Transformerless Multi-Output Hybrid Converter Based on L_nC_{2n-2} Network with Minimised Leakage Current for Solar PV Applications

Thesis submitted in partial fulfillment for the

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by

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Content

Abstract

This This thesis addresses the growing importance of renewable energy sources in replacing conventional fuels like coal and gas, offering cleaner and more sustainable power without harmful emissions. Among various renewable sources, solar photovoltaic (PV) systems have gained significant popularity due to their wide-ranging applications, from large solar farms to small household setups. This widespread adoption is driven by advancements in semiconductor technology, improvements in power electronics, and the decreasing cost of PV panels.

One of the key advantages of PV systems is their ability to support both DC and AC outputs by power electronic converter, essential for the increasing use of DC-powered devices alongside traditional AC loads. However, conventional solutions typically require separate DC-DC and DC-AC converters, leading to bulkier, heavier systems with reduced efficiency. To overcome these challenges, Multi-Output Hybrid Converter (MOHC) has emerged, capable of delivering both outputs using a single power electronic converter. These converters manage two key control parameters, i.e., duty ratio (d) and modulation index (m_i) where d is responsible for DC gain and m_i is responsible for AC gain. Since, the same set of switches are responsible for the simultaneous DC and AC operation, leading to an operational constraint ($d + m_i \leq 1$) and a trade-off between DC voltage gain and AC output quality. Moreover, this constraint makes the MOHC difficult to operate at the standard voltage rating with low input solar PV voltage.

A photovoltaic (PV) module consists of an electrically conductive surface placed opposite a grounded support frame. Due to this configuration, when a voltage is applied, the PV module behaves like a capacitor, storing electrical charge. This inherent capacitance, known as parasitic capacitance (C_{PV}), arises from the cumulative effect of the individual capacitances formed between different layers of the PV structure. Since power converters or inverters operate at high switching frequencies. This rapid switching induces a voltage variation across the parasitic capacitance, mathematically expressed as $d(V_{CPV})/dt$, which creates electrical stress. As the AC grid or electrical loads connected to the inverter are also grounded for safety, this voltage fluctuation can result in leakage currents flowing through the system.

One effective way to eliminate leakage currents is by introducing an isolation transformer between the PV system and the grid or AC loads. While transformers provide excellent isolation and mitigate leakage current issues, they also come with drawbacks such as increased system size, cost, complexity, and energy losses. To overcome these limitations, transformerless inverter designs have gained popularity, offering higher efficiency and cost savings. However, these designs are more susceptible to common-mode leakage currents, which must be carefully managed in AC loads or with grid-connected applications.

Another challenge in PV systems is the non-uniform power generation characteristics of PV panels. A typical PV panel has a single maximum power point (MPP) where it operates at peak efficiency. However, under partial shading conditions, PV modules exhibit a multi-peak power curve, meaning multiple local maxima exist, but only one is the true global maximum. This makes it difficult to extract the highest possible power, as conventional maximum power point tracking (MPPT) algorithms may get stuck at a local maximum instead of reaching the true global peak. Additionally, in a grid-connected PV system requires precise grid synchronization while simultaneously maintaining a stable DC supply and tracking the MPP. This adds another layer of complexity, as the system must continuously adjust its operation to ensure efficient power conversion while adhering to grid regulations and minimizing power losses.

In traditional two-stage power electronic systems, energy conversion typically relies on electrolytic capacitors for intermediate energy storage. While these capacitors are widely used due to their high energy density and ability to handle voltage fluctuations, they are also one of the most failure-prone components in a power converter. This is primarily because electrolytic capacitors degrade over time due to factors such as high operating temperatures, voltage stresses, and aging effects, ultimately reducing the overall lifespan and reliability of the system. Additionally, the bulky DC-link capacitor used in two-stage architectures further impacts system efficiency and longevity. These capacitors not only increase the physical size of the converter but also introduce higher losses, limiting the system's power density and thermal performance. This trade-off between capacitance value, reliability, and footprint is a major design challenge, particularly in applications where compactness and long-term durability are critical.

To address these issues, this thesis proposes an expandable L_nC_{2n-2} network, scalable up to n stages, where each stage introduces additional cells composed of one inductor, two capacitors, and one diode. The voltage gain for an n-stage configuration is given by $1/(1-nd)$, enabling higher voltage gain at lower duty cycles with the addition of each stage. This network-based DC-DC converter, controlled by a single switch, uses minimal components while achieving superior voltage gain compared to other expandable topologies.

Building on this concept, the single switch of the L_nC_{2n-2} network-based DC-DC converter is replaced with an inverter, creating a MOHC capable of simultaneously catering to DC and AC loads. Since the MOHC is enabled with the L_nC_{2n-2} network thus higher DC voltage gain at lower duty can be achieved which widens the operating range for m_i despite the constraint $d + m_i \leq 1$. Moreover, the transformerless design of the proposed MOHC minimizes leakage current and further reduces the number of switches compared to existing topologies. Additionally, the MOHC is seamlessly integrated with PV panels by enabling the MOHC with an Incremental conductance-based MPPT algorithm to extract maximum power from the PV panel and synchronize with the grid as a result while catering the DC load any surplus power left to achieve Maximum power point of the PV is fed to the grid.

Moreover, this thesis introduces an impedance-based isolated resonant converter using the L_nC_{2n-2} network a two-stage system, replacing traditional DC-link electrolytic capacitors with film capacitors for improved reliability, longevity, and ripple-free voltage output. Additionally, a Particle Swarm Optimization (PSO)-based algorithm is implemented to track the global maximum power point (GMPP) under partial shading conditions, ensuring optimal power extraction and enhanced PV system efficiency. This approach minimizes component failures, reduces maintenance costs, and improves overall system performance. The proposed solution is well-suited for next-generation high-efficiency PV and power electronics applications.

To validate the proposed design, an expandable L_nC_{2n-2} network-based DC-DC converter was developed for n-stage configurations and tested for n=3 under Continuous Conduction Mode (CCM), Discontinuous Conduction Mode (DCM), and dynamic irradiance variations. Additionally, a 960 W experimental prototype of the L_nC_{2n-2} network-based Multi-Output Hybrid Converter (MOHC) was built and tested

for closed-loop operation, AC grid connectivity, and PV-to-grid integration. Furthermore, a two-stage electrolytic capacitorless impedance-based isolated resonant converter was implemented for n=3, demonstrating its effectiveness in tracking the GMPP under multi-peak PV characteristics caused by partial shading. This was achieved using a PSO algorithm. The system was experimentally validated using Texas Instruments’ F28335 DSP microcontroller, a Chroma PV emulator, and a grid emulator, ensuring practical feasibility and real-world applicability.

Through theoretical analysis and experimental validation, this research demonstrates the proposed hybrid converter topologies' effectiveness in addressing existing systems' limitations and offering efficient, compact, and reliable solutions for solar PV applications.

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List of Acronyms

AC	Alternating current
ADC	Analog to digital controller
ANN	Artificial Neural Networks
BDHC	Boost-derived hybrid converter
CCM	Continuous conduction mode
CSC	Current source converter
DC	Direct current
DCM	Discontinuous conduction mode
EC	Electrolytic capacitors
EIIS	Expandable impedance input-sourced
EIISIRC	Expandable input impedance-sourced isolated resonant converter
EMI	Electromagnetic interference
ESR	Equivalent Series Resistance
FBI	Full-Bridge Inverter
FC	Film capacitors
GWO	Grey Wolf Optimization
HERIC	Highly Efficient and Reliable Inverter Concept
HFT	High-frequency transformer

IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistors
INC	Incremental conductance
LF	Low frequency
MOHC	Multi-output hubrid converter
MPC	Model predictive control
MPP	Maximum power point
MPPT	Maximum Power Point Tracking
P&O	Perturb and observe
PI	Proportional Integral
PLL	Phase-locked loops
PSO	Particle Swarm Optimization
PV	Photovoltaic
PWM	Pulse width modulation
qZSC	quasi-Z Source Converter
RCMD	Residual Current Monitoring Device
RES	Renewable energy sources
RF	Ripple factor
RMS	Root mean square
SDG	Sustainable development Goals

SPWM	Sinusoidal pulse-width modulation
THD	Total Harmonic Distortion
TI	Texas Instruments
VCO	Voltage controlled oscillator
VSC	Voltage source converter
VSI	Voltage source inverters
ZSC	Z source converter
ZVS	Zero-voltage switching

Symbols Used

d	Duty ratio
m_{i}	Modulation index
C_{PV}	Parasitic capacitance
ε_0	Permittivity of free space
ε_{r}	Relative permittivity of the material
t	separation distance between conductive surfaces
T_{s}	switching cycle
V_{PV}	Input PV voltage
I_{pv}	Input PV current
V_O, and V_{dc}	Output DC voltage
L_{Cr}	Critical inductance
f_{s}	Switching frequency
$P_{\mathrm{S,S}}$	Switching loss of S_{t}
$P_{\mathrm{D,R}}$	Conduction loss of the diode
$P_{\mathrm{D,F}}$	Loss resulting from the diode's forward voltage drop
G_{Real}	Voltage gain of the proposed circuit
η	Effeciency
R_{dc}	DC load resistance
R_{M}	Equivalent PV resistance at MPP

V_{ac}	Output AC voltage
f_0	Fundamental frequency
L_{grid}	Grid inductance
V_{dm} and V_{cm}	Differential voltage and common voltage
V_{tcm}	Total common mode voltage
ω and Ø	Angular frequencies
θ and ϕ	Phase Constant
α-β	Alpha-Bita
dq	Direct and quadrature
V_{B}, Z_{B}, and ω_{B}	Base voltage, base impedance, and base angular frequency
ξ	Normalized switching frequency
n_{t}	Turns ratio