DESIGN AND DEVELOPMENT OF LIGHT ELECTRIC VEHICLE CHARGERS

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

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CERTIFICATE

It is certified that the thesis entitled "**Design and Development of Light Electric Vehicle Chargers**," being submitted by **Mr. Jitendra Gupta** 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.

Dated: 23.01.2024

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ABSTRACT

This work deals with the design and development of high performance chargers for the light electric vehicles (LEVs), i.e., electric two wheelers (E2Ws) and electric three wheelers (E3Ws). Several desirable performance features of LEVs chargers from consumers, manufacturers, and power suppliers' perspectives are identified and correspondingly, novel LEV chargers have been designed, analyzed, and implemented in this work. A comprehensive classification of LEV chargers based on the direction of power flow (unidirectional or bidirectional), number of power conversion stages (single or double stages), and need for isolation (nonisolated or isolated) is made in this work. Notably, a wide range of supply and battery voltage conditions are considered when designing and implementing all charger topologies to ensure a general purpose/single charging solution for different classes of LEVs. In this work, the pros and cons of transformers are comprehensively analyzed, and accordingly, different novel nonisolated charging solutions are proposed for the LEV applications. In the proposed nonisolated LEV charging solutions, the applicability of the transformerless gain adjustment techniques, is comprehensively analyzed to achieve desired performance objectives under wide AC and DC side operating conditions. Further, the impact of input-output current ripples on the filter size is explored in these charger topologies, and some novel LEV chargers with continuous input-output current characteristics and low filters size are proposed in this work.

Further, the feasibility of the bidirectional charging system for the LEVs is comprehensively assessed in this work. Correspondingly, various novel bidirectional LEV chargers with grid-to-vehicle (G2V), vehicle-to-grid (V2G), and vehicle-to-home (V2H) modes operational capabilities are proposed for ensuring greater benefits to the LEVs consumers and power suppliers. Further, the seamless mode transfer capability of proposed bidirectional LEV chargers under grid disconnection and reconnection events, is critically analyzed, and correspondingly, a simple yet robust control framework is formulated to achieve desired performance characteristics under normal/abnormal operating conditions.

Notably, all the proposed unidirectional and bidirectional charger configurations are designed and developed to realize improved power quality performance at the supply side and strictly comply with set national/international standards while operating under defined operating conditions. Each charger configuration's operational analysis, design, and control are analyzed comprehensively, considering wide operating conditions. Further, the overall performance of the proposed LEV

chargers is validated through software simulation and hardware implementation, and the obtained results are discussed in detail. Notably, the design, control, and overall performance objectives of the proposed unidirectional LEV chargers are validated under various steady state and dynamic operating conditions. Likewise, the bidirectional LEV chargers’ performance is analyzed under G2V, V2G, and V2H mode conditions during normal/abnormal grid conditions and grid disconnection/reconnection events. Finally, the AC and DC side performance of the proposed unidirectional and bidirectional chargers are matched with set national/international standards to justify their compliance as high-performance LEV charging systems.

सार

यह कार्य हल्के इलेक्ट्रिक वाहनों (एलईवी), यानी इलेक्ट्रिक दोपहिया वाहनों (ई2डब्ल्यू) और इलेक्ट्रिक थ्री व्हीलर (ई3डब्ल्यू) के लिए उच्च प्रदर्शन चार्जर के डिजाइन और विकास से संबंधित है। उपभोक्ताओं, निर्माताओं और बिजली आपूर्तिकर्ताओं के दृष्टिकोण से एलईवी चार्जर की कई वांछनीय प्रदर्शन विशेषताओं की पहचान की गई है और तदनुसार, इस कार्य में नए एलईवी चार्जर को डिजाइन, विश्लेषण और कार्यान्वित किया गया है। इस कार्य में बिजली प्रवाह की दिशा (यूनिडायरेक्शनल या द्विदिश), बिजली रूपांतरण चरणों की संख्या (एकल या डबल चरण), और अलगाव की आवश्यकता (गैर-पृथक या पृथक) के आधार पर एलईवी चार्जर का एक व्यापक वर्गीकरण किया गया है। विशेष रूप से, एलईवी के विभिन्न वर्गों के लिए एक सामान्य उद्देश्य/एकल चार्जिंग समाधान सुनिश्चित करने के लिए सभी चार्जर टोपोलॉजी को डिजाइन और कार्यान्वित करते समय आपूर्ति और बैटरी वोल्टेज स्थितियों की एक विस्तृत श्रृंखला पर विचार किया जाता है। इस कार्य में, ट्रांसफार्मर के पेशेवरों और विपक्षों का व्यापक रूप से विश्लेषण किया जाता है, और तदनुसार, एलईवी अनुप्रयोगों के लिए अलग-अलग उपन्यास नॉनसोलेटेड चार्जिंग समाधान प्रस्तावित किए जाते हैं। प्रस्तावित नॉनसोलेटेड एलईवी चार्जिंग समाधानों में, व्यापक एसी और डीसी साइड ऑपरेटिंग स्थितियों के तहत वांछित प्रदर्शन उद्देश्यों को प्राप्त करने के लिए ट्रांसफार्मर रहित लाभ समायोजन तकनीकों की प्रयोज्यता का व्यापक विश्लेषण किया जाता है। इसके अलावा, इन चार्जर टोपोलॉजी में फ़िल्टर आकार पर इनपुट-आउटपुट वर्तमान तरंगों के प्रभाव का पता लगाया जाता है, और इस कार्य में निरंतर इनपुट-आउटपुट वर्तमान विशेषताओं और कम फ़िल्टर आकार वाले कुछ नए LEV चार्जर प्रस्तावित किए गए हैं।

इसके अलावा, इस कार्य में एलईवी के लिए द्विदिशात्मक चार्जिंग प्रणाली की व्यवहार्यता का व्यापक मूल्यांकन किया गया है। तदनुसार, एलईवी उपभोक्ताओं और बिजली के लिए अधिक लाभ सुनिश्चित करने के लिए ग्रिड-टू-व्हीकल (जी2वी), व्हीकल-टू-ग्रिड (वी2जी), और व्हीकल-टू-होम (वी2एच) मोड परिचालन क्षमताओं के साथ विभिन्न नवीन द्विदिश एलईवी चार्जर प्रस्तावित हैं। आपूर्तिकर्ता। इसके अलावा, ग्रिड डिस्कनेक्शन और रीकनेक्शन घटनाओं के तहत प्रस्तावित द्विदिश एलईवी चार्जर्स की निर्बाध मोड ट्रांसफर क्षमता का गंभीर रूप से विश्लेषण किया जाता है, और तदनुसार, सामान्य/असामान्य परिचालन स्थितियों के तहत वांछित प्रदर्शन विशेषताओं को प्राप्त करने के लिए एक सरल लेकिन मजबूत नियंत्रण ढांचा तैयार किया जाता है।

विशेष रूप से, सभी प्रस्तावित यूनिडायरेक्शनल और बाइडायरेक्शनल चार्जर कॉन्फ़िगरेशन को आपूर्ति पक्ष में बेहतर बिजली गुणवत्ता प्रदर्शन का एहसास करने और परिभाषित परिचालन स्थितियों के तहत संचालन करते समय निर्धारित राष्ट्रीय/अंतर्राष्ट्रीय मानकों का सख्ती से अनुपालन करने के लिए डिज़ाइन और विकसित किया गया है। व्यापक परिचालन स्थितियों पर विचार करते हुए, प्रत्येक चार्जर कॉन्फ़िगरेशन के परिचालन विश्लेषण, डिज़ाइन और नियंत्रण का व्यापक विश्लेषण किया जाता है। इसके अलावा, प्रस्तावित एलईवी चार्जर्स के समग्र प्रदर्शन को सॉफ्टवेयर सिमुलेशन और हार्डवेयर कार्यान्वयन के माध्यम से मान्य किया गया है, और प्राप्त परिणामों पर विस्तार से चर्चा की गई है। विशेष रूप से, प्रस्तावित यूनिडायरेक्शनल एलईवी चार्जर्स के डिजाइन, नियंत्रण और समग्र प्रदर्शन उद्देश्यों को विभिन्न स्थिर स्थिति और गतिशील परिचालन स्थितियों के तहत मान्य किया गया है। इसी तरह, सामान्य/असामान्य ग्रिड स्थितियों और ग्रिड डिस्कनेक्शन/रीकनेक्शन घटनाओं के दौरान जी2वी, वी2जी और वी2एच मोड स्थितियों के तहत द्विदिश एलईवी चार्जर्स के प्रदर्शन का विश्लेषण किया जाता है। अंत में, प्रस्तावित यूनिडायरेक्शनल और बाइडायरेक्शनल चार्जर्स के एसी और डीसी साइड प्रदर्शन को उच्च-प्रदर्शन वाले एलईवी चार्जिंग सिस्टम के रूप में उनके अनुपालन को उचित ठहराने के लिए निर्धारित राष्ट्रीय/अंतर्राष्ट्रीय मानकों के साथ मिलान किया जाता है।

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Fig. 4.28. Simulated Performance of FBLPOBB PFC AC-DC Converter based LEV Charger Under Steady State Nominal Operating Condition (a) v_s, i_s, v_{bat}, i_{bat}, v_{Cf1}, v_{cf2}, i_{pri1}, and i_{sec1} (b) v_s, v_{S1}, i_{S1}, v_{S2}, i_{S2}, v_{Do1}, i_{Do1}, v_{Do2}, and i_{Do2}.

Fig. 4.29. Experimental performance of FBLPOBB PFC AC-DC converter based LEV charger under steady state nominal operating condition (a) v_s, i_s, v_{bat}, and i_{bat} (b) v_s, v_{Cf2}, and v_{Cf1} (c) v_s, v_{S1}, v_{S2}, and i_{S1} (d) v_s, v_{Do1}, v_{Do2}, and i_{Do1}.

Fig. 4.30. Simulated performance of FBLPOBB PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V to 85 V and (b) 220 V to 265 V.

Fig. 4.31. Experimental performance of FBLPOBB PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 85 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.

Fig. 4.32. Simulated performance of FBLPOBB PFC AC-DC converter based LEV charger under charging current dynamics from (a) 100% to 50%, and (b) 50% to 100% Rated Conditions.

Fig. 4.33. Experimental performance of FBLPOBB PFC AC-DC converter based LEV charger under charging current dynamics (a) 100% to 50%, and (b) 50% to 100% of Rated Conditions.

Fig.4.34. Simulated supply side power quality performance of FBLPOBB PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a) 220 V, (b) 265 V, and (c) 85 V.

Fig.4.35. Experimental validation of supply side power quality performance of FBLPOBB PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a)-(c) 220 V (d)-(f) 250 V, and (g)-(i) 95 V.

Fig. 4.36. Experimental validation of supply side power quality performance of FBLPOBB PFC AC-DC converter based LEV charger at low power conditions and supply voltage of (a)-(c) 220 V (d)-(f) 250 V, and (g)-(i) 85 V.

Fig. 4.37. Experimental performance of FBLPOBB PFC AC-DC converter based LEV during (a) Starting and (b) Stopping battery charging process at rated power condition.

Fig. 4.38. Simulated Performance of BLPOL PFC AC-DC Converter based LEV Charger Under Steady State Nominal Operating Condition (a) v_s, i_s, v_{bat}, i_{bat}, v_{C1}, i_{Lo}, and i_{sec} (b) v_s, v_{S1}, i_{S1}, v_{S2}, i_{S2}, v_{Do}, and i_{Do}.

Fig. 4.39. Experimental performance of BLPOL PFC AC-DC converter based LEV charger under steady state nominal operating condition (a) v_s, i_s, v_{bat}, and i_{bat} (b) v_s, v_{C1}, i_{Lo}, and i_{Do} (c) v_s, v_{S1}, i_{S1}, and i_{Do} (d) v_s, v_{S2}, v_{S1}, and v_{Do}, (e) v_{S1}, v_{S2}, v_{Db1}, and v_{Db2}.

Fig. 4.40. Simulated performance of BLPOL PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 85 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.

Fig. 4.41. Experimental performance of BLPOL PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 85V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.

Fig.4.42. Simulated supply side power quality performance of BLPOL PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a) 220 V, (b) 265 V, and (c) 85 V.

Fig.4.43. Experimental validation of supply side power quality performance of BLPOL PFC AC-DC converter-based LEV charger at rated power condition and supply voltage of (a)-(c) 220 V (d)-(f) 265 V, and (g)-(i) 85 V.

Fig. 4.44. Simulated Performance of FBLPOL PFC AC-DC Converter based LEV Charger Under Steady State Nominal Operating Condition (a) v_s, i_s, v_{bat}, i_{bat}, v_{Cf1}, v_{cf2}, v_{C1}, and i_{Lo} (b) v_s, v_{S1}, i_{S1}, v_{S2}, i_{S2}, v_{Do1}, i_{Do1}, v_{Do2}, and i_{Do2}.

Fig. 4.45. Experimental performance of FBLPOL PFC AC-DC converter based LEV charger under steady state nominal operating condition (a) v_s, i_s, v_{bat}, and i_{bat} (b) v_s, v_{Cf1}, v_{C1}, and i_{Lo} (c) v_s, v_{Cf1}, and v_{Cf2} (c) v_s, v_{S2}, v_{S1}, and i_{S1} (d) v_s, v_{Do1}, v_{Do2}, and i_{Do1}.

Fig. 4.46. Simulated performance of FBLPOL PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 85 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.

Fig. 4.47. Experimental performance of FBLPOL PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 85 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.

Fig. 4.48. Simulated performance of FBLPOL PFC AC-DC converter based LEV charger under charging current dynamics from (a) 100% to 50% and (b) 50% to 100% of Rated Condition.

Fig. 4.49. Experimental performance of FBLPOL PFC AC-DC converter based LEV charger under charging current dynamics (a) 100% to 50%, and (b) 50% to 100% of Rated Conditions.

Fig.4.50. Simulated supply side power quality performance of FBLPOL PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a) 220 V, (b) 265 V, and (c) 85 V.

Fig.4.51. Experimental validation of supply side power quality performance of FBLPOL PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a)-(c) 220 V (d)-(f) 250 V, and (g)-(i) 95 V.

Fig. 4.52. Experimental validation of supply side power quality performance of FBLPOL PFC AC-DC converter based LEV charger at low power conditions and supply voltage of (a)-(c) 220 V (d)-(f) 250 V, and (g)-(i) 85 V.

Fig. 4.53. Experimental performance of FBLPOL PFC AC-DC converter based LEV during (a) Starting and (b) Stopping battery charging process at rated power condition.

Fig. 4.54. Simulated Performance of BLSEPIC PFC AC-DC Converter based LEV Charger Under Steady State Nominal Operating Condition (a) v_s, i_s, v_{bat}, i_{bat}, i_{pri}, v_{C1}, v_{C2}, i_{Li1}, and i_{Li2} (b) v_s, v_{S1}, i_{S1}, v_{D1}, v_{D2}, v_{Do}, i_{Do}, $v_{Db1}$and v_{Db2}.

Fig. 4.55. Experimental performance of BLSPEIC PFC AC-DC converter based LEV charger under steady state nominal operating condition (a) v_s, i_s, v_{bat}, and i_{bat} (b) v_{C1}, v_{C2}, i_{Li2}, and i_{Li1} (c) v_s, v_{D2}, and v_{D1} (d) v_{S1}, i_{pri}, v_{Do}, and i_{sec}.

Fig. 4.56. Simulated performance of BLSEPIC PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V to 160 V and (b) 220 V to 265 V.

Fig. 4.57. Experimental performance of BLSEPIC PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 150 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.

Fig. 4.58. Simulated performance of BLSEPIC PFC AC-DC converter based LEV charger under charging current dynamics from (a) 100% to 50% and (b) 50% to 100% of Rated Condition.

Fig. 4.59. Experimental performance of BLSEPIC PFC AC-DC converter based LEV charger during charging current dynamics (a) 100% to 50%, and (b) 50% to 100% of Rated Condition.

Fig.4.60. Simulated supply side power quality performance of BLSEPIC PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a) 220 V, (b) 265 V, and (c) 160 V.

Fig.4.61. Experimental validation of supply side power quality performance of BLSEPIC PFC AC-DC converter-based LEV charger at rated power condition and supply voltage of (a)-(c) 220 V (d)-(f) 260 V, and (g)-(i) 150 V.
Fig.4.62. Experimental validation of supply side power quality performance of BLSEPIC PFC AC-DC converter-based LEV charger at low power conditions and supply voltage of (a)-(c) 220 V (d)-(f) 265 V, and (g)-(i) 85 V.
Fig. 4.63. Experimental performance of BLSEPIC PFC AC-DC converter-based LEV during Starting of battery charging process at rated power condition.
Fig. 4.64. Simulated Performance of BLPOC PFC AC-DC Converter based LEV Charger Under Steady State Nominal Operating Condition (a) v_s, i_s, v_{bat}, i_{bat}, v_{C1}, v_{C2}, and i_{Lo} (b) v_s, v_{S1}, i_{S1}, v_{S2}, i_{S2}, v_{Do}, and i_{Do}.
Fig. 4.65. Experimental performance of BLPOC PFC AC-DC converter-based LEV charger under steady state nominal operating condition (a) v_s, i_s, v_{bat}, and i_{bat} (b) v_s, v_{C1}, v_{C2}, and i_{Lo} (c) v_{S1}, v_{S2}, v_{Do}, and i_{Lo} (d) v_s, v_{S2}, v_{S1}, and v_{Do}.
Fig. 4.66. Simulated performance of BLPOC PFC AC-DC converter-based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.
Fig. 4.67. Experimental performance of BLPOC PFC AC-DC converter-based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.
Fig. 4.68. Simulated performance of BLPOC PFC AC-DC converter-based LEV charger under charging current dynamics from (a) 100% to 50% and (b) 50% to 100% of Rated Conditions.
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Fig.4.70. Simulated supply side power quality performance of BLPOL PFC AC-DC converter-based LEV charger at rated power condition and supply voltage of (a) 220 V, (b) 265 V, and (c) 160 V.
Fig.4.71. Experimental validation of supply side power quality performance of BLPOC PFC AC-DC converter-based LEV charger at rated power condition and supply voltage of (a)-(c) 220 V (d)-(f) 250 V, and (g)-(i) 160 V.
Fig.4.72. Experimental validation of supply side power quality performance of BLPOC PFC AC-DC converter-based LEV charger at low power conditions and supply voltage of (a)-(c) 220 V (d)-(f) 250 V, and (g)-(i) 85 V.
Fig. 4.73. Experimental performance of BLPOC PFC AC-DC converter-based LEV during (a) Starting and (b) Stopping battery charging process at rated power condition.
Fig. 4.74. Simulated Performance of BLMSPEIC PFC AC-DC Converter based LEV Charger Under Steady State Nominal Operating Condition (a) v_s, i_s, v_{bat}, i_{bat}, v_{C1}, v_{Cs1}, v_{Cs2}, i_{Lo}, and i_{sec}, (b) v_s, v_{S1}, i_{S1}, v_{S2}, i_{S2}, v_{Ds1}, i_{Ds1}, v_{Ds2}, and i_{Ds2}.

Fig. 4.75. Experimental performance of BLMSPEIC PFC AC-DC converter-based LEV charger under steady state nominal operating condition (a) v_s, i_s, v_{bat}, and i_{bat} (b) v_{C1}, v_{Cs1}, v_{Cs2}, and i_{Lo} (c) v_{Ds1}, v_{Ds2}, i_{pri}, and i_{sec}, (d) v_s, v_{S1}, v_{S2}, and v_{Ds1}.
Fig. 4.76. Simulated performance of BLMSEPIC PFC AC-DC converter-based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.
Fig. 4.77. Experimental performance of BLMSEPIC PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.
Fig. 4.78. Simulated performance of BLMSEPIC PFC AC-DC converter based LEV charger under charging current dynamics from (a) 100% to 50% and (b) 50% to 100% of Rated Conditions.
Fig. 4.79. Experimental performance of BLMSPEIC PFC AC-DC converter-based LEV charger during charging current dynamics (a) 100% to 50%, and (b) 50% to 100% of Rated Condition.
Fig.4.80. Simulated supply side power quality performance of BLMSEPIC PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a) 220 V, (b) 265 V, and (c) 160 V.
Fig.4.81. Experimental validation of supply side power quality performance of BLMSEPIC PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a)-(c) 220 V (d)-(f) 250 V, and (g)-(i) 160 V.
Fig.4.82. Experimental validation of supply side power quality performance of BLMSEPIC PFC AC-DC converter based LEV charger at low power conditions and supply voltage of (a)-(c) 220 V (d)-(f) 260 V, and (g)-(i) 90 V.
Fig. 4.83. Experimental performance of BLMSEPIC PFC AC-DC converter based LEV Charger during (a) Starting and (b) Stopping battery charging process at rated power condition.
Fig. 4.84. Efficiency Versus Battery Current Graph for (a) FBLPOBB, (b) BLPOL, (c) FBLPOL, (d) BLSEPIC, (e) BLPOC, and (f) BLMSEPIC PFC AC-DC converter based LEV Chargers.
Fig. 5.1. PBLCSC PFC Converter based Unidirectional Double Stage Non-isolated LEV Charger.
Fig. 5.2. FBLCSC PFC Converter based Unidirectional Double Stage Nonisolated LEV Charger.
Fig. 5.3. Equivalent Circuit of PBLCSC PFC AC-DC Converter based LEV Charger during (a) Positive and (b) Negative Half Cycle of v_s.
Fig. 5.4. Operating Modes of PBLCSC PFC AC-DC Converter Based LEVs Charger within a Switching Cycle (during Positive Half of v_s) (a) *Mode–P*(*I*) $\{0 < t \leq D_S T_S\}$ (b) *Mode*–P(II) $\{D_S T_S < t \leq (D_S + D_D)\, T_S\}$ (c) *Mode–P*(*III*) $\{(D_S + D_D)\, T_S < t \leq T_S\}$

Fig. 5.5. Switching Cycle Voltage/Current Waveforms of PBLCSC PFC AC-DC Converter Based LEV Charger during (a) Positive and (b) Negative Half of v_s.
Fig. 5.6. Operating Modes of PBLCSC PFC AC-DC Converter Based LEVs Charger within a Switching Cycle (Negative Half of v_s) (a) *Mode–N*(*I*) $\{0 < t \le D_S T_S\}$ (b) *Mode–N*(*II*) $\{D_S T_S < t \le (D_S+D_D)\, T_S\}$ (c) *Mode–N*(*III*) $\{(D_S+D_D)\, T_S < t \le T_S\}$.
Fig. 5.7. (a)-(b) Operating Modes of HGB DC-DC Stage within a Switching Cycle (a) *Mode–1* $\{0 < t \le D_b T_s\}$ (b) *Mode–2* $\{D_b T_s < t \le T_s\}$and (c) Switching Cycle Voltage/Current Waveforms.
Fig. 5.8. Equivalent Circuit of FBLCSC PFC AC-DC Converter based LEV Charger during (a) Positive and (b) Negative Half Cycle of v_s.
Fig. 5.9. Operating Modes of FBLCSC PFC AC-DC Converter Based LEVs Charger within a Switching Cycle (during Positive Half of v_s) (a) *Mode–P*(*I*) $\{0 < t \le D_S T_s\}$ (b) *Mode*–P(II) $\{D_S T_s < t \le (D_S+D_D)\, T_s\}$ (c) *Mode–P*(*III*) $\{(D_S+D_D)\, T_s < t \le T_s\}$.
Fig. 5.10. Operating Modes of FBLCSC PFC AC-DC Converter Based LEVs Charger within a Switching Cycle (during Negative Half of v_s) (a) *Mode–N*(*I*) $\{0 < t \le D_S T_s\}$ (b) *Mode–N*(*II*) $\{D_S T_s < t \le (D_S+D_D)\, T_s\}$ (c) *Mode–N*(*III*) $\{(D_S+D_D)\, T_s < t \le T_s\}$.
Fig. 5.11. Switching Cycle Voltage/Current Waveforms of FBLCSC PFC AC-DC Converter Based LEV Charger during (a) Positive and (b) Negative Half of v_s.
Fig. 5.12. Control Block Diagram for PBLCSC PFC AC-DC Stage of Unidirectional Double Stage Non-isolated LEV Charger.
Fig. 5.13. Control Block Diagram for HGB DC-DC Stage of Unidirectional Double Stage Nonisolated LEV Charger.
Fig. 5.14. Variation of HGB Switch Duty Ratio at Different V_{bat} with and without V_{DC} Variations.
Fig. 5.15. Control Block Diagram for FBLCSC PFC AC-DC Stage of Unidirectional Double Stage Nonisolated LEV Charger.
Fig. 5.16. General Block Diagram for Software Modelling and MATLAB Simulation of Unidirectional Double Stage Non-isolated LEV Chargers.
Fig. 5.17. Test Bench Photograph for Unidirectional Double Stage Nonisolated LEV Chargers.
Fig. 5.18. Simulated Performance of PBLCSC PFC AC-DC Converter based LEV Charger Under Steady State Nominal Operating Condition (a) v_s, i_s, v_{DC}, v_{bat}, i_{bat}, v_{C1}, v_{C2}, i_{Li1}, i_{Li2}, i_{Ls1}, and i_{Ls2} (b) v_s, v_{S1}, v_{S2}, i_{S1}, v_{D1}, v_{D2}, i_{D1}, v_{S3}, v_{Ds1}, and v_{Ds2}.
Fig. 5.19. Experimental performance of PBLCSC PFC AC-DC converter based LEV charger under steady state nominal operating condition (a) v_s, i_s, v_{DC}, and i_{bat} (b) v_s, i_s, v_{bat}, and i_{bat} (c) v_s, v_{S1}, v_{D1}, and i_{Li1} (d) v_s, v_{S2}, v_{D2}, and i_{Li2} (e) v_s, v_{C1}, v_{C2}, and v_{DC} (f) v_{S2}, v_{S1}, v_{D1}, and v_{D2} (g) v_{S3}, v_{Ds1}, i_{Ls1}, and i_{Ls2} (h) v_{DC}, v_{S3}, v_{Ds1}, and v_{Ds2}.
Fig. 5.20. Simulated performance of PBLCSC PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.

Fig. 5.21. Experimental performance of PBLCSC PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.

Fig. 5.22. Simulated performance of PBLCSC PFC AC-DC converter based LEV charger under charging current dynamics from (a) 100 % to 50%, and (b) 50 % to 100 % Conditions.

Fig. 5.23. Experimental performance of PBLCSC PFC AC-DC converter-based LEV charger under charging current dynamics (a) Rated to Half of Rated, and (b) Half of Rated to Rated Conditions.

Fig. 5.24. Simulated supply side power quality performance of PBLCSC PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a) 220 V, (b) 160 V, and (c) 265 V.

Fig. 5.25. Experimental validation of supply side power quality performance of PBLCSC PFC AC-DC converter based LEV charger at P_{rated} and v_s of (a)-(c) 220 V (d)-(f) 160 V, and (g)-(i) 255 V.

Fig. 5.26. Experimental validation of supply side power quality performance of PBLCSC PFC based LEV charger at low power condition and v_s of (a)-(c) 220 V (d)-(f) 250 V, and (g)-(i) 110 V.

Fig. 5.27. Simulated Performance of FBLCSC PFC AC-DC Converter based LEV Charger Under Steady State Nominal Operating Condition (a) v_s, i_s, v_{DC}, v_{bat}, i_{bat}, v_{Cf1}, v_{Cf2}, v_{C1}, v_{C2}, i_{Li1}, i_{Li2}, i_{Ls1}, and i_{Ls2} (b) v_s, v_{S1}, i_{S1}, v_{S2}, i_{S2}, v_{D1}, i_{D1}, v_{D2}, i_{D2}, v_{S3}, i_{S3}, v_{Ds1}, and v_{Ds2}.

Fig. 5.28. Experimental performance of FBLCSC PFC AC-DC converter based LEV charger under steady state nominal operating condition (a) v_s, i_s, v_{DC}, and i_{bat} (b) v_s, i_s, v_{bat}, and i_{bat} (c) v_s, v_{S1}, v_{D1}, and i_{Li1} (d) v_s, v_{S2}, v_{D2}, and i_{Li2} (e) v_{S1}, v_{D1}, v_{S2}, and v_{D2} (f) v_{Cf1}, v_{C2}, v_{Cf2}, and v_{C1} (g) v_{DC}, v_{S3}, v_{Ds1}, and v_{Ds2} (h) v_{S3}, v_{Ds1}, i_{Ls1}, and i_{Ls2}.

Fig. 5.29. Simulated performance of FBLCSC PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.

Fig. 5.30. Experimental performance of FBLCSC PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.

Fig. 5.31. Simulated performance of FBLCSC PFC AC-DC converter based LEV charger under charging current dynamics from (a) 100 % to 50%, and (b) 50 % to 100 % Conditions.

Fig. 5.32. Experimental performance of FBLCSC PFC AC-DC converter based LEV charger under charging current dynamics (a) Rated to Half of Rated, and (b) Half of Rated to Rated Conditions.

Fig. 5.33. Variable DC Link Voltage Control of FBLCSC PFC AC-DC converter based LEV charger.

Fig. 5.34. Simulated supply side power quality performance of FBLCSC PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a) 220 V, (b) 160 V, and (c) 265 V.

Fig. 5.35. Experimental validation of supply side power quality performance of FBLCSC PFC AC-DC converter based LEV charger at P_{rated} and v_s of (a)-(c) 220 V (d)-(f) 160 V, and (g)-(i) 250 V.

Fig. 5.36. Experimental validation of supply side power quality performance of FBLCSC PFC-based LEV charger at low power conditions and v_s of (a)-(c) 220 V (d)-(f) 250 V, and (g)-(i) 110 V.

Fig. 5.37. Efficiency Versus Power Graph for PBLCSC and FBLCSC PFC AC-DC Stages under Wide v_s and Power Range Condition (@ V_{DC} = 300 V).

Fig. 5.38. Efficiency Versus Power Graph for HGB DC-DC Stage and PBLCSC/FBLCSC PFC Based Charger at Rated Operating Conditions (i.e., VDC = 300 V, Vbatn = 60 V, Vs = 220 V).

Fig. 6.1 ILCSC PFC AC-DC Converter based Unidirectional Double Stage Isolated LEV Charger.

Fig. 6.2 MSCCSC PFC AC-DC Converter based Unidirectional Double Stage Isolated LEV Charger.

Fig. 6.3. ILCSC PFC AC-DC Converter Switching Devices Operating States within a Switching Cycle during (a) Overlapped (b) Non-overlapped Inductor Current Conditions.

Fig. 6.4. Switching Equivalent Circuits of ILCSC PFC AC-DC Stage under Overlapped Inductor Current Condition during (a) State-I (b) State-II (c) State-III (d) State-IV (e) State-V (f) State-VI.

Fig. 6.5. Switching Equivalent Circuits of ILCSC PFC AC-DC Stage under Non-Overlapped Inductor Current Condition during (a) State-I (b) State-II (c) State-III (d) State-IV (e) State-V (f) State-VI.

Fig. 6.6. Waveforms across ILCSC PFC Converter's Components under all Six Switching Modes for Inductor Current (a) Overlapping (b) Non-overlapping Conditions.

Fig. 6.7. (a)-(b) Operating Modes of IPOC DC-DC Stage within a Switching Cycle (a) *Mode–1* $\{0 < t \leq D_bT_s\}$ (b) *Mode–2* $\{D_bT_s < t \leq T_s\}$and (c) Switching Cycle Voltage/Current Waveforms.

Fig. 6.8. Circuit Schematic of (a) Conventional CSC [40], (b) Modified CSC, and (c) Proposed MSCCSC PFC AC-DC Converters.

Fig. 6.9. Switching Cycle Equivalent Circuits of MSCCSC PFC AC-DC Converter (a) State–I, (b) State–II, (c) State–III, and (d) Switching Cycle Voltage and Current Waveforms

Fig. 6.10. Voltage Gain of Conventional CSC [40] and MSCCSC PFC AC-DC Converters.

Fig. 6.11. Control Block Diagram for ILCSC PFC AC-DC Stage of Unidirectional Double Stage Isolated LEV Charger.

Fig. 6.12. Control Block Diagram for IPOC DC-DC Stage of Unidirectional Double Stage Isolated LEV Charger.
Fig. 6.13. Control Block Diagram for MSCCSC PFC AC-DC Stage of Unidirectional Double Stage Isolated LEV Charger.
Fig. 6.14. General Block Diagram for Software Modelling and MATLAB Simulation of Unidirectional Double Stage Isolated LEV Chargers.
Fig. 6.15. Simulated Performance of ILCSC PFC AC-DC Converter based LEV Charger Under Steady State Nominal Operating Condition (a) v_s, i_s, v_{DC}, v_{bat}, i_{bat}, v_{C1}, v_{C2}, i_{Li1}, i_{Li2}, v_{S1}, v_{S2}, v_{D1}, and v_{D2}, and (b) v_{DC}, v_{bat}, i_{bat}, v_{C1c}, v_{C2c}, i_{Lic}, i_{Loc}, v_{Sc}, i_{Sc}, v_{Dc}, and i_{Dc}.
Fig. 6.16. Experimental performance of ILCSC PFC AC-DC converter based LEV charger under steady state nominal operating condition (a) v_s, i_s, v_{DC}, and i_{bat} (b) v_{C1}, v_{C2}, i_{Li1}, and i_{Li2} (c) v_{S1}, v_{S2}, i_{Li1}, and i_{Li2} (d) v_{S2}, v_{S1}, v_{D1}, and v_{D2} (e) v_{Sc}, v_{Dc}, i_{Lic}, and i_{Loc}, and (f) v_{DC}, v_{C1c}, v_{C2c}, and v_{bat}.
Fig. 6.17. Simulated performance of ILCSC PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V to 160 V and (b) 220 V to 265 V.
Fig. 6.18. Experimental performance of ILCSC PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V to 160 V and (b) 220 V to 265 V_{RMS}.
Fig. 6.19. Simulated performance of ILCSC PFC AC-DC converter based LEV charger under charging current dynamics from (a) 100 % to 50%, and (b) 50 % to 100 % Conditions.
Fig. 6.20. Experimental performance of ILCSC PFC AC-DC converter-based LEV charger under-charging current dynamics (a) 100%-50%, and (b) 50 %-100 % Conditions.
Fig. 6.21. Simulated supply side power quality performance of ILCSC PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a) 220 V, (b) 265 V, and (c) 160 V.
Fig. 6.22. Experimental validation of supply side power quality performance of ILCSC PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a)-(c) 220 V (d)-(f) 265 V, and (g)-(i) 160 V.
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Fig. 6.24. Simulated Performance of MSCCSC PFC AC-DC Converter based LEV Charger Under Steady State Nominal Operating Condition (a) v_s, i_s, v_{DC}, v_{bat}, i_{bat}, v_{C1}, v_{Cs1}, v_{Cs2}, i_{Li}, i_{Lo}, v_{S1}, v_{Ds1}, and v_{Ds2}, and (b) v_{DC}, v_{bat}, i_{bat}, v_{C1c}, v_{C2c}, i_{Lic}, i_{Loc}, v_{Sc}, i_{Sc}, v_{Dc}, and i_{Dc}.
Fig. 6.25. Experimental performance of MSCCSC PFC AC-DC converter based LEV charger under steady state nominal operating condition (a) v_s, i_s, v_{DC}, and i_{bat} (b) v_{C1}, v_{Cs1}, v_{Cs2}, and i_{Lo} (c) v_s, v_{S1}, v_{Ds1}, and i_{Li} (d) v_s, v_{S1}, v_{Ds1}, and v_{Ds2} (e) v_{DC}, v_{C1c}, v_{C2c}, and v_{bat}, and (f) v_{Sc}, v_{Dc}, i_{Lic}, and i_{Loc}.

Fig. 6.26. Experimental performance of MSCCSC PFC AC-DC converter based LEV charger under Wide Operating Range Condition, V_s, I_s, and V_{DC}, when (a) V_s = 85 V_{RMS} & V_{DC} = 400 V, (b) V_s = 85 V_{RMS} & V_{DC} = 200 V, (c) V_s = 265 V_{RMS} & V_{DC} = 400 V, and (d) V_s = 265 V_{RMS} & V_{DC} = 200 V.
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Fig. 6.28. Experimental performance of MSCCSC PFC AC-DC converter based LEV charger under supply voltage dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS}.
Fig. 6.29. Simulated performance of MSCCSC PFC AC-DC converter based LEV charger under charging current dynamics from (a) 100 % to 50%, and (b) 50 % to 100 % Conditions.
Fig. 6.30. Experimental performance of MSCCSC PFC AC-DC converter-based LEV charger under charging current dynamics (a) 100 % to 50%, and (b) 50 % to 100 % Conditions.
Fig. 6.31. Simulated supply side power quality performance of MSCCSC PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a) 220 V, (b) 265 V, and (c) 160 V.
Fig. 6.32. Experimental validation of supply side power quality performance of MSCCSC PFC AC-DC converter based LEV charger at rated power condition and supply voltage of (a)-(c) 220 V (d)-(f) 265 V, and (g)-(i) 165 V.
Fig. 6.33. Experimental validation of supply side power quality performance of MSCCSC PFC AC-DC converter-based LEV charger at low power conditions and supply voltage of (a)-(c) 220 V (d)-(f) 250 V, and (g)-(i) 85 V.
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Fig. 7.1 ASIC Converter based Bidirectional Single Stage Nonisolated LEV Charger.
Fig. 7.2. ASISEPIC Converter based Bidirectional Single Stage Nonisolated LEV Charger.
Fig. 7.3. Operating Modes of ASIC Converter Based Bidirectional LEVs Charger during (a) G2V (b) V2G (for positive half of v_s) and (c) V2G (for negative half of v_s).
Fig. 7.4. Switching Cycle Operating Modes of ASIC Converter Based Bidirectional LEVs Charger during G2V Mode Operation (a) Mode–G2V (I) ($t_0 < t \leq t_1$) (b) Mode–G2V (II) ($t_1 < t \leq t_2$) (c) Mode–G2V (III) ($t_2 < t \leq t_3$).
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Fig. 7.6. Switching Cycle Voltage and Current Waveforms for ASIC Converter Based Bidirectional LEVs Charger during (a) G2V and (b) V2G (Positive Half of v_s) Modes of Operation.

Fig. 7.7. Operating Modes of ASISEPIC Converter Based Bidirectional LEVs Charger during (a) G2V (b) V2G (positive half of v_s) and (c) V2G (for negative half of v_s).
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Fig. 7.9. Switching Cycle Operating Modes of ASISEPIC Converter Based Bidirectional LEVs Charger during V2G Mode Operation (Positive Half of v_s) (a) Mode–V2G (P_1) ($t_0 < t \leq t_1$) (b) Mode–V2G (P_2) ($t_1 < t \leq t_2$) (c) Mode–V2G (P_3) ($t_2 < t \leq t_3$).
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Fig. 7.11. Control Block Diagram for Bidirectional Single Stage Nonisolated LEV Chargers.
Fig. 7.12. General Block Diagram for Software Modelling and MATLAB Simulation of Bidirectional Single Stage Nonisolated LEV Chargers.
Fig. 7.13. Proof-of-Concept Test Bench Set-up for Bidirectional Single Stage Nonisolated LEV Chargers.
Fig. 7.14. Simulated Steady State Performance of ASIC Converter-based Bidirectional LEV Charger during G2V Mode Operation (a) v_s, i_s, v_{bat}, i_{bat}, i_{Li}, v_{C1}, i_{Ls1}, and i_{Ls2} (b) v_s, v_{S1}, i_{S1}, v_{Ss1}, v_{Ss2}, i_{Ss1}, v_{Sa1}, i_{Sa1}, v_{Sa2}, i_{Sa2}, v_{Sa3}, and v_{Sa4}.
Fig. 7.15. Experimental Steady State performance of ASIC Converter based Bidirectional LEV charger during G2V Mode Operation (a) v_s, i_s, v_{bat}, and i_{bat} (b) v_s, i_s, i_{Li}, and v_{C1} (c) v_{Ss1}, v_{Ss2}, i_{Ls1}, and i_{Ls2} (d) v_s, v_{S1}, v_{Ss1}, and v_{Ss2}.
Fig. 7.16. Simulated performance of ASIC Converter based Bidirectional LEV charger during G2V Mode Operation under (a)-(b) v_s dynamics from (a) 220 $\mathrm{V}_{\mathrm{RMS}}$ to 160 $\mathrm{V}_{\mathrm{RMS}}$ and (b) 220 $\mathrm{V}_{\mathrm{RMS}}$ to 265 $\mathrm{V}_{\mathrm{RMS}}$ and (c)-(d) i_{bat} dynamics from (c) 100% to 50%, and (d) 50% to 100% Conditions.
Fig. 7.17. Experimental performance of ASIC Converter based Bidirectional LEV charger during G2V Mode Operation under (a)-(b) v_s dynamics from (a) 220 $\mathrm{V}_{\mathrm{RMS}}$ to 160 $\mathrm{V}_{\mathrm{RMS}}$ and (b) 220 $\mathrm{V}_{\mathrm{RMS}}$ to 265 $\mathrm{V}_{\mathrm{RMS}}$ and (c)-(d) i_{bat} dynamics from (c) 100% to 50%, and (d) 50% to 100% Conditions.
Fig. 7.18. Simulated supply side power quality performance of ASIC Converter based Bidirectional LEV charger during G2V Mode and supply voltage of (a) 220 V, (b) 160 V, and (c) 265 V.
Fig. 7.19. Experimental validation of supply side power quality performance of ASIC Converter-based LEV charger during G2V and supply voltage of (a)-(c) 220 V (d)-(f) 160 V, and (g)-(i) 255 V.
Fig. 7.20. Simulated Steady State Performance of ASIC Converter based Bidirectional LEV Charger during V2G Mode Operation (a) v_s, i_s, v_{bat}, i_{bat}, i_{Li}, v_{C1}, i_{Ls1}, and i_{Ls2} (b) v_s, v_{S1}, i_{S1}, v_{Ss1}, v_{Ss2}, i_{Ss1}, v_{Sa1}, i_{Sa1}, v_{Sa2}, i_{Sa2}, v_{Sa3}, and v_{Sa4}.

Fig. 7.21. Experimental Steady State performance of ASIC Converter based Bidirectional LEV charger during V2G Mode Operation (a) v_s, i_s, v_{bat}, and i_{bat} (b) v_s, i_s, i_{Li}, and v_{C1} (c) v_{Ss1}, v_{Ss2}, i_{Ls1}, and i_{Ls2} (d) v_s, v_{S1}, v_{Ss1}, and v_{Ss2} (e) v_{Sa1}, v_{Sa2}, v_{Sa3}, and v_{Sa4}.

Fig. 7.22. Simulated performance of ASIC Converter based Bidirectional LEV charger during V2G Mode Operation under (a)-(b) v_s dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS} and (c)-(d) i_{bat} dynamics from (c) 100% to 50%, and (d) 50% to 100% Conditions.

Fig. 7.23. Experimental performance of ASIC Converter based Bidirectional LEV charger during V2G Mode Operation under (a)-(b) v_s dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS} and (c)-(d) i_{bat} dynamics from (c) 100% to 50%, and (d) 50% to 100% Conditions.

Fig. 7.24. Simulated supply side power quality performance of ASIC Converter based Bidirectional LEV charger during V2G Mode and v_s of (a) 220 V, (b) 160 V, and (c) 265 V.

Fig. 7.25. Experimental validation of supply side power quality performance of ASIC Converter-based LEV charger during V2G and v_s of (a)-(c) 220 V (d)-(f) 165 V, and (g)-(i) 255V.

Fig. 7.26. Simulated Steady State Performance of ASISEPIC Converter-based Bidirectional LEV Charger during G2V Mode (a) v_s, i_s, v_{bat}, i_{bat}, i_{Li}, v_{C1}, i_{Ls1}, and i_{Ls2} (b) v_s, v_{S1}, i_{S1}, v_{Ss1}, v_{Ss2}, i_{Ss1}, v_{Sa1}, i_{Sa1}, v_{Sa2}, i_{Sa2}, v_{Sa3}, and v_{Sa4}.

Fig. 7.27. Experimental Steady State performance of ASISEPIC Converter based Bidirectional LEV charger during G2V Mode Operation (a) v_s, i_s, v_{bat}, and i_{bat} (b) v_s, i_s, i_{Li}, and v_{C1} (c) v_{Ss1}, v_{Ss2}, i_{Ls1}, and i_{Ls2} (d) v_s, v_{S1}, v_{Ss1}, and v_{Ss2}.

Fig. 7.28. Simulated performance of ASISEPIC Converter-based Bidirectional LEV charger during G2V Mode Operation under (a)-(b) v_s dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS} and (c)-(d) i_{bat} dynamics from (c) 100% to 50 %, and (d) 50% to 100 % Conditions.

Fig. 7.29. Experimental performance of ASISEPIC Converter-based Bidirectional LEV charger during G2V Mode Operation under (a)-(b) v_s dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS} and (c)-(d) i_{bat} dynamics from (c) 100 % to 50 %, and (d) 50% to 100% Conditions.

Fig. 7.30. Simulated supply side power quality performance of ASISEPIC Converter based Bidirectional LEV charger during G2V Mode and v_s of (a) 220 V, (b) 160 V, and (c) 265 V.

Fig. 7.31. Experimental validation of supply side power quality performance of ASISEPIC Converter-based LEV charger during G2V and v_s of (a)-(c) 220 V (d)-(f) 165 V, and (g)-(i) 250 V.

Fig. 7.32. Simulated Steady State Performance of ASISEPIC Converter-based Bidirectional LEV Charger during V2G Mode (a) v_s, i_s, v_{bat}, i_{bat}, i_{Li}, v_{C1}, i_{Ls1}, and i_{Ls2} (b) v_s, v_{S1}, i_{S1}, v_{Ss1}, v_{Ss2}, i_{Ss1}, v_{Sa1}, i_{Sa1}, v_{Sa2}, i_{Sa2}, v_{Sa3}, and v_{Sa4}.

Fig. 7.33. Experimental Steady State performance of ASISEPIC Converter based Bidirectional LEV charger during V2G Mode Operation (a) v_s, i_s, v_{bat}, and i_{bat} (b) v_s, i_s, i_{Li}, and v_{C1} (c) v_{Ss1}, v_{Ss2}, i_{Ls1}, and i_{Ls2} (d) v_s, v_{S1}, v_{Ss1}, and v_{Ss2} (e) v_{Sa1}, v_{Sa2}, v_{Sa3}, and v_{Sa4}.

Fig. 7.34. Simulated performance of ASISEPIC Converter-based Bidirectional LEV charger during V2G Mode Operation under (a)-(b) v_s dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS} and (c)-(d) i_{bat} dynamics from (c) 100% to 50%, and (d) 50% to 100% Conditions.

Fig. 7.35. Experimental performance of ASISEPIC Converter-based Bidirectional LEV charger during V2G Mode Operation under (a)-(b) v_s dynamics from (a) 220 V_{RMS} to 160 V_{RMS} and (b) 220 V_{RMS} to 265 V_{RMS} and (c)-(d) i_{bat} dynamics from (c) 100% to 50%, and (d) 50% to 100% Conditions.

Fig. 7.36. Simulated supply side power quality performance of ASISEPIC Converter-based Bidirectional LEV charger during V2G Mode and v_s of (a) 220 V, (b) 160 V, and (c) 265 V.

Fig. 7.37. Experimental validation of supply side power quality performance of ASISEPIC Converter-based LEV charger during V2G and v_s of (a)-(c) 220 V (d)-(f) 165 V, and (g)-(i) 255 V.

Fig. 8.1. FBLBSEPIC Converter based Bidirectional Single Stage Isolated LEV Charger.

Fig. 8.2. FBLBL Converter based Bidirectional Single Stage Isolated LEV charger.

Fig. 8.3. Equivalent Circuit of FBLBSEPIC Converter based Bidirectional LEV Charger during (a) Grid Connected Mode (G2V/V2G) and (b) Grid Disconnected Mode (V2H).

Fig. 8.4. Line Cycle Operation of FBLBSEPIC Converter Based Bidirectional LEV Charger during G2V Operations (a) Positive, and (b) Negative Half Cycle of v_s.

Fig. 8.5. Switching Cycle Operation of FBLBSEPIC Converter Based Bidirectional LEV Charger during G2V Operation (a) Mode – G2V(P_1) (b) Mode – G2V(P_2) and (c) Mode – G2V(P_3)

Fig. 8.6. Line Cycle Operation of FBLBSEPIC Converter Based Bidirectional LEV Charger during V2G Operation (a) Positive, and (b) Negative Half Cycle of v_s.

Fig. 8.7. Switching Cycle Operation of FBLBSEPIC Converter Based Bidirectional LEV Charger during V2G Operation (a) Mode – V2G(P_1) (b) Mode – V2G(P_2) and (c) Mode – V2G(P_3).

Fig. 8.8. Switching Cycle Voltage/Current Waveforms of FBLBSEPIC Converter Based LEV Charger during (a) G2V and (b) V2G Mode Operation.

Fig. 8.9. Equivalent Circuit of FBLBL Converter based Bidirectional LEV Charger during (a) Grid Connected Mode (G2V/V2G) and (b) Grid Disconnected Mode (V2H).

Fig. 8.10. Line Cycle Operation of FBLBL Converter Based Bidirectional LEV Charger during G2V Operation (a) Positive (b) Negative Half Cycle of v_s.

Fig. 8.11. Switching Cycle Operation of FBLBL Converter Based Bidirectional LEV Charger during G2V Operation (a) Mode – G2V(P_1) (b) Mode – G2V(P_2) and (c) Mode – G2V(P_3)

Fig. 8.12. Line Cycle Operation of FBLBL Converter Based Bidirectional LEV Charger during V2G Operation (a) Positive and (b) Negative Half Cycle of v_s.

Fig. 8.13. Switching Cycle Operation of FBLBL Converter Based Bidirectional LEV Charger during V2G Operation (a) Mode – V2G(P_1) (b) Mode – V2G(P_2) and (c) Mode – V2G(P_3).

Fig. 8.14. Switching Cycle Voltage/Current Waveforms of FBLBL Converter Based LEV Charger during (a) G2V and (b) V2G Mode Operation.

Fig. 8.15. Control Block Diagram for Bidirectional Single Stage Isolated LEV Chargers during (a) G2V/V2G and (b) V2H Mode Operation.

Fig. 8.16. General Block Diagram for Software Modelling and MATLAB Simulation of Bidirectional Single Stage Isolated LEV Chargers.

Fig. 8.17. Simulated Performance of FBLBSEPIC Converter-based Bidirectional LEV Charger Under Steady State G2V Operating Condition (a) v_s, i_s, v_{bat}, i_{bat}, v_{C1}, v_{C2}, i_{pri1}, i_{pri2}, i_{sec1}, and i_{sec2} (b) v_s, v_{S1}, i_{S1}, v_{S2}, i_{S2}, v_{So1}, i_{So1}, v_{So2}, and i_{So2}.

Fig. 8.18. Experimental Performance of FBLBSEPIC Converter-based Bidirectional LEV Charger Under Steady State G2V Operating Conditions (a) v_s, i_s, i_{bat}, and v_{bat} (b) v_s, v_{C2}, v_{C1}, and v_{bat} (c) v_{S1}, v_{S2}, i_{pri1}, and i_{pri2} (d) v_{So1}, v_{So2}, i_{sec1}, and i_{sec2} (e) v_{S1}, v_{S2}, v_{So1}, and v_{So2}.

Fig. 8.19. Simulated performance of FBLBSEPIC Converter-based Bidirectional LEV charger during G2V Mode and under (a)-(b) v_s dynamics (a) 220 V_{RMS} to 160 V_{RMS}, (b) 220 V_{RMS} to 265 V_{RMS}, (c)-(d) i_{bat} dynamics (c) 100% to 50% and (d) 50% to 100%.

Fig. 8.20. Experimental performance of FBLBSEPIC Converter based Bidirectional LEV charger during G2V Mode and under (a)-(b) v_s dynamics (a) 220 V_{RMS} to 160 V_{RMS}, (b) 220 V_{RMS} to 265 V_{RMS}, (c)-(d) i_{bat} dynamics (c) 100% to 50% and (d) 50% to 100%.

Fig.8.21. Simulated supply side power quality performance of FBLBSEPIC Converter based Bidirectional LEV charger during G2V Mode at P_{rated} and v_s of (a) 220 V, (b) 265 V, and (c) 160 V.

Fig.8.22. Experimental supply side power quality performance of FBLBSEPIC Converter based Bidirectional LEV charger during G2V Mode at P_{rated} and v_s of (a) 220 V, (b) 265 V, and (c) 160 V.

Fig. 8.23. Simulated Performance of FBLBSEPIC Converter-based Bidirectional LEV Charger Under Steady State V2G/V2H Operating Condition (a) v_s, i_s, v_{bat}, i_{bat}, v_{C1}, v_{C2}, i_{pri1}, i_{pri2}, i_{sec1}, and i_{sec2} (b) v_s, v_{S1}, i_{S1}, v_{S2}, i_{S2}, v_{So1}, i_{So1}, v_{So2}, and i_{So2}.

Fig. 8.24. Experimental Performance of FBLBSEPIC Converter-based Bidirectional LEV Charger Under Steady State V2G Operating Conditions (a) v_s, i_s, i_{bat}, and v_{bat} (b)

v_s, v_{C2}, v_{C1}, and v_{bat} (c) v_{S1}, v_{S2}, i_{pri1}, and i_{pri2} (d) v_{So1}, v_{So2}, i_{sec1}, and i_{sec2} (e) v_{S1}, v_{S2}, v_{So1}, and v_{So2}.

Fig. 8.25. Performance of FBLBSEPIC Converter-based Bidirectional LEV Charger Under Steady State V2H Operating Conditions (a) Simulation (v_s, i_s, i_{bat}, and v_{bat}) and (b) Experimental (v_s, i_s, i_{bat}, and v_{bat}) Validation.

Fig. 8.26. Simulated performance of FBLBSEPIC Converter-based Bidirectional LEV charger during V2G Mode and under (a)-(b) v_s dynamics (a) 220 V to 160 V, (b) 220 V to 265 V, (c)-(d) i_{bat} dynamics (c) 100% to 50% and (d) 50% to 100%.

Fig. 8.27. Experimental performance of FBLBSEPIC Converter-based Bidirectional LEV charger during V2G Mode and under (a)-(b) v_s dynamics (a) 220 V to 160 V, (b) 220 V to 265 V, (c)-(d) i_{bat} dynamics (c) 100% to 50% and (d) 50% to 100%.

Fig.8.28. Simulated supply side power quality performance of FBLBSEPIC Converter based Bidirectional LEV charger during (a)-(c) V2G Mode at P_{rated} and v_s of (a) 220 V, (b) 265 V, and (c) 160 V, and during (d) V2H Mode at v_s of 220 V.

Fig.8.29. Experimental supply side power quality performance of FBLBSEPIC Converter based Bidirectional LEV charger during (a)-(i) V2G Mode at P_{rated} and v_s of (a)-(c) 220 V, (d)-(f) 265 V, and (g)-(i) 160 V.

Fig. 8.30. Simulated Performance of FBLBL Converter based Bidirectional LEV Charger Under Steady State G2V Operating Condition (a) v_s, i_s, v_{bat}, i_{bat}, v_{Cf1}, v_{Cf2}, i_{pri1}, i_{pri2}, i_{sec1}, i_{sec2}, v_{C1}, and i_{Lo} (b) v_s, v_{S1}, i_{S1}, v_{S2}, i_{S2}, v_{So1}, i_{So1}, v_{So2}, and i_{So2}.

Fig. 8.31. Experimental Performance of FBLBL Converter-based Bidirectional LEV Charger Under Steady State G2V Operating Conditions (a) v_s, i_s, i_{bat}, and v_{bat} (b) v_s, v_{Cf1}, v_{C1}, and i_{Lo} (c) v_{S1}, v_{S2}, i_{pri1}, and i_{pri2} (d) v_{So1}, v_{So2}, i_{sec1}, and i_{sec2} (e) v_{S1}, v_{S2}, v_{So1}, and v_{So2}.

Fig. 8.32. Simulated performance of FBLBL-based LEV charger during G2V Mode (a)-(b) v_s dynamics (a) 220 V -160 V, (b) 220 V-265 V, (c)-(d) i_{bat} dynamics (c) 100% - 50% and (d) 50%-100%.

Fig. 8.33. Experimental performance of FBLBL Converter based Bidirectional LEV charger during G2V Mode and under (a)-(b) v_s dynamics (a) 220 V_{RMS} to 160 V_{RMS}, (b) 220 V_{RMS} to 265 V_{RMS}, (c)-(d) i_{bat} dynamics (c) 100% to 50% and (d) 50% to 100%.

Fig.8.34. Simulated supply side power quality performance of FBLBL Converter based Bidirectional LEV charger during G2V Mode at P_{rated} and v_s of (a) 220 V, (b) 265 V, and (c) 160 V.

Fig.8.35. Experimental supply side power quality performance of FBLBL Converter based Bidirectional LEV charger during G2V Mode at P_{rated} and v_s of (a) 220 V, (b) 265 V, and (c) 160 V.

Fig. 8.36. Simulated Performance of FBLBL Converter-based Bidirectional LEV Charger Under Steady State V2G/V2H Operating Condition (a) v_s, i_s, v_{bat}, i_{bat}, v_{Cf1}, v_{Cf2}, i_{pri1}, i_{pri2}, i_{sec1}, i_{sec2}, v_{C1}, and i_{Lo}, (b) v_s, v_{S1}, i_{S1}, v_{S2}, i_{S2}, v_{So1}, i_{So1}, v_{So2}, and i_{So2}.

Fig. 8.37. Experimental Performance of FBLBL Converter-based Bidirectional LEV Charger Under Steady State V2G Operating Conditions (a) v_s, i_s, i_{bat}, and v_{bat} (b) v_s, v_{Cf1}, v_{C1}, and i_{Lo} (c) v_{S1}, v_{S2}, i_{pri1}, and i_{pri2} (d) v_{So1}, v_{So2}, i_{sec1}, and i_{sec2} (e) v_{S1}, v_{S2}, v_{So1}, and v_{So2}.

Fig. 8.38. Performance of FBLBL Converter-based LEV Charger Under Steady State V2H Operating Conditions (a) Simulation (v_s, i_s, i_{bat}, and v_{bat}) and (b) Experimental (v_s, i_s, i_{bat}, and v_{bat}) Validation.

Fig. 8.39. Simulated performance of FBLBL-based LEV charger during V2G Mode under (a)-(b) v_s dynamics (a) 220 V–160 V, (b) 220 V–265 V, (c)-(d) i_{bat} dynamics (c) 100%-50% and (d) 50%-100%.

Fig. 8.40. Experimental performance of FBLBL-based Bidirectional LEV charger during V2G Mode and under (a)-(b) v_s dynamics (a) 220 V_{RMS} to 160 V_{RMS}, (b) 220 V_{RMS} to 265 V_{RMS}, (c)-(d) i_{bat} dynamics (c) 100% to 50% and (d) 50% to 100%.

Fig.8.41. Simulated supply side power quality performance of FBLBL Converter based Bidirectional LEV charger during (a)-(c) V2G Mode at P_{rated} and v_s of (a) 220 V, (b) 265 V, and (c) 160 V, and during (d) V2H Mode at v_s of 220 V.

Fig.8.42. Experimental supply side power quality performance of FBLBL Converter based Bidirectional LEV charger during (a)-(i) V2G Mode at P_{rated} and v_s of (a)-(c) 220 V, (d)-(f) 265 V, and (g)-(i) 160 V.

Fig. 9.1. ASIBB BDC-based Bidirectional Double Stage Non-isolated LEV Charger.

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog to Digital Controller
ASIBB	Active Switched Inductor Buck-Boost
ASIC	Active Switched Inductor Cuk
ASISEPIC	Active Switched Inductor SEPIC
BDC	Bidirectional DC-DC Converter
BEV	Battery Electric Vehicle
BLPOC	Bridgeless Positive Output Cuk
BLPOL	Bridgeless Positive Output Luo
BSIC	Bridgeless Switched Inductor Cuk
BLSEPIC	Bridgeless SEPIC
BLMSEPIC	Bridgeless Modified SEPIC
BSISEPIC	Bridgeless Switched Inductor SEPIC
CC	Constant Current
CCM	Continuous Conduction Mode
CP	Constant Power
CrCM	Critical Conduction Mode
CSC	Canonical Switching Cell
CV	Constant Voltage
DAB	Dual Active Bridge
DBR	Diode Bridge Rectifier
DC	Direct Current
DCM	Discontinuous Conduction Mode
DF	Displacement Factor
DIS	Domestic Inverter System
DSO	Digital Signal Oscilloscope
E2W	Electric Two-Wheeler
E3W	Electric Three-Wheeler
E4W	Electric Four-Wheeler
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EPWM	Enhanced Pulse Width Modulation
EV	Electric Vehicle
FBLBSEPIC	Fully Bridgeless Bidirectional SEPIC
FBLBL	Fully Bridgeless Bidirectional Luo
FBLCSC	Fully Bridgeless CSC
FBLPOBB	Fully Bridgeless Positive Output Buck-Boost
FBLPOL	Fully Bridgeless Positive Output Luo
FLL	Frequency Locked Loop
GaN	Gallium Nitride
GI	Generalized Integrator

G2V	Grid to Vehicle
HEV	Hybrid Electric Vehicle
HGB	High Gain Buck
HVBEV	High Voltage Battery Electric Vehicle
IC	Integrated Circuit
ICE	Internal Combustion Engine
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
ILCSC	Interleaved CSC
IM	Inductor Motor
IMSTOGI	Improved Mixed Second and Third-Order Generalized Integrator
IPOC	Isolated Positive Output Cuk
kWh	Kilo-Watt-Hour
LEV	Light Electric Vehicle
LPF	Low Pass Filter
LVBEV	Low Voltage Battery Electric Vehicle
MSCCSC	Modified Switched Capacitor CSC
MSEPIC	Modified SEPIC
MTS	Mode Transfer Switch
OBC	On Board Charger
OSG	Orthogonal Signal Generator
PBLCSC	Partial Bridgeless CSC
PF	Power Factor
PFC	Power Factor Corrected
PHEV	Plugin Hybrid Electric Vehicle
PI	Proportional-Integral
PLL	Phased Locked Loop
PMBLDCM	Permanent Magnet Brushless DC Motor
PMSM	Permanent Magnet Synchronous Motor
PQ	Power Quality
PR	Proportional Resonant
QSG	Quadrature Signal Generator
RCD	Resistor Capacitor Diode
RMS	Root Mean Square
SAE	Society of Automotive Engineers
SEPIC	Single Ended Primary Inductor Converter
SIC	Silicon Carbide
SOC	State of Charge
SOGI	Second Order Generalized Integrator
SOH	State of Health
SOSOGI	Second Order SOGI
SRF	Synchronous Reference Frame

SRM	Switched Reluctance Motor
THD	Total Harmonics Distortions
TI	Texas Instrument
VRLA	Valve Regulated Lead Acid
VSI	Voltage Source Inverter
VTR	Voltage Transfer Ratio
V2G	Vehicle to Grid
V2H	Vehicle to Home
V2L	Vehicle to Load
V2V	Vehicle to Vehicle
V2X	Vehicle to Anything
1P1S	One Primary and One Secondary
1P2S	One Primary and Two Secondary
2P2S	Two Primary and Two Secondary
2P1S	Two Primary and One Secondary

LIST OF SYMBOLS

C_1, C_2, C_3	Intermediate Energy Transfer Capacitors
C_{1c}	Primary Side Capacitor of Isolated Cuk Converter
C_{2c}	Secondary Side Capacitor of Isolated Cuk Converter
C_{DC}	DC Link Capacitor
C_o	Battery End Filter Capacitor
C_f, C_{f1}, C_{f2}	Supply Side Filter Capacitor
C_{s1}, C_{s2}	Capacitors of Switched Capacitor Cell
D_1, D_2, D_3, D_4	High frequency Diodes
D_b	Duty Ratio of back end DC-DC Converter switch
D_c, D_{c1}, D_{c2}	Diodes of Cuk Converter
D_D	Diode Duty Ratio
D_{Dcr}	Critical Value of Diode Duty Ratio
D_{G2V}	Duty Ratio of back end DC-DC Converter switch (G2V Mode)
D_{s1}, D_{s2}	Diodes of Switched Inductor/Capacitor Cell
D_S	Switch Duty Ratio
D_{Smin}	Minimum Value of D_S
D_{Smax}	Maximum Value of D_S
D_{V2G}	Duty Ratio of back end DC-DC Converter switch (V2G Mode)
$D_{b1}, D_{b2}, D_{b3}, D_{b4}$	Diodes of Diode Bridge Rectifier
D_o, D_{o1}, D_{o2}	Output Diodes at Secondary Side of Transformer
f_L	Line Frequency
f_s	Switching Frequency
f_{sb}	Switching frequency of Back end DC-DC converter
G_C	DC Gain of Isolated Cuk DC-DC Converter
G_{HGB}	DC Gain of High Gain Buck (HGB) DC-DC Converter
i_{bat}	Battery Current
I_{bat}	Average Value of i_{bat}
I_{batmin}	Minimum value of I_{bat}
I_{batmax}	Maximum value of I_{bat}
I_{bat}^*	Reference Battery Current
i_{bate}	Error between i_{bat} and I_{bat}^*
i_{Co}	Current through C_o

i_{DC}	DC Link Current
I_{in}	Switching cycle average value of i_s
i_{Ls1}, i_{Ls2}	Current through L_{s1}, L_{s2}
I_{Ls1RMS}, I_{Ls2RMS}	RMS Current through L_{s1}, L_{s2}
I_{Ls1}, I_{Ls2}	Switching Cycle Average value of i_{Ls1}, i_{Ls2}
i_s	Instantaneous Supply Current
I_s	RMS Value of i_s
I_{smin}	Minimum value of I_s
I_{smax}	Maximum value of I_s
i_{Cs1}, i_{Cs2}	Current through C_{s1}, C_{s2}
i_{Ds1}, i_{Ds2}	Current through D_{s1}, D_{s2}
$i_{Ds1peak}$, $i_{Ds2peak}$	Peak Current through D_{s1}, D_{s2}
I_{Ds1RMS}, I_{Ds2RMS}	RMS Current through D_{s1}, D_{s2}
I_{Ds1}, I_{Ds2}	Switching Cycle Average value of i_{Ds1}, i_{Ds2}
i_{Ss1}, i_{Ss2}	Current through S_{s1}, S_{s2}
i_{Sa1}, i_{Sa2}, i_{Sa3}, i_{Sa4}	Current through $S_{a1} - S_{a4}$
i_{Lm}, i_{Lm1}, i_{Lm2}	Current through L_m, L_{m1}, L_{m2}
i_{pri}, i_{pri1}, i_{pri2}	Current through primary windings of T_x, T_{x1}, T_{x2}
i_{sec}, i_{sec1}, i_{sec2}	Current through secondary windings of T_x, T_{x1}, T_{x2}
i_{Lic}	Current through L_{ic}
i_{Loc}	Current through L_{oc}
i_{C1c}	Current through C_{1c}
i_{C2c}	Current through C_{2c}
i_{Sc}, i_{Sc1}, i_{Sc2}	Current through S_c, S_{c1}, S_{c2}
i_{Dc}, i_{Dc1}, i_{Dc2}	Current through D_c, D_{c1}, D_{c2}
i_{Db1}, i_{Db2}, i_{Db3}, i_{Db4}	Current through D_{b1}, D_{b2}, D_{b3}, D_{b4}
$i_{Db1/Db2/Db3/Db4peak}$	Peak Current through D_{b1}, D_{b2}, D_{b3}, D_{b4}
$I_{Db1/Db2/Db3/Db4RMS}$	RMS Current through D_{b1}, D_{b2}, D_{b3}, D_{b4}
i_{C1}, i_{C2}, i_{C3}	Current through C_1, C_2, C_3
i_{Li}, i_{Li1}, i_{Li2}	Current through L_i, L_{i1}, L_{i2}
i_{Lo}	Current through L_o
i_{Do}, i_{Do1}, i_{Do2}	Current through D_o, D_{o1}, D_{o2}
$i_{Do/Do1/Do2peak}$,	Peak Current through D_o, D_{o1}, D_{o2}

$I_{Do/Do1/Do2RMS}$	RMS Current through D_o, D_{o1}, D_{o2}
i_{D1}, i_{D2}, i_{D3}, i_{D4}	Current through D_1, D_2, D_3, D_4
$i_{D1/D2/D3/D4peak}$	Peak Current through D_1, D_2, D_3, D_4
$I_{D1/D2/D3/D4RMS}$	Peak Current through D_1, D_2, D_3, D_4
i_{S1}, i_{S2}, i_{S3}, i_{S4}	Current through S_1, S_2, S_3, S_4
$i_{S1/S2/S3/S4peak}$	Peak Current through S_1, S_2, S_3, S_4
$I_{S1/S2/S3/S4RMS}$	RMS Current through S_1, S_2, S_3, S_4
I_{S1}, I_{S2}, I_{S3}, I_{S4}	Average Current through S_1, S_2, S_3, S_4
L_{eq}	Equivalent Inductance of L_i and L_{s1}/L_{s2}
L_g	Supply Impedance
L_f, L_{f1}, L_{f2}	Supply Side Filter Inductor
L_{s1}, L_{s2}	Inductors of Switched Inductor Cell
L_s	Switched Inductor Inductance Considering $L_{s1} = L_{s2}$
L_{scr}	Critical Value of $\mathrm{L_s}$
L_m, L_{m1}, L_{m2}	Magnetizing Inductance of T_x, T_{x1}, T_{x2}
L_{mcr}	Critical Value of L_m, L_{m1}, L_{m2}
L_{ic}	Input Inductor of Isolated Cuk Converter
L_i, L_{i1}, L_{i2}	Input Inductors
L_{icr}, L_{i1cr}, L_{i2cr}	Critical values of L_i, L_{i1}, L_{i2}
L_{oc}	Output Inductor of Isolated Cuk Converter
L_o	Output Inductor
L_{ocr}	Critical Values of $\mathrm{L_o}$
M_{VDC}	Switching Cycle DC Voltage Gain of Converters
M_{IDC}	Switching Cycle DC Current Gain of Converters
M_{VDCmin}	Minimum value of M_{VDC}
M_{VDCmax}	Maximum value of M_{VDC}
N	Primary to Secondary Turns Ratio of T_x, T_{x1}, T_{x2}
N_{pri}, N_{pri1}, N_{pri2}	Number of Primary turns of T_x, T_{x1}, T_{x2}
N_{sec}, N_{sec1}, N_{sec2}	Number of Secondary turns of T_x, T_{x1}, T_{x2}
P_{rated}	Rated power level of Charger
R_f	AC Side R-C Filter’s Resistance
R_L	Fictitious Load Resistance
R_{Lmin}	Minimum value of $\mathrm{R_L}$

R_{Lmax}	Maximum value of $\mathrm{R_L}$
R_{in}	Fictitious Input Resistance
S_1, S_2, S_3, S_4	Switches
S_{s1}, S_{s2}	Switches of Active Switched Inductor/Capacitor Cell
S_{a1}, S_{a2}, S_{a3}, S_{a4}	Active Full Bridge AC-DC Converter Switches
S_c, S_{c1}, S_{c2}	Switches of Cuk Converter
T_x, T_{x1}, T_{x2}	High Frequency Transformers
T_s	Switching Time Period
v_{bat}	Battery Voltage
V_{bat}	Switching Cycle Average Value of v_{bat}
V_{bat}^*	Reference Battery Voltage
v_{bate}	Error between v_{bat} and V_{bat}^*
V_{batn}	Nominal voltage of battery packs
$V_{batnmin}$	Minimum Nominal voltage of battery packs
$V_{batnmax}$	Maximum Nominal voltage of battery packs
v_{Cf}, v_{Cf1}, v_{Cf2}	Voltage across C_f, C_{f1},C_{f2}
v_{DC}	DC Link Voltage
V_{DC}^*	Reference DC Link Voltage
v_s	Instantaneous Supply Voltage
V_s	RMS Value of v_s
V_{smin}	Minimum value of V_s
V_{smax}	Maximum value of V_s
V_{in}	Switching Cycle Average Value of v_s
v_{Ls1}, v_{Ls2}	Voltage across L_{s1}, L_{s2}
v_{Cs1}, v_{Cs2}	Voltage across C_{s1}, C_{s2}
v_{Ds1}, v_{Ds2}	Voltage across D_{s1}, D_{s2}
v_{Ss1}, v_{Ss2}	Voltage across S_{s1}, S_{s2}
v_{Sa1}, v_{Sa2}, v_{Sa3}, v_{Sa4}	Voltage Across $S_{a1} – S_{a4}$
v_{pri}, v_{pri1}, v_{pri2}	Voltage across primary windings of T_x, T_{x1}, T_{x2}
v_{sec}, v_{sec1}, v_{sec2}	Voltage across secondary windings of T_x, T_{x1}, T_{x2}
v_{Lic}	Voltage across L_{ic}
v_{Loc}	Voltage across L_{oc}
v_{C1c}	Voltage across C_{1c}

v_{C2c}	Voltage across C_{2c}
v_{Sc}, v_{Sc1}, v_{Sc2}	Voltage across S_c, S_{c1}, S_{c2}
v_{Dc}, v_{Dc1}, v_{Dc2}	Voltage across D_c, D_{c1}, D_{c2}
v_{C1}, v_{C2}, v_{C3}	Voltage across C_1, C_2, C_3
V_{C1}, V_{C2}, V_{C3}	Switching Cycle Average Voltage across C_1, C_2, C_3
v_{Li}, v_{Li1}, v_{Li2}	Voltage across L_i, L_{i1}, L_{i2}
v_{Lo}	Voltage across L_o
$v_{Db1/Db2/Db3/Db4}$	Voltage across D_{b1}, D_{b2}, D_{b3}, D_{b4}
v_{S1}, v_{S2}, v_{S3}, v_{S4}	Voltage across S_1, S_2, S_3, S_4
$v_{S1/S2/S3/S4peak}$	Peak Voltage stress across S_1, S_2, S_3, S_4
v_{D1}, v_{D2}, v_{D3}, v_{D4}	Voltage across D_1, D_2, D_3, D_4
v_{Do}, v_{Do1}, v_{Do2}	Voltage across D_o, D_{o1}, D_{o2}
γ_{Li}	Percentage Ripple in L_i Current
γ_{Ls}	Percentage Ripple in L_{s1} and L_{s2} Currents
γ_{Lic}	Percentage Ripple in L_{ic} Current
γ_{Li1}	Percentage Ripple in L_{i1} Current
γ_{Li2}	Percentage Ripple in L_{i2} Current
α_{C1c}	Percentage Ripple in C_{1c} Voltage
α_{C2c}	Percentage Ripple in C_{2c} Voltage
ξ	Percentage Ripple in Cuk Converter Transformer i_{Lm}
β	Percentage Ripple in v_{C2}
δ	Percentage Ripples in v_{DC}
χ	Percentage Ripple in v_{C1}
φ	Output Inductor Current Ripples i_{Lo}
κ	Percentage Ripples in v_{Cs}
λ	Percentage Ripples in v_{Co}
ω_{res}, ω_{res1}, ω_{res2}	Resonance Frequency
ψ	Percentage of Source Impedance
f_c	Cutoff frequency of filter