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Faculty of Engineering and Information Technology

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

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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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# List of Original Publications

The following publications are part of the thesis.

**Peer reviewed international journal publications**

[1] **Md N. H. Khan,** Yam P. Siwakoti, M. Scott, L. Li, S. A. Khan, D. Lu, R. Barzegarkhoo, F. Sidorski, F.Blaabjerg, and S. A. Hasan "A Common Grounded Type Dual Mode Five-Level Transformerless Inverter for Photovoltaic Applications." *IEEE Transaction on Industrial Electronics,* Sep. 2020. doi: 10.1109/TIE.2020.3028810.

[2] **Md N. H. Khan,** M. Forouzesh, Yam P. Siwakoti, L. Li, & Blaabjerg, F. " Switched Capacitor Integrated (2n+1)-Level Step-up Inverter." *IEEE Transaction on Power Electronics,* vol. 35, no. 8, pp. 8248-8260, Aug. 2020. doi: 10.1109/TPEL.2019.2963344.

[3] **Md Noman H. Khan,** M. Forouzesh, Yam P. Siwakoti, L. Li, T. Kerekes, and F. Blaabjerg, " Transformerless Inverter Topologies for Single-Phase Photovoltaic Systems: An Analytical Overview." *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. 8, no. 1, pp. 805-835, Mar. 2020. doi: 10.1109/JESTPE.2019.2908672.

[4] **Md N. H. Khan,** Yam P. Siwakoti, L. Li, and F. Blaabjerg, "H-Bridge Zero-Voltage Switch Controlled Rectifier (HB-ZVSCR) Transformerless Mid-Point-Clamped Inverter for Photovoltaic Applications." *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 4, pp. 4382 - 4394, Dec. 2020. doi: 10.1109/JESTPE.2019.2938224.

[5] Yam P. Siwakoti, A. Mostaan, A.Abdelhakim, P. Davari, M. Soltani, **Md N. H. Khan,** and F. Blaabjerg, "High Voltage Gain Quasi-SEPIC DC-DC Converter." *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 2, pp. 1243-1257, Jul. 2018. doi: 10.1109/JESTPE.2018.2859425.

**Peer reviewed international scientific conference publications**

[1] **Md N. H. Khan,** Yam P. Siwakoti, L. Li, and T. K.S Freddy "Constant Common-Mode Voltage Transformerless Inverter for Grid-Tied Photovoltaic Application." *in proc. IEEE Energy Conversion Congress and Exposition (ECCE),* Baltimore, Maryland, Nov. 2019, pp. 616-621. doi: 10.1109/ECCE.2019.8912808.

[2] **N. H. Khan,** Yam P. Siwakoti, S. A. Khan, L. Li, and F. Blaabjerg, "A Dual Mode Single-Phase Five-Level Switched Capacitor Transformerless Inverter with a Common Ground." *in proc. The Applied Power Electronics Conference, (APEC),* New Orlands, LA, Mar.2020, pp. 436-441. doi: 10.1109/APEC39645.2020.9124205.

[3] **N. H. Khan,** Yam P. Siwakoti, S. A. Khan, L. Li, and F. Blaabjerg, "Model Predictive Controller based Seven-Level Single-Phase Boost Inverter for Grid-Tied Photovoltaic Application." *in proc. The Applied Power Electronics Conference, (APEC),* New Orlands, LA, Mar. 2020, pp. 3238-3243. doi: 10.1109/APEC39645.2020.9124559.

[4] **N. H. Khan**, Yam P. Siwakoti, S. A. Khan, L. Li, and F. Blaabjerg, "Leakage Current Analysis of the HB-ZVSCR Transformerless Inverter for Grid-Tied Photovoltaic Application." *in proc. IEEE Energy Conversion Congress and Exposition (ECCE)-Asia,* 2020. (Accepted)

[5] **Khan, M. N. H**., Li, L., Siwakoti, Y., & Khan, S. "Switched-Capacitor Integrated Single-Phase (2N+ 1)-Levels Boost Inverter for Grid-Tied Photovoltaic (PV) Applications." *in proc. IEEE International Conference on Industrial Technology (ICIT),* Melbourne, Feb. 2019, pp. 1655-1660. doi: 10.1109/ICIT.2019.8755024.

[6] **Md Noman H. Khan,** M. Forouzesh, Yam P. Siwakoti, L. Li, T. Kerekes, and F. Blaabjerg, " A Classification of Single-Phase Transformerless Inverter Topologies for Photovoltaic Applications." *in proc. IEEE Region 10 Symposium (TENSYMP),* Sydney, Apr. 2018, pp. 174-179. doi: 10.1109/TENCONSpring.2018.8692013.

[7] **Md Noman H. Khan,** M. Forouzesh, Yam P. Siwakoti, and L. Li" Novel High Efficiency H-Bridge Transformerless Inverter for Grid-Connected Single-Phase Photovoltaic Systems." *in proc. IEEE Region 10 Symposium (TENSYMP),* Sydney, Apr. 2018, pp. 95-99. doi: 10.1109/TENCONSpring.2018.8692008.

[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 (TENSYMP),* Sydney, Apr. 2018, pp. 25-29. doi: 10.1109/TENCONSpring.2018.8692066.

[9] S. A. Khan, **N. H. Khan,** Y. Guo, Yam P. Siwakoti, and J. Zhu"A novel five-level switched capacitor type inverter topology for grid-tied photovoltaic application analysis." *in proc. The Applied Power Electronics Conference, (APEC),* New Orlands, LA, Mar. 2020, pp. 442-447. doi: 10.1109/APEC39645.2020.9124267.

[10] Shakil Ahamed Khan, Youguang Guo, **Md N. H. Khan,** Yam Siwakoti and Jianguo Zhu," Model Predictive Control without Weighting Factors for T-type Multilevel Inverters with Magnetic-Link and Series Stacked AC-DC Modules." *in proc. IEEE Energy Conversion Congress and Exposition (ECCE),* Baltimore, Maryland, Nov. 2019, pp. 5603-5609. doi: 10.1109/ECCE.2019.8912486.

[11] S. A. Khan, **N. H. Khan,** Y. Guo, Yam P. Siwakoti, J. Zhu, and F. Blaabjerg "A Step up Three-Phase Seven-Level Switched Capacitor Inverter for grid-tied Photovoltaic Application." *in proc. IEEE Energy Conversion Congress and Exposition (ECCE)-Asia,* 2020. (Accepted)

# Abtract

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.

# Contents

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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

| | | |
|---|---|---|
| $\eta$ | = | Efficiency |
| $\eta_{EU}$ | = | European Efficiency, weighted |
| $\eta_{CEC}$ | = | California Energy Commission Efficiency, weighted |
| $V_{in}$ | = | Input Voltage |
| $V_{dc}/V_{PN}$ | = | DC Link Voltage |
| $V_{AB}$ | = | Inverter Voltage |
| $(C = 2\times C_1)$ & $(C_1 = C_2)$ | = | DC Link Capacitor |
| $i_{cm}$ | = | 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 |
| $\omega_s$ | = | Angular Frequency |
| $\omega_r$ | = | 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 |
| $\tau$ | = | 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 |
| $\omega_g$ | = | Angular Frequency |
| $\varphi_{pf}$ | = | Power Factor |
| $\Delta I_{Factor}$ | = | Current Ripple Factor |
| $\Delta I_{in}$ | = | Input Current Ripple |
| $T_J$ | = | Junction Temperature |
| $\Delta T_j$ | = | Avarage 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 $W_2$ |