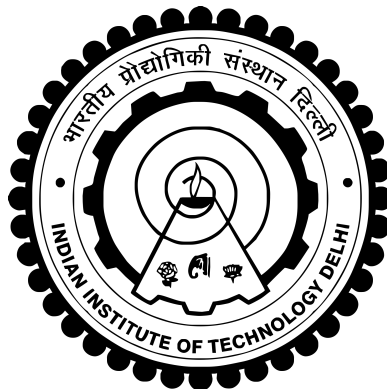


ANALYSIS AND DEVELOPMENT OF CURRENT FED DUAL ACTIVE BRIDGE BASED CONVERTER FOR ELECTRIC VEHICLE CHARGING APPLICATION

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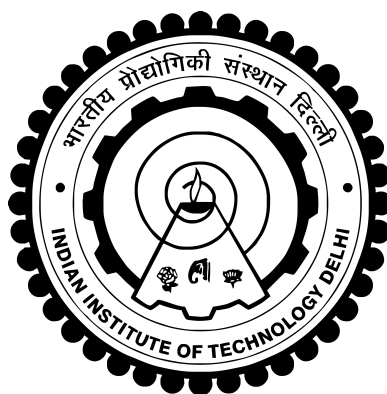
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by
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Submitted
in fulfillment of requirements of degree of
DOCTOR OF PHILOSOPHY

to the



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MAY 2025

CERTIFICATE

It is certified that the thesis entitled “Analysis and Development of Current Fed Dual Active Bridge Based Converter for Battery Charging Application” being submitted by Mr. Sayan-dev Ghosh 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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Dated: May 27 , 2025

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Sayandev Ghosh

ABSTRACT

A conventional voltage fed dual active bridge (VFDAB) converter poses as a prominent solution for bidirectional DC-DC power conversion in high gain high power region. It presents multiple advantages like high power density, wide ZVS operation, high voltage gain and isolation. However, it suffers from high output ripple current, which is undesirable, particularly for low voltage high current applications. In this regard, current fed dual active bridge (CFDAB) converter is a potential converter for low voltage battery charging applications. The output inductors, which are present on the low voltage side of CFDAB, provide ripple-free battery current and shoot through protection under fault conditions. The behavior of this converter slightly differs from the conventional voltage fed dual active bridge converter and is less studied in literature. In this thesis, an accurate steady state model and simplified small signal model are developed for the CFDAB converter under PWM plus Phase shift (PPS) modulation. Using the steady state model, behaviour of the converter for entire range of operation in terms of some important electrical quantities are presented. The effect of carrier signal on the phase shift definition and power characterization of the CFDAB converter under PPS modulation are also studied. It is observed that the triangular carrier provides correct phase shift measurement than the sawtooth carrier.

Then the small signal analysis of the converter is performed using the improved HSS model. The improved HSS model considers only the effect on the dominant harmonics for the small signal perturbation. It discusses the presence of two resonances in the small signal model of CFDAB. One of them lies at switching frequency while other lies at converter natural frequency. The latter resonance either increases the steady state ripple or decreases the bandwidth of the conventional closed loop current controller. Hence, it presents adaptive notch integrated PI controller in order to overcome above drawbacks of simple PI controller.

Finally, a new perspective of considering EV as power transport device to underprivileged

households is considered in this work. A converter solution is presented that enables battery charging of light electric vehicle (LEV) from AC as well as DC supply. Besides that, it is also capable to power the rural household appliances from the LEV battery. The converter system comprises of active bridge based single stage AC/DC converter with auxiliary DC port. The merit of the converter is that it provides solutions for multiple applications with reduced switch count. The single stage power conversion reduces the high frequency switch count for AC/DC conversion. The DC/DC interface utilizes partial circuitry to achieve the desired operation without any need for additional high frequency switches. The operation of the converter is categorized in three modes. Mode I comprises of LEV battery charging from AC grid. Mode II comprises of LEV battery charging from another EV or battery. Mode III conducts powering of household appliances by the LEV battery. The performance of the converter system is analysed under individual modes independently. The AC/DC interfacing supports unity power factor operation within the standard of IEC61000-3-2.

सारांश

एक पारंपरिक वोल्टेज फेड ड्यूल एक्टिव ब्रिज (VFDAB) कन्वर्टर उच्च गेन और उच्च पावर क्षेत्रों में द्विदिश डीसी-डीसी पावर रूपांतरण के लिए एक प्रमुख समाधान के रूप में प्रस्तुत होता है। यह उच्च शक्ति घनत्व, विस्तृत ZVS संचालन, उच्च वोल्टेज गेन और पृथक्करण जैसी कई विशेषताएँ प्रदान करता है। हालांकि, यह उच्च आउटपुट रिपल करंट की समस्या से ग्रस्त होता है, जो विशेष रूप से निम्न वोल्टेज, उच्च करंट अनुप्रयोगों के लिए अवांछनीय है। इस संदर्भ में, करंट फेड ड्यूल एक्टिव ब्रिज (CFDAB) कन्वर्टर निम्न वोल्टेज बैटरी चार्जिंग अनुप्रयोगों के लिए एक संभावित समाधान है।

CFDAB कन्वर्टर की निम्न वोल्टेज साइड पर मौजूद आउटपुट इंडक्टर्स बैटरी को रिपल-फ्री करंट प्रदान करते हैं और फॉल्ट की स्थिति में शूट-थ्रू सुरक्षा भी देते हैं। इस कन्वर्टर का व्यवहार पारंपरिक वोल्टेज फेड ड्यूल एक्टिव ब्रिज कन्वर्टर से थोड़ा भिन्न होता है और साहित्य में इसका कम अध्ययन किया गया है। इस शोध में, PWM प्लस फेज शिफ्ट (PPS) माड्यूलेशन के अंतर्गत CFDAB कन्वर्टर के लिए एक सटीक स्थिर स्थिति मॉडल और सरलीकृत स्मॉल सिग्नल मॉडल विकसित किया गया है। स्थिर स्थिति मॉडल का उपयोग करके, कन्वर्टर के पूरे ऑपरेशन रेंज में कुछ महत्वपूर्ण विद्युत मानों के संदर्भ में इसका व्यवहार प्रस्तुत किया गया है।

PPS माड्यूलेशन के अंतर्गत, फेज शिफ्ट की परिभाषा और पावर कैरेक्टराइजेशन पर कैरियर सिग्नल के प्रभाव का भी अध्ययन किया गया है। यह पाया गया कि त्रिकोणीय कैरियर (triangular carrier) ने फेज शिफ्ट का अधिक सटीक मापन प्रदान किया, जबकि सॉ-टूथ कैरियर ने नहीं।

इसके बाद, बेहतर HSS मॉडल का उपयोग करके कन्वर्टर का स्मॉल सिग्नल विश्लेषण किया गया है। यह मॉडल स्मॉल सिग्नल गड़बड़ी के लिए प्रमुख हार्मोनिक्स के प्रभाव को ही ध्यान में रखता है। CFDAB के स्मॉल सिग्नल मॉडल में दो रेज़ोनेंस की उपस्थिति पाई गई: एक स्विचिंग फ्रिक्वेंसी पर और दूसरा कन्वर्टर की नैसर्गिक आवृत्ति (natural frequency) पर। यह दूसरा रेज़ोनेंस या तो स्थिर अवस्था में रिपल को बढ़ाता है या पारंपरिक क्लोज़्ड लूप करंट कंट्रोलर की बैंडविड्थ को घटाता है। इसलिए, इस समस्या के समाधान के लिए एक एडेप्टिव नॉच इंटीग्रेटेड PI कंट्रोलर प्रस्तावित किया गया है।

अंततः, इस शोध में एक नई दृष्टिकोण प्रस्तुत की गई है जिसमें ईवी (EV) को वंचित परिवारों के लिए पावर ट्रांसपोर्ट डिवाइस के रूप में प्रयोग करने की संभावना को दर्शाया गया है। एक कन्वर्टर समाधान प्रस्तावित किया गया है जो लाइट इलेक्ट्रिक व्हीकल (LEV) की बैटरी को एसी और डीसी दोनों सप्लाई से चार्ज करने में सक्षम है। इसके अलावा, यह LEV बैटरी से ग्रामीण घरेलू उपकरणों को भी पावर दे सकता है।

यह कन्वर्टर प्रणाली एक एक्टिव ब्रिज आधारित सिंगल स्टेज AC/DC कन्वर्टर और एक सहायक डीसी पोर्ट से मिलकर बनी है। इस कन्वर्टर की विशेषता यह है कि यह कम स्विच संख्या के साथ कई अनुप्रयोगों के लिए समाधान प्रदान करता है। सिंगल स्टेज पावर रूपांतरण AC/DC रूपांतरण के लिए हाई फ्रिक्वेंसी स्विच की संख्या को कम करता है। DC/DC इंटरफेस आंशिक सर्किट्री का उपयोग करके वांछित संचालन प्राप्त करता है, बिना अतिरिक्त हाई फ्रिक्वेंसी स्विच की आवश्यकता के।

कन्वर्टर के संचालन को तीन मोड में वर्गीकृत किया गया है:

- मोड I: AC ग्रिड से LEV बैटरी चार्जिंग
- मोड II: किसी अन्य EV या बैटरी से LEV बैटरी चार्जिंग
- मोड III: LEV बैटरी से घरेलू उपकरणों को पावर देना

कन्वर्टर प्रणाली के प्रदर्शन का स्वतंत्र रूप से प्रत्येक मोड में विश्लेषण किया गया है। AC/DC इंटरफेसिंग IEC61000-3-2 मानक के अंतर्गत यूनिटी पावर फैक्टर ऑपरेशन को भी सपोर्ट करता है।

TABLE OF CONTENTS

CERTIFICATE	i
ACKNOWLEDGEMENTS	ii
ABSTRACT	iii
TABLE OF CONTENTS	vii
LIST OF FIGURES	x
LIST OF TABLES	xiv
ABBREVIATIONS	xv
CHAPTER I INTRODUCTION	1
1.1 General	1
1.2 State of Art	1
1.3 Scope of Work	3
1.4 Outline of the Chapters	4
CHAPTER II LITERATURE REVIEW	6
2.1 General	6
2.2 Review on Modeling Techniques For DAB Converter	7
2.3 Review on Modeling, Modulation and Control of CFDAB converter	8
2.4 Review on Multiport Converter	10
2.5 Identified Research Areas	12
CHAPTER III HARMONIC STATE SPACE MODELING OF CON- VENTIONAL DUAL ACTIVE BRIDGE CONVERTER	13
3.1 General	13
3.2 Circuit Description	13
3.3 HSS Modeling Framework	14
3.3.1 Toeplitz Operator	14
3.3.2 Modeling Framework	16
3.4 HSS Model of Conventional Dual Active Bridge Converter	17
3.4.1 Large Signal Model of DAB Converter	17
3.4.2 Small Signal Model of DAB Converter	19
3.4.3 Linearization of the model	21
3.5 Design of the dual active bridge converter prototype	22
3.6 Results and Discussion	24
3.6.1 Steady State Response	25
3.6.2 Dynamic Response	28

3.6.3	Model Order Reduction Using Pole Zero Map	34
3.6.4	Discussion on FFT Spectrum of Steady State Output	34
3.7	Conclusion	37
CHAPTER IV	ANALYSIS OF STEADY STATE BEHAVIOR OF CURRENT FED DUAL ACTIVE BRIDGE CONVERTER	38
4.1	General	38
4.2	Circuit Description of CFDAB	38
4.3	Full Order Steady State Model of CFDAB	39
4.4	Switching Signal Functions	41
4.5	Some Important Steady State Parameters	41
4.6	Design of the Converter System Prototype	43
4.7	Analysis of Steady State Performance of CFDAB	44
4.7.1	Steady State Waveforms	45
4.7.2	Power Characteristics	47
4.7.3	RMS HFL Current Characteristics	47
4.7.4	Peak HFL current Characteristics	47
4.7.5	Experimental Results	48
4.8	Discussion on the Comparative Analysis With Other Modeling Methods	50
4.9	Conclusion	51
CHAPTER V	EFFECT OF CARRIER SIGNAL POWER CHARACTERIZATION OF CURRENT FED DUAL ACTIVE BRIDGE CONVERTER UNDER PWM PLUS PHASE SHIFT MODULATION	52
5.1	General	52
5.2	Converter Model	52
5.3	Switching Signals For Two Different Versions of Phase Shift	53
5.4	Characteristics of Transmitted Power	55
5.5	Experimental Results	57
5.6	Discussion on the Discrepancy of the Power Characteristics	57
5.7	Conclusion	62
CHAPTER VI	IMPROVED FOURIER DOMAIN MODEL AND LINEAR CONTROLLER DESIGN FOR CURRENT FED DUAL ACTIVE BRIDGE CONVERTER	63
6.1	General	63
6.2	Improved HSS Model	63
6.3	Improved HSS Model of CFDAB	64
6.3.1	Converter Circuit	64
6.3.2	Large Signal Model of the converter	65
6.3.3	Small Signal Model and Linearization of the converter model	69
6.4	Analysis of Resonances in Small Signal Model	71
6.5	Resonance Effects on Closed Loop Performance and Controller Design	73
6.6	Solution for Mitigation of Resonance Effects	75
6.6.1	Lossy Approach	75
6.6.2	PI Controller With Fixed Notch Filter	76
6.6.3	Proposed Approach	77
6.7	Experimental Results	79
6.8	Comparative Analysis of the Closed Loop Controls	83

6.9	Conclusion	84
CHAPTER VII	SINGLE STAGE MULTIPORT CHARGER FOR CONSUMER APPLICATION	86
7.1	General	86
7.2	Circuit Description	86
7.2.1	Interleaved Totem Pole	86
7.2.2	Current Fed Dual Active Bridge	87
7.2.3	Interleaved Buck	88
7.3	Application Based Operating Modes	88
7.3.1	LEV / Battery Charging From AC Grid (Mode I)	88
7.3.2	LEV/Battery Charging From Other EV/battery (Mode-II)	93
7.3.3	LEV/Battery Powering Passive DC Loads (Mode-III)	94
7.3.4	Mode Selection	95
7.4	Loss Analysis	95
7.5	Design of the Converter System	98
7.6	Performance of the Converter System	101
7.6.1	Mode-I	101
7.6.2	Mode-II	103
7.6.3	Mode-III	106
7.7	Experimental Results	106
7.8	Conclusion	110
CHAPTER VIII	MAIN CONCLUSIONS AND SUGGESTION FOR FURTHER WORK	111
8.1	General	111
8.2	Main Conclusions	111
8.3	Suggestion for Further Work	112
REFERENCES		113
LIST OF PUBLICATIONS		120
BIODATA		122

LIST OF FIGURES

2.1	(a) DAB topology and (b) TAB topology	10
2.2	(a) Topology in [66], [67] (b) Topology in [68]	11
2.3	Topology in [70] for standalone PV load application	11
3.1	(a) Circuit diagram and (b) operating waveforms of VFDAB converter	14
3.2	Pictorial representation of convolution of two signals using Toeplitz matrix	15
3.3	Block diagram of linear model of phase shift modulated DAB converter	22
3.4	Experimental set up	24
3.5	Comparison of the bridge voltages and transformer current waveforms derived from HSS models with the simulation model under (a) SPS ($d=-0.5$, $d_1=d_2=1$) (b) DPS ($d=-0.5$, $d_1=d_2=0.7$) (c) TPS ($d=-0.5$, $d_1=0.9$, $d_2=0.5$)	26
3.6	Experimental waveform of Transformer voltage and current at steady state condition under SPS modulation with $d=-0.5$	27
3.7	Comparison of battery current waveforms derived from HSS models with the time domain simulation model under SPS modulation with $d=-0.5$	27
3.8	Experimental waveform of battery current at steady state condition under SPS modulation with $d=-0.5$	28
3.9	Battery Current at different phase shift obtained from analytical, simulation and experimental models	29
3.10	Mapping of harmonics of the switching waveform with the harmonics of the battery current	30
3.11	Analytical and simulation result of dynamic response of battery current when phase shift is changed from 0 to -0.5	30
3.12	Experimental result of dynamic response of battery current when phase shift is changed from 0 to -0.5	31
3.13	Bode plot of phase shift to battery current transfer function obtained from HSS model under different harmonic considerations at $d=-0.28$	32
3.14	Comparison of Bode plot of phase shift to battery current transfer function obtained from analytical, simulation and experimental models	33
3.15	Pole Zero Map of the phase shift to DC component of battery current transfer function	33
3.16	Comparison of dynamic response of DC component of battery current obtained from full order and reduced order models when phase shift is changed from 0 to -0.5	35

3.17	Steady state battery current waveforms at $d=-0.5$ and corresponding FFT spectrum obtained from analytical model without considering ESR of capacitors(a) and (b), analytical model considering ESR of capacitors (c) and (d), time domain simulation model(e) and (f) and experiment (g) and (h)	36
4.1	(a) Converter Diagram (b) Switching waveforms in PPS modulation	39
4.2	Analytical and simulated steady state waveforms of v_{hv}, v_{lv}, i_{L_t} and i_b when $\langle V_b \rangle_0 = 12V$ at (a) $d = -0.2$ (b) $d = 0$ and (c) $d = 0.2$	46
4.3	Analytical and simulated steady state waveforms of v_{hv}, v_{lv}, i_{L_t} and i_b when $\langle V_b \rangle_0 = 18V$ at (a) $d = -0.2$ (b) $d = 0$ and (c) $d = 0.2$	46
4.4	Analytical and simulated steady state waveforms of v_{hv}, v_{lv}, i_{L_t} and i_b when $\langle V_b \rangle_0 = 24V$ at (a) $d = -0.2$ (b) $d = 0$ and (c) $d = 0.2$	46
4.5	Surface of transmitted power for entire span of the two degree of freedoms, d and d_{lv} . (a) 3D view (b) 2D view from x-axis (c) 2D view from y-axis	47
4.6	Surface of RMS HFL current for entire span of the two degree of freedoms, d and d_{lv} . (a) 3D view (b) 2D view from x-axis (c) 2D view from y-axis	48
4.7	Surface of peak HFL current for entire span of the two degree of freedoms, d and d_{lv} . (a) 3D view (b) 2D view from x-axis (c) 2D view from y-axis	48
4.8	Experimental set up of converter prototype	49
4.9	Experimental steady state waveforms of v_{hv}, v_{lv}, i_{L_t} and i_b when $\langle V_b \rangle_0 = 12V$ at (a) $d = -0.2$ (b) $d = 0$ and (c) $d = 0.2$	49
4.10	Experimental steady state waveforms of v_{hv}, v_{lv}, i_{L_t} and i_b when $\langle V_b \rangle_0 = 18V$ at (a) $d = -0.2$ (b) $d = 0$ and (c) $d = 0.2$	49
4.11	Experimental steady state waveforms of v_{hv}, v_{lv}, i_{L_t} and i_b when $\langle V_b \rangle_0 = 24V$ at (a) $d = -0.2$ (b) $d = 0$ and (c) $d = 0.2$	49
4.12	3D surfaces of (a) transmitted power (b) RMS HFL current (c) peak HFL current for entire operating region obtained experimentally	50
4.13	Comparison of 3D surfaces of peak HFL current for entire operating region obtained using (a) GAM1 (b) GAM3 (3) HSS models	51
5.1	Converter Diagram	53
5.2	Switching waveforms with (a) ramp up sawtooth carrier signal (b) Triangular carrier signal	54
5.3	(a) 3-D power transmission surfaces for entire operating region (b) 2-D power transmission curves for entire d_ϕ at different duty cycle, d_s , considering PS_1 and (c)-(d) illustrates similar characteristics considering PS_2 .	56
5.4	Experimental steady state waveforms of v_{hv}, v_{lv}, i_{L_t} and I_b under PPS modulation at $d=-0.25$, $d=0$ and $d=0.25$. The battery voltage is set at (a) $v_b = 12V$ (b) $v_b = 16V$	58
5.5	Experimental steady state waveforms of v_{hv}, v_{lv}, i_{L_t} and I_b under PPS modulation at $d=-0.25$, $d=0$ and $d=0.25$. The battery voltage is set at (a) $v_b = 20V$ (b) $v_b = 24V$	59
5.6	Experimental curves of transmitted power at varying phase shifts, d , with different battery voltages considering PS_2	60
5.7	Illustration of the phase shift between the two high frequency switching voltages across the high frequency link and also the phase shift between their corresponding fundamental components under (a) SPS modulation (b) PPS modulation	61
6.1	Graphic illustration of improved HSS model	64

6.2	Converter Diagram and operational waveforms	65
6.3	Comparison of steady state waveforms obtained from analytical model and simulation model when the converter is delivering 5A to battery of 24V.	68
6.4	Bode plot of open loop transfer function, G_{id} , of converter at $d = 0.1$	72
6.5	Effect of variation of C_b , L_{b1} and L_{b2} on the converter natural frequency in G_{id}	72
6.6	Current control of the converter with PI controller only	73
6.7	(a) Bode plot of converter loop transfer function with PI controller (b) step response of analytical model of the converter with PI controller at different K_i (c) Simulated converter response when reference current is changed from 2A to 5A with different K_i	74
6.8	Current control of converter with fixed notch integrated PI controller	76
6.9	(a)Bode plot of notch filter at different attenuation with natural frequency of 5.7 kHz (b) zoomed view of the bode plot showing variation of stop bands with attenuation coefficient	77
6.10	(a) Bode plot of converter loop transfer function with proposed controller with present notch frequency of 5.7kHz (b) step response of proposed closed loop transfer function of the converter at $K_i=153$ (c) Response of the battery current obtained from Simulink model when reference current is changed from 2A to 5A with proposed control approach	78
6.11	Proposed controller	79
6.12	Experimental set up of converter prototype	80
6.13	Steady state operational waveforms of converter prototype when the output current is delivering 5A to a battery pack of 24V	80
6.14	(a) Sweep response of the battery current, I_b , when phase shift duty of the converter is swept from 100 Hz to 10 kHz (b) zoomed view of the sweep response of battery current near resonance at converter natural frequency	81
6.15	(a) Sweep response of the battery current, I_b , when phase shift duty is swept from 100 Hz to 10 kHz in presence of notch filter (b) zoomed view of the sweep response of the battery current near converter natural frequency	82
6.16	Experimental results of dynamic performance of the battery current when its reference set point is changed from 2 A to 5 A at $d_{lv} = 0.5$ with a) conventional PI controller b) proposed PI controller	83
7.1	(a) Black Box structure of the converter system (b) Detailed circuit diagram of the proposed solution (c)-(e) illustrates the different sections of the presented solution	87
7.2	Working circuit under (a) mode I and (b) mode II and mode III. Red line indicates active part of the circuit.	89
7.3	Voltage waveform across capacitor C_g	90
7.4	Switching signals and operating waveforms at HFT at around 45° of grid cycle	91
7.5	Detailed control logic for all the modes of operation	92
7.6	Comparative bode plot of the transfer function of the (a) in phase voltage output and (b) quadrature voltage output with respect to grid voltage under SOGI and FOGI.	93
7.7	Mode selection logic diagram	96

7.8	Conditions for ZVS of the switches	96
7.9	(a) Voltage and current waveforms at the grid side and the battery side under mode I operation when the LEV/battery is being charged at 50 A current (b) FFT spectrum of the grid current	102
7.10	Voltage across capacitors at HVS and LVS under mode I	103
7.11	(a) Voltage and current waveforms at HFL at rated operating condition. (b) The HFL voltages and current are zoomed at 45° of the grid cycle. (c) The above quantities are zoomed around peak of the grid voltage.	104
7.12	Dynamic response of the converter system under mode I	104
7.13	Steady state voltage and current waveforms of the converter system under mode II. The operating waveforms are obtained with the input DC voltage set at (a) 72 V (b) 96 V	105
7.14	Dynamic response of voltages and currents of the converter system under mode II with the input DC voltage set at (a) 72V (b) 96V	105
7.15	Operating voltages and current waveforms under mode III at (a) steady state condition (b) dynamic condition	106
7.16	Experimental Prototype	107
7.17	(a) Experimental waveforms of Voltage, current and LVS duty obtained under mode I (b) Waveforms of grid voltage and current obtained from power analyzer and (c) %THD measurement of the grid current	108
7.18	Experimental waveforms of the voltages and current across the HFL and the battery current under mode I	109
7.19	Comparison of the experimental efficiency with other state of art works	109
7.20	Losses in the presented solution in mode I at rated operation	109
7.21	Experimental voltage and current waveforms obtained under (a) mode II and (b) mode III with steady state and transient conditions	110

LIST OF TABLES

3.1	Parameters of DAB	24
3.2	Harmonic content in battery current, i_2	35
4.1	Parameters of converter	45
6.1	Converter Parameters	69
6.2	Comparative Analysis of the closed loop control methods	84
7.1	ZVS conditions of HVS switches	97
7.2	ZVS conditions of LVS switches	97
7.3	Parameters of converter	101
7.4	Circuit parameters of experimental prototype	107

ABBREVIATIONS

CFDAB	Current Fed Dual Active Bridge
DAB	Dual Active Bridge
DC	Direct Current
DPS	Dual Phase Shift
EPS	Extended Phase Shift
EV	Electric Vehicle
G2V	Grid to Vehicle
GAM	Generalized Average Modeling
HSS	Harmonic State Space
LEV	Light Electric Vehicle
LTP	Linear Time Periodic
PFC	Power Factor Correction
PPS	PWM plus Phase Shift
PSM	Phase Shift Modulation
PWM	Pulse Width Modulation
SPS	Single Phase Shift
TPS	Triple Phase Shift
V2G	Vehicle to Grid
V2H	Vehicle to Home
V2V	Vehicle to Vehicle
VFDAB	Voltage Fed Dual Active Bridge
ZVS	Zero Voltage Switching