Sensorless Control of Permanent Magnet Brushless DC Motors

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Sensorless Control of Permanent Magnet Brushless DC Motors

by

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submitted

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CERTIFICATE

This is to certify that the thesis entitled, **"Sensorless Control of Permanent Magnet Brushless DC Motors"** being submitted by **Mr. SATISHBABU BHOGINENI** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him under my guidance and supervision in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Satishbabu Bhogineni has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained here in have not been submitted to any other University or Institute for the award of any degree.

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ABSTRACT

Permanent magnet brushless DC (BLDC) motor drives are increasingly used in a variety of applications starting with the most critical ones in aerospace to high quality toys. As on today, almost all two-wheeler and three-wheeler electric vehicles are driven by these motors. Apart from its wide acceptance in industry and also for agricultural pumps, energy efficient domestic appliances such as refrigerators, air conditioners, washing machines and ceiling fans are being increasingly driven by these BLDC motors.

These motors are equipped with hall sensors for the rotor position feedback which is essential in switching currents to the appropriate stator windings in synchronism with the obtained rotor position. Typically, in a three-phase BLDC motor, apart from the three main power cables, five extra wires are needed for the rotor position sensors, two for supplying power to these sensor units and the remaining three for the position signals. These sensor units will occupy some space anyway and are also sensitive to temperature variations. Use of hall sensors reduces the reliability and at the same time increases the cost. Coupled to this with the problems associated with the assembly and accuracy, it's always advantageous to have a position sensor free system for driving this BLDC motor.

The back EMF based sensorless control is widely used in BLDC motors nowadays owing to its easy implementation and cost effectiveness. In this method, the zero crossing point (ZCP) of the back EMF is estimated by detecting the ZCPs of

either the phase or the line voltages given to the motor. Among these two voltage detection based methods, the line voltage ZCP based sensorless control method uses simple circuits compared to the phase voltage ZCP based method. Moreover, the line voltage ZCPs can be obtained directly from motor terminals. The investigations carried out in this work on the line voltage ZCP method had brought out more information on the errors associated with this method and remedial solutions are successfully implemented. The available current in sensorless control can be advantageously used to improve the line voltage ZCP based sensorless control method. By using current in addition to terminal voltages, a novel line back EMF based sensorless control technique is proposed in this work which improved the performance of the drive. This has been done without using any costly processors and hence is very economical which is one of the prime concerns addressed in this work so as to make these sensorless schemes viable for low cost and medium performance applications like majority of the domestic appliances and automotive components. Hardware implementation of this proposed scheme is done and the test results are in agreement with designed and simulated ones. Further studies are carried out to improve these techniques and some improvements are also suggested to eliminate the delay caused by the filter used for voltage sensing.

In a three phase BLDC motor, six power devices are usually used in an inverter configuration. So as to decrease the cost of the drive, reduced parts converters are being used with induction and permanent magnet synchronous motors. These are also used in BLDC motors, but with a penalty of having an additional current sensor. The use of four switches three phase inverter (FSTPI) with BLDC motor necessitates extra high side current sensing. Addition of extra sensor nullifies the benefit of having reduced number of switches. In this work, by appropriate logic, the requirement of this additional current sensor is eliminated thus bringing back the cost advantage of the reduced number of switches and that too on the sensorless control mode.

To eliminate high side current sensing, a current reconstruction method is proposed with a simple low side resistive current sensing which reduces the cost of the drive. By using the reconstructed current, two direct current control techniques are proposed. The first one is the constant ON/OFF control, where the current is sensed during lower switch conduction period by fixing the upper switch conduction time. The second method is the fixed frequency sensing control. Here, a current sensing state is inserted at fixed intervals in to the operation of motor. The same logic is extended to PWM control and proposed a modified symmetric PWM for inserting the sensing states in to the operation. The hardware implementation of the single resistive current sensing with modified symmetric PWM is carried out and the test results are again in agreement with the designed and simulated ones which definitely is a step ahead in having economic sensorless control of BLDC motors.

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Abbreviations

AC	**A**lternating **C**urrent
ACP	**A**ctual **C**ommutation **P**oint
ADC	**A**nalog to **D**igital **C**onverter
ALV	**A**verage **L**ine **V**oltage
AlNiCo	**Al**luminium **Ni**clel **Co**balt
ANN	**A**rtificial **N**eural **N**etworks
ASIC	**A**pplication **S**pecific **I**ntegrated **C**ircuit
BLDC	**B**rush**L**ess **DC**
BLDCM	**B**rush**L**ess **DC** **M**otor
DC	**D**irect **C**urrent
DSP	**D**igital **S**ignal **P**rocessor
EMF	**E**lectro **M**otive **F**orce
EMI	**E**lectro **M**agnetic **I**nterference
EV	**E**lectrc **V**ehicle
FSTPI	**F**our **S**witch **T**hree **P**hase **I**nverter
H	**H**all **S**ignal
IC	**I**ntegrated **C**ircuit
ICP	**I**deal **C**ommutation **P**oint
IGBT	**I**nsulated **G**ate **B**ipolar **T**ransistor
IM	**I**nduction **M**otor
IPM	**I**ntellignet **P**ower **M**odule
LPF	**L**ow **P**ass **F**ilter
MMF	**M**agneto **M**otive **F**orce
MOSFET	**M**etal **O**xide **S**emiconductor **F**eild **E**ffect **T**ransistor
NdFeB	**N**eo**d**ymium **Fe**rrous **B**oran
PAM	**P**ulse **A**mplitude **M**odulation
PCB	**P**rinted **C**ircuit **B**oard
PI	**P**roportional **I**ntegral
PID	**P**roportional **I**ntegral **D**erivative
PM	**P**ermanent **M**agnet

PM BLDC	**P**ermanent **M**agnet **B**rush**L**ess **DC**
PMDC	**P**ermanent **M**agnet **DC**
PMSM	**P**ermanent **M**agnet **S**ynchronous **M**otor
PMBL	**P**ermanent **M**agnet **B**rush**L**ess
PSO	**P**article **S**wam **O**ptimisation
PWM	**P**ulse **W**idth **M**odulation
RMS	**R**oot **M**ean **S**quare
RTOS	**R**eal **T**ime **O**perating **S**ystem
RTW	**R**eal **T**ime **W**orkshop
SmCo	**S**a**m**arium **Co**balt
SPM	**S**mart **P**ower **M**odule
SSTPI	**S**ix **S**witch **T**hree **P**hase **I**nverter
SVM	**S**pace **V**ector **M**odulation
TI	**T**exas **I**nstruments
VH	**V**irtual **H**all **S**ignal
VLSI	**V**ery **L**arge **S**cale **I**ntegration
VSI	**V**oltage **S**ource **I**nverter
ZCP	**Z**ero **C**rossing **P**oint

Symbols

D	Duty ratio
K_E	EMF constant
K_T	Torque constant
K_p	Proportional gain
K_i	Integral gain
p	Time derivative operator
T_e	Electromagnetic torque developed
T_L	Applied load torque
X	Any switch state
Z	High impedance state/ leg both switches are off
ω	Angular rotor speed
ω_e	Electrical rotor speed
ω_r	Rotor speed
ω_m	mechnical rotor speed
N	Rotor speed in rpm
T_s	Sampling time
F	Frequency
t	Time
F_s	Switching frequency
$d-axis$	Direct axis
$q-axis$	Quadrature axis
V_d	$d-$ axis voltage
V_d	$q-$ axis voltage
I_d	$d-$ axis current
I_q	$q-$ axis current
τ_x	Time constant
P_{ag}	Air gap power
P_{ave}	Average power
P_{cap}	Power capability

P_{loss}	Power loss
I_{dc}	DC-link current
S_x	Switch x
e_{max}	Phase back EMF maximum value
$S_x - S_y$	Switch x to y in numerical order
y_x*	Reference value of that variable y_x
I_{dm}	Maximum DC-link current
V_{dc}	DC-link voltage
R_a, R_b, R_c	Phase resistances
L_a, L_b, L_c	Phase inductances
e_a, e_b, e_c	Phase back-EMFs
e_{ab}, e_{bc}, e_{ca}	Line back-EMFs
i_a, i_b, i_c	Phase currents
v_a, v_b, v_c	Terminal voltages of the
	A, B and C phases respectively
v_{an}, v_{bn}, v_{cn}	Terminal voltages of the
	A, B and C with respect to neutral
H_a, H_b, H_c	Hall signals
	corresponding to A, B, C phases
θ	Angular position
ϕ	Difference angle
J	Rotor inertia
B	Friction factor