DESIGN, DEVELOPMENT AND IMPLEMENTATION OF BIDIRECTIONAL BATTERY CHARGERS OF LIGHT ELECTRIC VEHICLES

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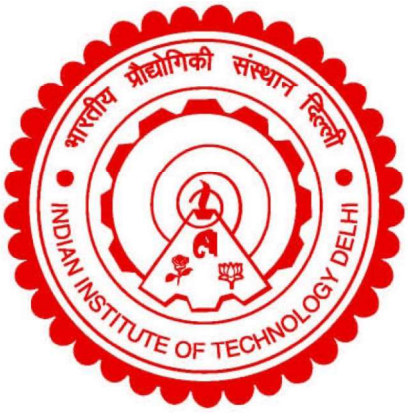

DEPARTMENT OF ELECTRICAL ENGINEERING
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DESIGN, DEVELOPMENT AND IMPLEMENTATION OF BIDIRECTIONAL BATTERY CHARGERS OF LIGHT ELECTRIC VEHICLES

by

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Department of Electrical Engineering

Submitted

in fulfillment of the requirements of the degree of

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CERTIFICATE

It is certified that the thesis entitled "**Design, Development, and Implementation of Bidirectional Chargers for Light Electric Vehicle**," being submitted by **Mr. Utsav Sharma** for an 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 any other degree or diploma award.

Dated: 30 June 2025

(Prof. Bhim Singh)

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ABSTRACT

The increasing demand for sustainable transportation solutions has significantly advanced research into bidirectional battery chargers for electric vehicles (EVs), with a particular focus on low-voltage battery-powered EVs, commonly referred to as light electric vehicles (LEVs). This thesis comprehensively explores various topologies and control strategies designed to enhance the efficiency and versatility of bidirectional chargers tailored specifically for LEVs.

The research begins with an extensive review of existing literature and market trends, highlighting the evolution and importance of bidirectional chargers in enabling vehicle-to-grid (V2G), vehicle-to-home (V2H), and other vehicle-to-anything (V2X) operations. It underscores state-of-the-art technologies and ongoing global projects that demonstrate the critical role bidirectional chargers play in integrating EVs with smart grids and smart homes.

Following this foundational review, the thesis delves into the design, development, and implementation of multiple bidirectional charger topologies. Key challenges addressed include ensuring wide-input voltage range operation, accommodating wide-output current range capabilities, and adapting to wide-output voltage ranges. Each topology is rigorously evaluated through detailed simulation analyses and practical hardware validations to ensure compliance with power quality standards and efficiency benchmarks. The integration of solar photovoltaic arrays with bidirectional chargers is also explored, expanding the scope of the research to address energy management challenges and promote sustainability in LEV operations. Additionally, the thesis investigates the feasibility of bridgeless bidirectional chargers, which aim to reduce component count and improve overall efficiency.

Through detailed chapters that provide theoretical insights, practical implementations, and performance evaluations, this research makes significant contributions to the advancement of bidirectional charger technology for LEVs. It highlights the adaptability and effectiveness of the developed chargers across a variety of operational scenarios.

In conclusion, the findings of this thesis underscore the efficacy and adaptability of the developed bidirectional chargers, laying a solid foundation for further research. They pave the way for optimizing the performance of bidirectional chargers, enhancing their integration into smart home ecosystems, and furthering sustainable transportation initiatives.

सारांश

सतत परिवहन समाधानों की बढ़ती माँग के कारण इलेक्ट्रिक वाहनों (EVs) के लिए bidirectional चार्जरों पर हो रहा अनुसंधान तेज़ी से आगे बढ़ा है, विशेषकर उन वाहनों के लिए जो कम वोल्टेज बैटरियों पर चलते हैं, जिन्हें *लाइट इलेक्ट्रिक व्हीकल्स (LEVs)* कहा जाता है। यह शोध प्रबंध LEVs के लिए उपयुक्त bidirectional चार्जरों की दक्षता और बहुपरिप्रेक्ष्यता बढ़ाने हेतु विभिन्न टोपोलॉजी और नियंत्रण विधियों का समग्र अध्ययन प्रस्तुत करता है।

शोध की शुरुआत मौजूदा साहित्य और बाज़ार प्रवृत्तियों की विस्तृत समीक्षा से होती है, जिसमें यह स्पष्ट किया गया है कि bidirectional चार्जर किस प्रकार V2G (Vehicle-to-Grid), V2H (Vehicle-to-Home) और V2X (Vehicle-to-Anything) जैसे अनुप्रयोगों को संभव बनाते हैं। साथ ही, यह अध्ययन उन नवीनतम तकनीकों और वैश्विक परियोजनाओं पर भी प्रकाश डालता है जो EVs को स्मार्ट ग्रिड और स्मार्ट होम्स से एकीकृत करने में मदद कर रही हैं।

इसके पश्चात, शोध विभिन्न bidirectional चार्जर टोपोलॉजी के डिज़ाइन, विकास और कार्यान्वयन पर केंद्रित है। इसमें प्रमुख तकनीकी चुनौतियों — जैसे विस्तृत इनपुट वोल्टेज रेंज, आउटपुट करंट और वोल्टेज रेंज में अनुकूलता — को संबोधित किया गया है। सभी टोपोलॉजी का मूल्यांकन गहन सिमुलेशन और प्रयोगात्मक हार्डवेयर परीक्षणों के माध्यम से किया गया है, ताकि यह सुनिश्चित किया जा सके कि वे पावर क्वालिटी मानकों और दक्षता मापदंडों पर खरी उतरें।

इसके अतिरिक्त, सौर फोटावोल्टिक (PV) प्रणाली के साथ bidirectional चार्जरों के एकीकरण की संभावनाओं का भी अध्ययन किया गया है, जो ऊर्जा प्रबंधन और स्थायित्व की दिशा में एक सकारात्मक कदम है। साथ ही, ब्रिजलेस bidirectional चार्जर की संभाव्यता पर भी शोध किया गया है, जिनका उद्देश्य घटकों की संख्या को कम कर दक्षता में सुधार लाना है।

इस शोध के विभिन्न अध्यायों में सैद्धांतिक अवधारणाएं, व्यावहारिक कार्यान्वयन, और प्रदर्शन मूल्यांकन शामिल हैं, जो LEVs के लिए bidirectional चार्जर तकनीक के विकास में उल्लेखनीय योगदान प्रदान करते हैं। यह शोध विभिन्न परिचालन परिदृश्यों में विकसित चार्जरों की अनुकूलता और प्रभावशीलता को रेखांकित करता है।

अंततः, यह शोध प्रबंध यह सिद्ध करता है कि विकसित bidirectional चार्जर न केवल प्रभावी हैं, बल्कि भविष्य के अनुसंधान, स्मार्ट होम इंटीग्रेशन और सतत परिवहन पहलों के लिए एक सशक्त आधार भी प्रदान करते हैं।

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LIST OF ABBREVIATIONS

AL-QSG	Adaptive Lyapunov Quadrature Signal Generator
CAGR	Compounded Annual Growth Rate
CC	Constant Current
CCCV	Constant Current Constant Voltage
CCM	Continuous Conduction Mode
CF	Crest Factor
CI-Cuk	Coupled Inductor Cuk
CSOGI	Cascaded Second-Order Generalized Integrator
CV	Constant Voltage
DAB	Dual Active Bridge
DCM	Discontinuous Conduction Mode
DER	Distributed Energy Resource
DF	Distortion Factor
DISM	Double Integral Sliding Mode
DISMC	Double Integral Sliding Mode Control
DPCC	Deadbeat Predictive Current Control
DPF	Displacement Power Factor
DSC	Delay Signal Cancellation
DSP	Digital Signal Processor
E2W	Electric Two-Wheeler
E3W	Electric Three-Wheeler
EV	Electric Vehicle
FEC	Front End Converter
FLL	Frequency-Locked Loop
FLNN	Functional Link Neural Network
G2V	Grid To Vehicle
GCC	Grid-Connected Converter
Htan-PLL	Half-Tangent Phase-Locked Loop
HVCR	High Voltage Conversion Ratio
IEC	International Electrochemical Commission
IEEE	International Electrical And Electronics Engineering
IGBT	Insulated Gate Bipolar Transistor
ii-SEPIC	Isolated Interleaved Single-Ended Primary-Inductor Converter
i-SB	Interleaved Synchronous Buck
LD	Lyapunov's Demodulator
LEV	Light Electric Vehicle
LMS	Least Mean Square
LPF	Legendre Polynomial Function
L-QSG	Lyapunov Quadrature Signal Generator
MAF	Moving Average Filter
m-MVF	Modified Multivariable Filter
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MSCC	Multi Step Constant Current
MSOGI	Multilayer Second-Order Generalized Integrator
NEMA	National Manufacturers Association
NLF-PLL	Nonlinear Loop Filter-Based PLL
OEM	Original Equipment Manufacturer

PCC	Point Of Common Coupling
PF	Power Factori
PFC	Power Factor Correction
PI	Proportional Integral
PLL	Phase-Locked Loop
PR	Proportional Resonant
PWM	Pulsewidth Modulation
RMS	Root Mean Square
SAE	
SC	Switched Capacitor
SC-SEPIC	Switched Capacitor Single-Ended Primary-Inductor Converter
SEPIC	Single-Ended Primary-Inductor Converter
SI	Switched Inductor
SI-SEPIC	Switched Inductor Single-Ended Primary-Inductor Converter
SOGI	Second-Order Generalized Integrator
SPR	Strictly Positive Real
SPS	Single-Phase Shift
SPV	Solar Photovoltaic
THD	Total Harmonic Distortion
UPF	Unity Power Factor
V2G	Vehicle To Grid
V2H	Vehicle To Home
V2L	Vehicle To Load
V2V	Vehicle To Vehicle
VSC	Voltage Source Converter

LIST OF VARIABLES

Δi_g	Allowable ripples in grid current in one switching cycle
Δi_{L1}	Allowable ripple in inductor L_1
C	Constant matrix calculated from frequency of grid voltage
C_1	Capacitor in SEPIC/Cuk converter
C_1, C_2	Capacitors of bridgeless bidirectional converter
C_{DC}	DC link capacitor
C_{i1}, C_{i2}	Primary side capacitors of isolated SEPIC/Cuk converter
C_o	Output capacitor of DC/DC converter
C_{o1}, Co_2	Secondary side capacitors of isolated SEPIC/Cuk converter
D	Duty ratio of DC/DC converter
D	Duty ratio of non-isolated DC/DC converter
d	Control law for switching of VSC
D_1, D_2	Fraction of discharging time of output inductors
D_{max}	Maximum duty ratio of DC/DC converter
D_{min}	Minimum duty ratio of DC/DC converter
D_n	Nominal duty ratio of DC/DC converter
E	Disturbance matrix
e	General error signal
e_i	Current error between measured and reference grid current
e_I	Current error between measured and reference battery current
f(x)	State matrix function of input variable in state-space equation
$f_{cut\text{-}off}$	Cut-off frequency of the low pass filter
f_g	Grid frequency in Hz
f_s	Switching frequency of DC/DC converter
f_{sw}	Switching frequency of VSC
g(x)	Input matrix function of input variable in state-space equation
G_p and G_q	transfer functions of m-MVF
I	Identity matrix
I_{AUX}	Current to auxiliary loads in LEV
I_b	Battery current
$I_{b,err}$	Error in measured and reference battery current
$I_{b,ref}$	Reference battery current
I_{b1}	Charging current in provided by available solar power
I_{b2}	Charger's output current in SPV assisted battery charger
i_{C1}, i_{C2}	Current through capacitors C_1 and C_2
i_g	Grid current
$i_{g,err}$	Error in measured and reference grid current
$i_{g,r}$	Reference grid current
$I_{g,r}$	Intermediate grid reference current amplitude
$i_{g,ref}$	Reference grid current
I_i	Amplitude of grid current reference value
i_{Lin}	Current through inductors L_{in}
i_{Lo1} and i_{Lo2}	Current through inductors L_{o1} and L_{o2}
I_P	Current from SPV array
i_r	Amplitude of the grid reference current
I_{SP}	Battery current reference value
k	Battery current amplitude multiplier constant
k_1, k_2, k_3	Sliding mode controller constants

K_I	Integral constant in voltage controller of VSC
k_i	m-MVF multiplication factor
K_{II}	Integral constant in current controller of DC/DC convertor
k_m, α_m	m-MVF control variables
K_p	Proportional constant in voltage controller of VSC
K_{PI}	Proportional constant in current controller of DC/DC convertor
K_{VI}	Integral constant in voltage controller of DC/DC convertor
K_{VP}	Proportional constant in voltage controller of DC/DC convertor
L_i	Interfacing inductor of VSC
L_{i1}, L_{i2}	Input inductors of DC/DC converter
L_{in}	Input inductor of bridgeless bidirectional converter
L_{m1}, L_{m2}	Magnetizing inductance of transformer of isolated DC/DC converter
L_o	Equivalent output inductor of the DAB
L_{o1}, L_{o2}	Output inductors of DC/DC converter
L_s	Inductor in series with primary winding of an isolated DC/DC converter
m	Modulation factor
M	Mutual inductance
N	Transformer ratio
$P_1/P_2/P_3/P_4$	Switching signals to Primary side switches of isolated DC/DC converter
P_o	Power transfer capacity of DC/DC converter
P_P	Calculated PV power at SPV array terminal
$Q_1/Q_2/Q_3/Q_4$	Switching signals to secondary side switches of isolated DC/DC converter
r	Coupling coefficient
r_f-C_f	RC filter
R_o	Equivalent output resistance of the DAB
S	Sliding surface
$S_1/S_2/S_3/S_4$	Switching signal to VSC switches
T_o	Cycle time of input signal
T_S	Sampling period for FLNN algorithm
u	Input variable matrix in state-space equation
u_t	Unit template of the grid voltage
v_g	Grid voltage
V_b	Battery voltage
$V_{b,err}$	Error in measure and reference battery voltage
$V_{b,ref}$	Reference battery voltage
v_{C1}, v_{C2}	Instantaneous voltage across capacitors C_1 and C_2
V_{C1}, V_{C2}	Average voltage across capacitors C_1 and C_2
V_{DC}	DC link voltage
$V_{DC,err}$	Error in measured and reference DC link voltage
v_e	Reconstructed/calculated grid voltage
V_{Lin}	Voltage across inductor L_{in}
V_m	Amplitude of grid voltage
$V_{m,e}$	Estimated amplitude of grid voltage
V_P	SPV array terminal voltage
V_{PCC}	Voltage across point of common coupling
V_{Q1}, V_{Q2}, V_{Q3}, V_{Q4}	Voltage across switches Q_1, Q_2, Q_3, and Q_4
V_{ref}	Reference DC link voltage

v_{rip}	Ripple in DC link voltage
v_α, v_β	Quadrature component of the grid voltage
x	Input variable matrix of a generalized state-space equation
y	Output variable matrix of a generalized state-space equation
Z	Impedance of the transformer in DAB
α	Ratio of the inductance considered in control algorithm to actual inductance
γ	Frequency multiplier factor
δ	Phase shift angle
Δi_{Li1}, Δi_{Li2}	Ripples in input inductor current
Δi_{Lm}	Ripples in magnetizing inductance
Δi_{Lo1}, Δi_{Lo2}	Ripples in output inductor current
ΔI_P	Change in SPV array output current
δ_{nom}	Nominal phase shift angle
Δv_{C1}	Ripples in voltage across capacitor C_1
ΔV_P	Change in SPV voltage
ε	Error between calculated grid voltage and measured grid voltage
κ	Feedforward multiplier constant
λ	Convergence variable in Lyapunov approach
μ	Constant to define hyperbolic tangent thickness
μ_S	Step size of LMS algorithm
ρ	Step size of the least-mean-square (LMS) algorithm
σ	Lyapunov gain parameter
$\varphi(t)$	Phase of the grid voltage
$\varphi_e(t)$	Estimated phase of the grid voltage
χ	Constant in gradient descent method
ψ	Generalized desired signal
ψ_e	Estimated value of desired signal
ψ_o	Initial value of desired signal
ω	Grid frequency
ω_1, ω_2, ω_3, ω_4	Legendre coefficients
ω_c	Grid frequency calculated from PLL
ω_n	nominal grid frequency
$\omega_{n,e}$	Estimated nominal grid frequency
ω_r	resonance frequency
Γ	Lyapunov Constant