THE UNIVERSITY OF ADELAIDE

Low-Cost Current-Source 1-ph Photovoltaic Grid-Connected Inverter

by

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Dedicated to my brother, Ahmet Bülent Ertaşgın

CONTENTS

Abstract

This research investigates a complete analysis and investigation of a single-phase currentsource (CSI) grid-connected inverter topology that is based on a photovoltaic array as a supply and a DC link inductor acting as a constant-current source. The proposed low-cost system is implemented using an open-loop control to prove the concept. Then a well-known feedforward compensation control is implemented to achieve acceptable total harmonic distortion of the inverter output current. A single boost switch (based on a switched-mode rectifier) has a duty-cycle that is modulated sinusoidally at the mains (grid) frequency such that it produces an output current that appears a full-wave rectified sinewave that is synchronised to the grid voltage. Additionally, a H-bridge inverter circuit and a capacitive-inductive low-pass grid filter is used to unfold, filter and feed the sinusoidal output current into the grid.

A number of detailed PV array models are studied and used in the simulations. The relationship between the PV array output ripple and the DC link energy storage (element) for single-phase grid-connected inverters is analysed. The "balanced" ripple definition is introduced to estimate the PV array output power reduction due to ripple.

The proposed grid-connected CSI topology is idealised which ignores : component losses, voltage drops, PWM switching and low-pass output filter resonance effects. Normalised simulations are carried out to investigate DC link energy storage, modulation index and irradiance variation effects with an emphasis on meeting the power factor (PF) and total harmonic distortion (THD) grid requirements.

The low-pass grid filter optimisation for the proposed topology is studied showing a trade-off between the output current THD, power loss, and quality factor. A 160 W inverter is implemented and a set of comprehensive test results obtained to verify the simulations using open-loop and feedforward compensation control. To conclude, a 1.2 kW grid-connected inverter based on the proposed low-cost topology was designed and simulated. Its simulated efficiency of 95% was higher than that of the 160 W inverter.

Statement of Originality

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PUBLICATIONS

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ABBREVIATIONS

AC	**A**lternating **C**urrent
AS	**A**ustralian **S**tandards
CC	**C**onstant **C**urrent
CCS	**C**onstant **C**urrent **S**ource
CL	**C**apacitive-**I**nductive
CSI	**C**urrent-**S**ource **I**nverter
CWS	**C**urrent **W**aveshaper
DC	**D**irect **C**urrent
ESR	**E**quivalent **S**eries **R**esistance
FC	**F**ilter **C**onfiguration
FFD	**F**eed**f**orwar**d**
GC	**G**rid-**C**onnected
GCI	**G**rid-**C**onnected **I**nverter
I-V	**C**urrent vs. **V**oltage
LC	**I**nductive-**C**apacitive
LCL	**I**nductive-**C**apacitive-**I**nductive
MLT	**M**ean **L**ength per **T**urn
MPP	**M**aximum **P**ower **P**oint
MPPT	**M**aximum **P**ower **P**oint **T**racking

OL	**O**pen-**L**oop
PF	**P**ower **F**actor
PM	**P**ermanent **M**agnet
PV	**P**hoto**v**oltaic
P-V	**P**ower vs. **V**oltage
PWL	**P**iece**w**ise **L**inear
PWM	**P**ulse **W**idth **M**odulation
T	**T**hyristor
THD	**T**otal **H**armonic **D**istortion
UC	**U**nfolding **C**ircuit
VSI	**V**oltage-**S**ource **I**nverter
WS	**W**ave**s**haper

PHYSICAL CONSTANTS

Boltzman constant	k	$=$	1.38×10^{-23}	$\mathrm{J\,K^{-1}}$
Charge on electron	q	$=$	1.602×10^{-19}	C
Permeability of free space (air)	μ_0	$=$	$4\pi \times 10^{-7}$	$\mathrm{H\,m^{-1}}$

SYMBOLS

a	temperature coefficient of copper	%/°C
A_W	radius value of copper wire	m
A_{WT}	total winding area	m^2
B	flux density	T
C	capacitance	F
C_{DC}	DC link capacitor	F
C_F	filter capacitor	F
C_{PV}	PV array output capacitor	F
d	duty cycle	%
E	energy storage	J/W
E_0	average energy storage	J
f_1	grid (inverter fundamental) frequency	Hz
f_c	cutoff frequency	Hz
f_R	resonant frequency	Hz
f_{sw}	switching frequency	Hz
g	airgap	m
G	irradiance	W/m^2
g_E	equivalent gap	m
g_T	total gap	m

H_1	the rms value of the first harmonic	V or A
H_n	the rms value of the n^{th} harmonic	V or A
I_0	current at the maximum power	A
I_B	base current	A
i_G	inverter output or grid current	pu
I_G	grid current (fundamental)	pu
i_{IN}	waveshaper input current	pu
i_{IN}^*	desired PV array output current	A
i_L	inductor current	A
i_{L-CC}	inductor current (constant-current)	A
$i_{L-Clipped}$	inductor current (clipped)	A
i_{L-FFD}	inductor current (feedforward control)	A
i_{L-MPP}	inductor current (MPP)	A
I_{L0}	nominal PV array output current (constant)	A
i_{L-OL}	inductor current (open-loop control)	A
i_{OUT}	waveshaper output current	pu
i_{PV}	PV array output current	A or pu
I_{rms}	the rms value of distorted current	A
I_{SC}	short circuit current	A
i_{WS-FFD}	waveshaper output current (feedforward control)	A
i_{WS-OL}	waveshaper output current (open-loop control)	A
L	inductor	H
l_C	mean core magnetic path length	m
L_{DC}	DC link inductor	H
L_F	filter inductor	H or pu
m_A	modulation index	% or pu
n	diode ideality factor	
N	number of turns	
N_S	module cell number	
P	active power	W
P_0	rated maximum power	W

P_0	average output power	W
P_{CU}	inductor power loss	W
P_d	damping resistance power loss	W
pF	packing factor	%
p_{IN}	waveshaper input power	W
p_{LOSS}	ripple loss	W
P_{OUT}	inverter output power	W
R_{CU}	coil resistance	Ω
R_D	damping resistance	Ω
R_S	module series resistance	Ω
S	apparent power	V A
T	period	s
V_0	voltage at the maximum power	V
V_B	base voltage	V
V_{dcMAX}	ripple voltage (maximum)	V
V_{dcMIN}	ripple voltage (minimum)	V
V_g	band gap	V
V_G	grid voltage	pu
v_{IN}	inverter input voltage	V
v_{IN}	waveshaper input voltage	pu
v_{IN-CC}	waveshaper input voltage (constant-current)	V
$v_{IN-Clipped}$	waveshaper input voltage (clipped)	V
v_{IN-MPP}	waveshaper input voltage (MPP)	V
V_{L_F}	applied voltage to the filter inductor	pu
V_{OC}	open circuit voltage	V
v_{OUT}	waveshaper output voltage	pu
V_{PK}	peak grid voltage	V or pu
v_{PV}	PV array output voltage	V or pu
V_{UC}	unfolding circuit output voltage	pu
X_L	inductor impedance	pu
Z_0	characteristic impedance	Ω

Z_B	base impedance	Ω
α	phase advance in simulation	deg
α	temperature coefficient of I_{SC}	%/°C
β	temperature coefficient of V_{OC}	V m/°C
Δ	difference	
η	efficiency	%
λ	flux-linkage	V s
ρ	static resistivity	V m/A
φ	phase advance or difference	deg
Φ	flux	V m
ω	angular frequency	rad/s
ω_{cn}	normalised cutoff frequency (relative to f_1)	pu