Solar Power Generation Capability and Three-Port Converters for PV-Battery Powered Applications

by

Mohammad Al-Soeidat

A Thesis Submitted in Fulfillment of the Requirements for the Degree

Doctor of Philosophy

University of Technology Sydney

Faculty of Engineering and Information Technology

School of Electrical and Data Engineering

Sydney, Australia

January, 2020

Certificate of Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as part of the collaborative doctoral degree and/or fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This research is funded by the Al-Hussein Bin Talal University scholarship. This research is supported by Australian Government Research Training Program.

Production Note:
Signature: Signature removed prior to publication.

Date: 7/1/2020

Mohammad Al-Soeidat

ABSTRACT

Solar energy is one of the most useful sources of sustainable energy. Intermittency negatively affects the efficiency and reliability of solar power. To mitigate such a problem, a power electronic converter is used to enhance the solar power generation capability, such as detecting faulty solar photovoltaic (PV) cells to be eliminated from the solar system or tracking the maximum power point (MPPT). Other advantages of power converters are integrating energy storage systems (ESS) with the solar energy system and managing power flow.

Solar cell power performance is greatly affected by two critical factors, aging and cracks. In order to mitigate their negative effects on the solar system, these cells are to be substituted by new cells; therefore, replacing the solar panels. In this research, an active crack detection method is proposed that can detect the cracked cells within a solar string by using AC parameter characterization without a need to have a physical inspection.

In this research, an analog voltage-based MPPT algorithm for individual PV module is proposed and experimentally verified. The maximum power points of solar cell can be joined by an approximately linear line. The slope of this line varies depending on the type and characteristic of the panels. Utilizing this characteristic, a bipolar junction transistor (BJT) is used to implement a variable voltage reference as the DC load line of the BJT can be designed to match the MPP line of the PV panel. This improves the accuracy of the maximum power point reference voltage without the need for a digital controller or PID controller.

This research also proposes two novel compact three-port converters. The proposed converters are used to interface a PV module, battery and load. The proposed converters are able to achieve MPPT, battery power management and output voltage regulation simultaneously. The first converter can be used for a stand-alone system or in a microgrid structure. The second converter is useful when bidirectional power flow is needed at the output port for some applications, such as grid-connected

solar system and electric vehicle where regenerative braking is used. Each converter combines three converters to form one integrated converter by sharing some components such as switches, inductors and capacitors. Thus, the converters have a high power density and fewer components compared to the traditional DC-DC converters. The integrated PV-battery system is the promised solution for both intermittency and the unpredictable load demand.

I would like to dedicate my thesis

To my parents:

Raja Al-Soeidat and Hadieh Khlifat

for their unconditional love.

To my academic advisor:

A/Prof. Dylan Dah-Chuan Lu

To my wife and daughter:

Lina Dweirj and Farah Al-Soeidat

To my family and friend

for their immense support.

Acknowledgements

First and foremost, it is one of the greatest pleasures to be able to pursue my PhD at the University of Technology Sydney, a stimulating environment in which I could grow academically. Throughout this endeavour, I have received a great deal of support and assistance. I would like to express my gratitude to those who believed and trusted in me throughout my study.

In particular, I would like to express my gratitude to my supervisor A/Prof. Dylan Dah-Chuan Lu, whose expertise was invaluable in the formulating of the research topic and for his guidance through each stage of the process to dig deeper into my research area. Your contribution and time are very much appreciated.

In addition, I would like to extend my thanks to Al-Hussein Bin Talal University for their generosity and financial support as they funded my PhD study through the university scholarships. Thank you for enabling this opportunity!

I am grateful for my co-supervisor, Prof. Jianguo Zhu, for his advice and encouragement. I am grateful to my colleagues in our research group. I wish to acknowledge an incomplete list of group members: Alexis Cembrano, Tian Cheng, Habes Khawaldeh, Hamzeh Aljarajreh, Qi Yao, Kaixin Wel, Nurhakimah Mohd Mukhtar and Muhammad Mubashir Alam.

Last and not least, I would like to thank my parents, wife and family for their wise counsel and sympathetic ear. Finally, there are my friends, who were of great support in deliberating over our problems and findings, as well as providing a happy distraction to rest my mind outside of my research.

Mohammad Al-Soeidat

Sydney, Australia, 2020.

List of Publications

Journal Papers

J-1. T. Cheng, **M. Al-Soeidat**, D.D.C. Lu and V. Agelidis, "Experimental study of PV strings affected by cracks," *IET The Journal of Engineering*, vol. 2019, no. 18, pp. 5124-5128, 2019. Available: 10.1049/joe.2018.9320.

J-2. **M. Al-Soeidat**, D.D.C. Lu, and J. Zhu, "An analog BJT-tuned maximum power point tracking technique for PV systems," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 66, no. 4, pp. 637-641, April 2019. doi: 10.1109/TCSII.2018.2865804

J-3. **M. Al-Soeidat**, H. Aljarajreh, H. Khawaldeh, D.D.C. Lu, and J. Zhu, "A Reconfigurable Three-Port DC-DC Converter for Integrated PV-Battery System," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, doi: 10.1109/JESTPE.2019.2941595

J-4. **M. Al-Soeidat**, T. Cheng, D. D. Lu and V. G. Agelidis, "Experimental study of static and dynamic behaviours of cracked PV panels," *IET Renewable Power Generation*, vol. 13, no. 16, pp. 3002-3008, 9 12 2019. doi: 10.1049/iet-rpg.2019.0359

Conference Papers

C-1. **M. Al-Soeidat**, H. Khawaldeh, and D.D.C. Lu, "A Novel High Step-up Three-Port Bidirectional DC/DC Converter for PV-Battery Integrated System," *2020 IEEE Applied Power Electronics Conference (APEC)*, March 2020.

C-2. **M. Al-Soeidat**, H. Khawaldeh, H. Aljarajreh, and D.D.C. Lu, "A compact three-port DC-DC converter for integrated PV-battery system," *2018 IEEE International Power Electronics and Application Conference and Exposition (PEAC)*, Nov 2018, pp. 1-6.

C-3. H. A. Khawaldeh, H. Aljarajreh, **M. Al-Soeidat**, D.D.C. Lu, and L. Li, "Performance investigation of a PV emulator using current source and diode string," *2018 26th International Conference on Systems Engineering (ICSEng)*, Dec 2018, pp. 1-5.

C-4. **M. R. Al-Soeidat**, D.D.C. Lu and J. Zhu, "A more accurate analog voltage based photovoltaic maximum power point tracking technique," *2017 8th International Renewable Energy Congress (IREC)*, March 2017, pp. 1-5.

C-5. **M. R. Al-Soeidat**, A. Cembrano, and D.D.C. Lu, "Comparing effectiveness of hybrid MPPT algorithms under partial shading conditions," *2016 IEEE International Conference on Power System Technology (POWERCON)*, Sep. 2016, pp. 1-6.

Contents

List of Figures

List of Tables

Abbreviation

PV	Photovoltaics
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
DMPPT	Distributed Maximum Power Point Tracking
ESS	Energy Storage Systems
SC	Supercapacitor
DC	Direct Current
AC	Alternating Current
I-V Curve	Current-voltage Characteristic Curve
P-V Curve	Power-Voltage Characteristic Curve
FF	Fill Factor
MPC	Multiport Converter
TPC	Three-port Converter
STC	Standard Testing Condition (nominal condition)
HS-NITPC	High Step-up Non-isolated Three-port DC-DC Converter
PSC	Partial Shading Condition
Btu	British Thermal Units
RES	Renewable Energy Sources
BJT	Bipolar Junction Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
SoC	State of Charge

EV	Electric Vehicle
FOC	Fraction Open Circuit
FSC	Fraction Short Circuit
P&O	Perturb and Observe
InC	Incremental Conduction Method
OCC	One-cycle Control
KVL	Kirchhoff's voltage law
MIMO	Multi-input Multi-output
SISO	Single-input Single-output
SIDO	Single-input Dual-output
DO	Dual-output
DI	Dual-input
DISO	Dual-input Single-output
DIDO	Dual-input Dual-output
CCM	Continuous Conduction Mode
DCM	Discontinuous Conduction Mode
PFM	Pulse-frequency Modulation
TPHBC	Three-port Half-bridge Converter
TPHBC-PR	Three-port Half-bridge Converter with Post Regulation
TPHBC-SR	Three-port Half-bridge Converter Synchronous Regulation
TPHBC-PF	Three-port Half-bridge Converter with Primary Freewheeling
SSPS	Secondary-side Phase-shift
FB-TPC	Full-bridge Three-port Converter

Nomenclature

P_{mpp}	Solar cell power at the maximum power point
I_{sc}	Solar cell short circuit current
V_{oc}	Solar cell open-circuit voltage
I_{ph}	Solar cell light-generated current
D_f	Forward-biased diode
R_{sh}	Shunt resistance
R_s	Series resistance
C_p	Parallel capacitance
$I_{sc;n}$	Short-circuit light-generated current at the nominal condition
K_i	Temperature coefficient of the short circuit current
T	Temperature
T_n	Temperature at nominal condition
G	Irradiance
G_n	Irradiance at nominal condition
V_t	Diode thermal voltage
k	Boltzmann's constant
q	Electron charge.
N_s	Number of series cells
I_d	Diode current
I_0	Diode reverse saturation current
n	Ideality factor of the solar cell diode
I_{sh}	Shunt resistance current
I_{pv}	Solar cell current
Z	Impedance
ω	Angular frequency

C_d	Diffusion capacitance
C_t	Transition capacitance
b	Constant depends on the solar cell
V_j	Junction voltage
V_a	Applied voltage
A	Area of the solar cell
ϵ_0	Permittivity of free space
ϵ_r	Permittivity of the solar cell material
N_D	Doping concentration for n region
N_A	Doping concentration p region
N_i	Intrinsic concentration of electrons & holes for the base semiconductor
τ	Minority carrier lifetime
K_1	Voltage proportional constant
R_B	BJT base resistor
R_C	BJT collector resistor
R_E	BJT emitter resistor
I_B	BJT base current
I_C	BJT collector current
I_E	BJT emitter current
β	BJT DC current gain
V_{BE}	BJT base-emitter voltage
V_{CE}	BJT collector-emitter voltage
R_{PV}	Equivalent resistance seen by the PV panel
R_O	Equivalent resistance of the PV panel
V_{ref}	Reference voltage from BJT

V_{init} Initial reference voltage to BJT

R_{sens} Small resistor that is used to measure the PV module output current

V_{sens} Sensed PV module voltage