under the highway driving cycle HWFET.

Increased disturbance rejection, as compared to current vector control (CVC), is achieved via simulation and experiment. Minimization of harmonics in current and a reduction of total loss are measured on a 5.5kW synchronous reluctance machine (SynRM) testbench. Moreover, real-time flux observer-based torque ripple estimation is presented. When flux estimation is accurate, instantaneous torque is fed back and unwanted pulsating torque is inherently minimized. FEM-simulations validate the torque ripple minimization.

Kurzfassung

Die direkte Regelung von Drehmoment und magnetischem Fluss zusammen mit einer Deadbeat-Regelung (DB-DTFC - Deadbeat-Direct Torque and Flux Control) hat sich in den letzten Jahren für Asynchron- und permanenterregte Synchronmaschinen als anerkannte Alternative zur weitverbreiteten Stromvektorregelung durchgesetzt. Viele Vorteile wie beispielsweise das verlustoptimale Regeln des magnetischen Flusses und die optimale Regelung an der Umrichterspannungsgrenze im Feldschwächbereich machen DB-DTFC prädestiniert für automobiler Traktionsanwendungen. In dieser Arbeit wird der Stand der Technik von DB-DTFC um hoch nichtlineare, anisotrope Synchronmaschinen erweitert. Besonderes Augenmerk liegt hierbei auf hochausgenutzten Synchronreluktanzmaschinen für automobiler Traktionsanwendungen.

Zunächst wird ein optimiertes Verfahren vorgestellt, welches mit Hilfe eines Zustandsstromreglers ermöglicht, die durch Sättigungs- und Kreuzsättigungseffekte beeinträchtigten nichtlinearen Induktivitäten messtechnisch mit reduziertem Zeitaufwand zu ermitteln. Danach werden die Möglichkeiten zur Verlustminimierung von Maschine und Umrichter untersucht. Im letzten Teil werden Oberschwingungen in Strom und Fluss und deren Einfluss auf Drehmomentwelligkeit und Effizienz untersucht. Hierbei werden Stromvektorregelung und DB-DTFC hinsichtlich optimalem Störverhalten direkt miteinander verglichen und bewertet.

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Nomenclature

Symbol	Description
θ, Θ	angular position
ω, Ω	angular velocity
ϕ	angular phase
θ_e, Θ_e	kinematic position error
ω_{re}	rotor electrical velocity
ω_{rm}	rotor mechanical velocity
T_s	sample period
T, T_{em}	electro-mechanical torque
T_d	disturbance torque
P_m	motor power
P_L	load power
\underline{u}_{dq}	stator voltage complex space vector ($u_d + ju_q$)
\underline{i}_{dq}	stator current complex space vector ($i_d + ji_q$)
p	machine pole pair number
J_m, J_L	motor, load inertia
R_s	stator resistance
L_d, L_q	d- and q-axis stator apparent inductance
l_d, l_q	d- and q-axis stator differential inductance
M_{dq}, m_{dq}	mutual apparent/differential inductance
ψ_{pm}	permanent magnet flux linkage
$\text{Im}\{ \}$	imaginary part of complex quantity
$\text{Re}\{ \}$	real part of complex quantity

Superscripts

$()^{\cdot}$	time derivative operator d/dt ()
$()^s$	stationary reference frame
$()^r$	rotor reference frame
$()^e$	excitation/synchronous reference frame

Subscripts

$()_s$	stator
$()_r$	rotor
$()_{dq}$	complex vector of the form $()_d + j()_q$

Abbreviations

EV	eigenvalue
FEA, FEM	finite element analysis/method
SynRM	synchronous reluctance machine
IPMSM	interior permanent magnet synchronous machine
IM	induction machine
FOC	field oriented control
DTC	direct torque control
DB-DTFC	deadbeat direct torque and flux control
FSS	finite settling step
CVC	current vector control
MTPA	maximum torque per ampere
MTPV	maximum torque per voltage
MTPL	maximum torque per losses
MTPL _D	maximum torque per losses of the drive (machine+inverter)
VSI	voltage source inverter
LUT	look-up table
HFI	high frequency injection
BEV	battery electric vehicle
MUT	machine under test
OSE	ordinary Steinmetz equation
DID	disturbance input decoupling
SVM	space vector modulation