DESIGN AND DEVELOPMENT OF IMPROVED POWER QUALITY CONVERTERS FED PERMANENT MAGNET BRUSHLESS DC MOTOR DRIVES

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CERTIFICATE

It is certified that the thesis entitled "**Design and Development of Improved Power Quality Converters fed Permanent Magnet Brushless DC Motor Drives**," being submitted by **Mr. Vashist Bist** for award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of the student work carried out by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma.

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ABSTRACT

Energy efficiency and cost reduction in the development of permanent magnet brushless DC (PMBLDC) motors drives have gained importance due their advantageous features over existing motors. High efficiency, high power density, compact size, silent operation, high reliability and low wear and tear of the PMBLDC motor, makes it a suitable choice in many low and medium power applications. Due to these features, PMBLDC motors are widely used in household equipments, industrial tools, heating, ventilation and air conditioning (HVAC), robotics, automation and medical applications.

This research work aims at the development of the power factor correction converters for feeding PMBLDC motor drives as a cost effective solution for low power household appliances. The PMBLDC motor requires a three phase voltage source inverter (VSI) for achieving an electronic commutation based on rotor position as sensed by Hall-Effect position sensors. This PMBLDC motor drive is driven by single phase AC supply via an uncontrolled diode bridge rectifier (DBR) and high value of DC bus capacitor. Such combination draws peaky current from the supply system, which is rich in harmonics and has very high total harmonic distortion (THD) of supply current at AC mains. This leads high crest factor (CF) of the supply current and very low power factor (PF) at AC mains. Such power quality indices are not acceptable within the limit of IEC 61000-3-2. Hence, single phase PFC converters are used to improve the power quality of PMBLDC motor drive at AC mains.

The selection of suitable PFC converter for particular application depends upon various aspects such as total number of components of PFC converter, voltage and power rating of BLDC motor, requirement of galvanic isolation, cost and efficiency of the overall system. There are many available configurations of the PFC converters, which are classified into five different

categories of non-isolated PFC converters, bridgeless non-isolated PFC converters, isolated PFC converters, bridgeless isolated PFC converters and integrated and high quality rectifiers. Among them, the bridgeless configurations are designed for reducing the conduction losses in the front end PFC converter by partial elimination of the diode bridge rectifier. Moreover, the control strategy of the PFC converter also plays in vital role in deciding the performance and cost of the overall system. In this work, PFC converter operating in discontinuous conduction mode (DCM) is used to control the PFC converter via an approach of voltage follower; which requires a single voltage sensor for PFC and DC link voltage control.

Analysis, design and control of buck-boost PFC converters for improvements in power quality at AC mains of the PMBLDC motor drive is presented in this work. The other major aspect of the work includes simplicity in control, reducing the number of sensors and cost and increasing the overall efficiency of the system. Many new configurations of single phase PFC converters are presented in this work for feeding the PMBLDC motor drive. Moreover, the speed of PMBLDC motor is controlled by adjusting the DC link voltage of the VSI feeding PMBLDC motor. This allows the VSI to operate in fundamental frequency switching for reducing the switching losses in VSI.

Moreover, a new sensorless control scheme of PMBLDC motor is also developed to operate it with variable DC link voltage control method of speed control of PMBLDC motor. A two step starting method of PMBLDC motor drive is also proposed for satisfactory starting of PMBLDC motor at rated loading conditions. The performance of these PFC based PMBLDC motor drives are validated on the models developed in MATLAB/Simulink environment. Moreover, the performance of selected configurations of PFC converters feeding PMBLDC motor drives is also verified experimentally on a developed hardware prototype. This performance evaluation includes the steady state performances at various speeds and dynamic performance during starting, speed control, loading of PMBLDC motor and supply voltage fluctuations at AC mains. The steady state performance also includes the voltage and current waveforms of various components (semiconductors, magnetic and capacitive) of PFC converters for selection criteria of these components. An acceptable power quality indices of these PFC converters fed PMBLDC motor drives are also evaluated at AC mains. These power quality indices are found within the acceptable limits of international power quality standard IEC 61000-3-2.

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LIST OF ABBREVIATIONS

AC	Alternating Current
BIBRED	Boost Integrated Buck Rectifier Energy Storage DC-DC Converter
BIFRED	Boost Integrated Flyback Rectifier Energy Storage DC-DC Converter
BL	Bridgeless
BLDC	Brushless DC Motor
CCM	Continuous Conduction Mode
CCVM	Continuous Capacitor Voltage Mode
CF	Crest Factor
CICM	Continuous Inductor Current Mode
CSI	Current Source Inverter
CSC	Canonical Switching Cell
DBR	Diode Bridge Rectifier
DC	Direct Current
DCM	Discontinuous Conduction Mode
DCVM	Discontinuous Capacitor Voltage Mode
DF	Distortion Factor
DICM	Discontinuous Inductor Current Mode
DPF	Displacement Power Factor
DSC	Digital Signal Controller
DSP	Digital Signal Processor / Digital Signal Processing
DTC	Direct Torque Control
EMI	Electro Magnetic Interference
FFS	Fundamental Frequency Switching
HFT	High Frequency Transformer
HVAC	Heating, Ventilation and Air Conditioning
IEC	International Electrotechnical Commission
IHQRR	Integrated High Quality Rectifiers Regulators

IPQC	Improved Power Quality Converters
PF	Power Factor
PFC	Power Factor Correction
PMBL	Permanent Magnet Brushless
PMBLDC	Permanent Magnet Brushless DC
PMSM	Permanent Magnet Synchronous Motor
PQ	Power Quality
PWM	Pulse Width Modulation
SC	Switched Capacitor
SEPIC	Single Ended Primary Inductance Converter
SSIPP	Single Stage, Single Phase Isolated Power Factor Corrected Power Supplies
ST	Sheppard-Taylor
THD	Total Harmonic Distortion
UPF	Unity Power factor
VOPFC	Variable Output Voltage Power Factor Correction
VSI	Voltage Source Inverter

LIST OF SYMBOLS

C_1, C_{11}, C_{12}	Capacitance of Input Side Intermediate Capacitors (F)
C_2, C_{21}, C_{22}	Capacitance of Output Side Intermediate Capacitors (F)
C_{1c}	Critical Capacitance of Input Side Intermediate Capacitors (F)
C_{2c}	Critical Capacitance of Output Side Intermediate Capacitors (F)
C_d	Capacitance DC Link Capacitor (F)
C_f	Capacitance of Filter Capacitor (F)
C_{fmax}	Maximum Capacitance of Filter Capacitor (F)
D	Duty Ratio
D_{max}	Maximum Duty Ratio
D_{min}	Minimum Duty Ratio
f_c	Filter Cut-off frequency (Hz)
f_L	Line frequency (Hz)
f_{sw}	Switching frequency (Hz)
I_{dc}	DC Link Current (A)
i_a, i_b, i_c	Phase currents of BLDC motor (A)
i_a^*, i_b^*, i_c^*	Reference Phase currents of BLDC motor (A)
i_{Li}, i_{Li1}, i_{Li2}	Input Side Inductor Current (A)
i_{Lo}, i_{Lo1}, i_{Lo2}	Output Side Inductor Current (A)
i_{sw}, i_{sw1}, i_{sw2}	PFC converter's Switch Current (A)
I_{s_peak}	Peak Value of Supply Current (A)
J	Moment of Inertia of BLDC Motor (Kg/m^2)
K_a	Torque (Current) Constant of BLDC motor (Nm/A)
K_{pi}	Proportional Gain of Current Controller
K_{ii}	Integral Gain of Current Controller
K_{pv}	Proportional Gain of Voltage Controller
K_{iv}	Integral Gain of Voltage Controller
$K_{p\omega}$	Proportional Gain of Speed Controller

$K_{i\omega}$	Integral Gain of Speed Controller
K_v	Voltage Constant of BLDC motor (V/krpm)
L_f	Filter Inductance (H)
L_i, L_{i1}, L_{i2}	Inductance of Input Side Inductor (H)
L_{ic}	Critical Inductance of Input Side Inductor (H)
L_m, L_{m1}, L_{m2}	Magnetizing Inductance of HFT (H)
L_{mc}	Critical Magnetizing Inductance of HFT (H)
L_{ph}	Per Phase Inductance of BLDC Motor (Ω)
L_o, L_{o1}, L_{o2}	Inductance of Output Side Inductor (H)
L_{oc}	Critical Inductance of Output Side Inductor (H)
L_s	Source Inductance (H)
m_{dv}	Modulating signals for Voltage PWM Generator
$m_{d\omega}$	Modulating signals for Speed PWM Generator
N	Speed of BLDC motor (rpm)
N_1	Number of Primary Turns of High Frequency Transformer
N_2	Number of Secondary Turns of High Frequency Transformer
N_2 / N_1	Transformation ratio of High Frequency Transformer
P_i	Instantaneous Power (W)
P_{max}	Maximum Power (W)
P_{min}	Minimum Power (W)
P_{rated}	Rated Power of BLDC Motor (W)
R_L	Emulated Load Resistance (Ω)
R_{ph}	Per Phase Resistance of BLDC Motor (Ω)
T_e	Electromagnetic Torque of BLDC Motor (Nm)
T_e^*	Maximum Electromagnetic Torque of BLDC Motor (Nm)
T_{rated}	Rated Torque of BLDC Motor (Nm)
V_{cc}	Output of PI Controller (V)
V_{dc}	DC Link Voltage (V)
V_{dc}^*	Reference DC Link Voltage (V)

V_{dcm}	Rated DC Link Voltage of BLDC Motor (V)
V_{dcmax}	Maximum DC Link Voltage (V)
V_{dcmin}	Minimum DC Link Voltage (V)
v_G	Gate voltage
v_{in}	Input Voltage after DBR (V)
V_{in}	Average Value of Input Voltage after DBR (V)
V_m	Peak Value of Input Supply Voltage (V)
v_s	Supply Voltage (V)
V_{smin}	Minimum Supply Voltage (V)
V_{smax}	Maximum Supply Voltage (V)
V_{s_peak}	Peak Value of Supply Voltage (V)
v_{C1}, v_{C11}, v_{C12}	Input Side Intermediate Capacitor's Voltage (V)
v_{C2}, v_{C21}, v_{C22}	Output Side Intermediate Capacitor's Voltage (V)
v_{sw}, v_{sw1}, v_{sw2}	PFC converter's Switch Voltage (V)
ω	Speed of BLDC motor (rad/sec)
ω^*	Reference Speed of BLDC motor (rad/sec)
ω_e	Speed Error of BLDC motor (rad/sec)
ω_L	Line frequency (rad/sec)
ω_{rated}	Rated Speed of BLDC Motor (rad/sec)
Δi_{Li}, Δi_{Li1}, Δi_{Li2}	Ripple Current in Input Side Inductor (A)
Δi_{Lo}, Δi_{Lo1}, Δi_{Lo2}	Ripple Current in Output Side Inductor (A)
Δv_{C1}, Δv_{C11}, Δv_{C12}	Ripple Voltage across Input Side Intermediate Capacitor (V)
Δv_{C2}, Δv_{C21}, Δv_{C22}	Ripple Voltage across Output Side Intermediate Capacitor (V)
η	Percentage of Ripple Current in Input Inductor (%)
λ	Percentage of Ripple Current in Output Inductor (%)
γ	Percentage of Ripple Current in Magnetizing Inductance of HFT (%)
κ	Percentage of Ripple Voltage in Input Side Intermediate Capacitor (%)
ξ	Percentage of Ripple Voltage in Output Side Intermediate Capacitor (%)
δ	Percentage of Ripple Voltage in DC Link Capacitor (%)