DESIGN AND CONTROL OF GRID-INTERACTIVE EV CHARGING ARCHITECTURE UNDER MULTIPLE GRID NON-IDEALITIES

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DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JULY 2024

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by

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Submitted

in fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2024

CERTIFICATE

This is to certify that the thesis entitled, **"Design and Control of Grid-Interactive EV Charging Architecture under Multiple Grid Non-Idealities"** being submitted by **Mr. Debasish Mishra** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Debasish Mishra has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results obtained here in have not been submitted to any other University or Institute for the award of any degree.

Date: July 3, 2024

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ACKNOWLEDGEMENTS

I am immensely grateful to Prof. Bhim Singh and Prof. B.K. Panigrahi for their invaluable guidance and unwavering support throughout my Ph.D. journey. Working under their supervision has been an enriching experience, providing me with profound insights into research. Prof. Bhim Singh's determination, dedication, innovation, resourcefulness, and discipline have been a constant source of inspiration for me. His encouragement, diligent oversight, and unwavering commitment to excellence have motivated me to strive for improvement and utilize my capabilities to the fullest extent. Due to his blessing I have earned various experiences, other than research, which will help me throughout my life. Prof. B.K.Panigrahi's steadfast determination, innovative mindset, and resourcefulness have been a perpetual source of inspiration for me. My sincere thanks and deep gratitude are to Prof. Nilanjan Senroy, Prof. Anandrup Das, 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. M. Veerachary, Prof. Shubhendu Bhasin and Dr. Ramkrishan Maheshwari for their valuable inputs during my course work, which has made the foundation for my research work. I am grateful to Prof. Santanu Mishra, Prof. Sumit Pramanick, Prof. Rabindra Behera and Prof. Soumya Shubhra Nag for their valuable support and motivation during my research work. I am grateful to IIT Delhi for providing me the research facilities. I wish to express my sincere gratitude to Prof. Bhim Singh and Prof. B.K. Panigrahi and Prof. Sukumar Mishra, as professors in charge of the PG Machine Lab, provided me with immense facilities for experimental work. Thanks are due to Puran Singh, Sh. Jitendra, Sh. Gourav Kumar, Sh. Anand Kumar PG Machines Lab and Power System Lab., IIT Delhi for providing me the facilities and assistance during this work. I want to thank all my seniors, Dr. Saleem Mir, Dr. Sreejith R., Dr. Anjeet Verma, Dr.

Seema Kewat, Dr. Rishikant Sharma, Dr. Piyush Kant, Dr. Nishant Kumar, Dr. Saurabh Shukla, Dr. Nidhi Mishra, Dr. Shailendra Kumar Dwivedi, Dr. Shadab Murshid, Dr. Subarni Pradhan, Dr. Sachin Devassy, and Dr. Anjanee Kumar Mishra, Dr. SivRaman, Dr. Deepak Pullugram, to motivate me in the starting of my research work. I want to use this opportunity to thank Dr. Pankaj Achlekar, Mr. Gurmeet Singh, Mr. Yalavarthi Amarnath, Mr. Suri Praneeth, Mr. Priyvrat Vats who have constantly helped me with all technical issues, and all other colleagues for their valuable aid and cooperation. My heartfelt thanks to Dr. Utkarsh Sharma, Mr. P. Sambasivaiah, Mr. Saran Kumar Chaurasia, Dr. Jitendra Gupta, Dr.Pavitra Shukl, Dr. Farheen Chishti, Mr. Aryadip Sen, Dr. Mohd. Kashif, Ms.Hina Parveen, Ms. Rashmi Rai, Dr.. Souvik Das,Mr. Sudip Bhattacharya, Mr. Sandeep Kumar Sahoo, Mr. Gaurav Modi, Mr.Syed Bilal Qaiser Naqvi, Mr. Sayandev Ghosh, Dr. Vivek Narayanan, Mr. Sharankumar Shastri, Mr. Deepak Saw, Mr.Shivam Kumar Yadav, Ms. Kousalya V, Ms. Sanjenbam Chandrakala Devi, Mr. Saurabh Mishra, Mr. Muhammad Zarkab Farqooi, Ms.Kripa Tiwari, Mr. Rohit Kumar, Mr. Arjun Kumar, Mr. Biswajit Saha, Ms. Farha Siddique, Mr. Rakesh Patnekar, Ms. Arjita Pal, Ms. Akshita Sharma, Mr. Arup Anshuman, Mr. Arun Chaudhry and all other Lab mates for their help and informal support in pursuing this research work. I would also like to thank Mr. Yatindramani Tripathi, Mr. Satish Saha, Mr. Narendra Kumar, Mr. Sandeep Kumar and all other Electrical Engineering Department office staff for support. I am thankful to those who have directly or indirectly helped me finish my dissertation study. Moreover, I would like to thank the Department of Science and Technology (DST), Govt. of India for funding this research work under the fund for the improvement of S and T infrastructure in higher educational institutions (FIST), UKICERI (RP03391), UI-ASSIST (RP03443), SERI-II, J C Bose Fellowship (RP03128) and SERB NSC fellowship. My deepest love, appreciation and indebtedness go to my father, Mr. Godabarish Mishra for his dreams, sacrifices and wholeheartedly endorses. His trust in my capabilities have always motivated me to reach higher academic degrees. I want to convey my unbounded love to my mother, Mrs. Manjulata Mishra, as I spent a major part of my childhood in her lap. The immense effort, endurance, encouragement, and unwavering support from my beloved wife, Mrs. Rakhee Das, and my son, Master Shreyasish Mishra, throughout my entire research journey have been invaluable to me. Their presence has been a pillar of strength, providing me with the motivation and resilience to overcome challenges and succeed. Moreover, I would like to thank my sister, Mrs. Anima Mishra, Mrs. Sikha Das, brother, Mr. Shrinibas Mishra, and my parents-in-law for giving me inner strength and wholehearted support. Their trust in my capabilities had been a key factor in all my achievements. I pray for their benediction in my future endeavors. Their blessings may be showered on me for strength, wisdom, and determination to achieve in the future. At last, I am indebted to the almighty Lord Shree Jagannath for his blessings to stand with me in every stage of my life.

Date: 03 July, 2024 **Debasish Mishra**

ABSTRACT

Advanced regulatory frameworks aimed at curbing CO_2 emissions, coupled with supportive policies worldwide promoting sustainable transportation, have led to a notable increase in the adoption of electric vehicle fleets. A growing preference for fast charging, facilitated by high-density batteries, underscores the necessity for a robust charging infrastructure and specialized control architecture to ensure optimal charging power quality, particularly during peak hour demand. However, the proliferation of EV fleets and unregulated charging units poses a significant challenge to distribution utilities, potentially impacting other connected DC and AC ancillary services. To address this concern, it is crucial to explore cleaner and renewable energy sources integration into the grid. Recent literature surveys suggest that without integrating renewable energy sources and reinforcing the grid, clusters of EV charging loads may overwhelm the grid, leading to significant congestion. Issues such as fast charging, peak-hour charging, grid stability, and converter non-linearity further complicate voltage regulation. In response, multi-objective energy management strategies and grid integration offer promising avenues to reduce grid dependency. Coordinated energy management and voltage regulation leveraging various auxiliary energy resources can help maintain utility power quality during high-power EV charging operations. The integration of renewable infrastructures with the grid and their standalone operations have proven beneficial for distribution operators in ensuring healthy utility power quality during periods of peak demand. The current thesis offers a comprehensive examination of existing technologies and proposed controllers and topologies for EV charging operations. Typically, EV chargers connect to the grid power via both on-board chargers and off-board charging stations to extend a four-quadrant charging mode, facilitating vehicle-to-grid and grid-to-vehicle operations.

सारांश

उन्नत नियामक ढांचे जो CO_2 उत्सर्जन को कम करने के उद्देश्य से हैं, के साथ-साथ दुनिया भर में स्थायी परिवहन को बढ़ावा देने वाली सहायक नीतियों के कारण इलेक्ट्रिक वाहन बेड़ों को अपनाने में उल्लेखनीय वृद्धि हुई है। उच्च घनत्व बैटरियों द्वारा सुगम त्वरित चार्जिंग के प्रति बढ़ती प्राथमिकता एक मजबूत चार्जिंग बुनियादी ढांचे और विशेष नियंत्रण वास्तुकला की आवश्यकता को रेखांकित करती है ताकि विशेष रूप से चरम समय की मांग के दौरान इष्टतम चार्जिंग पावर गुणवत्ता सुनिश्चित की जा सके। हालांकि, EV बेड़ों का प्रसार और अनियमित चार्जिंग इकाइयाँ वितरण उपयोगिताओं के लिए एक महत्वपूर्ण चुनौती प्रस्तुत करती हैं, जो अन्य जुड़े हुए DC और AC सहायक सेवाओं को प्रभावित कर सकती हैं।

इस चिंता का समाधान करने के लिए, ग्रिड में स्वच्छ और नवीकरणीय ऊर्जा स्रोतों के एकीकरण का पता लगाना महत्वपूर्ण है। हाल के साहित्यिक सर्वेक्षणों से पता चलता है कि यदि नवीकरणीय ऊर्जा स्रोतों को एकीकृत और ग्रिड को मजबूत नहीं किया गया तो EV चार्जिंग लोड के समूह ग्रिड को भारी कर सकते हैं, जिससे महत्वपूर्ण भीड़भाड़ हो सकती है। त्वरित चार्जिंग, चरम समय चार्जिंग, ग्रिड स्थिरता, और कनवर्टर गैर-रैखिकता जैसे मुद्दे वोल्टेज विनियमन को और जटिल बनाते हैं।

जवाब में, बहुउद्देश्यीय ऊर्जा प्रबंधन रणनीतियाँ और ग्रिड एकीकरण ग्रिड निर्भरता को कम करने के लिए आशाजनक मार्ग प्रदान करते हैं। विभिन्न सहायक ऊर्जा संसाधनों का लाभ उठाकर समन्वित ऊर्जा प्रबंधन और वोल्टेज विनियमन उच्च-शक्ति EV चार्जिंग संचालन के दौरान उपयोगिता पावर गुणवत्ता बनाए रखने में मदद कर सकते हैं। ग्रिड के साथ नवीकरणीय बुनियादी ढांचे का एकीकरण और उनके स्टैंडअलोन संचालन वितरण ऑपरेटरों के लिए चरम मांग की अवधि के दौरान स्वस्थ उपयोगिता पावर गुणवत्ता सुनिश्चित करने में लाभकारी सिद्ध हुए हैं।

वर्तमान शोध प्रबंध EV चार्जिंग संचालन के लिए मौजूदा प्रौद्योगिकियों और प्रस्तावित नियंत्रकों और टोपोलॉजी का व्यापक परीक्षण प्रस्तुत करता है। आमतौर पर, EV चार्जर ऑन-बोर्ड चार्जर और ऑफ-बोर्ड चार्जिंग स्टेशनों के माध्यम से ग्रिड पावर से जुड़ते हैं ताकि वाहन-से-ग्रिड और ग्रिड-से-वाहन संचालन को सुविधाजनक बनाने के लिए चार-चतुर्थांश चार्जिंग मोड का विस्तार किया जा सके।

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LIST OF ABBREVIATIONS

EV	Electric Vehicle
CS	Charging Station
ICE	Internal Combustion Engine
ZEV	Zero Emission Vehicle
CAN	Controller Area Network
PFC	Power Factor Correction
PSFB	Phase-shifted Full-bridge
DAB	Dual Active Bridge
DBR	Diode Bridge Rectifier
EVSE	Electric Vehicle Supply Equipments
PV	photovoltaic
AC	Alternating Current
DC	Direct Current
V2G	vehicle-to-grid
G2V	Grid-to-Vehicle
V2X	Vehicle-to-Auxiliary supply
IM	Islanded Mode
GCM	Grid Connected Mode
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
IEEE	Institute of Electrical and Electronics Engineers
INC	Incremental Conductance
PCC	Point of Common Coupling
PI	Proportional Integral
SOGI	Second Order Generalized Integrator
PLL	Phase Locked Loop
FLL	Frequency Locked Loop
S/H	Sample and Hold

THD	Total Harmonic Distortion
VSC	Voltage Source Converter
ZCD	Zero Crossing Detection
UPF	Unity Power Factor
IGBT	Insulated Gate Bipolar Transistor
ADC	Analog to Digital Converter
DAC	Digital to Analog Converter
PWM	Pulse Width Modulator
RC	Resistor-Capacitor
CC/CV	Constant Current/Constant Voltage
DSO	Digital Storage Oscilloscope
SMC	Sliding Mode Controller
SOC	State of Charge
PR	Proportional resonant controller
MRC	Multi-resonant controller
ASMC	Adaptive sliding mode controller
LFC	Lyapunov function candidate
FD	First-order dynamics
BSU	Battery storage unit
BESS	Battery energy storage system
PEMFC	Proton exchange membrane fuel cell
PMAE	Projection Modified Adaptive Estimation
DSMC	Double integral sliding mode controller
THD	Total Harmionic Distortion

LIST OF SYMBOLS

C_{dc}	DC-link capacitor (F)
V_{dc}	DC-link voltage (V)
v_s	Single phase instantaneous grid voltage (V)
v_c	Single phase instantaneous PCC voltage (V)
i_s	Single phase instantaneous grid current (A)
i_c	Single phase instantaneous PCC current (A)
R_f	Ripple filter resistance (Ω)
C_f	Ripple filter capacitor (F)
i_e	Single phase instantaneous EV current (A)
i_h	Single phase instantaneous household load current (A)
E	Synchronizing signal
C_b	Storage battery capacitor (F)
C_e	EV battery capacitor (F)
I_b	Storage battery current (A)
$I_e v$	EV battery current (A)
V_{PV}	PV array voltage (V)
I_{PV}	PV array current (V)
P_s	Grid active power (kW)
Q_s	Grid reactive power (kVAR)
S	Grid apparent power (kVA)
ω	Angular frequency of grid (rad/s)
k	is safety factor
k_w	is window factor
A_w	is window area
A_c	is core area
A_e	is the product of A_w and A_c
B_m	is maximum flux density
J	is current density A/mm^2
α	is convergence factor
P_b	Storage battery active power (kW)
P_e	EV active power (kW)
P_{ev}	EV battery power (kW)
P_h	Household load active power (kW)
P_{PV}	PV array power (kW)

P_W	WECS power (kW)
L_c	Interfacing inductor (H)
L_b	Interfacing inductor (H)
V_m	Amplitude pf PCC voltage
v_{ca}, v_{cb}, v_{cc}	Three phase instantaneous PCC voltage (V)
v_{sa}, v_{sb}, v_{sc}	Three phase instantaneous grid voltage (V)
v_{ga}, v_{gb}, v_{gc}	Three phase instantaneous DG set voltage (V)
i_{ca}, i_{cb} and i_{cc}	Three phase instantaneous PCC current (A)
i_{sa}, i_{sb} and i_{sc}	Three phase instantaneous grid current (A)
i_{ga}, i_{gb} and i_{gc}	Three phase instantaneous DG set current (A)