



MODELING AND CONTROL OF PHOTOVOLTAIC CONNECTED TO GRID BASED ON ADVANCED EVOLUTIONARY TECHNIQUES

By

Dima Omar Fadel El-Hassan

**A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree
of**

MASTER OF SCIENCE

in

ELECTRICAL POWER AND MACHINES ENGINEERING

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2019**

MODELING AND CONTROL OF PHOTOVOLTAIC CONNECTED TO GRID BASED ON ADVANCED EVOLUTIONARY TECHNIQUES

By

Dima Omar Fadel El-Hassan

**A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree
of**

MASTER OF SCIENCE

in

ELECTRICAL POWER AND MACHINES ENGINEERING

**Under the Supervision
of**

Prof. Dr. M. A. Mostafa Hassan

.....

Assoc. Prof. Dr. Mostafa Ahmed El-Shahed

.....

**Professor of Control of Power Systems
Electrical Power and Machines Department
Faculty of Engineering, Cairo University**

**Associate Professor
Electrical Power and Machines Department
Faculty of Engineering, Cairo University**

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2019**

**MODELING AND CONTROL OF PHOTOVOLTAIC
CONNECTED TO GRID BASED ON ADVANCED
EVOLUTIONARY TECHNIQUES**

By

Dima Omar Fadel El- Hassan

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ELECTRICAL POWER AND MACHINES ENGINEERING

Approved by the Examining Committee

Prof. Dr. M. A. Moustafa Hassan, Thesis Main Advisor

Prof. Dr. Dr. Essam El-Din Abo-El-Dahab, Internal Examiner

Prof. Dr. Adel El-Samahy, External Examiner

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2019**

Engineer's Name: Dima El-Hassan
Date of Birth: 29/7/1979
Nationality: Egyptian
E-mail: elhassandema@gmail.com
Phone: 01007717028
Address: El Atibae st, Mohandessine
Registration Date: 1 / 10 /2014
Awarding Date: / /2019
Degree: Master of Science
Department: Electric Power and Machines Engineering



Supervisors: Prof. Dr. Mohamed Ahmed Mostafa Hassan
Assoc. Prof. Mostafa Ahmad El-Shahed

Examiners:

Prof. Dr. Mohamed Ahmed Mostafa Hassan	(Thesis Main Advisor)
Professor Dr. Essam El-Din Abo-El-Dahab	(Internal Examiner)
Professor Dr. Adel El-Samahy	(External Examiner)

Faculty of Engineering, Helwan University

Title of Thesis: Modeling and Control of Photovoltaic Connected to Grid Based on Advanced Evolutionary Techniques

Key Words:

Grid Connected PV; Maximum Power Point Tracking techniques (MPPT); (PID) and (PI); Computational Evolutionary Techniques.

Summary:

Grid interconnection of Photovoltaic power generation system has the advantage of more effective utilization of generated power. Power quality issues are one of the challenges associated with increasing photovoltaic power generation. The Maximum Power Point Tracking Techniques (MPPT) are adopted to obtain maximum power during all-day irradiance. Conventional MPPT techniques (P&O, INC) are presented and detailed with an overall approach. This Thesis discusses the advantages and the drawbacks of the conventional algorithm and proposes a Variable-Step Incremental Conductance algorithm (VS-IC) and a Modified Variable-Step Incremental Conductance algorithm (MVS-IC) that responds more accurately to the changes in the solar irradiation. The PI controller is used to improve the performance of the DC voltage controller in the inverter. Combined with the evolutionary computational techniques, each technique is used to set optimal and tune PI parameters. Finally, the Total Harmonic Distortion (THD) of the voltage and the current prior to connection to grid shall be computed.

Disclaimer

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledged all sources used and have cited them in the references section.

Name: Dima Omar Fadel El Hassan

Date : .11.2019

Signature:

Dedication

I dedicate this thesis to my small family for their understanding, passion, and for being a great motivation to success in my life.

Acknowledgments

I would like to express my sincerest gratitude and appreciation to my advisor **Prof. Dr. Mohammed A. Moustafa Hassan** Professor Dept. of Electrical Engineering for his continued guidance and support in preparing this thesis, and I also remain really thankful to him for the outstanding technical content that gave birth to the this thesis.

I am sincerely thankful to **Dr. Mostafa El-Shahed** for the great input he supported me with and I remain truly appreciating his esteemed guidance and encouragement during the work progress.

Last, but not least, I would like to extend my thanks and gratitude to my small family and especially my husband for his unconditional support and understanding

Table of Contents

TABLE OF CONTENTS	IV
LIST OF TABLES	VI
LIST OF FIGURES	VII
NOMENCLATURE.....	VIII
ABSTRACT.....	X
CHAPTER ONE: INTRODUCTION AND SOLAR ENERGY	1
1.1 Introduction.....	1
1.2 Advantages and Disadvantages of Photovoltaic Systems.....	1
1.3 Problem Diagnosis.....	1
1.4 Thesis Objectives.....	2
1.5 Thesis Main Outlines.....	2
CHAPTER TWO: LITERATURE REVIEW AND GENERAL OVERVIEW ON PV SYSTEMS.....	4
2.1 General Overview of PV systems.....	4
2.2 Overview on Solar Cells.....	5
2.2.1 Mono-Crystalline Silicon Cells.....	5
2.2.2 Multi-Crystalline Cells.....	5
2.2.3 Non-silicon Based Thin film Technology.....	5
2.3 Parameters of the PV module.....	5
2.4 Single-Diode PV Cell Modeling.....	6
2.5 Module-Array Modeling.....	8
2.6 Composition of PV Panel.....	14
2.7 DC-DC Converter.....	14
2.7.1 DC-DC Boost Converter and Controller.....	14
2.8 DC-AC Inverter.....	16
2.9 Phase Locked Loop.....	16
2.10 Control of Grid Voltage.....	17
2.11 DC-Voltage Controller.....	17
2.11.1 Inner Current Controller.....	17
2.12 Low-Pass Filter.....	18
2.13 Utility Grid Requirements.....	19
2.14 Summary of the Chapter.....	19
CHAPTER THREE: MAXIMUM POWER POINT TRACKING TECHNIQUES... 20	20
3.1 Introduction.....	20
3.2 Review of MPPT Techniques.....	20
3.3 Perturb-and-Observe (P&O) Technique.....	21
3.4 Incremental Conductance (IC) Technique.....	22
3.5 Variable Step-Size IC MPPT Algorithm.....	23
3.6 Modified Variable Step-Size Incremental Conductance.....	25
3.7 Summary of the Chapter.....	26
CHAPTER FOUR: VOLTAGE CONTROL THROUGH PI CONTROLLER AND EVOLUTIONARY COMPUTATION	27
4.1 Introduction.....	27
4.2 Proportional-Integral Derivative Controller.....	28
4.2.1 Proportional Term in PID Controller.....	29
4.2.2 Integral Term.....	29
4.2.3 Derivative Term.....	30

4.3	Tuning of PID Controller.....	31
4.4	Performance Indices	32
4.4.1	Integral of the Square of the Error	32
4.4.2	Integral of the Absolute Magnitude of the Error	32
4.4.3	Integral of the Time Absolute Magnitude of the Error.....	32
4.4.4	Integral of the Time Square Magnitude of the Error	32
4.5	Controller Design.....	32
4.6	PI Controller Parameter Tuning.....	33
4.6.1	Conventional Particle Swarm Optimization (PSO)	33
4.6.1.1	PSO Algorithms.....	34
4.6.1.2	Selection of Acceleration Constants	35
4.6.2	Adapted Weighted Particles Swarm Optimization	36
4.6.2.1	AWPSO Algorithm.....	37
	The main steps of the AWPSO algorithm are as follows:	37
4.6.3	Adapted Accelerated Coefficient PSO	37
4.6.4	Modified Adapted Accelerated Coefficient PSO (MAACPSO).....	39
4.6.5	Cuckoo Search	39
4.6.5.1	Lévy Flight.....	39
4.6.5.2	Flowchart	39
4.7	Summary of the Chapter	40
CHAPTER FIVE: SIMULATION RESULTS AND DISCUSSIONS		41
5.1	Introduction.....	41
5.2	Objective Function.....	41
5.3	Case Studies	41
5.4	Tuning of PI Parameters by Evolutionary Techniques	48
5.4.1	Parameters of Optimization Techniques.....	49
5.4.2	Simulation and Results	50
5.4.2.1	With Initial Values.....	50
5.4.2.2	Using (PSO, AWPSO, ACCPSO, MAACPSO and CS)	50
5.4.3	Results Comparison Between the Five Evolutionary Techniques.....	53
5.5	Total Harmonic Distortion (THD).....	53
CHAPTER SIX :CONCLUSION AND FUTURE WORK		57
6.1	Conclusion	57
6.2	Recommended Future Work.....	58
CHAPTER 7: REFERENCES.....		59

List of Tables

TABLE (1. 1): ADVANTAGES AND DISADVANTAGES OF PV SYSTEMS.....	1
TABLE (2. 1):ELECTRICAL CHARACTERISTIC DATA OF SUNPOWER SPR-305	6
TABLE (4. 1): EFFECT OF INCREASING EACH PARAMETER INDEPENDENTLY.....	31
TABLE (4. 2): PSO PARAMETERS DESCRIPTION	35
TABLE (4. 3): AWPSO PARAMETERS DESCRIPTION.....	37
TABLE (4. 4): AACPSO VARIABLES DESCRIPTION.....	39
TABLE (5. 1): COMPARISON BETWEEN THE STUDIED MPPT ALGORITHMS.....	45
TABLE (5. 2): VARIATION OF IRRADIANCE AND TEMPERATURE (CASE 3).....	47
TABLE (5. 3): PARAMETERS VALUE OF TECHNIQUES (PSO, AWPSO, AACPSO, MACCP SO).....	49
TABLE (5. 4): PARAMETERS VALUE OF TECHNIQUE (CS).....	49
TABLE (5. 5): COMPARISON BETWEEN THE FIVE STUDIED EVOLUTIONARY TECHNIQUES	53

List of Figures

FIGURE (2. 1): GENERAL DIAGRAM OF PV SYSTEMS.....	4
FIGURE (2. 2): PV CELL MODELED AS DIODE CIRCUIT.....	6
FIGURE (2. 3): SIMULINK MODEL PHOTON CURRENT (I_{ph}).....	8
FIGURE (2. 4): SIMULINK MODEL REVERSE SATURATION CURRENT (I_{rs}).....	8
FIGURE (2. 5): CELL -MODULE -ARRAY CONFIGURATION.....	9
FIGURE (2. 6) : SIMULINK MODEL SATURATION CURRENT.....	9
FIGURE (2. 7) : SIMULINK MODEL PV CURRENT.....	10
FIGURE (2. 8): COMPLETE SIMULINK MODEL OF PV MODULE.....	10
FIGURE (2. 9): I-V AND P-V CHARACTERISTICS AT DIFFERENT IRRADIANCES AND CONSTANT TEMPERATURE (25°C).....	11
FIGURE (2. 10): I-V AND P-V CHARACTERISTICS AT DIFFERENT TEMPERATURES AND CONSTANT IRRADIANCE (1 KW/M ²).....	11
FIGURE (2. 11): COMPLETE SIMULINK MODEL OF THE PV SYSTEM.....	12
FIGURE (2. 12): COMPLETE BLOCK DIAGRAM OF THE MODELED PV SYSTEM.....	13
FIGURE (2. 13) :DC-DC BOOST CONVERTER.....	14
FIGURE (2. 14) : DC-DC BOOST CONVERTER AND CONTROLLER.....	14
FIGURE (2. 15) : BOOST CONVERTER WAVEFORMS.....	15
FIGURE (2. 16) : TOPOLOGY OF 3-PHASE INVERTER.....	16
FIGURE (2. 17) : SCHEMATIC DIAGRAM OF THE PHASE LOCKED LOOP (PLL).....	17
FIGURE (2. 18) : VOLTAGE DC REGULATION USING PI CONTROLLER.....	17
FIGURE (2. 19) : TOTAL CONVERTER CONTROL SCHEME.....	18
FIGURE (2. 20) :LOW-PASS FILTER.....	18
FIGURE (3. 1) : PV PANEL (I-V) CHARACTERISTICS CURVES.....	21
FIGURE (3. 2) : FLOWCHART OF PERTURB & OBSERVATION METHOD.....	21
FIGURE (3. 3) : (P-V) AND (I-V) CURVES AND SLOPES.....	22
FIGURE (3. 4) : FLOWCHART OF THE IC MPPT ALGORITHM.....	23
FIGURE (3. 5) : FLOWCHART OF THE VARIABLE STEP-SIZE IC MPPT ALGORITHM.....	24
FIGURE (3. 6) : FLOWCHART OF THE MVS-IC MPPT ALGORITHM.....	25
FIGURE (4. 1) : (VSC) CONTROL FOR GRID-CONNECTED PV SYSTEMS.....	27
FIGURE (4. 2) : VOLTAGE DC REGULATION BY USING PI CONTROLLER.....	28
FIGURE (4. 3) : CLOSED LOOP AND STRUCTURE OF PID CONTROLLER.....	28
FIGURE (4. 4) : CHANGE FOR THREE VALUES OF K_p (K_i AND K_d HELD CONSTANT).....	29
FIGURE (4. 5) : CHANGE FOR THREE VALUES OF K_i (K_p AND K_d HELD CONSTANT).....	30
FIGURE (4. 6) : CHANGE FOR THREE VALUES OF K_d (K_p AND K_i HELD CONSTANT).....	31
FIGURE (4. 7) : SCHEMATIC REPRESENTATION OF PARTICLE MOTION IN PSO.....	33
FIGURE (4. 8) : FLOWCHART OF CUCKOO SEARCH.....	40
FIGURE (5. 1): VARIATION OF IRRADIANCE AND TEMPERATURE (CASE 1).....	42
FIGURE (5. 2) : VARIATION OF IRRADIANCE AND TEMPERATURE (CASE 2).....	42
FIGURE (5. 3) : POWER GENERATED BY FOUR MPPT TECHNIQUES (CASE 1).....	43
FIGURE (5. 4) : POWER GENERATED BY FOUR MPPT TECHNIQUES (CASE 2).....	43
FIGURE (5. 5) : DUTY CYCLE GENERATED BY FOUR MPPT TECHNIQUES.....	44
FIGURE (5. 6) : V_{DC} GENERATED BY FOUR MPPT TECHNIQUES (MAGNIFIED).....	44
FIGURE (5. 7) : VARIATION OF IRRADIANCE AND TEMPERATURE (CASE 3).....	46
FIGURE (5. 8) : POWER GENERATED (CASE STUDY 3).....	48
FIGURE (5. 9) : BLOCK DIAGRAM OF DC VOLTAGE REGULATED.....	48
FIGURE (5. 10) : VOLTAGE V_{DC} RESPONSE WITHOUT CONTROLLER.....	50
FIGURE (5. 11) : PI CONTROLLER V_{DC} RESPONSE BY EVOLUTIONARY TECHNIQUES.....	50
FIGURE (5. 12) : PI CONTROLLER V_{DC} RESPONSE BY EVOLUTIONARY TECHNIQUES (MAGNIFIED).....	51
FIGURE (5. 13) : PI CONTROLLER ERROR BY EVOLUTIONARY TECHNIQUES.....	51
FIGURE (5. 14) : PI CONTROLLER ERROR BY EVOLUTIONARY TECHNIQUES (MAGNIFIED).....	52
FIGURE (5. 15) : PI CONTROLLER POWER RESPONSE BY EVOLUTIONARY TECHNIQUES.....	52
FIGURE (5. 16) : TOTAL HARMONIC DISTORTION OF VOLTAGE WITHOUT LC FILTER.....	54
FIGURE (5. 17) : TOTAL HARMONIC DISTORTION OF CURRENT AFTER CONNECTING LC FILTER.....	55
FIGURE (5. 18) : TOTAL HARMONIC DISTORTION OF VOLTAGE AFTER CONNECTING LC FILTER.....	56

Nomenclature

A	: An ideality factor (= 1.6)
AACPSO	: Adapted Accelerated Coefficient Particle Swarm Optimization
AC	: Alternating Current
ANFIS	: Adaptive Neuro-Fuzzy Inference System
ANN	: Artificial Neural Network
AWPSO	: Adapted Weighted Particles Swarm Optimization
CS	: Cuckoo Search
D	: Duty Cycle
DC	: Direct Current
E (k)	: Error Signal
E _{go}	: Band Gap for Silicon (= 1.1 eV)
I	: Current
IAE	: Integral of Absolute Error
IC	: Incremental–Conductance
IGBT	: Insulated-gate Bipolar Transistor
I _o	: PV Module Saturation Current
I _{ph}	: Light-generated Current in PV Module
I _{pv}	: Output current of a PV module (A)
I _{SCr}	: PV module short-circuit current at 25°C and 1000W/m ² (= 2.55A)
ISE	: Integral of Squared Error
ITAE	: Integral of Time Weighted Absolute Error
ITSE	: Integral of Time Weighted Squared Error
k	: Boltzman Constant (=1.3805 x 10 ⁻²³ J/K)
K _i	: Short-circuit Current Temperature Coefficient at I _{SCr} (=0.0017 A/°C)
MAACPSO	: Modified Adapted Accelerated Coefficient Particle Swarm Optimization
Ma	: Modulation Index
MHA	: Meta-heuristic Algorithms
MVS-IC	: Modified Variable Step Incremental Conductance
MPP	: Maximum Power Point

MPPT	: Maximum Power Point Tracking
N_p	: Number of Cells connected in parallel
N_s	: Number of Cells connected in series
O	: Overshoot
P	: Power
P&O	: Perturb and Observe
PE	: Power Electronic
PI	: Proportional-integral
$P_{pv}(k)$: Instantaneous Output Power
PSO	: Particle Swarm Optimization
PV	: PhotoVoltaic
PWM	: Pulse Width Modulation
q	: Electron Charge ($=1.6 \times 10^{-19}$ Coulomb)
R_s	: Series Resistance of PV Module
RT	: Rise Time
SPVS	: Stand-alone Photovoltaic System
SSE	: Steady State Error
ST	: Settling Time
STC	: Standard Test Condition
T	: Module Operating Temperature (in degree Kelvin)
Temp	: Temperature
T_r	: Reference Temperature ($= 298^\circ K$)
V	: Voltage
V_{pv}	: Output Voltage of PV module
$V_{pv}(k)$: Instantaneous Output Voltage
VS-IC	: Variable Step-Size Incremental Conductance
λ	: PV Module Irradiation

Abstract

Photovoltaic energy systems have grown over the past period as one of the most favorable renewable energy sources due to the probable high costs, and negative environmental effects of conventional energy sources, whereas Photovoltaic remains a pollution-free and everlasting energy source. PV has been extensively used in numerous applications in remote and isolated regions all around the world.

Photovoltaic arrays should be arranged in such a way that their exposure to the sun is maximized, and their performance needs to be addressed and approached from several engineering perspective so as to ensure optimum conditions are reached. Accordingly, this thesis discusses the modeling of a standard 33 kW power of photovoltaic connected to grid.

This thesis addresses the concept of Maximum Power Point Tracking (MPPT), which rises the efficiency of the solar photovoltaic System. In order to acquire maximum power from the solar panels, they have to function at their maximum power point (MPP) regardless any variations in the environment conditions. The purpose of MPPT is to guarantee that the system can always exploit the maximum power generated by the Photovoltaic (PV) arrays. Solar panels have a non-linear voltage-current characteristic, which counts on the environmental factors, such as temperature and insolation.

This Thesis analyses the conventional MPPT techniques “Perturb and Observe” (P&O), “Incremental Conductance” (IC), discusses the Variable Step-size Incremental Conductance (VS-IC) and proposes an improved maximum power point tracking for solar photovoltaic system using “Modified Variable Step Incremental Conductance”(MVS-IC) algorithm. Results of the modified, conventional algorithms are duly presented and compared.

This Thesis also presents voltage regulation of Photovoltaic Generation (PVG) system connected to 3-phase grid for any situation of solar radiation using PI controller. The “Integral Square of Error” (ISE) performance index is one of four performance indices to be investigated for the objective function. Using the best MPPT technique, a comparison between the “Proportional Integral Derivative” (PID) controller and the “Proportional Integral controller” (PI) is performed by checking the ISE with aim to minimize errors. This is done by means of the evolutionary computational techniques: Particle Swarm Optimization (PSO), Adapted Weighted Particle Swarm Optimization (AWPSO), Adapted Accelerated Coefficient Particle Swarm Optimization (AACPSO), Modified Adapted Accelerated Coefficient PSO (MAACPSO), in addition to Cuckoo Search (CS). All such techniques are based upon PI gains so as to minimize the objective function, and hence reaching optimal solution that ensures minimum Overshoot (O), Rise Time (RT), Steady-State Error (SSE) and Settling Time (ST).

Moreover, the Total Harmonic Distortion “THD” at the output of the inverter shall be computed.

All studied techniques were implemented in Matlab/Simulink and resulted in satisfactory output consistent with the objective and conclusions of this Thesis.

Chapter One: Introduction and Solar Energy

1.1 Introduction

Photovoltaic power into utility grids is acquiring more and more credibility seeing the rather problematic situation of the traditional world power sources (oil and natural gas for instance) owing to its unconditional availability and environmental friendliness. Nonetheless, yet the efficiency and control still represent significant disadvantages for the photovoltaic systems, especially when combined with the strict requirements often imposed by the utility grid operators in terms of the control philosophy and controller types so as to ensure power stability as much as possible. Consequently, research efforts are nowadays being focused onto the enhancement of the PV systems control and efficiency.

1.2 Advantages and Disadvantages of Photovoltaic Systems

Table (1.1) presents the advantages and disadvantages of PV systems, as discussed in [1].

Table (1.1): Advantages and Disadvantage of PV Systems

Advantages of PV Systems	Disadvantages of PV Systems
<ul style="list-style-type: none">▪ PV systems require no costly fuel and convert freely available daylight into electricity.▪ PV systems produce “quiet” electricity without emitting exhaust gases or pollutants.▪ PV systems require small amount of maintenance.▪ Solar modules have no moving parts and last for more than 20 years.▪ Cost saving and earnings when connected the grid.	<ul style="list-style-type: none">▪ Sun is not present all day long.▪ PV systems higher initial costs.▪ Most off-grid PV systems require batteries to store electric power.

1.3 Problem Diagnosis

The non-linearity of the PV systems and output dependency on the terminal voltage and prevailing environmental conditions impose more complications and challenges on the widespread use of PV systems.

The main challenges are the PV efficiency, intensity of source radiation and storage techniques, knowing that the PV cells efficiency is still bound by the industry materials used in their manufacture.

Besides the obvious problematic variation of the Sun irradiance and temperature during the day (which results in fluctuating output voltage), the low efficiency and high cost of solar cells represent another considerable hurdle, even though the efficiency of the PV systems has increased significantly in the last decade owing to innovative “maximum power point tracking” (MPPT) approaches.

Another problematic characteristic of the PV systems is the DC/AC conversion, which often requires some sophisticated filters to reduce the induced ripples almost always associated with such systems.