

POWER QUALITY IMPROVEMENT IN MULTI- PULSE CONVERTER FED MULTILEVEL INVERTER BASED INDUCTION MOTOR DRIVES

PIYUSH KANT



**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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by

PIYUSH KANT

Department of Electrical Engineering

Submitted

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CERTIFICATE

This is to certify that the thesis entitled, “**Power Quality Improvement In Multi-Pulse Converter Fed Multilevel Inverter Based Induction Motor Drives**” being submitted by **Mr. Piyush Kant** 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. Piyush Kant has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained herein have not been submitted to any other University or Institute for the award of any degree.

Dated:

Place: New Delhi

(Prof. Bhim Singh)
Department of Electrical Engineering
Indian Institute of Technology Delhi
New Delhi-110016, India

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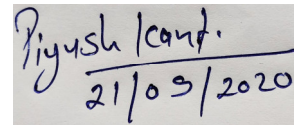
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Dated: 21/09/2020

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A rectangular box containing a handwritten signature in blue ink. The signature reads 'Piyush Kant.' followed by a horizontal line and the date '21/09/2020' written below it.

(Piyush Kant)

Research Scholar

Department of Electrical Engineering

Indian Institute of Technology Delhi

New Delhi-110016, India

ABSTRACT

In this research work, various configurations of multi-pulse AC-DC converters fed multilevel inverters (MLIs) based induction motor drive (IMDs) are presented for medium voltage and medium power applications. This research work provides conventional single-stage multi-winding transformer (SS-MWT) based 12-pulse and 18-pulse AC-DC converters at utility end. This single-stage multi-winding transformer (MWT) has phase-shift in secondary windings only. With the help of this convention SS-MWT, one can achieve up to 36-pulse AC-DC converter, which requires very small phase-shift. Due to which, the manufacturing process of this MWT becomes very complex. Therefore, in this research work, new configuration of modular MWT is proposed to achieve 36-pulse AC-DC converter, which has phase-shift in both primary and secondary windings and it does not require small phase-shift. Due to which the manufacturing process of proposed MWT is quite easier than conventional MWT. With the help of modular MWT, a 54-pulse AC-DC converter is utilized in this research work to shape the supply current closer to sinusoidal and to reduce its total harmonic distortion (THD) to a very low value. This modular MWT is more suitable, when more numbers of isolated DC-supplies are required such as cascaded H-bridge (CHB) inverter fed IMD. Therefore, in this research work, a new multiphase MWT is proposed at the utility end, which convert input three-phase AC-supply in to five-phase output AC-supply. With the help of this multiphase MWT, a 20-pulse, 30-pulse, 40-pulse and 60-pulse AC-DC converters are proposed at the utility end, which has good power quality even at light load conditions.

From above discussion, it is observed that different configurations of multi-pulse AC-DC converters are proposed at the utility end. Apart from it, different types of MLIs are utilized at the motor end to drive an induction motor (IM). A 3-level three-leg neutral point clamped (NPC) and 5-level six-leg NPC MLI are utilized at the motor end to drive an IM. The structure of NPC MLI becomes quite complex for more than 5-level. Therefore, in this research work,

CHB-inverter is used at the motor end to drive an IM. The 5-level and 7-level symmetrical CHB-inverters are used at the drive end. However, this symmetrical CHB-inverter needs more numbers of DC-supplies and power semiconductor switches (PSSs) to get higher numbers of output voltage levels. Therefore, in this research work, binary (1:2) principle is utilized to get more numbers of output voltage levels. The 7-level and 15-level binary CHB-inverters are utilized at the drive end, which requires same numbers of isolated DC-supplies and power semiconductor switches as 5-level and 7-level symmetrical CHB-inverters needed, respectively. In this research work, ternary (1:3) principle is also utilized to get more numbers of output voltage level with same numbers of isolated DC-supplies and power semiconductor switches. The 9-level and 27-level ternary CHB-inverters are utilized at the motor end to drive an IM, which requires same numbers of isolated DC-supplies and power semiconductor switches as 7-level and 15-level binary CHB-inverters needed, respectively.

Apart from this NPC and CHB-inverters, a new cascaded inverter is also utilized in this research work to drive an IM, which requires less numbers of isolated DC-supplies than CHB-inverters and easy structure than NPC MLI. The 3-level, 5-level and 7-level cascaded MLIs are used, which are cascading two, four and six numbers of three-phase voltage source inverters (VSIs), respectively. Moreover, a 4-level cascaded inverter is also used, which is cascading a 3-level NPC and three-phase VSI in unique manner.

From above discussion, it is observed that different configurations of multi-pulse AC-DC converters at utility end and various configurations of MLIs at drive end are presented in this research work. Apart from it, an indirect vector control with and without speed sensor and direct torque control (DTC) without speed sensor schemes are utilized to control an IM. Moreover, various types of modulations techniques are utilized to control these MLIs. Due to which, these MLIs are operated at quite low switching frequency and fundamental frequency switching, to reduce switching losses in IMDs.

सार

इस शोध कार्य में, मल्टी-पल्स एसी-डीसी कन्वर्टर के विभिन्न विन्यासों को मल्टीलेवल इनवर्टर (एमएलआई) आधारित इंडक्शन मोटर ड्राइव (आईएमडी) को मध्यम वोल्टेज और मध्यम कोरेंट अनुप्रयोगों के लिए प्रस्तुत किया गया है। यह शोध कार्य इनपुट एंड में पारंपरिक सिंगल-स्टेज मल्टी-वाइंडिंग ट्रांसफार्मर (एसएस एमडब्ल्यूटी) आधारित 12-पल्स और 18-पल्स एसी-डीसी कन्वर्टर प्रदान करता है। इस सिंगल-स्टेज मल्टी-वाइंडिंग ट्रांसफार्मर (एमडब्ल्यूटी) में सेकंडरी वाइंडिंग्स में ही फेज-शिफ्ट होता है। इस कन्वेंशन एसएस एमडब्ल्यूटी की मदद से कोई भी 36-पल्स एसी-डीसी कनवर्टर प्राप्त कर सकता है, जिसे बहुत छोटे फेज-शिफ्ट की आवश्यकता होती है। जिसके कारण, इस एमडब्ल्यूटी की निर्माण प्रक्रिया बहुत जटिल हो जाती है। इसलिए, इस शोध कार्य में, मॉड्यूलर एमडब्ल्यूटी के नए कॉन्फिगरेशन को 36-पल्स एसी-डीसी कनवर्टर प्राप्त करने का प्रस्ताव है, जिसमें प्राथमिक और द्वितीयक दोनों विंडिंग्स में फेज-शिफ्ट है और इसके लिए छोटे फेज-शिफ्ट की आवश्यकता नहीं है। जिसके कारण पारंपरिक एमडब्ल्यूटी की तुलना में प्रस्तावित एमडब्ल्यूटी की निर्माण प्रक्रिया काफी आसान है। मॉड्यूलर एमडब्ल्यूटी की मदद से, इस शोध कार्य में 54-पल्स एसी-डीसी कनवर्टर का उपयोग साइनसॉइडल के करीब इनपुट कोरेंट को आकार देने और कुल हार्मोनिक विरूपण (टीएचडी) को बहुत कम करने के लिए किया गया है। यह मॉड्यूलर एमडब्ल्यूटी अधिक उपयुक्त है, जब अधिक संख्या में पृथक डीसी-स्पलाई की आवश्यकता होती है जैसे कि कैस्केड एच-ब्रिज (सीएचबी) इन्वर्टर आधारित आईएमडी। इसलिए, इस शोध कार्य में स्पलाई एंड पर एक नया मल्टीफेज एमडब्ल्यूटी प्रस्तावित है जो इनपुट तीन-फेज एसी-स्पलाई को पांच-फेज आउटपुट एसी-स्पलाई में परिवर्तित करता है इस मल्टीफेज एमडब्ल्यूटी की सहायता से, एक 20-पल्स, 30-पल्स, 40-पल्स और 60-पल्स एसी-डीसी कन्वर्टर को इनपुट एंड पर प्रस्तावित किया गया है, जिसमें लाइट लोड की स्थिति में भी अच्छी बिजली की गुणवत्ता है।

उपरोक्त चर्चा से, यह देखा गया है कि स्पलाई एंड पर मल्टी-पल्स एसी-डीसी कन्वर्टर के विभिन्न कॉन्फिगरेशन प्रस्तावित हैं। इसके अलावा, इंडक्शन मोटर (आईएम) को चलाने के लिए विभिन्न प्रकार के एमएलआई का उपयोग मोटर एंड पर किया गया है। आईएम को चलाने के लिए मोटर एंड पर 3-लेवल वाला थ्री-लेग न्यूट्रल पॉइंट क्लैंड (एनपीसी) और 5-लेवल सिक्स-लेग एनपीसी एमएलआई का उपयोग किया गया है। 5-लेबल से अधिक के लिए एनपीसी एमएलआई की संरचना काफी जटिल हो जाती है। इसलिए, इस शोध कार्य में, आईएम को ड्राइव करने के लिए सीएचबी-इनवर्टर का उपयोग मोटर एंड पर किया गया है। ड्राइव- एंड पर 5-लेबल और 7-लेबल सममित सीएचबी-इनवर्टर का उपयोग किया गया है। हालांकि, इस सममित सीएचबी-इनवर्टर को

आउटपुट वोल्टेज लेबल की उच्च संख्या प्राप्त करने के लिए डीसी-स्पलाई और पावर अर्धचालक स्विच (पीएसएस) की अधिक संख्या की आवश्यकता होती है। इसलिए, इस शोध कार्य में, आउटपुट वोल्टेज लेबल की अधिक संख्या प्राप्त करने के लिए बाइनरी (1: 2) सिद्धांत का उपयोग किया जाता है। 7-लेबल और 15-लेबल बाइनरी सीएचबी-इनवर्टर ड्राइव एंड पर उपयोग किए गए हैं, जिन्हें क्रमशः 5-लेबल और 7-लेबल सममित सीएचबी-इनवर्टर के रूप में अलग-अलग डीसी-स्पलाई और पावर सेमीकंडक्टर स्विच की आवश्यकता होती है। इस शोध कार्य में, समान डीसी-स्पलाई और पावर सेमीकंडक्टर स्विच की समान संख्या के साथ आउटपुट वोल्टेज लेबल की अधिक संख्या प्राप्त करने के लिए टर्नरी (1: 3) सिद्धांत का भी उपयोग किया गया है। आईएम को चलाने के लिए मोटर-एंड पर 9-लेबल और 27-लेबल टर्नरी सीएचबी-इनवर्टर का उपयोग किया गया है, जिसके लिए समान लेबल पर डीसी-स्पलाई और पावर सेमीकंडक्टर स्विच की समान संख्या की आवश्यकता होती है जितना कि 7-लेबल और 15-लेबल बाइनरी सीएचबी-इनवर्टर में आवश्यकता होती है।

इस एनपीसी और सीएचबी-इनवर्टर के अलावा, आईएम को चलाने के लिए इस शोध कार्य में एक नया कैस्केड इनवर्टर भी उपयोग किया गया है, जिसे सीएचबी-इनवर्टर की तुलना में पृथक डीसी-स्पलाई की कम संख्या और एनपीसी एमएलआई की तुलना में आसान संरचना की आवश्यकता होती है। 3-लेबल, 5-लेबल और 7-लेबल कैस्केड एमएलआई का उपयोग किया गया है, जो क्रमशः तीन-फेज वोल्टेज स्रोत इनवर्टर (वीएसआई) की दो, चार और छह संख्याओं का कैस्केडिंग करते हैं। इसके अलावा, एक 4-लेबल कैस्केड इनवर्टर का भी उपयोग किया गया है, जो कि 3-लेबल एनपीसी और तीन-फेज वीएसआई को अनूठे तरीके से कैस्केडिंग करता है।

उपरोक्त चर्चा से, यह देखा गया है कि इनपुट एंड पर मल्टी-पल्स एसी-डीसी कन्वर्टर्स के विभिन्न कॉन्फिगरेशन और ड्राइव एंड पर एमएलआई के विभिन्न कॉन्फिगरेशन इस शोध कार्य में प्रस्तुत किए गए हैं। इसके अलावा, गति संवेदक योजनाओं के बिना और बिना गति संवेदक और प्रत्यक्ष टोक्र नियंत्रण (डीटीसी) के एक अप्रत्यक्ष वेक्टर नियंत्रण का उपयोग आईएम को नियंत्रित करने के लिए किया गया है। इसके अलावा, इन एमएलआई को नियंत्रित करने के लिए विभिन्न प्रकार की मॉड्यूलेशन तकनीकों का उपयोग किया गया है। जिसके कारण, इन एमएलआई को आईएमडी में स्विचिंग लॉस को कम करने के लिए काफी कम स्विचिंग फिरीकेन्स और मौलिक फिरीकेन्स स्विचिंग पर संचालित किया गया है।

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog to Digital
AEMS	Area Equalizations Modulation Strategy
APOD	Alternative Phase Opposition Disposition
ASIMD	Adjustable Speed Induction Motor Drive
CPU	Central Processing Unit
CHB	Cascaded H-Bridge
DAC	Digital to Analog
DBR	Diode Bridge Rectifier
DC	Direct Current
DF	Distortion Factor
DPF	Displacement Power Factor
DSP	Digital Signal Processor
DSO	Digital Storage Oscilloscope
DTC	Direct Torque Control
EPSS	Equal Power Sharing Strategy
FFT	Fast Fourier Transform
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IM	Induction Motor
IMD	Induction Motor Drive
IVC	Indirect Vector Control
MATLAB	Matrix Laboratory
MLI	Multilevel Inverter
MRAS	Model Reference Adaptive Systems
MWT	Multi-Winding Transformer
MVIMD	Medium Voltage Induction Motor Drive
NLMT	Nearest Level Modulation Technique
NPC	Neutral Point Clamped
PCB	Printed Circuit Board
PD	Phase Disposition
PF	Power Factor
PFC	Power Factor Correction
PI	Proportional Integral
POD	Phase Opposition Disposition
PWM	Pulse Width Modulation
RMS	Root Mean Square
RPM	Revolutions Per Minute
SHE	Selective Harmonic Elimination
SPWM	Sinusoidal Pulse Width Modulation

SS-MWT	Single Stage Multi-Winding Transformer
SVM	Space Vector Modulation
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
VFIMD	Variable Frequency Induction Motor Drive
VSC	Voltage Source Converter
VSI	Voltage Source Inverter

LIST OF SYMBOLS

E	Numbers of positive levels
f_{sw}	Switching frequency (Hz)
$i_{sa}, \dot{i}_{sa}, \ddot{i}_{sa}$	Supply current (A)
$i_{sta}, \dot{i}_{sta}, \ddot{i}_{sta}$	Stator current (A)
I_{dc}	DC link current (A)
I_d^*	Reference direct axis current (A)
i_{p1}	Primary winding current of transformer T ₁
i_{p2}	Primary winding current of transformer T ₂
i_{p2}	Primary winding current of transformer T ₃
I_q^*	Reference quadrature axis current (A)
i_s	Three-phase supply current (A)
$i_{s1} \dots \dots i_{s10}$	Secondary windings currents
i_{st}	Three-phase stator current (A)
$I_{sen.d}$	Sensed direct axis current (A)
$I_{sen.q}$	Sensed quadrature axis current (A)
i_α, i_β	Two-phase stator currents (A)
J	Moment of inertia (Kg/m ²)
k_p, k_i	Proportional and integral gains of the speed PI controller
k_{pd}, k_{id}	Proportional and integral gains of the direct axis stator current controller
k_{pq}, k_{iq}	Proportional and integral gains of the quadrature axis stator current controller
L_{lr}	Rotor leakage inductance (H)
L_{ls}	Stator leakage inductance
L_m	Magnetizing inductance (H)
L_r	Rotor self-inductance (H)
ω_s	Synchronous speed (rad./s)
ω_{sl}	Slip speed (rad./s)
ω_m^*	Reference speed (rad./s)
ω_m	Rotor speed (rad./s)
$\omega_{est.}$	Estimated rotor speed (rad./s)
P	Number of poles
Ψ_e	Flux error input for flux hysteresis controller
$\Psi_{\alpha r}, \Psi_{\beta r}$	Two-phase rotor flux vectors (Wb)
$\Psi_{\alpha s}, \Psi_{\beta s}$	Two-phase stator flux vectors (Wb)
$\Psi_{s_est.}$	Stator estimated flux (Wb)
$\Psi_{r_est.}$	Rotor estimated flux (Wb)
Ψ_{HC_output}	Flux hysteresis controller output
m_i	Modulation index
N	Numbers of levels
N_s	Numbers of secondary isolated windings

N_{DBR}	Numbers of diode bridge rectifiers
R_r	Rotor resistance (Ω)
R_s	Stator resistance (Ω)
$S_1, S_2, \dots, S_n$	IGBT switches
$S_{a1}, S_{a2}, \dots, S_{an}$	IGBT switches of a-phase
$S_{b1}, S_{b2}, \dots, S_{bn}$	IGBT switches of b-phase
$S_{c1}, S_{c2}, \dots, S_{cn}$	IGBT switches of c-phase
T_e	Torque error input for torque hysteresis controller
$T_{est.}$	Reference torque
T_{HC_output}	Torque hysteresis controller output
$T_{ref.}^*$	Reference torque
ΔT_{HB}	Torque hysteresis band
θ_r	Rotor speed position (radians)
θ_T	Required phase-shift angles on secondary side of three-phase to five-phase transformer
$v_{ref_a}, v_{ref_b}, v_{ref_c}$	Modulating signals produced from indirect vector control
v_s	Three-phase supply voltage (V)
v_{sa}, v_{sb}, v_{sc}	Supply voltages (V)
v_{st}	Three-phase stator voltage (V)
$v_{stab}, v_{stbc}, v_{stca}$	Stator voltages (V)
v_1, v_2, v_4	Output voltages of power modules of binary CHB-inverters
v_1, v_3, v_9	Output voltages of power modules of ternary CHB-inverters
v_α, v_β	Two-phase stator voltages (V)
$\vec{V}_1, \vec{V}_2, \dots, \vec{V}_n$	Voltage space vectors
V_{pN1}	Small winding voltage of extended delta connected primary winding
V_{pN2}	Large winding voltage of extended delta connected primary winding
V_{LL}	Input line voltage of a three-phase diode bridge rectifier
V_{NS}	Small winding voltage of a delta-polygon connected secondary winding
V_{NL}	Large winding voltage of a delta-polygon connected secondary winding
V_{dc}	Capacitor DC-link voltage
$\hat{V}_{ao1}$	Peak of fundamental phase voltage
α_{prm}	Phase-shift angle in primary winding voltage
α_{sec}	Phase-shift angle in secondary winding voltage
$\alpha_1, \alpha_2, \dots, \alpha_n$	Switching angles
z_s	Source impedance