EV CHARGERS FOR TWO, THREE, FOUR WHEELERS AND E-BUSES WITH POWER FACTOR CORRECTION

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by

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CERTIFICATE

This is to certify that the thesis entitled **"EV Chargers for Two, Three, Four Wheelers and E-Buses with Power Factor Correction,"** being submitted by **Mr. Rahul Pandey** for the award of the degree of Doctor of Philosophy is a record of a bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Rahul Pandey has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained herein have not been submitted to any other University or Institute for the award of any degree.

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ABSTRACT

For long enough, whole automobile industry has utilized internal combustion engines (ICE) to drive the public and private transport system. Consequently, toxic emissions owing due to exhaustive petroleum and gasoline fuel consumption, have raised serious health concerns and resulted in environmental pollution. According to world health organization (WHO) report, nation wise, India stands fourth in contributing to total percentage of global CO_2 emissions with a figure of 7%. Moreover, amongst the list of top ten most polluted cities of world, nine cities are situated in India. This is largely accounted by the population density, energy requirement, localisation of various industries and emissions from transport. India is dedicated to curtail its greenhouse gas (GHG) emissions by 35% from $2005-2030$. Electric vehicles (EV) are going to dominate the automobile market in near future, which requires that everyone should have easy access to the facility to charge their vehicles. Anticipating an exponential growth in electric vehicles/hybrid electric vehicles (EV/HEV) in near future, the requirement of domestic and bulk charging stations with varying power ratings, is evident. Fluctuating fuel prices, frequent and costly vehicular maintenance and health concerns, have paved way for use of cleaner energy source in form of batteries to propel the automotive drive system. However, capacitive nature of batteries, results in drawing non- sinusoidal and harmonic rich current from utility grid resulting in humongous burden on the distribution transformer and malfunctioning of other connected equipment nearby.

However, international standards for power quality (PQ), such as $IEEE-519$ and $IEC-61000-3-2$ impose stern restrictions on any such solutions, which leads to poor PQ. Thus, a power factor correction stage to comply with this standard becomes absolutely mandatory and requires to be the part of any EV charging solution. Contrary to the growth of type EV's globally, the Indian EV sector observes great opportunity in EV charger solutions for small two wheelers $(2-W)$ and three wheelers $(3-W)$ since almost 80% of total vehicle population is accounted to them. Moreover, the power requirements and system architecture vary widely with different types of vehicles owing to different capacity of EV battery and charging voltages and current. Thus, in light of varying battery ampere hour (Ah) and kilo watt hour (kWh) capacity, the EV battery charger solution is not unique. Moreover, since the single phase AC utility supply switches are rated to a maximum current rating of $16A$, the charging solution for EV batteries in four wheelers $(4-W)$ and public transport require a battery charger power from three phase AC mains supply.

This work presents battery charging solutions for various types of transport starting from $(2-W)$, $(3-W)$, $(4-W)$ and e-buses. The work is segmented in two parts. The first part

aims to maintain good PQ indices at input AC mains by shaping sinusoidal current and regulating the DC link voltage. Thus, this power factor correction (PFC) solution adheres to the international standard of power quality such as $IEC-61000-3-2$. The second part is a DC-DC converter with transformer isolation, which imbibes the constant current (CC) and constant voltage (CV) algorithm for charging the EV battery. The practical converters for EV chargers are categorised according to the type of EV, such as $2-W, 3-W, 4-W$ and e-buses.

For small $2-W$ and $3-W$, the input current shaping can be achieved by operating the PFC inductor in discontinuous inductor conduction mode (DICM) or continuous inductor conduction mode (CICM). The DICM control uses single voltage loop and provides a simple control structure. However, EV's with larger battery capacity requires larger charging current and shorter charging duration, therefore the control of front end PFC is CICM to limit the current stress in the switching devices and reduced electromagnetic interferences. This work investigates both DICM and CICM control for achieving power factor correction at input mains. Moreover, since the modern day EV chargers are intended to facilitate charging of EV batteries with different nominal voltages, the buck-boost PFC converters with PFC feature are proposed and investigated for wide range output voltages. A unique variable DC link algorithm is proposed, which not only provides wide output voltage, but in addition it reduces the switching loss in back end DC-DC inductor-inductor-capacitor (LLC) resonant converter.

Moving forward, EV chargers for $3-W$ and $4-W$ using boost converters and their variations along with LLC resonant converter are proposed. Comprehensive analysis with clear research objective of higher efficiency and small package is carried out in this work. Detailed design and experimental validation of various boost PFC based topologies like bridgeless, semi-bridgeless, interleaved and totem pole boost are presented in this work. Furthermore, three phase EV chargers for $4-W$ are investigated and design is extended for wide output voltage, typically $200V - 1000V$ to cover entire range of e-buses. Lastly, bidirectional capability of proposed fully controlled EV charger is presented to demonstrate EV chargers ability to perform vehicle to home ($V2H$) and vehicle to grid ($V2G$) applications. The presented work aims to provide best in class efficiency, hence back end DC-DC converters with zero voltage switching (ZVS) features such as half bridge-LLC (HB-LLC) converter, full bridge-LLC (FB-LLC) converter and three level phase shifted half bridge converter (3L-PSHBC) along with synchronous rectifiers (SR) are designed, developed, analysed and presented in detail.

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LIST OF ABBREVIATIONS

WHO	World health organization
GHG	Greenhouse gas
ICE	Internal combustion engines
AC	Alternating current
DC	Direct current
2W	Two wheelers
3W	Three wheelers
4W	Four wheelers
Ah	Ampere hour
kW	Kilo-watt
kWh	Kilo-watt-hour
PQ	Power quality
PF	Power factor
CICM	Continuous inductor conduction mode
DICM	Discontinuous inductor conduction mode
PFC	Power factor correction corrected
THD	Total harmonic distortion
SR	Synchronous rectifier
ZVS	Zero voltage switching
PSZVS	Phase shifted zero voltage switching
LLC	Inductor inductor capacitor
SOC	State of charge
G2V	Grid to vehicle
V2H	vehicle to home
V2G	vehicle to grid
HB-LLC	Half bridge LLC
FB-LLC	Full bridge LLC
CNG	Compressed natural gas
EV	Electric vehicles
HEV	Hybrid electric vehicles
LFP	Lithium ion phosphate
NMC	Lithium Nickel manganese zinc
NiMH	Nickel-metal hydride
NCA	Lithium nickel cobalt aluminium

LMO	Lithium manganese-spinel
LTO	Lithium titanate
WIPT	Wireless inductive power transfer
CC	Constant current
CV	Constant voltage
FAME	Faster adaption and manufacturing of electric vehicles
ARAI	Automotive research association of India
IEC	International electrotechnical commission
PHEV	Plug in hybrid electric vehicles
EVSE	EV supply equipment
EMC	Electromagnetic compatibility
PCC	Point of common coupling
CF	Crest factor
SMPS	Switched mode power supply
SCR	Silicon controlled thyristor
MOSFET	Metal oxide field effect transistors
IGBT	Insulated gate bipolar transistors
DSP	Digital signal processors
FPGA	Field-programmable gate array
PWM	Pulse width modulation
PFM	Pulse frequency modulation
ZCS	Zero current switching
LCC	Inductor inductor capacitor
SRC	Sinusoidal ripple current
LC	Inductor capacitor
DBR	Diode bridge rectifier
EMI	Electro-magnetic interference
GAN	Gallium nitride
SiC	Silicon carbide
SEPIC	Single ended primary inductor converter
HB	Half bridge
FB	Full bridge
MRC	Multi-resonant converters
CLL	Capacitor-inductor-inductor
FHA	Fundamental harmonic approximation
CLLC	capacitor-inductor- inductor-capacitor
HBDAB	Half bridge dual active bridge
FBDAB	Full bridge dual active bridge
HBCLLC	Half bridge capacitor-inductor- inductor-capacitor
FBCLLC	Full bridge capacitor-inductor- inductor-capacitor

HBPSZVS	Half bridge phase shifted zero voltage switching
IC	Integrated circuit
VRLA	Valve regulated lead acid
HBDAB	Half bridge dual active bridge
FBDAB	Full bridge dual active bridge
HBDAB	Half bridge dual active bridge
3L-PSHBC	Three level phase shifted half bridge converter
SPS	Sim-power systems
CSC	Canonical switching cell
SOC	State of charge
ESR	Equivalent series resistance
STM	State transition matrix
ISR	Interrupt service routine
VCO	Voltage controlled oscillator
TI	Texas instruments
EVBC	EV battery charger
CLA	Control law accelerator
ZCS	Zero current switching
AH	Ampere-hour
PIV	Peak inverse voltage
RHP	Right half plane
ADC	Analog to digital conversion
PI	Proportional integral
PCB	Printed circuit board
ILB	Interleaved boost
BLB	Bridgeless boost
HEMT	High electron mobility transistors
BLTPBC	Bridgeless totem-pole boost converter
BLTPIBC	Bridgeless totem-pole interleaved boost converter
ACM	Average current mode

LIST OF SYMBOLS

v_s	Input single phase AC mains supply voltage (V)
v_{sa}, v_{sb}, v_{sc}	Input three phase AC mains supply voltage (V)
i_s	Input single phase AC mains supply current (A)
i_{sa}, i_{sb}, i_{sc}	Input three phase AC mains supply current (A)
V_{in}	Rectified AC voltage (V)
V_{dc}	DC link voltage (V)
I_b	Battery charging current (A)
V_o	Output voltage of EV charger (V)
$C_{dc}, C_{dc1}, C_{dc2}, C_{dc3}, C_{dc4}$	DC link capacitors (μF)
$L_i, L_{i1}, L_{i2}, L_{ia}, L_{ib}, L_{ic}$	PFC inductors (mH)
C_o	Output capacitor (μF)
C_f	Filter capacitor (μF)
L_f, L_{of}	Filter inductor (mH)
C_{ip}, C_{in}, C_{of}	Filter capacitors (μF)
C_1	PFC capacitor (nF)
C_b	DC blocking capacitor (μF)
C_r, C_{r1}, C_{r1}	Resonant capacitor (nF)
L_r, L_{r1}, L_{r1}	Resonant inductor (μH)
L_m, L_{m1}, L_{m2}	Magnetising inductor (μH)
T_x, T_{x1}, T_{x2}	High frequency transformer
V_g, V_{g2}, V_{g3}, V_{g4}	Gate drives (V)
R_L	Equivalent resistance on DC link (Ω)
R_o	Load resistance(Ω)
N	Turns ratio
i_{Li}, i_{Li1}, i_{Li2}, i_{Lia}, i_{Lib}, i_{Lic},	PFC inductor current
i_{Lr}	Resonant current
i_{Lm}	Magnetising current
i_{tx}	Current through transformer primary winding
V_{C1}	Voltage across the capacitor
V_{Cr}, V_{Cr1}, V_{Cr2}	Voltage across the resonant capacitor