ENHANCED CONTROL ALGORITHMS IN PERMANENT MAGNET SYNCHRONOUS MACHINES

by

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A DISSERTATION

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Doctor of Philosophy

Major: Electrical Engineering

Under the Supervision of Professors Yi Qian and Sohrab Asgarpoor

Lincoln, Nebraska

August 2020

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University of Nebraska, 2020

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Permanent magnet synchronous machines (PMSMs) are gaining increasing popularity in various applications due to their advantages, such as high efficiency, high power density, and superior control performance. A well-designed machine control algorithm is indispensable for a PMSM system to secure its good performance.

In this work, enhanced control algorithms in PMSMs are developed. Online machine current trajectory tracking, source power management, hardware overcurrent regulation, and machine current sensor fault detection and isolation (FDI) are included in the developed algorithms. The online machine current trajectory tracking ensures the maximum torque per ampere (MTPA) or maximum torque per voltage (MTPV) control in a PMSM to maximize system efficiency or torque. The source power management regulates the power flow between a power source and a PMSM to enhance the reliability of power source and PMSM subsystems. The hardware overcurrent regulation limits the maximum machine current in a PMSM to reduce overcurrent risk in power inverter and electric machine. The sensor FDI checks various machine current sensor fault scenarios in a PMSM including single and multiple machine current sensor faults under the disturbance of non-sensor fault(s) to avoid unexpected system shutdown caused by machine current sensor fault(s).

The developed enhanced control algorithms in PMSMs have the advantages of providing online machine current MTPA/MTPV trajectory tracking without offline calibration, providing enhanced hardware protection for power source, inverter and electric machine, and mitigating the impact of machine current sensor fault(s) considering non-sensor fault(s) disturbance.

ACKNOWLEDGMENT

I would like to thank Dr. Yi Qian and Dr. Sohrab Asgarpoor for their support on my PhD study. I was fortunate to have met them during my journey to pursue an advanced degree in Nebraska.

I would also like to thank Dr. Hamid Sharif and Dr. Benjamin Terry for their valuable comments on my PhD research. Their support has been an indispensable resource for the successful completion of this work.

I am grateful to many of the faculty, staff and friends I have met, who helped build up a wonderful life experience in the past days. Special gratitude goes towards: Dr. Jerry Hudgins, Dr. Shu Liu, Dr. Ning Zhu, Prerit Pramod, Zhitong Guo, Claremont Park Old Boys, and California Book-Writing Club.

Lastly, I would like to thank my parents, Zhengyin Shao and Deyan Li, for their love, which encourages me to always seek what I truly love in my life.

Haibo Li

San Jose, CA

03/31/2020

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List of Acronyms

ADAS	advanced driver-assistance system
COKF	combined observer and Kalman filter
EB	estimation-based
FDI	fault detection and isolation
FFT	fast Fourier transform
FOC	field-oriented control
FTC	fault tolerant control
GFM	general fault model
GKSVM	Gaussian kernel support vector machine
IM	induction machine
LCC	life cycle cost
LUT	look-up table
MTPA	maximum torque per ampere
MTPV	maximum torque per voltage
NN	neural network
O&M	operation and maintenance
PMSM	permanent magnet synchronous machine
PWM	pulse width modulation
SOC	state of charge
SRM	switched reluctance motor
SVPWM	space vector pulse width modulation

UAV	unmanned aerial vehicle
UDC	up-down counter
E_{off}	one turn-off loss under I_N and V_N condition
E_{on}	one turn-on loss under I_N and V_N condition
F_D	false detection rate
f_e	machine stator frequency
i_b	measured DC link battery current (source current)
$\hat{i}_b$	estimated DC link battery current
$I_{b,max}$	maximum source current
$I_{b,max1}$	maximum source supply current
$I_{b,max2}$	maximum source regenerative charging current
i_d	*d*-axis current
i_D	current going through device
i_d^*	*d*-axis current command
$i_{d,final}^*$	final *d*-axis current command
$i_{d,MTPA}^*$	MTPA *d*-axis current command
$i_{d,MTPV}^*$	MTPV *d*-axis current command
$i_{d,RII}^*$	region II *d*-axis current command
I_f	synchronous machine field current
i_m	machine phase current amplitude
$\boldsymbol{i_m}$	machine current vector

i_{ma}	phase A machine current
$\hat{i}_{ma,b}$	estimated phase A current from phase B measurement
$\hat{i}_{ma,c}$	estimated phase A current from phase C measurement
i_{mb}	phase B machine current
$\hat{i}_{mb,a}$	estimated phase B current from phase A measurement
$\hat{i}_{mb,c}$	estimated phase B current from phase C measurement
i_{mc}	phase C machine current
$\hat{i}_{mc,a}$	estimated phase C current from phase A measurement
$\hat{i}_{mc,b}$	estimated phase C current from phase B measurement
$I_{m,max}$	maximum machine current
$i_{m,min}$	minimum machine current
I_N	device current rating
i_q	q-axis current
i_q^*	q-axis current command
$i_{q,final}^*$	final q-axis current command
$i_{q,max}$	maximum q-axis current
$i_{q,MTPA}^*$	MTPA q-axis current command
$i_{q,MTPV}^*$	MTPV q-axis current command
$i_{q,RII}^*$	region II q-axis current command
J	moment of inertia of rotor
k	torque factor
K_e	back EMF constant

L_d	stator *d*-axis self-inductance
L_{dm}	stator *d*-axis magnetizing inductance
L_{ls}	stator leakage inductance
L_q	stator *q*-axis self-inductance
L_{qm}	stator *q*-axis magnetizing inductance
M_D	missed detection rate
n	iteration number
N	number of semiconductor devices in inverter
P	number of pole pairs in PMSM
p_{con}	conduction loss of one semiconductor device
p_e	PMSM input electrical power
p_{in}	DC link power
$p_{inv,loss}$	inverter power loss
p_m	output mechanical power
$p_{m,loss}$	machine losses
p_{sw}	switching loss of one semiconductor device
$r_{a,b}$	phase A current residual between i_{ma} and $\hat{i}_{ma,b}$
$r_{a,c}$	phase A current residual between i_{ma} and $\hat{i}_{ma,c}$
$r_{b,a}$	phase B current residual between i_{mb} and $\hat{i}_{mb,a}$
$r_{b,c}$	phase B current residual between i_{mb} and $\hat{i}_{mb,c}$
$r_{c,a}$	phase C current residual between i_{mc} and $\hat{i}_{mc,a}$

$r_{c,b}$	phase C current residual between i_{mc} and $\hat{i}_{mc,b}$
r_{ib}	DC link battery current residual
$r_{ib,a}$	DC link battery current residual from i_{ma}, $\hat{i}_{mb,a}$, and $\hat{i}_{mc,a}$
$r_{ib,b}$	DC link battery current residual from i_{mb}, $\hat{i}_{ma,b}$, and $\hat{i}_{mc,b}$
$r_{ib,c}$	DC link battery current residual from i_{mc}, $\hat{i}_{ma,c}$, and $\hat{i}_{mb,c}$
r_{ib,a,b,c_a}	DC link battery current residual from i_{ma}, i_{mb}, and $\hat{i}_{mc,a}$
r_{ib,a,b,c_b}	DC link battery current residual from i_{ma}, i_{mb}, and $\hat{i}_{mc,b}$
$r_{ib,a,b\_a,c}$	DC link battery current residual from i_{ma}, $\hat{i}_{mb,a}$, and i_{mc}
$r_{ib,a,b\_c,c}$	DC link battery current residual from i_{ma}, $\hat{i}_{mb,c}$, and i_{mc}
$r_{ib,a\_b,b,c}$	DC link battery current residual from $\hat{i}_{ma,b}$, i_{mb}, and i_{mc}
$r_{ib,a\_c,b,c}$	DC link battery current residual from $\hat{i}_{ma,c}$, i_{mb}, and i_{mc}
R_m	machine stator resistance
R_{on}	device on-state resistance
t	time
$T_{b,max}$	maximum allowable torque under $I_{b,max}$ constraint
T_d	fault detection time
T_e	electromagnetic torque
T_e^*	torque command
$T_{e,final}^*$	final torque command
$T_{e,max}$	maximum torque
T_m	mechanical torque from machine shaft

$T_{m,max}$	maximum allowable torque under $I_{m,max}$ constraint
T_s	switching period
v_d	*d*-axis voltage
V_{DC}	DC link voltage
v_m	machine phase voltage amplitude
$\boldsymbol{v_m}$	machine voltage vector
$v_{m,ll}$	machine line-to-line voltage amplitude
$v_{m,llmax}$	maximum machine line-to-line voltage amplitude
$v_{m,max}$	maximum machine phase voltage amplitude
V_N	device voltage rating
v_q	*q*-axis voltage
V_T	device threshold voltage
x_a	phase A signal in *abc* frame
x_b	phase B signal in *abc* frame
x_c	phase C signal in *abc* frame
x_d	*d*-axis signal in *dq* rotating frame
x_q	*q*-axis signal in *dq* rotating frame
α	angle between machine current vector $\boldsymbol{i_m}$ and *d*-axis
δ_{ib}	DC link battery current residual threshold
δ_{im}	phase current residual threshold
δ_v	angle between machine voltage vector $\boldsymbol{v_m}$ and *d*-axis

ΔL_d	machine stator *d*-axis self-inductance variation
ΔL_q	machine stator *q*-axis self-inductance variation
ΔR_m	machine stator resistance variation
$\Delta \lambda_m$	permanent magnet flux linkage variation
ΔT	torque updating step
θ_o	initial rotor position of an electric machine
θ_r	rotor position angle of an electric machine
λ_{ds}	*d*–axis stator flux linkage
λ_m	permanent magnet flux linkage
λ_{qs}	*q*–axis stator flux linkage
ω_e	PMSM electrical angular speed
ω_m	PMSM mechanical angular speed

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