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Analysis and Design of Single-Phase Transformerless Inverter for Photovoltaic Applications

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Certificate of Original Authorship

I, Md Noman Habib Khan declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy in the School of Electrical and Data Engineering at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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- [8] **Md Noman H. Khan**, Yam P. Siwakoti, L. Li, and M. Forouzesh " Single-Phase Switched-Capacitor Integrated-Boost Five-level Inverter." *in proc. IEEE Region 10 Symposium (TENSYP)*, Sydney, Apr. 2018, pp. 25-29. doi: 10.1109/TENCONSpring.2018.8692066.
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Abstract

This thesis provides a comprehensive analysis of different transformerless inverter topologies (TLIs) and their control and modulation techniques. Considering the challenges and merits of the transformerless inverter, four different types of transformerless inverter topologies for PV applications have been investigated, analysed and designed in this thesis.

The first topology is H-bridge Zero Voltage Switch Controlled Rectifier (HB-ZVSCR) transformerless mid-point-clamped inverter. The operating principle and CM effect of the proposed topology are analysed and compared with the conventional topologies. This is followed by the thermal analysis and loss calculation which shows better efficiency over the conventional topologies. Validation is carried out using MATLAB-Simulink using the PLECS toolbox followed by a scale-down prototype of 1.5 kW.

The second topology is a single-phase switched-capacitor (SC) based $(2n+1)$ -level inverter with reduced number of components and input DC voltage supply magnitude. The total number of output voltage levels can reach up to $(2n+ 1)$ levels, where $n \geq 2$ is the number of switching cells consisting of three power switches and two switched-capacitors. The operating principle is presented in detail followed by comparative analysis, thermal modelling and design guidelines. Finally, measurement results are carried out for a 5-level inverter with two SC cells as an example to verify the performance of the proposed $(2n+1)$ -level inverter over different operating conditions.

The third topology is a novel dual-mode five-level common grounded type (5L-DM-CGT) transformerless inverter topology for a medium-power application with a wide input voltage range (200 V – 400 V). The theoretical analysis shows the advantages of the dual-mode inverter for various industrial applications. Finally, the laboratory test results are presented to verify the theoretical analysis.

The final topology is a novel configuration of switched capacitor multilevel inverters (SCMLIs) with a lower number of power components with inherent voltage boost. The

proposed topology is compared with other existing five-level inverter topologies to show its superior capabilities/advantages. The performance of the proposed topology is validated by OPAL-RT.

Overall, this thesis provides a comprehensive analysis of all transformerless inverter topologies and their control and modulation techniques and come up with the concept of new single-phase transformerless inverter topologies. The new topologies utilizes minimal components with low voltage stress and offers high power quality output with low total harmonic distortion (THD), high efficiency and power density, low cost and size, and simple modulation techniques.

Keywords: Solar Photovoltaic (PV); Thermal Modelling; Switched Capacitor Converter, Common Mode Voltage; Leakage Current; Multilevel Converter; Quasi Resonant Charging.

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Abbreviations

AC	=	Alternative Current
ANPC	=	Active Neutral Point Clamped
B-ANPC	=	Boost-Active Neutral Point Clamped
CEC	=	California Energy Commission
CGT	=	Common Ground Type
CHB	=	Cascaded H-Bridge
CM	=	Common Mode
CMV	=	Common Mode Voltage
CL	=	Conduction Loss
CSI	=	Current source Inverter
DBFBI	=	Dual Buck Full bridge Inverter
DC	=	Direct Current
DMV	=	Differential Mode Voltage
DSP	=	Digital Signal Controller
EMI	=	Electro Magnetic Interference
EVA	=	Ethylene-Vinyl Acetate
EU	=	European
ESR	=	Equivalent Series Resistances
EVs	=	Electric Vehicles
F-B	=	Full-Bridge
FC	=	Flying Capacitor
FPGA	=	Field Programmable Gate Array
GW	=	Giga Watt
HB-ZVR	=	H-Bridge Zero Voltage Rectifier
HB-ZVR-D	=	H-Bridge Zero Voltage Rectifier-Diode
HB-ZVSCR	=	H-Bridge Zero Voltage Switch controlled Rectifier
HERIC	=	Highly Efficient and Reliable Inverter Concept
HF	=	High Frequency
IEA-PVPS	=	International Energy Agency Photovoltaic Power Systems Program
IGBT	=	Insulated Gate Bipolar Transistor
LF	=	Low Frequency
LS-SPWM	=	Level-Shifted Sinusoidal Pulse Width Modulation
MMC	=	Modular Multilevel Converter
MOSFET	=	Metal Oxide Field Effect Transistor
MPC	=	Model Predictive Controller
MPP	=	Maximum Power Point
MPPT	=	Maximum Power Point Tracker
MW	=	Mega Watt
NI	=	National Instrument

NPC	=	Neutral Point Clamped
PCB	=	Printed Circuit Board
PF	=	Power Factor
PN-NPC	=	Positive Negative- Neutral Point Clamped
PWM	=	Pulse Width Modulation
PV	=	Photovoltaic
QSC	=	Quasi Resonant Charging
RES	=	Renewable Energy System
RMS	=	Root Mean Square
RTP	=	Reactive Power Capability
SC	=	Switched-Capacitor
SD-DBFBI	=	Series-Diode-Dual Buck Full bridge Inverter
SL	=	Switching Loss
SPWM	=	Sinusoidal Pulse Width Modulation
SS-DBFBI	=	Series-Switch-Dual Buck Full bridge Inverter
T-type	=	Transistor-type
TSV	=	Total Standing Voltage
THD	=	Total Harmonic Distortion
U-SPWM	=	Unipolar- Sinusoidal Pulse Width Modulation
VA	=	Volt-Ampere
VSI	=	Voltage Source Inverter
WTs	=	Wind Turbines

Nomenclature

η	=	Efficiency
η_{EU}	=	European Efficiency, weighted
η_{CEC}	=	California Energy Commission Efficiency, weighted
V_{in}	=	Input Voltage
V_{dc}/V_{PN}	=	DC Link Voltage
V_{AB}	=	Inverter Voltage
$(C = 2 \times C_1) \ \&$	=	DC Link Capacitor
$(C_1 = C_2)$		
i_{cm}	=	Leakage Current
S_B	=	Boost Switch
D_B	=	Boost Diode
D_{DB}	=	Boost Duty Cycle
L_B	=	Boost Inductor
V_{ECM}	=	Equivalent Common Mode Voltage
I_F	=	Forward Current
V_F	=	Forward Voltage
I_{PRR}	=	Peak Reverse Recovery Current
I_{ce}	=	Instantaneous Current
C_{in}	=	Input Capacitor
C_F	=	Flying Capacitor
L_m	=	Flying Inductor
CS	=	Switched Capacitor
v_g or v_{out}	=	Output Voltage
f_g or f_m	=	Line Frequency
f_{sw}	=	Switching Frequency
i_o or i_{out}	=	Output Current
M	=	Modulation Index
P_o	=	Rated Power
L_r	=	Resonant Inductor
ω_s	=	Angular Frequency
ω_r	=	Voltage Factor Coefficient of Switched Capacitor
T_s	=	Sampling Period
C_o or C_f	=	Filter Capacitor
N_S	=	Number of Switches
N_D	=	Number of Diodes
N_L	=	Number of Voltage Levels
PT_s	=	Prototype Size
C_T	=	Total Cost

FC_{Loss}	=	Flying Capacitor Losses
F_{Loss}	=	Filter Losses
L_1, L_2, L_f	=	Filter Inductor
L_r	=	Quasi-Resonant Inductor
τ	=	Time Constant
R	=	Resistive Load
$R-L$	=	Resistive-Inductive Load
C_{pv1}, C_{pv2}	=	Parasitic Capacitor
R_{sig} or $-R_{sig}$	=	Reference Signal
C_{sig} or $-C_{sig}$	=	Carrier Signal
A	=	Reference Amplitude
N	=	Carrier Amplitude
Q_N or Q_{SC}	=	Capacitor Discharging Value
ω_g	=	Angular Frequency
ϕ_{pf}	=	Power Factor
ΔI_{Factor}	=	Current Ripple Factor
ΔI_{in}	=	Input Current Ripple
T_j	=	Junction Temperature
ΔT_j	=	Average Junction Temperature
T_C	=	Case Temperature
T_A	=	Ambient Temperature
T_H	=	Heat Sink Temperature
Z_{C2}	=	Impedance of DC-link Capacitor (C_2)
Z_{CPV}	=	Impedance of Parasitic Capacitor
Z_{L1} or Z_{L2}	=	Impedance of Filter Inductor
R_G	=	Ground Resistor
$Z_{(J-C)}$	=	Thermal Impedance (Junction to Ambient)
$Z_{(C-H)}$	=	Thermal Impedance (Case to Ambient)
$Z_{(H-A)}$	=	Thermal Impedance (Heat Sink to Ambient)
P_{L_D}	=	Diode Power Loss
P_{L_M}	=	MOSFET Power Loss
P_{L_PD}	=	Anti-Parallel Diode of the MOSFET Power Loss
R_{Mb}	=	Magnetic Resistance for Winding W_1
R_{Mf}	=	Magnetic Resistance for Winding W_2
R_{Cb}	=	Magnetic Core Elements for Winding W_1
R_{Cf}	=	Magnetic Core Elements for Winding W_2
R_{C1}	=	Core Loss Resistance for Winding W_1
R_{C2}	=	Core Loss Resistance for Winding W_2
M_{Cb}	=	Magnetic Core Elements for Winding W_1
M_{Cf}	=	Magnetic Core Elements for Winding W_2