Performance Analysis of Photovoltaic Systems with Energy Storage Systems

Adel A. Elbaset
Saad Awad Mohamed Abdelwahab
Hamed Anwer Ibrahim
Mohammed Abdelmowgoud Elsayed Eid

Performance Analysis of Photovoltaic Systems with Energy Storage Systems

Springer

Adel A. Elbaset
Minia University
El-Minia, Egypt

Saad Awad Mohamed Abdelwahab
Suez University
Suez, Egypt

Hamed Anwer Ibrahim
Suez University
Suez, Egypt

Mohammed Abdelmowgoud Elsayed Eid
Suez University
Suez, Egypt

ISBN 978-3-030-20895-0 ISBN 978-3-030-20896-7 (eBook)
https://doi.org/10.1007/978-3-030-20896-7

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Dedicated to
Our parents, brothers, sisters, teachers, and friends for their love, encouragement, and endless support.
We give all thanks and gratitude to our beloved wife and to our daughters and sons wishing from God to protect them.

بسم الله الرحمن الرحيم
"يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ وَاللَّهُ بِمَا تَعْمَلُونَ خَبِيرٌ "
صدق الله العظيم
المجادلة/ 11

Acknowledgment

﴾In the name of Allah, most Gracious, most Merciful﴿

Firstly, all gratitude to Allah who guides and aides us to attain the achievements of this book.

We would like to express our greatest gratitude to the Faculty of Industrial Education, Suez University, and Minia University for helping us to finish our book. Our deepest gratitude goes to our mothers, to whom we are most indebted. We thank them for their constant love and prayers; without their prayers, we could have never been able to achieve this book. Special words to our wives for their unlimited help, patience, care, endless support, and continuous encouragement throughout our life.

Abstract

Recently, the permanent growth of the energy demand and the rapid depletion of the conventional power sources have attracted the research interests of the authors toward the renewable energy sources, especially the photovoltaic (PV) energy as alternative sources of energy. The PV energy can be utilized only during the daylight. Therefore, the integration of the PV energy and the energy storage system as the battery supercapacitor can attenuate their individual fluctuations, increase the overall output power, and generate more reliable power with higher quality to the electrical loads in the rural areas. The aim of this book is to study and design the performance analysis of the PV stand-alone systems with energy storage systems as follows:

- This book investigates dynamic modeling, simulation, and control strategy of the PV stand-alone system during variation of the environmental conditions. Moreover, the effectiveness of the implemented maximum power point tracking (MPPT) techniques and the employed control strategy will be evaluated during variations of the solar irradiance and the cell temperature. The simulation results are based on the reliability of the MPPT techniques applied in extracting the maximum power from the PV system during the rapid variation of the environmental conditions. Furthermore, it introduces a review of two MPPT techniques that are implemented in the PV systems, namely, the perturb and observe (P&O) MPPT technique and the incremental conductance (InCond) MPPT technique. The two MPPT techniques were simulated by the MATLAB/Simulink, and the results response of the PV array from voltage, current, and power are compared to the effect of solar irradiation and temperature change.
- Then, the proposed PV stand-alone system is utilized to supply the demanded power of variable loads. The PV array is connected to battery energy storage (BES) through the DC bus in order to supply the demanded power of the variable loads. Moreover, the power flow control strategy is proposed to feed the demanded power of the variable loads. The BES can act as a buffer store to eliminate the mismatch between PV power and load demand. Furthermore, the BES helps to improve the performance of the system through the control used in the

process of charge and discharge to manage the sudden load changes and helps to maintain a stable voltage level on the load and PV terminals.

- Improving the performance of the PV stand-alone system by leveraging the properties of the battery-supercapacitor hybrid energy storage system (BS-HESS), this book proposes an efficient control strategy to enhance the BS-HESS capable of the PV stand-alone system.
- The PV panels are not an ideal source for battery charging; the output is unreliable and heavily dependent on weather conditions. Therefore, an optimum charge/discharge cycle cannot be guaranteed, resulting in a low battery state of charge (SOC%). Low battery SOC leads to sulfation and stratification, both of which shorten battery life. A control strategy is essential for the BS-HESS to optimize the energy utilization and energy sustainability to a maximum extent as it is the algorithm which manages the power flow of the battery supercapacitor.
- Performance analysis of the PV stand-alone system with BS-HESS during the high fluctuation solar irradiation and variable load power for rural household load profile.

Contents

List of Figures

List of Tables

List of Abbreviations

PV	Photovoltaic energy
MPPT	Maximum Power Point Tracking
MPP	Maximum Power Point
DC	Direct Current
AC	Alternating Current
InCond	Incremental Conductance MPPT Technique
P&O	Perturb and Observe MPPT Technique
DOD	Depth of Discharge
BES	Battery Energy Storage
BESS	Battery Energy Storage Systems
SOC	State of Charge
AGM	Absorbent Glass Mat
SCs	Supercapacitors
ESR	Equivalent Series Resistance
HESS	Hybrid Energy Storage System
PWM	Pulse Width Modulation
IGBT	Insulated-Gate Bipolar Transistor
THD	Total Harmonic Distortion
BS-HESS	Battery-Supercapacitor Hybrid Energy Storage System
FFT	Fast Fourier Transform
FBC	Filtration-Based Controller
HPF	High-Pass Filter
LPF	Low-Pass Filter
SOC_{SC}	Supercapacitor State of Charge
MFs	Membership Functions

List of Symbols

Symbol	**Meaning**
E_{SC}, C	Energy stored in the SC, capacitance
Q, V	The stored charge (in Coulombs) and voltage (in Volt)
ε, ε_0	Dielectric constant and the permittivity of a vacuum
A, d	The thickness and the area between double layers of the capacitor
C_1, C_2	The equivalent capacitances in each electrical double layer
τ, R_{ESR}	Time constant and the equivalent series resistance of the SC
CdTe, a − Si	Cadmium telluride and amorphous silicon
$CuInSe_2$	Copper indium selenium
I, V	Output current and output voltage of PV cell
I_{pv}, V_{pv}	The terminal current and terminal voltage of PV array
I_{ph}, I_s	Light-generated current and PV saturation current
N_p, N_s	Number of parallel and series modules
R_s, R_{sh}	Series resistance and parallel resistance of PV cell
I_{sc}	Short-circuit current at STC (Standard Test Condition)
K_i, q	Short-circuit temperature coefficient and charge of electron
A, K	Ideality factor and Boltzmann's constant
E_g	Band-gap energy of semiconductor used in PV cell
T_{ref}, T	Reference temperature (25 °C) and actual temperature of PV cell
I_{rs}, G	Reverse saturation current at $\mathrm{T_{ref}}$ and solar irradiance
V_{oc}, N_{ser}	Open circuit voltage and number of series-connected PV cells
P_{PV}, f_S	Nominal power of the PV and switching frequency
C_a, C_1	PV array link capacitance and DC link capacitance
L_a, D	Boost converter inductor and diode
Dy, K_1	Duty cycle of the boost converter and constant of proportionality
V_{dc}, ΔV_0	Output voltage from boost converter and ripple of output voltage
ΔV_{PV}, ΔI_{La}	Change in PV voltage and ripple current of boost inductor
V_{mpp}, P_{pv}	PV array voltage at the MPP and PV array output power
f_{res}, R_d	Cut-off frequency and damping resistor
L_i, L_g	Inverter side inductance and grid side inductance
C_f, C_b	Filter capacity and system base capacitance
i, i^*	The battery current and the low-frequency current dynamics

it, Exp(s)	The battery extracted current and the extracted capacity
E_0, Q_b	The constant voltage and maximum battery capacity
Sel(s)	Represents the battery mode
P_{Batt}, P_{SC}	Battery power and SC power
P_{Load}	Power demand of the load
i_{self_dis}	Self-discharge current of SC
P_{LF}, P_{HF}	Power low-frequency components and power high-frequency components
dP	Mismatch power between PV power and load demand
I_{batt_peak}	Battery peak current
P_{batt_peak}	Battery peak power
SOC_{batt_avarge}	Average battery SOC
SOC_{batt_final}	Final battery SOC
I_{SC_peak}	SC peak current
P_{SC_peak}	SC peak power
SOC_{SC_final}	SC final SOC
A_i	Interfacial area between electrodes and electrolyte
C_m	Molar concentration
R_d, F	Molecular radius and Faraday constant
i_{SC}, V_{SC}	Supercapacitor current and voltage
C_T, R_{SC}	Total capacitance of the SC and total resistance of SC
N_e, N_A	Number of layers of electrodes and Avogadro constant
N_{pc}, N_{sc}	Number of parallel SCs and number of series SCs
α_1, α_2, and α_3	The rates of change of the SC voltage