POWER QUALITY IMPROVEMENT IN BATTERY CHARGERS OF LIGHT ELECTRIC VEHICLES

RADHA KUSHWAHA

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

AUGUST 2020

POWER QUALITY IMPROVEMENT IN BATTERY CHARGERS OF LIGHT ELECTRIC VEHICLES

by

RADHA KUSHWAHA

Department of Electrical Engineering

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

AUGUST 2020

CERTIFICATE

It is certified that the thesis entitled "**Power Quality Improvement in Battery Chargers of Light Electric Vehicles**," being submitted by **Ms. Radha Kushwaha** 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 her under my supervision and guidance. The matter embodied in this thesis, has not been submitted for the award of any other degree or diploma.

Dated: 20th August, 2020

(Dr. Bhim Singh)

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

ACKNOWLEDGEMENTS

I wish to express my deepest gratitude and indebtedness to **Prof. Bhim Singh** for providing me guidance and consistant supervision to carry out the Ph.D. work. Working under him has been a wonderful experience, which has provided a deep insight to the world of research. Determination, dedication, innovativeness, resourcefulness and discipline of **Prof. Bhim Singh** have been the inspiration for me to complete this work. His consistent encouragement, continuous monitoring and commitments to excellence have always motivated me to improve my work and use the best of my capabilities. Due to his blessing, I have earned various experiences other than research, which will help me throughout my life.

My sincere thanks and deep gratitude are to **Prof. Sukumar Mishra, Prof. N. Senroy**, and **Prof. Ashu Verma** all SRC members for their valuable guidance and consistent support during my research work.

I wish to convey my sincere thanks to **Prof. Bhim Singh**, **Prof. Sukumar Mishra, Prof. N. Senroy, Dr. Ramkrishnan Maheshwari** and **Dr. Anandrup Das** for their valuable inputs during my coursework, which made the foundation for my research work. I am grateful to **IIT Delhi** for providing me the research facilities. I wish to express my sincere gratitude to **Prof. G. Bhuvaneswari**, Prof. in-charge, PG Machine Lab., for providing me immense facilities to carry out experimental work. Thanks are due to Sh. Srichand, Sh. Puran Singh, and Sh. Jitendra of PG Machines Lab, IIT Delhi for providing me the facilities and assistance during this work.

I would like to offer my sincere thanks to Dr. Nishant Kumar, who was the source of inspiration for me to pursue PhD at IIT Delhi. Moreover, I would like to thank all my seniors, Dr. Chinmay Jain, Dr. Rajan Sonkar, Dr. Ikhlaq Hussain, Dr. Arun Kumar Verma, Dr. Aman Jha, Dr. Swati Narula, Dr. Shikha Singh, Dr. Vashist Bist, Dr. Shailendra Kumar Dwivedi, Dr.

Aniket Anand, Mr. Anshul Varshney, Dr. Saurabh Shukla, Mr. Sai Pranith Girimaji, Ms. Nidhi Mishra, Dr. Geeta Pathak and Mr. Anjanee Mishra to motivate me in the starting of my research work. I would like to use this opportunity to thank Ms. Seema Kewat, Ms. Vandana Jain, Mr. Anjeet Verma, and Mr. Utkarsh Sharma who have constantly helped me on all technical issues. My sincere thanks are due to Ms. Yashi and Ms. Shatakshi Jha for co-operation and informal support in pursuing this research work. I would like to thank Mr. Priyank Shah, Mr. VL Srinivas, Mr. Deepu Vijay M, Ms. Aakanksha Rajput, Mr. Shadab Murshid, Mr. Piyush Kant, Mr. Tripurari Nath, Mr. Sudip Bhattacharyya, Mr. Nikhil Krishna, Ms. Jyoti Prakash Shukla, Ms. Akshita Mishra, Ms. Vasudha Agrawal and all other colleges for their valuable aid and co-operation. Moreover, I would like to thank Ms. Nupur, Mr. Arayadip, Mr. Bilal, Mr. Debashish, Mr. Gaurav, Mr. Gurmeet, Mr. Jitendra, Mr. Munesh, Mr. Priyabrat, Ms. Rashmi, Mr. Sambasivaiah, Mr. Sandeep, Ms. Shalvi, Mr. Sharan, Mr. Shivam, Mr. Shreejith, Mr. Somnath, Mr. Souvik, Ms. Tabish, Mr. Vineet, Mr. Utsav, Mr. Kashif, Ms. Shubhra, Mr. Khusro, Mr. Amar, Mr. Sunil, Mr. Vivek, Mr. Rahul, Ms. Hina, Mr. Deepak, Mr. Sayan, Ms. Farheen, Mr. Tomar, Ms. Rohini, Ms. Pavitra, and all PG machines lab group for their valuable support. How could I forget my hostel mates, Ms. Abhilasha Panwar and Ms. Shruti Sharma, who supported and inspired me during my stay in 'Himadri' house. I would also like to thank Mr. Satish, Mr. Yatindra, Mr. Narendra, Mr. Sandeep and all other electrical engineering office staff for being supportive throughout. I am likewise thankful to those who have directly or indirectly helped me to finish my dissertation study.

Moreover, I would like to thank **Department of Science and Technology (DST)**, India for funding this research work under project grant number RP03128.

I owe it all to my loving father, Late **Mr. Ramphal**, mother, **Mrs. Sarojani Devi**, brother, **Mr. Ravi**, **Mr. Rishabh** and **Mr. Arun**, sisters, **Ms. Pramila, Ms. Anjula, Ms. Garima,** and **Ms Archana** for their dreams, blessings and constant encouragement. Their trust in my capabilities had been a key factor to all my achievements. Finally I would like to thank my loving husband **Mr. Vinay Kumar,** who has stood rock solid during every phase of my life with his constant support in all possible ways to ensure my research goes well thoroughly. I would like to thank my loving father in law, **Mr. Kashi Prasad**, mother in law, **Mrs. Asha Devi** and whole family for their valuable faith in me throughout this phase of life. I take this opportunity to thank the great assets of my life, my friends **Ms. Nibedita Parida, Ms. Neelakshi, Ms. Shilpi, Ms. Vidhi, Ms. Alankrita and Ms. Kshipra** to share my joy and happiness always.

At last, I am beholden to Almighty for their blessings to help me to raise my academic level to this stage. I pray for their benediction in my future endeavors. Their blessings may be showered on me for strength, wisdom and determination to achieve in future.

Date: 20th Aug, 2020

Radha Kushwaha

ABSTRACT

The objective of this work is the design and development of improved power quality based converters with improved efficiency and high power density for power factor correction at the front end of the conventional charger of light EVs. These converters are designed for low cost EVs such as E-rickshaw battery, either in two stage or single stage configurations. A diode bridge rectifier (DBR) is the basic circuit to convert available AC mains voltage into DC voltage for charging, which leaves behind many harmonics in the input side current owing to its nonlinear behavior resulting in poor power quality indices e.g. voltage distortion, high THD in source current, low PF, low DPF (Displacement Factor) and high CF (Crest Factor). For the conventional EV chargers with DBR and capacitor filter, the line current has high current THD in the order of 50-60% at rated battery current and a poor power factor (PF) in the range of 0.8-0.85. Hence, single phase PFC converters are used to improve the power quality of EV battery charger at AC mains.

Several topologies of single phase EV chargers with front-end PFC are reported in the literature, which are divided into five classes namely non-isolated PFC converters based charger, bridgeless non-isolated PFC converters based charger, isolated PFC converters based charger, bridgeless isolated PFC converters based charger and interleaved PFC converters based chargers. All these configuration has different advantages such as high efficiency, high power density, reduced semiconductor stress, low charge current ripple and low cost. The size and cost of the charger, are significantly affected by the control technique used for PFC converter. This work aims at the design of PFC converter in discontinuous conduction mode (DCM), which employs the voltage feedback based control with single voltage sensor to be used for inherent PFC and output voltage regulation. However, a constant current-constant voltage based charging method is used to

control the battery current at rated line and loading conditions. For two stage battery charger configuration, a flyback converter is used to regulate the charge current through the battery.

Many charger configurations with front-end single phase buck-boost PFC converters are designed and developed in this work to exhibit the improved PQ based operation in two stage EV chargers. Some overlooked features of bridged and bridgeless PFC converters, such as Cuk, Zeta, SEPIC, CSC and Landsman converter, with or without isolation, are discussed for single phase EV chargers. Moreover, many new and improved versions of bridged or bridgeless configuration such as Cuk, SEPIC, Luo and Zeta converters are presented along with interleaved configuration of PFC Cuk, Luo and Landsman converters.

The improved circuit performance and unity PF based charging performance of these EV battery chargers are assessed in MATLAB/Simulink based environment using a developed model. The obtained results are seen to be corroborated with the experimental validation of the hardware prototype, for all the configurations. The performance of PFC converters based chargers is evaluated at steady state as well as during dynamic condition for rated line voltage and loading conditions. Various input and output side quantities, device stresses as well as the voltage and current through different components are recorded as per the design and selection parameter. The improved power quality indices are observed as per the international regulations such as the IEC 61000-3-2 standard throughout the charging duration.

सार

इस कार्य का उद्देश्य लाइट ईवी के पारंपरिक चार्जर के सामने के छोर पर बिजली की गुणवत्ता में सुधार के लिए बेहतर दक्षता और उच्च शक्ति घनत्व के साथ बेहतर गुणवत्ता वाले बिजली आधारित कन्वर्टर्स का डिजाइन और विकास है। इन कन्वर्टर्स को ई-रिक्शा बैटरी जैसे कम लागत वाले ईवी के लिए डिज़ाइन किया गया है, या तो दो चरण या एकल चरण कॉन्फ़िगरेशन में। एक डायोड ब्रिज रेक्टिफायर डीबीआर चार्जिंग के लिए उपलब्ध एसी मैन्स वोल्टेज को डीसी वोल्टेज में परिवर्तित करने के लिए बुनियादी सर्किट है, जो नॉनलीनियर व्यवहार के कारण इनपुट साइड करंट में कई हार्मोनिक्स को छोड़ देता है जिसके परिणामस्वरूप खराब बिजली की गुणवत्ता वाले सूचकांक उदाहरणतः वोल्टेज विरूपण, स्रोत करेंट में उच्च टीएचडी, कम पीएफ, कम डीपीएफ (विस्थापन कारक) और उच्च सीएफ (क्रेस्ट फैक्टर) प्राप्त होते हैं। । डीबीआर और कैपेसिटर फिल्टर के साथ पारंपरिक ईवी चार्जर्स के लिए, लाइन करेंट में 50-60% के क्रम में उच्च टीएचडी और 0.8-0.85 की सीमा में खराब पावर फैक्टर देखा गया है। इसलिए, एसी मैन्स में ईवी बैटरी चार्जर की बिजली की गुणवत्ता में सुधार के लिए एकल फेज पीएफसी कन्वर्टर्स का उपयोग किया जाता है।

फ्रंट-एंड पीएफसी के साथ सिंगल फेज ईवी चार्जर के कई टोपोलॉजी साहित्य में बताए गए हैं, जिन्हें पांच वर्गों में विभाजित किया गया है, गैर-पृथक पीएफसी कन्वर्टर्स आधारित चार्जर, ब्रिजलेस गैर-पृथक पीएफसी कन्वर्टर्स आधारित चार्जर, पृथक पीएफसी कन्वर्टर्स आधारित चार्जर, ब्रिजेज पृथक पीएफसी कन्वर्टर्स आधारित चार्जर और पीएफसी कन्वर्टर्स आधारित चार्जर। इन सभी विन्यासों में उच्च दक्षता, उच्च शक्ति घनत्व, कम अर्धचालक तनाव, कम चार्ज करेंट तरंग और कम लागत जैसे विभिन्न फायदे हैं। चार्जर का आकार और लागत, पीएफसी कनवर्टर के लिए उपयोग की जाने वाली नियंत्रण तकनीक से काफी प्रभावित होते हैं। इस कार्य का उद्देश्य पीएफसी कनवर्टर के बंद प्रवाह मोड (डीसीएम) में डिज़ाइन करना है, जो अंतर्निहित पीएफसी और आउटपुट वोल्टेज विनियमन के लिए उपयोग किए जाने वाले एकल वोल्टेज सेंसर के साथ वोल्टेज फीडबैक आधारित नियंत्रण को

नियोजित करता है। हालांकि, रेटेड लाइन और लोडिंग स्थितियों पर बैटरी करेंट को नियंत्रित करने के लिए एक निरंतर करेंट-निरंतर वोल्टेज आधारित चार्जिंग विधि का उपयोग किया जाता है। दो चरण बैटरी चार्जर कॉन्फ़िगरेशन के लिए, एक फ़्लाईबैक कनवर्टर का उपयोग बैटरी की चार्ज करंट को विनियमित करने के लिए किया जाता है।

फ्रंट-एंड सिंगल फेज बक-बूस्ट पीएफसी कन्वर्टर्स के साथ कई चार्जर कॉन्फ़िगरेशन डिज़ाइन और विकसित किए गए हैं जो दो चरण ईवी चार्जर में सुधार किए गए पीक्यू आधारित ऑपरेशन को प्रदर्शित करता है । एकल फेज ईवी चार्जर्स के लिए गैर-पृथक या पृथक, कक, ज़ीटा, सेपिक. सीएससी और लैंड्समैन कनवर्टर जैसे ब्रिजेड और ब्रिजलेस पीएफसी कन्वर्टर्स की कुछ अनदेखी विशेषताओं पर चर्चा की गई है। इसके अलावा कक, सेपिक, लुओ और ज़ीटा कन्वर्टर्स जैसे ब्रिजेड या ब्रिजलेस कॉन्फ़िगरेशन के कई नए और बेहतर संस्करणों को पीएफसी कक, लुओ और लैंड्समैन कन्वर्टर्स के इंटरलीव्ड कॉन्फ़िगरेशन के साथ प्रस्तुत किया गया है।

इन ईवी बैटरी चार्जर्स के बेहतर सर्किट प्रदर्शन और एकक पीएफ आधारित चार्जिंग प्रदर्शन का मूल्यांकन एक विकसित मॉडल का उपयोग करके मैटलैब / सिमुलिंक आधारित वातावरण में किया जाता है। प्राप्त किए गए परिणामों को सभी कॉन्फ़िगरेशन के लिए हार्डवेयर प्रोटोटाइप की प्रयोगात्मक मान्यता के साथ पुष्टि की जाती है। पीएफसी कन्वर्टर्स आधारित चार्जर्स के प्रदर्शन का मूल्यांकन स्थिर स्थिति के साथ-साथ रेटेड लाइन वोल्टेज और लोडिंग स्थितियों के लिए गतिशील स्थिति के दौरान किया जाता है। विभिन्न इनपुट और आउटपुट साइड मात्राएं, डिवाइस तनाव के साथ-साथ विभिन्न घटकों के वोल्टेज और करेंट डिजाइन और चयन पैरामीटर के अनुसार दर्ज किए जाते हैं। चार्जिंग अवधि के दौरान सुधारित विद्युत गुणवत्ता सूचकांकों को आईईसी 61000-3-2 मानक जैसे अंतर्राष्ट्रीय नियमों के अनुसार देखा जाता है।

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CHARGER

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LIST OF ABBREVIATIONS

AC	Alternating Current
BL	Bridgeless
BLDCM	Brushless DC Motor
CC-CV	Constant Current-Constant Voltage mode
CCM	Continuous Conduction Mode
CF	Crest Factor
CSC	Canonical Switching Cell
DBR	Diode Bridge Rectifier
DC	Direct Current
DCM	Discontinuous Conduction Mode
DF	Distortion Factor
DICM	Discontinuous Inductor Current Mode
DPF	Displacement Power Factor
DSP	Digital Signal Processor / Digital Signal Processing
EMI	Electro Magnetic Interference
EV	Electric Vehicle
HFT	High Frequency Transformer
IEC	International Electrotechnical Commission
IPQC	Improved Power Quality Converters
PF	Power Factor
PFC	Power Factor Correction
PQ	Power Quality
PWM	Pulse Width Modulation
SAE	Society of Automotive Engineers
SEPIC	Single Ended Primary Inductance Converter
THD	Total Harmonic Distortion
UPF	Unity Power factor

LIST OF SYMBOLS

C_1, C_{i1}, C_{i2}	Capacitance of Input Side Energy Transfer Capacitors (F)
C_2, C_{o1}, C_{o2}	Capacitance of Output Side Energy Transfer Capacitors (F)
C_{1c}	Critical value of Input Side Energy Transfer Capacitance (F)
C_{2c}	Critical value of Output Side Energy Transfer Capacitance (F)
C_{dc}	Capacitance of DC Link Capacitor (F)
C_b	Output Capacitor of Charger at battery side (F)
C_f	Capacitance of EMI filter Capacitor (F)
C_{fmax}	Maximum Capacitance of EMI filter Capacitor (F)
D	Nominal Duty Cycle
D_{max}	Maximum Duty Cycle
D_{min}	Minimum Duty Cycle
D_f	Duty ratio of flyback converter
f	supply frequency (Hz)
f_c	Filter Cut-off frequency (Hz)
f_s	PFC Converter Switching frequency (Hz)
f_{sw}	Flyback Converter Switching Frequency (Hz)
I_b	Rated battery current (A)
I_b^*	Reference battery current (A)
I_{bb}	Control output from current PI controller at battery side
I_{dc}	DC Link Current (A)
i_{Do}, i_{Do1}, i_{Do2}	Output Diode currents at PFC stage (A)
i_{Df}	Diode current in Flyback converter (A)
i_{Li}, i_{Li1}, i_{Li2}	Inductor Current at Input of PFC Converter(A)
i_{Lf}	Magnetizing inductor current of Flyback Converter (A)
i_{Lo}, i_{Lo1}, i_{Lo2}	Inductor Current at Output of PFC Converter (A)
i_s	Mains current
I_{s_pk}	Peak Value of mains Current (A)

i_{sw}, i_{s1}, i_{s2}	PFC converter's Switch Current (A)
k_{pI}	Proportional Gain of battery side Current PI Controller
k_{iI}	Integral Gain of battery side Current PI Controller
k	Proportional Gain of battery side Voltage PI Controller
k_{iV}	Integral Gain of battery side Voltage PI Controller
k_{pd}	Proportional gain of DCM PFC stage voltage PI controller
k_{id}	Integral gain of DCM PFC stage voltage PI controller
K_{ecrit}	Critical value of conduction parameter
L_f	Filter Inductance (H)
L_i, L_{i1}, L_{i2}	Inductance of Input Side Inductor (H)
L_f	HFT magnetizing inductance of Flyback Converter
L_{fc}	Critical value of HFT magnetizing inductance
L_{ic}	Critical value of Input Side Inductor (H)
L_m, L_{m1}, L_{m2}	HFT Magnetizing Inductance at PFC stage (H)
L_{mc}	Critical value of HFT Magnetizing Inductance at PFC stage (H)
L_o, L_{o1}, L_{o2}	Inductance of Output Side Inductor (H)
L_{oc}	Critical Inductance of Output Side Inductor (H)
L_s	Source Inductance (H)
m_{db}	Modulating signals for battery side PWM Generator
$n\ (N_1/N_2)$	HFT Transformation ratio for PFC converter
N_1	Number of Turns in Primary of High Frequency Transformer for PFC converter
N_2	Number of Turns in Secondary of High Frequency Transformer for PFC converter
N	Turns ratio of HFT in Flyback converter
N_p	Number of turns in Primary winding
N_s	Number of turns in Secondary winding
P	Rated Power of Charger
R_L	Emulated Resistance for PFC load (Ω)
V_{bb}	Control output from voltage PI controller at battery side

V_{cc}	Output of voltage PI Controller at PFC stage (V)
V_{dc}	DC Link Voltage at PFC converter output(V)
V_{dcref}	Reference value of DC Link Voltage (V)
V_b	Battery Voltage (V)
V_b^*	Reference Battery Voltage (V)
v_{in}	Input Voltage at the input of PFC converter (V)
V_{in}	Average Voltage at the input of PFC converter or after DBR(V)
V_m	Peak Value of Input Supply Voltage (V)
v_s	Mains Voltage (V)
V_{smin}	Minimum value of mains Voltage (V)
V_{smax}	Maximum value of mains Voltage (V)
V_{spk}	Peak Value of mains Voltage (V)
v_{C1}, v_{Ci1}, v_{Ci2}	Voltage across Input Side energy transfer Capacitors (V)
v_{C2}, v_{Co1}, v_{Co2}	Voltage across Output Side energy transfer Capacitors (V)
v_{sw}, v_{s1}, v_{s2}	Voltage stresses across PFC switches (V)
ω	Line frequency (rad/sec)
Δi_{Li}, Δi_{Li1}, Δi_{Li2}	Ripple in Input Side Inductor Current (A)
Δi_{Lo}, Δi_{Lo1}, Δi_{Lo2}	Ripple in Output Side Inductor Current (A)
Δv_{C1}, Δv_{C11}, Δv_{C12}	Ripple Voltage across Input Side Intermediate Capacitor (V)
Δv_{C2}, Δv_{C21}, Δv_{C22}	Ripple Voltage across Output Side Intermediate Capacitor (V)
ξ	Permissible Ripple in Input Inductor Current (%)
χ	Permissible Ripple in Output Inductor Current (%)
δ	Permissible Ripple in Magnetizing Inductor Current (%)
ζ	Permissible Ripple in Input side energy transfer capacitor voltage (%)
ρ	Permissible Ripple in Output side energy transfer capacitor voltage (%)
γ	Permissible Ripple in DC-link capacitor voltage (%)
κ	Permissible Ripple in battery side Output capacitor voltage (%)