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Contents

Abstract

In recent times, renewable sources of energy play an important role to replace the conventional energy resources like fuel and coal, as they provide clean and sustainable energy without any toxic pollution and global warming emissions. Among all the renewable energy sources, photovoltaic (PV) sources have gained wide spread popularity due to their uses in large solar plants to small household applications. Moreover, the PV systems are more reasonable option due to the advancement of semiconductor devices and power electronic applications and cost reduction of PV panels. Furthermore, the PV systems become a popular choice for hybrid output concept (simultaneous DC and AC outputs) because of gradual increment in DC loads along with the existing AC loads. For obtaining both DC and AC outputs simultaneously from a single source, one DC-DC converter along with an additional DC-AC converter is required. As, two separate converters are used to provide the hybrid output from a single source, number of switches and passive components increase. This increases the weight and size of the system and reduces the overall efficiency. In order to replace two different converters with a single converter for hybrid output, the concept of hybrid converter comes into picture. In case of hybrid converters, one single converter is capable of providing both DC and AC outputs simultaneously from a single DC source/solar PV panel. Since, both DC-DC and DC-AC conversion operations are performed through a single power electronic converter, both the control parameters, duty ratio (D) and modulation index (M_i) of the converter are decided by the same controlled switches. Moreover, as the value of D and M_i are decided by the switching operation of the same controlled switches whose operations are interdependent, the operating constraint of these hybrid converters are $D + M_i \leq 1$. So, there is a compromise between the DC gain and AC output quality for each operating condition of D and M_i. As the solar PV cells have lower voltage levels, to increase the voltage level, high DC gain boost derived hybrid converter topologies are used in PV applications. In case of boost derived hybrid converters, the non-minimum phase property is predominant, due to the presence of right half-plane zeros (RHPZs) in their control-to-output transfer function. Because of the presence of RHPZs, the hybrid converters show nonlinear behaviour during the dynamic conditions. Due to the nonlinear behaviour, if D is increased suddenly, the DC output voltage rather than following D, initially decreases and then follows D and vice-versa. Therefore, the dynamic performance of the hybrid converters is not good, which leads to the instability. Also, the

non-minimum phase behaviour of boost derived hybrid converter results in complex controller design, narrow bandwidth and reduced DC loading capability of the system.

The hybrid converter topologies used in PV systems are of two types: 1) converters with galvanic isolation between the PV panel and AC output and 2) converters without galvanic isolation (transformerless) between the PV panel and AC output. The topologies with galvanic isolation are either high frequency (HF) transformer on the DC side or low frequency (LF) transformer on the AC side. The presence of a HF transformer increases the power conversion complexity, whereas due to the presence of LF transformer; the overall cost, losses, weight and volume of the system increases. In addition, the overall efficiency of the system decreases due to the presence of a LF transformer. On the other hand, the transformerless PV topologies increase the overall efficiency and reduce the cost, weight and volume of overall system. However, they suffer from drawbacks of strong common mode leakage current that flows between the PV panel and ground for grid tied mode and for cases where the inverter neutral point of the hybrid converter is grounded.

Various hybrid converter topologies have been developed to supply the solar power to the residential DC and AC loads simultaneously for solar PV-based nanogrid/microgrid applications. In order to minimize the common mode leakage current flow, several transformerless inverter topologies have been reported. But so far, all the above issues like narrow operating range of D and M_i, non-minimum phase property, leakage current minimization, requirement of deadtime circuit and inherent shoot-through capability are not addressed in a single hybrid converter.

To address the above issues, a transformerless minimum phase hybrid converter (TLMPHC) is proposed in this work. However, while investigating all the key features of the proposed TLMPHC, it is observed that the TLMPHC operates only in the operating condition of $D + M_i \leq 1$, which results into a trade-off between the DC gain and better quality of AC output voltage. For achieving $D + M_i \geq 1$ operating condition (wide operating range of D and M_i) along with all the advantages of TLMPHC in a single transformerless hybrid converter (THC), the concept of interleaved converters is incorporated with the proposed TLMPHC. The newly developed THC is termed as transformerless interleaved hybrid converter (TLIHC). In this way, two different transformerless hybrid power electronic converters are proposed in this thesis. The performance of the proposed

TLMPHC is analyzed during stand-alone mode, whereas the performance of TLIHC is analyzed both in stand-alone mode and grid tied mode in this work.

In this thesis, the proposed TLMPHC is developed by replacing the controlled switch of a boost converter by a modified voltage source inverter to obtain both DC and AC outputs simultaneously. Also, by incorporating some circuit changes in the DC part of the proposed TLMPHC, the minimum phase property is achieved. The proposed TLMPHC has inherent shoot-through capability and the deadtime circuit for its switching operation is not required. A hybrid unipolar based sinusoidal pulse width modulation (SPWM) technique is developed to achieve constant total common mode voltage during the entire switching cycle of TLMPHC, which reduces the leakage current. A comparative analysis between the proposed TLMPHC and TLIHC is carried out in terms of DC and AC voltage gains along with voltage and current stresses. A 340 W laboratory prototype has been developed and implemented using field programmable gate array (FPGA) to verify the performance of the proposed TLMPHC. Also, the power losses in the various elements of the proposed TLMPHC are calculated. The proposed TLMPHC is capable of operating only in the operating condition $D + M_i \leq 1$. So, in each operating conditions of TLMPHC, there is a compromise between DC voltage gain and AC output quality. To overcome this drawback and retaining the advantages of TLMPHC, a new THC named as TLIHC is developed in this thesis.

The proposed TLMPHC is incorporated with a conventional DC-DC boost converter to develop the proposed TLIHC. The controlled switch of the DC-DC boost converter in TLIHC is responsible for controlling the value of D, whereas the controlled switches of TLMPHC are used for controlling the value of M_i. So, the proposed TLIHC can operate in both $D + M_i \geq 1$ and $D + M_i \leq 1$ conditions. The minimum phase behaviour of the proposed TLIHC has been validated for the operating condition $0.61 < D \leq 0.85$. Detailed mathematical modeling and steady-state analysis along with performance comparison with some similar topologies are carried out to show the effectiveness of the proposed TLIHC. A 950 W laboratory prototype has been developed and implemented using FPGA to verify the performance of the proposed TLIHC. The proposed TLIHC can operate in cases of both unity power factor and non-unity power factor loads. The power losses in the various elements of the proposed TLIHC has been calculated to determine the efficiency of TLIHC. A comparative study in terms of DC as well as AC voltage gain, voltage and current stresses and efficiency with other conventional hybrid converters is also carried out in this thesis.

The controller behaviour and dynamic response of TLIHC has been verified to check the performance of the controller. Also, the robustness of the designed controller has been verified by changing various passive parameters (L_1, L_2 and C) of the proposed TLIHC. Detailed mathematical modelling of AC side controller of TLIHC in terms of $d-q$ synchronous rotating frame control strategy is discussed. Further for the dynamic load conditions, the cross-regulation behaviour of TLIHC has been verified.

For the grid connected operation, a phase-locked loop (PLL) is used for the grid synchronization of TLIHC in this work. A passive LCL filter is designed to attenuate the harmonic currents injected into the grid. The robustness of the controller has been verified by instantly stepping-up and stepping-down of the grid currents. The FFT analysis of the grid current has been carried out to check the harmonics injected into the grid current. All the circuit operating features of TLIHC are also verified during the grid tied mode. Finally, the applications of the proposed TLIHC are presented in this thesis.

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(Simanta Kumar Samal)

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List of Acronyms

RES	Renewable energy source
PV	Photovoltaic
DC	Direct current
PEC	Power electronics converter
RHPZs	Right half-plane zeros
AC	Alternating current
HF	High frequency
LF	Low frequency
PLL	Phase-Locked Loop
THC	Transformerless hybrid converter
ESR	Equivalent series resistance
TLMPHC	Transformerless minimum phase hybrid converter
TLIHC	Transformerless interleaved hybrid converter
NPC	Neutral point clamping
TIBC	Two-phase interleaved boost converter
VSI	Voltage source inverter
CSI	Current source inverter
HB	H-bridge
IGBT	Insulated gate bipolar transistor
EMI	Electromagnetic interference
PWM	Pulse width modulation
qZSI	quasi-Z-source inverter
PM	Phase margin
GM	Gain margin
RCMD	Residual current monitoring device
IWJ	Inverse Watkins Johnson
VSI	Voltage source inverter
SBI	Switched boost inverter
BDHC	Boost-derived hybrid converter

QBDHC	Quadratic boost derived hybrid converter
CFSI	Current fed source inverter
FBI	Full bridge inverter
IHC	Interleaved hybrid converter
CHC	Conventional hybrid converter
KCL	Kirchhoff’s current law
KVL	Kirchhoff’s voltage law
CCM	Continuous conduction mode
SPWM	Sinusoidal pulse width modulation
STS	Shoot-through state
PS	Power state
ZS	Zero state
FPGA	Field programmable gate array
THD	Total harmonic distortion
MPPT	Maximum power point tracking
QSG	Quadrature signal generator
VCO	Voltage-controlled oscillator
PI	Proportional integral controller
HERIC	Highly efficient and reliable inverter concept

Symbols Used

V_{in}, V_c, V_{DC}	DC voltage
I_{in} and I_{DC}	DC current
V_{AC}	AC voltage
V_{CPV}	Voltage across the parasitic capacitance
I_{AC} and	AC current
$I_{leakage}$	Leakage current
C_{dc}, C_o	DC link capacitor
L_1, L_2 and M	Coupled inductors and mutual inductor
L	Inductor
$S_{1\rightarrow 6}$	Switches in TLMPHC
C, C_d, C_{PV}	Capacitor
S, $S_{1\rightarrow 6}$	Switches in TLIHC
D_1 D_2	Diode
P_{dc}	DC power
P_{ac}	AC power
R_{eq}	Equivalent resistance
R_{DC} and R_{AC}	DC and AC load resistances
L_{f1}, L_{f2} and C_f	Second-order low pass filter inductances and capacitance
$S_1 - S_4$	Switches in HB circuit
S_{inv}	Switch for entire inverter part of TLMPHC and TLIHC
D	Duty ratio
M_i	Modulation index
V_{inv}	Voltage across the inverter bridge
V_{Cd}	Voltage across the DC link capacitor
$V_{ac(pk)}$	Fundamental peak AC output voltage
T_S	Switching period
K_1 and K_2	Coefficient matrices

A_1 and A_2	State matrices
B_1 and B_2	Input matrices
X and U	State variable vector and input vector
$\frac{\tilde{v}_{DC}(s)}{\tilde{d}(s)}$	Control to output transfer function
I_C	Current flowing through capacitors
V_L	Voltage across inductors
I_{L1} and I_{L2}	Current flowing through inductors
$V_{D1}$and V_{D2}	Voltage across diodes
I_D	Current flowing through diodes
ΔI_{L1}	Ripple in inductor currents
ΔV_C	Ripple in capacitor voltages
V_{cm} and V_{dm}	Common mode voltage and differential mode voltage
V_{1N} and V_{2N}	Inverter output voltage with respect to reference point $\boldsymbol{N}$
P_{S_cond}	Conduction losses in switches
$r_{DS(on)}$	ON-state resistance of switches
P_{S_switc}	Switching losses in switches
P_{D_cond}	Conduction losses in diodes
$V_{F,D}$,$r_{F,D}$	Forward voltage drops and resistance of diodes
P_{D_switc}	Switching losses in diodes
f_S	Switching frequency
I_{RR}, T_{RR}	Reverse recovery current and time of diodes
r_c	ESR of capacitance
r_l	DCR of inductance
P_C	Power losses in capacitors
P_L	Power losses in inductors
f_{line}	Line frequency of AC output
V_{tr}(t)	Carrier signal
V_m(t) and - V_m(t)	Modulating signals
V_{st}	Constant signal

ω	Angular frequency rad/sec
L_{g1} and L_{g2}	Grid side filter inductors
f	Grid frequency
I_g and V_g	Grid current and grid voltage
S_{sw}	Controlled switch