TOPOLOGY AND CONTROL OF HIGH-RESOLUTION MULTILEVEL INVERTER FOR RENEWABLE ENERGY APPLICATION

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Topology and Control of High-Resolution Multilevel Inverter for Renewable Energy Application

by

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Dedicated to my beloved parents,

Arif Nizam Ansari and Farida Bano,

whose love, sacrifices, and prayers have been my greatest strength.

Certificate

This is to certify that the thesis titled,"**Topology and Control of High-Resolution Multilevel Inverter for Renewable Energy Application**", submitted by **Mr. Mohsin Karim Ansari**, to the **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy** is a record of bonafide the research work done by him. He has worked under my supervision and guidance and has fulfilled the requirements for the submission of this thesis, which, to my knowledge, has reached the requisite standard.

The results reported in the dissertation have not been submitted in part or in full to any other Institute or University for the award of any degree or diploma.

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Abstract

Power converters are playing a significant role in achieving sustainability, flexibility, and efficiency goals in the current utility systems. Multilevel converters for medium-voltage and high-power applications have gained significant acceptance because of their merits, such as lower harmonic generation and improved efficiency compared to conventional two-level converters. Asymmetric converters based on high-resolution converters can generate high-resolution voltage waveforms with a limited number of isolated supplies and semiconductor devices. This also reduces the switching losses and optimizes conduction losses. Enabling a selected multilevel converter topology for a particular application requires source and load matching, and it should address the challenges associated with the application to ensure proper operation. This thesis investigates an asymmetric multilevel inverter for medium-voltage, high-power applications. The dc-link voltages have an asymmetry ratio of 16:4:1, enabling the inverter to generate a high-resolution voltage waveform. This work proposes solutions for implementing the asymmetric multilevel inverter for isolated and grid-connected PV applications. The work explores its application in offline UPS systems by reducing device switching frequency, increasing the number of levels with the same number of devices, and introducing a battery optimization strategy for improved efficiency. For STATCOM applications, floating capacitor balancing and reactive power control are addressed using an auxiliary circuit and d-q control, resulting in higher power injection capability with minimal auxiliary bridge power requirements. The high-resolution voltage levels of the inverter are also shown to be suitable for active power filter applications, fulfilling current injection re-

quirements at the point of common coupling through effective reference generation, tracking, and dc-link balancing strategies. Finally, the topology is investigated for grid-connected PV systems, where a single dc-source configuration is realized using isolation transformers, with low power handled by the auxiliary bridges. All proposed solutions are validated through MATLAB/Simulink simulations and experimental verification using a hardware prototype built with the TI Launchpad F28379D DSP. The inverters low switching frequency enables the generation of gating signals using general-purpose I/O pins, eliminating the need for dedicated EPWM modules.

Keywords: Active power filter, asymmetric inverters, hexagonal decomposition, nearest space vector modulation, solar PV inverters, STATCOM, UPS.

संक्षेप

वर्तमान उपयोगिता प्रणालियों में स्थिरता, नम्यता और दक्षता लक्ष्यों को प्राप्त करने में पावर कन्वर्टर्स महत्वपूर्ण भूमिका निभा रहे हैं। मध्यम-वोल्टेज और उच्च-शक्ति अनुप्रयोगों के लिए मल्टीलेवल कन्वर्टर्स ने अपनी खूबियों, जैसे पारंपरिक द्वि-स्तरीय कन्वर्टर्स की तुलना में कम हार्मोनिक उत्पादन और बेहतर दक्षता, के कारण महत्वपूर्ण स्वीकृति प्राप्त की है। उच्च-रिज़ॉल्यूशन कन्वर्टर्स पर आधारित असममित कन्वर्टर्स सीमित संख्या में पृथक आपूर्तियों और अर्धचालक उपकरणों के साथ उच्च-रिज़ॉल्यूशन वोल्टेज तरंगरूप उत्पन्न कर सकते हैं। यह स्विचिंग हानियों को भी कम करता है और चालन हानियों को अनुकूलित करता है। किसी विशिष्ट अनुप्रयोग के लिए चयनित मल्टीलेवल कन्वर्टर टोपोलॉजी को सक्षम करने के लिए स्रोत और विद्युत भार मिलान की आवश्यकता होती है, और इसे उचित संचालन सुनिश्चित करने के लिए अनुप्रयोग से जुड़ी चुनौतियों का समाधान करना चाहिए। यह शोध प्रबंध मध्यम-वोल्टेज, उच्च-शक्ति अनुप्रयोगों के लिए एक असममित मल्टीलेवल इन्वर्टर की जाँच करता है। डीसी-लिंक वोल्टेज का असममित अनुपात १६:४:१ होता है, जिससे इन्वर्टर एक उच्च-रिज़ॉल्यूशन वोल्टेज तरंगरूप उत्पन्न कर सकता है। यह कार्य पृथक और ग्रिड-संबद्ध पीवी अनुप्रयोगों के लिए असममित मल्टीलेवल इन्वर्टर के कार्यान्वयन हेतु समाधान प्रस्तावित करता है। यह कार्य ऑफ़लाइन यूपीएस प्रणालियों में इसके अनुप्रयोग की पड़ताल करता है, जिसमें उपकरण स्विचिंग आवृत्ति को कम करके, समान उपकरणों के साथ स्तरों की संख्या बढ़ाकर, और बेहतर दक्षता के लिए बैटरी अनुकूलन रणनीति अपनाई गयी है। स्टैटकॉम अनुप्रयोगों के लिए, फ्लोटिंग कैपेसिटर संतुलन और प्रतिक्रियाशील शक्ति नियंत्रण को एक सहायक परिपथ और डी-क्यू नियंत्रण रणनीति का उपयोग करके संबोधित किया जाता है, जिसके परिणामस्वरूप न्यूनतम सहायक ब्रिज शक्ति आवश्यकताओं के साथ उच्च शक्ति अंतःक्षेपण क्षमता प्राप्त होती है। इन्वर्टर के उच्च-रिज़ॉल्यूशन वोल्टेज स्तरों को सक्रिय शक्ति फ़िल्टर अनुप्रयोगों के लिए भी उपयुक्त दिखाया गया है, जो प्रभावी संदर्भ निर्माण, ट्रैकिंग और डीसी-लिंक संतुलन रणनीतियों के माध्यम से सामान्य युग्मन बिंदु पर धारा अंतःक्षेपण आवश्यकताओं को पूरा करते हैं। अंत में, ग्रिड-संबद्ध पीवी प्रणालियों के लिए टोपोलॉजी की जाँच की गयी है, जहाँ एकल डीसी-स्रोत विन्यास को आइसोलेशन ट्रांसफ़ॉर्मरों का उपयोग करके साकार किया गया है, जिसमें सहायक ब्रिज द्वारा कम

विद्युत ऊर्जा खपत होती है। सभी प्रस्तावित समाधानों का MATLAB/Simulink में सिमुलेशन और एक हार्डवेयर प्रोटोटाइप का उपयोग करके जो कि TI Launchpad F28379D कंट्रोलर से संचालित किया गया उससे प्रायोगिक सत्यापन किया गया। इन्वर्टर की कम स्विचिंग आवृत्ति सामान्य-उद्देश्य वाले I/O पिनों का उपयोग करके गेटिंग सिग्नल उत्पन्न करने में सक्षम बनाती है, जिससे समर्पित EPWM मॉड्यूल की आवश्यकता समाप्त हो जाती है।

संकेतशब्द: सक्रिय पावर फ़िल्टर, असममित इन्वर्टर, षट्कोणीय अपघटन, निकटतम स्थान वेक्टर मॉडुलन, सौर पी वी इन्वर्टर, स्टैटकॉम , यू पी एस ।

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List of Abbreviations

PV	Photovoltaic
CHB	Cascaded H-bridge
NPC	Neutral-Point Clamped
FACTS	Flexible AC Transmission Systems
STATCOM	Static Compensators
APF	Active Power Filters
DVR	Dynamic Voltage Restorers
UPFC	Unified Power Flow Controllers
UPS	Uninterruptible Power Supplies
HFL	High-frequency Link
VA	Volt-Ampere
TNPC	T-type Neutral Point Clamped
CRGO	Cold Rolled Grain Oriented
PWM	Pulsewidth Modulation
MLI	Multilevel Inverter
FCC	Flying Capacitor-Clamped
MMC	Modular Multilevel Converter
ANPC	Active NPC
DCMLI	Diode-Clamped Multilevel Inverter
MVDC	Medium Voltage dc
HVDC	High Voltage dc
NNPC	Nested NPC
SMC	Stacked Multicell Converter
PUC	Packed U-Cell

EMI	electromagnetic interference
IGBT	Insulated Gate Bipolar Transistor
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
VSI	Voltage Source Inverter
CSI	Current Source Inverter
PCB	Printed Circuit Board
IC	Integrated Circuit
DSP	Digital Signal Processor
GPIO	General Purpose Input/Output
OP-AMP	Operational Amplifier
ADC	Analog-to-Digital conversion
EPWM	Enhanced Pulse Width Modulation
THD	Total Harmonic Distortion
NLC	Nearest Level Control
NSVM	Nearest Space Vector Modulation
PDR	Power Distribution Ratio
VAR	Reactive Volt-Ampere
PS-PWM	Phase-shifted pulse width modulation
SVM	Space Vector Modulation
SHE	Selective Harmonic Elimination
PI	Proportional-Integral
APF	Active Power Filter
SAPF	Shunt Active Power Filter
HMLI	High-resolution Multilevel Inverters
PCC	Point of common coupling
MLC	Multilevel converter
SOGI	Second-Order Generalized Integrator
DSOGI	Dual Second-Order Generalized Integrator
PLL	Phase-locked Loop
SVC	Static Var Compensators

List of Symbols

A	Unit of electric current
V	Unit of voltage
D	Duty cycle
R_{LS}	Level-to-switch ratio
f_{sw}	Switching frequency
V_{dc}	dc-link voltage
V_{ga}, V_{gb}, V_{gc}	Grid phase voltages
I_{ga}, I_{gb}, I_{gc}	Grid phase currents
R, L	Load resistance and inductance
P, Q	Active and reactive power
m_a, m	Modulation index
V_c	Total dc-link voltage per phase
ω	Angular frequency (rad/s)
T_s	Sampling period
α, β	Stationary reference frame components
d, q	Rotating reference frame components
θ	Grid voltage phase angle
ϕ	Power factor angle
ref	Reference quantity
rms	Root mean square value
avg	Average value