CONTROL OF MULTILEVEL CONVERTERS FOR SOLAR GRID INTERFACE

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Control of Multilevel Converters for Solar Grid Interface

by

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Dedicated to

My family and all the teachers whom I came across at different stages during my life.

CERTIFICATE

It is certified that the thesis entitled "**Control of Multilevel Converters for Solar Grid Interface**," being submitted by **Mr. Shivam Kumar Yadav** 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: 7 January, 2025

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ABSTRACT

Solar multilevel converters (MLCs) enhance power transfer efficiency with lower harmonic distortion and reduced electromagnetic interference, achieved by configuring semiconductor switches in arrangements in a modular manner to handle large scale power. The goal is to generate high-voltage stepped waveforms resembling pure sine waves. Topologies such as neutral point clamped (NPC), cascaded H-bridge (CHB), and flying capacitor (FC) converters are available for grid tied systems. Conventional topologies suffer from increased switch count, raising controller complexity, losses, and costs. To address these challenges, low switching frequency medium voltage solar power converters are designed to maximize efficiency and meet IEEE/CIGRE harmonic standards. Emerging reduced-switch and Ac side isolated topologies for solar grid-tied systems aim to lower semiconductor and capacitor requirements, enhancing efficiency and affordability for practical applications. Single phase AC side single PV source configuration is tested with minimal drift technique to have lesser drift in maximum power point (MPP). This drift control with pressure gradient based new optimization methodology is adopted for better performance. To have further improvement in power quality end, single phase converter is tested with new carrier pulse width modulation that uses pulse generator and triangular generator to have minimum weighted total harmonic distortion in five-level converter voltage. Fundamental modulation is ideal for better efficiency, and tested for single phase converter using Levenberg-Marquardt methodology. New reduced switch topologies are tested in real-time, which generates five-level, seven level, nine-level, thirteen and seventeen level waveforms with improved power quality for medium voltage grid integration. In these configurations, contributions are modified carrier schemes, dominant shift factor scheme, optimal third harmonic modulation, selective harmonic elimination, equal area criteria and nearest level control are presented for better

performance of medium voltage solar power converters. The irradiance profile is taken from the real-life locations for better insight of three-phase converter operation. The day and night mode of solar converters are also tested to utilize the reactive power capability in night time. Coming to the two-phase to three-phase power transfer, new nine level and twenty-seven level cascaded Scott-tied topologies are implemented with change in solar irradiances. The Scott connection made the system compact to feed power with converters, which are required only in two phases. The system become efficient with nearest level switching round function-based method, which is simpler in control implementation. The galvanic isolation provides inherent safety in the converter modules from grid end faults.

Research work in the thesis focuses on new topologies and their control with enhance power quality. Recorded results from laboratory hardware setup and implementation of large-scale power converters in OPAL-RT test bench shows the merits of modularity of converters in power conversion and promotes clean energy goals. New modulation techniques and control provides reduction in grid current THD, which meets the IEEE 519 standard. Individual harmonics are tested for CIGRE standards. Presented work motivates the researchers towards new intelligent and efficient renewable energy systems using different configurations of cascaded multilevel converters.

सार

सौर बहुस्तरीय कन्वर्टर्स (MLC) कम हार्मोनिक विरूपण और कम विद्युत चुम्बकीय हस्तक्षेप के साथ बिजली हस्तांतरण दक्षता को बढ़ाते हैं, जो बड़े पैमाने पर बिजली को संभालने के लिए मॉड्यूलर तरीके से व्यवस्था में सेमीकंडक्टर स्विच को कॉन्फ़िगर करके प्राप्त किया जाता है। लक्ष्य शुद्ध साइन तरंगों के समान उच्च-वोल्टेज स्टेप्ड वेवफॉर्म उत्पन्न करना है। न्यूट्रल पॉइंट क्लैम्प्ड (NPC), कैस्केडेड H-ब्रिज (CHB), और फ्लाइंग कैपेसिटर (FC) कन्वर्टर्स जैसी टोपोलॉजी ग्रिड से जुड़ी प्रणालियों के लिए उपलब्ध हैं। पारंपरिक टोपोलॉजी में स्विच की संख्या में वृद्धि, नियंत्रक की जटिलता, नुकसान और लागत में वृद्धि होती है। इन चुनौतियों का समाधान करने के लिए, कम स्विचिंग आवृत्ति मध्यम वोल्टेज सौर ऊर्जा कन्वर्टर्स को दक्षता को अधिकतम करने और IEEE/CIGRE हार्मोनिक मानकों को पूरा करने के लिए डिज़ाइन किया गया है। सौर ग्रिड से जुड़ी प्रणालियों के लिए उभरते कम-स्विच और एसी साइड आइसोलेटेड टोपोलॉजी का उद्देश्य सेमीकंडक्टर और कैपेसिटर की आवश्यकताओं को कम करना, व्यावहारिक अनुप्रयोगों के लिए दक्षता और सामर्थ्य को बढ़ाना है। सिंगल फेज एसी साइड सिंगल पीवी स्रोत कॉन्फ़िगरेशन को अधिकतम पावर पॉइंट (MPP) में कम बहाव के लिए न्यूनतम बहाव तकनीक के साथ परीक्षण किया जाता है। बेहतर प्रदर्शन के लिए दबाव प्रवणता आधारित नई अनुकूलन पद्धति के साथ इस बहाव नियंत्रण को अपनाया गया है। बिजली की गुणवत्ता में और सुधार करने के लिए, एकल चरण कनवर्टर का परीक्षण नए वाहक पल्स चौड़ाई मॉड्यूलेशन के साथ किया जाता है जो पांच-स्तरीय कनवर्टर वोल्टेज में न्यूनतम भारित कुल हार्मोनिक विरूपण के लिए पल्स जनरेटर और त्रिकोणीय जनरेटर का उपयोग करता है। मौलिक मॉड्यूलेशन बेहतर दक्षता के लिए आदर्श है, और लेवेनबर्ग-मार्क्वार्ड पद्धति का उपयोग करके एकल चरण कनवर्टर के लिए परीक्षण किया गया है। नए कम किए गए स्विच टोपोलॉजी का वास्तविक समय में परीक्षण किया जाता है, जो मध्यम वोल्टेज ग्रिड एकीकरण के लिए बेहतर बिजली की गुणवत्ता के साथ पांच-स्तर, सात स्तर, नौ-स्तर, तेरह और सत्रह स्तर

की तरंगें उत्पन्न करता है। इन विन्यासों में, मध्यम वोल्टेज सौर ऊर्जा कन्वर्टर्स के बेहतर प्रदर्शन के लिए संशोधित वाहक योजनाएँ, प्रमुख शिफ्ट कारक योजना, इष्टतम तीसरा हार्मोनिक मॉड्यूलेशन, चयनात्मक हार्मोनिक उन्मूलन, समान क्षेत्र मानदंड और निकटतम स्तर नियंत्रण प्रस्तुत किए जाते हैं। तीन-चरण कनवर्टर संचालन की बेहतर जानकारी के लिए विकिरण प्रोफ़ाइल वास्तविक जीवन के स्थानों से ली गई है। रात के समय में प्रतिक्रियाशील शक्ति क्षमता का उपयोग करने के लिए सौर कन्वर्टर्स के दिन और रात मोड का भी परीक्षण किया जाता है। दो-चरण से तीन-चरण बिजली हस्तांतरण की बात करें तो, सौर विकिरण में परिवर्तन के साथ नए नौ स्तर और सत्ताईस स्तर के कैस्केड स्कॉट-बंधे टोपोलॉजी को लागू किया जाता है। स्कॉट कनेक्शन ने कन्वर्टर्स के साथ बिजली खिलाने के लिए सिस्टम को कॉम्पैक्ट बना दिया, जिसकी आवश्यकता केवल दो चरणों में होती है। सिस्टम फ़ंक्शन-आधारित विधि के आसपास निकटतम स्तर स्विचिंग के साथ कुशल बन गया, जो नियंत्रण कार्यान्वयन में सरल है। गैल्वेनिक आइसोलेशन ग्रिड एंड फॉल्ट से कनवर्टर मॉड्यूल में अंतर्निहित सुरक्षा प्रदान करता है। थीसिस में शोध कार्य नई टोपोलॉजी और बिजली की गुणवत्ता बढ़ाने के साथ उनके नियंत्रण पर केंद्रित है। प्रयोगशाला हार्डवेयर सेटअप और OPAL-RT टेस्ट बेंच में बड़े पैमाने पर बिजली कन्वर्टर्स के कार्यान्वयन से दर्ज किए गए परिणाम बिजली रूपांतरण में कन्वर्टर्स की मॉड्यूलरिटी के गुणों को दर्शाते हैं और स्वच्छ ऊर्जा लक्ष्यों को बढ़ावा देते हैं। नई मॉड्यूलेशन तकनीक और नियंत्रण ग्रिड करंट THD में कमी प्रदान करता है, जो IEEE 519 मानक को पूरा करता है। व्यक्तिगत हार्मोनिक्स का परीक्षण CIGRE मानकों के लिए किया जाता है। प्रस्तुत कार्य शोधकर्ताओं को कैस्केड मल्टीलेवल कन्वर्टर्स के विभिन्न विन्यासों का उपयोग करके नई बुद्धिमान और कुशल अक्षय ऊर्जा प्रणालियों की ओर प्रेरित करता है।

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LIST OF ABBREVIATIONS

MLC	Multilevel Converters
CHB	Cascaded H-Bridge
DBU	DC Bus Utilization
NPC	Neutral Point Clamped
PUC	Packed U-Cell
THD	Total Harmonic Distortion
ANPC	Active Neutral Point Clamped
FC	Flying Capacitors
IGBT	Insulated Gate Bipolar Transistors
SPV	Solar Photovoltaic
PWM	Pulse Width Modulation
EAFC	Equal Area Fundamental Control
MPPT	Maximum Power Point Tracking
INC	Incremental Conductance
LBN	Level Building Network
NLM	Nearest Level Modulation
NLC	Nearest Level Control
VSC	Voltage Source Converter
FACTs	Flexible AC Transmission Systems
MOMD	Multi-objective Minimum Drift
NSOA	Novel Swarm Optimization Algorithm
LACS	Level Arranged Carrier Scheme
PSCS	Phase-Shifted Carrier Scheme
PLACS	Parabolic Level Arranged Carrier Scheme
MLACS	Modified Level Arranged Carrier Scheme
LMA	Levenberg Marquardt Algorithm

SHE	Selective Harmonic Elimination
OTHI	Optimal Third Harmonic Injection
MPM	Main Power Module
OSF	Optimal Shift Factor
EPM	Extended Power Module
CCSC	Cross-connected Solar Converter
DAI	Direct Average Solar Irradiance
DFAI	Diffused Average Solar Irradiance
GIS	Geographical Information System
ST	Scott Ternary
QD	Quadrature Displaced
RTDS	Real-time Digital Simulator