# DESIGN AND DEVELOPMENT OF PORTABLE AND OFF-BOARD CHARGERS FOR WIDE CATEGORIES OF ELECTRIC VEHICLES

**SARAN CHAURASIYA**

**DEPARTMENT OF ELECTRICAL ENGINEERING**

**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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# DESIGN AND DEVELOPMENT OF PORTABLE AND OFF-BOARD CHARGERS FOR WIDE CATEGORIES OF ELECTRIC VEHICLES

by

**SARAN CHAURASIYA**

**Electrical Engineering Department**

***Submitted***

***in fulfilment of the requirements of the degree of***

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*Dedicated*

*to*

*my father* ***Shri Kamal Kishore*** *Chaurasiya*

*and my mother* ***Shrimati Sneh Lata Chaurasiya***

# CERTIFICATE

It is certified that the thesis entitled “Design and Development of Portable and Off-Board Chargers for Wide Categories of Electric Automobiles” being submitted by Mr. Saran Chaurasiya 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 the award of my other degree or diploma.

Dated:

**(Dr. Bhim Singh)**

**Professor**
**Electrical Engineering Department**
**Indian Institute of Technology Delhi**
**Hauz Khas, New Delhi-110016, India**

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# ABSTRACT

The increment of transportation needs along with a rise in pollution and depletion of fossil fuels divert world researcher’s & original equipment manufacturers (OEMs) interest towards other energy sources, especially sustainable developments. In this manner, electrified way of transportation is most popular and old concept before internal combustion engine era. The wide-spread or equivalent deployment of electric or battery powered automobiles (both personal and commercial vehicles) require different Ampere-hour capacity of battery packs with a wide range of battery voltage segments. A variety of battery chemistries are adopted to serve multiple transportation requirements like improved energy density, fast/ultra-fast charging, longer charging/discharging cycles, higher thermal stability, and different cell voltage requirements. These prominent diverse technology development of battery packs for wide segment of electric automobiles simultaneously raise diverse charging requirements. In respect to these charging needs, a set of charging protocols & standards are proposed in the literature. These are especially defined based on type of charging (AC or DC), battery terminal voltage and power processing. All three ways of charging (portable, on-board and off-board charger) technologies are quite challenging due to wide battery voltage adaptation requirements, portability of reduced volumetric form-factor of complete design, higher efficiency, and higher durability requirements for grid connection along with bidirectional power transfer with vehicle to grid, vehicle to grid, and vehicle to home/vehicle/auxiliary loads.

In this manner, a commonly adopted power electronics design is inspired by multiple (2 or 3) isolated DC/DC stages and a common active power factor correction stage to facilitate wide battery voltage adaptability, which is not a good solution for portable design due to higher form-factor design. Moreover, there is no further modifications are introduced in conventional isolated DC/DC stages to facilitate higher conversion efficiency over wide variation range in battery terminal voltage and power. Since, conventionally similar half and full bridge isolated

DC/DC converters are proposed either for constant voltage or constant power applications (like LED drivers, energy routers, telecom/server power supplies, and other auxiliary power supply). In this manner, this research work is aimed to address all these aforementioned inadequacies and challenges by considering universal design concept for portable EV charger development.

It is started by incorporating the beauty of magnetizing inductance into conventional hardware architecture of dual active bridge (DAB) DC/DC converter. Based on this, conventional dual phase shift modulation is modified with an optimization law. It facilitate complete zero voltage switching (ZVS) of both full bridges over wide range of voltage conversion ratio and power transfer. On the active front end converter side, a modified pre-filtering stage is presented for consistent operation of charger over any grid anomalies as per IEEE 1547-2019. For low cost & high voltage charging needs, a three level DAB based DC/DC power conversion concept is presented and it is validated by scaled hardware prototype development. The concept facilitate utilization of low cost, lower break over voltage silicon MOSFETs instead of higher voltage breaking capacity silicon-carbide MOSFETs. It is achieved by identifying safe operating region of converter with half voltage stress across each MOSFETs of corresponding DC link voltage. An optimization law also applied to restrict converter operation within minimal current/voltage stress region over wide deviation in voltage conversion ratio for different EV segments.

A multi-parametric coordinated hybrid control techniques are proposed for the operation of LLC resonating converters. Based on the maximum possible degree of freedoms in either half or full bridge resonating network with active consideration of battery voltage profile variation, control maintains its operation within ZVS region. By considering different EV portfolios like light electric vehicles, PVs and CVs, different portable charger designs are proposed. All these are proposed by taking individual or multiple segment EV owners into consideration. Some of the designs possess portable DC fast charging of a wide segment of PVs and CVs using a single charger, which reduces customer’s dependency to invest into different EV chargers. On the other hand, it simultaneously helps OEMs to eliminate dependency on the incorporation of on-board charger into vehicle, which reduce total vehicle cost.

All these proposed design modifications in either control, hardware or both architectures are modelled, simulated (MATLAB/Simulink) and tested on experimental prototype. All validations are implemented over multiple possible grid and battery side scenarios. Moreover, a discrete time domain approach also presented to implement proposed control architectures into TI's C2000 microcontroller versions e.g. THDSDOCK28335 and TMS320F28379D boards. The presented work is aimed to increase electrified transportation trend by reducing cost, and impressive compact/reliable/durable mobile designs of different EV charger segments to meet the needs of all types of customers.

# सार

प्रदूषण में वृद्धि और जीवाश्म ईंधन की कमी के साथ-साथ परिवहन आवश्यकताओं में वृद्धि ने विश्व शोधकर्ताओं और मूल उपकरण निर्माताओं (ओईएम) की रुचि को अन्य ऊर्जा स्रोतों, विशेष रूप से टिकाऊ विकास की ओर मोड़ दिया है। इस प्रकार, परिवहन का विद्युतीकृत तरीका, आंतरिक दहन इंजन युग से पहले सबसे लोकप्रिय और पुरानी अवधारणा है। इलेक्ट्रिक या बैटरी चालित ऑटोमोबाइल (व्यक्तिगत और वाणिज्यिक वाहन दोनों) की व्यापक या समकक्ष तैनाती के लिए बैटरी वोल्टेज खंडों की एक विस्तृत श्रृंखला के साथ बैटरी पैक की अलग-अलग एम्पीयर-घंटे क्षमता की आवश्यकता होती है। बेहतर ऊर्जा घनत्व, तेज/अल्ट्रा-फास्ट चार्जिंग, लंबी चार्जिंग/डिस्चार्जिंग चक्र, उच्च तापीय स्थिरता और विभिन्न सेल वोल्टेज आवश्यकताओं जैसी कई परिवहन आवश्यकताओं को पूरा करने के लिए विभिन्न प्रकार की बैटरी रसायन विज्ञान को अपनाया जाता है। इलेक्ट्रिक ऑटोमोबाइल के व्यापक खंड के लिए बैटरी पैक के ये प्रमुख विविध प्रौद्योगिकी विकास एक साथ विविध चार्जिंग आवश्यकताओं को बढ़ाते हैं। इन चार्जिंग आवश्यकताओं के संबंध में, साहित्य में चार्जिंग प्रोटोकॉल और मानकों का एक सेट प्रस्तावित है। इन्हें विशेष रूप से चार्जिंग के प्रकार (एसी या डीसी), बैटरी टर्मिनल वोल्टेज और पावर प्रोसेसिंग के आधार पर परिभाषित किया गया है। चार्जिंग के सभी तीन तरीके (पोर्टेबल, ऑन-बोर्ड और ऑफ-बोर्ड चार्जर) प्रौद्योगिकियां व्यापक बैटरी वोल्टेज अनुकूलन आवश्यकताओं, पूर्ण डिजाइन के कम वॉल्यूमेट्रिक फॉर्म-फैक्टर की पोर्टेबिलिटी, उच्च दक्षता, और ग्रिड कनेक्शन के लिए उच्च स्थायित्व के साथ द्विदिशीय बिजली हस्तांतरण वाहन से ग्रिड, वाहन से ग्रिड, और वाहन से घर/वाहन/सहायक भार की आवश्यकताओं के कारण काफी चुनौतीपूर्ण हैं।

इस तरीके से, आमतौर पर अपनाया जाने वाला पावर इलेक्ट्रॉनिक्स डिज़ाइन व्यापक बैटरी वोल्टेज अनुकूलनशीलता की सुविधा के लिए कई (2 या 3) पृथक डीसी/डीसी चरणों और एक सामान्य सक्रिय पावर फैक्टर सुधार चरण से प्रेरित होता है, जो पोर्टेबल डिज़ाइन के लिए एक अच्छा समाधान नहीं है। उच्चतर रूप-कारक. इसके अलावा, बैटरी टर्मिनल वोल्टेज और पावर में व्यापक भिन्नता रेंज पर उच्च रूपांतरण दक्षता की सुविधा के लिए पारंपरिक पृथक डीसी/डीसी चरणों में कोई और संशोधन पेश नहीं किया गया है। चूंकि, पारंपरिक रूप से समान आधे और पूर्ण ब्रिज पृथक डीसी/डीसी कनवर्टर या तो निरंतर वोल्टेज या निरंतर बिजली अनुप्रयोगों (जैसे एलईडी ड्राइवर, ऊर्जा राउटर, दूरसंचार/सर्वर बिजली आपूर्ति, और अन्य सहायक बिजली आपूर्ति) के लिए प्रस्तावित हैं। इस प्रकार, इस शोध कार्य का उद्देश्य पोर्टेबल ईवी चार्जर विकास के लिए सार्वभौमिक डिजाइन अवधारणा पर विचार करके इन सभी उपरोक्त अपर्याप्तताओं और चुनौतियों का समाधान करना है।

इसकी शुरुआत डुअल एक्टिव ब्रिज (डीएबी) डीसी/डीसी कनवर्टर के पारंपरिक हार्डवेयर आर्किटेक्चर में मैग्नेटाइजिंग इंडक्शन की सुंदरता को शामिल करके की गई है। इसके आधार पर, पारंपरिक दोहरे चरण शिफ्ट मॉड्यूलेशन को एक अनुकूलन कानून के साथ संशोधित किया गया है। यह वोल्टेज रूपांतरण अनुपात और पावर ट्रांसफर की विस्तृत श्रृंखला पर

दोनों पूर्ण पुलों के पूर्ण शून्य वोल्टेज स्विचिंग (जेडवीएस) की सुविधा प्रदान करता है। सक्रिय फ्रंट एंड कनवर्टर साइड पर, *IEEE* 1547-2019 के अनुसार किसी भी ग्रिड विसंगतियों पर चार्जर के लगातार संचालन के लिए एक संशोधित प्री-फ़िल्टरिंग चरण प्रस्तुत किया गया है। कम लागत और उच्च वोल्टेज चार्जिंग आवश्यकताओं के लिए, एक तीन स्तरीय डीएबी आधारित डीसी/डीसी बिजली रूपांतरण अवधारणा प्रस्तुत की गई है और इसे स्केल किए गए हार्डवेयर प्रोटोटाइप विकास द्वारा मान्य किया गया है। यह अवधारणा उच्च वोल्टेज ब्रेकिंग क्षमता वाले सिलिकॉन-कार्बाइड MOSFETs के बजाय कम लागत, कम ब्रेक ओवर वोल्टेज सिलिकॉन MOSFETs के उपयोग की सुविधा प्रदान करती है। यह संबंधित डीसी लिंक वोल्टेज के प्रत्येक एमओएसएफईटी पर आधे वोल्टेज तनाव के साथ कनवर्टर के सुरक्षित ऑपरेटिंग क्षेत्र की पहचान करके प्राप्त किया जाता है। विभिन्न ईवी खंडों के लिए वोल्टेज रूपांतरण अनुपात में व्यापक विचलन पर न्यूनतम वर्तमान/वोल्टेज तनाव क्षेत्र के भीतर कनवर्टर संचालन को प्रतिबंधित करने के लिए एक अनुकूलन कानून भी लागू किया गया है।

एलएलसी प्रतिध्वनि कन्वर्टर्स के संचालन के लिए एक बहु-पैरामीट्रिक समन्वित हाइब्रिड नियंत्रण तकनीक प्रस्तावित है। बैटरी वोल्टेज प्रोफ़ाइल भिन्नता के सक्रिय विचार के साथ आधे या पूर्ण ब्रिज अनुनादी नेटवर्क में स्वतंत्रता की अधिकतम संभव डिग्री के आधार पर, नियंत्रण ZVS क्षेत्र के भीतर अपना संचालन बनाए रखता है। हल्के इलेक्ट्रिक वाहन, पीवी और सीवी जैसे विभिन्न ईवी पोर्टफोलियो पर विचार करके, विभिन्न पोर्टेबल चार्जर डिजाइन प्रस्तावित हैं। ये सभी व्यक्तिगत या एकाधिक खंड ईवी मालिकों को ध्यान में रखकर प्रस्तावित किए गए हैं। कुछ डिज़ाइनों में एक ही चार्जर का उपयोग करके पीवी और सीवी के विस्तृत खंड के लिए पोर्टेबल डीसी फास्ट चार्जिंग होती है, जो विभिन्न ईवी चार्जर में निवेश करने के लिए ग्राहक की निर्भरता को कम करती है। दूसरी ओर, यह ओईएम को वाहन में ऑन-बोर्ड चार्जर को शामिल करने पर निर्भरता को खत्म करने में मदद करता है, जिससे वाहन की कुल लागत कम हो जाती है।

सभी प्रस्तावित नियंत्रण, हार्डवेयर या दोनों आर्किटेक्चर डिज़ाइन संशोधनों को मॉडल, सिम्युलेटेड (MATLAB/Simulink), प्रयोगात्मक प्रोटोटाइप पर परीक्षण किया गया है। सभी सत्यापन कई संभावित ग्रिड और बैटरी साइड परिदृश्यों पर लागू किए जाते हैं। इसके अलावा, TI के C2000 माइक्रोकंट्रोलर संस्करणों, THDSDOCK28335 और TMS320F28379D बोर्ड, में प्रस्तावित नियंत्रण आर्किटेक्चर को लागू करने के लिए एक डिजिटल डोमेन दृष्टिकोण भी प्रस्तुत किया गया है। प्रस्तुत कार्य का उद्देश्य सभी प्रकार के ग्राहकों की जरूरतों को पूरा करने के लिए विभिन्न ईवी चार्जर सेगमेंट के प्रभावशाली कॉम्पैक्ट/विश्वसनीय/टिकाऊ मोबाइल डिजाइन और लागत को कम करके विद्युतीकृत परिवहन प्रवृत्ति को बढ़ाना है।

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| DAB | Dual active bridge |
| DPSM/TPSM | Dual phase shift modulation/ Triple phase shift modulation |
| ZVS/ZCS | Zero voltage switching/ Zero current switching |
| KKT | Karush-Kuhn-Tucker |
| MCU | Microcontroller unit |
| FET | Field effect transistor |
| *CMPx/y* | Compare register x & y |
| AFEC | Active front end converter |
| LL | Leakage and Magnetizing inductance |
| SOGI | Second order generalized integrator |
| PLL | Phase locked loop |
| SOSF | Second order sequence filter |
| PC-FFSOGI | Phase compensated second order generalized integrator |
| SHC | Selective harmonic compensation |
| HFT | High-frequency terminals |
| AFFSOGI | Adaptive fixed frequency second order generalized integrator |
| VCR | Voltage conversion ratio |
| DeSAT | Desaturation |
| *CC/CV* | Constant current/constant voltage |
| *DICM/CICM* | Discontinuous inductor current mode/ Continuous inductor current mode |
| *HBLLC* | Half-bridge inductor-inductor-capacitor |
| MPFT | Maximum power factor tracking |
| *RES* | Rising edge shift |
| SPCAM | switching pulse conduction angle modulation |
| SPFM | switching pulse frequency modulation |
| LUT | Look-up table |
| ePWM | Enhanced pulse width modulation |
| FBLLC/HBLLC | Full bridge LLC /Half bridge LLC |
| PFC | Power factor correction |
| APFC | Active power factor correction |

# LIST OF SYMBOLS

| | |
|---|---|
| $v_{ab}$ | Switching voltage of primary H-bridge |
| $v_{cd}$ | Switching voltage of secondary H-bridge |
| $L_t$, $L_m$ | Transfer, and magnetizing inductance |
| $i_{Lt} / i_m$ | Current of transfer/magnetizing inductance |
| $d / \varphi$ | Per unit conduction duty and phase shift |
| $D$ | Phase shift between diagonal MOSFETs |
| $T_{hs}$ | Half-switching time |
| $I_{base}$, $P_{base}$ | Base current and power |
| $k$ or $A$, $N$ | Voltage conversion ratio *'$V_{dc}/NV_b$'* and turn ratio |
| $t_o, t_1, t_2, t_3$ | Switching instants within $T_{hs}$ |
| $i(t_o)/(t_1)/i(t_2)/i(t_3)$ | Instantaneous switching currents. |
| $Q_1$, $Q_2$, $Q_3$, $Q_4$, $Q_5$, $Q_6$ | AFEC stage FETs |
| $P_1$, $P_2$, $P_3$, $P_4$ | Primary MOSFETs. |
| $S_1$, $S_2$, $S_3$, $S_4$ | Secondary MOSFETs. |
| $C_{oss}$ | Output capacitance of MOSFET |
| $I_{peak}$ | Peak value of $i_{Lt}$ |
| $\lambda$ , $\eta$ | KKT multipliers |
| $L$ | Lagrange's function |
| $P_t$, $P_r$ | Actual and reference power transfer |
| $d_{opt} / \varphi_{opt}$ | Optimum values of $d / \varphi$ |
| $V_{in}$, $V_b$, $V_{dc}$ | Input, output and intermediate DC link voltage |
| $V_p$, $V_s$ | Primary and secondary quasi-square voltage |
| $I_b$ | Battery charging current |
| $T_s$, $T_{sw}$, $T_r$, $t_s$ | DC bias propagation time, switching time, rise time, settling time |
| $fc$ | Cost function |
| $W_1$ & $W_2$ | Weighting factor |
| $\mathcal{E}_{dc,k}$ & $\mathcal{E}_{dc,k-1}$ | Error samples of outer voltage loop |
| $\mathcal{E}_{d,k}$ & $\mathcal{E}_{d,k-1}$ | Error samples of *'d'* axis current control loop |
| $\mathcal{E}_{q,k}$ & $\mathcal{E}_{q,k-1}$ | Error samples of *'q'* axis current control loop |
| $\omega$ & $\Delta\omega$ | Fundamental frequency and its deviation |
| $v_{g\alpha,f}$ & $v_{g\beta,f}$ | Filtered $\alpha$, $\beta$ quantities |
| $K$ or $K_1$ | Damping constant (SOGI gain) |
| $K`$ & $\omega`$ | Adaptive deviation in k & ω |
| $q$ | Adaptive fractional deviation in system order |
| $\Theta_{es}$ | Estimated grid voltage angle |
| $i_{b,\ ripple}$ | Ripples content in charging current |
| $i_{b,k}$, $i_{b,k-1}$ | Samples of charging current |
| $i_{b,k-1}^{p}$, $i_{b,k+2}^{p}$ | Predictive samples |

| | |
|---|---|
| $i_{b,k}^{S}$, $i_{b,k-1}^{S}$ | Sensed samples |
| $i_{b,k+2}^{C}$ | Compensated samples |
| $\Delta i_b$ | Deviation from reference and sensed samples |
| $\zeta$ | Coefficient for transition performance |
| $\Delta_{step}$ | Adaptive step change for compensation |
| $f_{sw}/f_{clock,MCU}$ | Marginal deviation provides by MCU |
| $R_{P1}$, $R_{P3}$ | Rising edge switching instant of $P_1$ & $P_3$ |
| $F_{P1}$, $F_{P3}$ | Falling edge switching instant of $P_1$ & $P_3$ |
| $R_{S1}$, $R_{S3}$ | Rising edge switching instant of $S_1$ & $S_3$ |
| $F_{S1}$, $F_{S3}$ | Falling edge switching instant of $S_1$ & $S_3$ |
| $t_s$ | Sampling time |
| $v_s$, $i_s$ | Grid voltage, grid current |
| $L_i$, $R_{if}$, $C_{if}$ | Input EMI filter elements |
| $L_{o1}$, $L_{o2}$, $C_1$, $C_2$ | Intermediate inductors and capacitors |
| $i_{Lo1}$, $i_{Lo2}$, $V_{C1}$, $V_{C2}$ | Intermediate inductor currents and voltages |
| $C_{o1}$, $C_{o2}$ | Split DC link capacitors |
| $D_V$, $D_{D1}$ | Conduction duty of Vienna switch and Diode *‘$D_1$’* |
| $L_r$, $C_r$, $L_m$ | Tank circuit elements (inductors and capacitor) |
| $i_{Lr}$, $v_{isq}$ | Resonating current and switching voltage |
| $V_{cr}$ | Voltage across resonating capacitor |
| $f_r$, $f_p$, $\omega_r$, $\omega_p$ | Resonant and pole frequency in Hz & rad/s |
| $t_d$ | Additional shift in dead duration |
| $C_n$, $L_n$, $\omega_n$, $t_n$ | Respective normalized quantities |
| $M_V$ | Equivalent voltage gain of PFC stage |
| $\varepsilon_{Vdc,k}$, $\varepsilon_{Vdc,k-1}$ | Samples of DC link voltage error |
| $n$ | Turn-ratio of isolation transformer |
| $V^*_{dc}$, $V_{dc,f}$ | Reference and filtered value of DC link voltage |
| $Z_c$ | Characteristics impedance |
| $\omega_{sw}$, $T_{sw}$ | Switching frequency and time of LLC stage |
| $C_n$ | Normalized capacitance |
| $f_c$ $(\omega_c)$, $t_s$ | Cut-off frequency in Hz (in rad/s), sampling time |
| $P_t$ | Terminal power |
| $V_{dc,nom}$, $V_{b,nom}$ | Nominal DC link and battery voltage |
| $\omega_{n,r}$ | Normalized reduced frequency of proposed work |
| $R_{ac}$, $R_L$, $R_D$ | Equivalent AC, load & diode forward resistance |
| $S_{w11}$, $S_{w12}$, $S_{w21}$, $S_{w22}$, | Bidirectional FETs of Vienna Rectifier |
| $D_f$, $D_b$ | Forward and backward conduction diodes of single FET Vienna |
| $N$ | Neutral point |
| $S_N$ | Switching function |
| *Suffix ‘b’* | Boundary conditions except battery side parameters ($V_b$ & $I_b$) |
| *Suffix ‘n’* | Normalized Quantities |

|  |  |
|---|---|
| $Sw_{xy}$ | Bidirectional FETs of respective node |
| $v_g$, $i_g$ | Grid voltage and current |
| $L_{i1}$, $L_{i2}$ | Interleaved inductors |
| $C_{o1}$, $C_{o2}$ | Grid side split capacitors |