Dedication

This thesis is dedicated

To

My parents

My Wife
ACKNOWLEDGMENTS

First of all we thank our GOD for establishment this work. I would like to express my sincere appreciation to my supervisor:

Prof. Dr. H. H. El-Tamaly

Vice-Dean for Postgraduate Studies and Researches, Faculty of Engineering, El-Minia University, for providing me an opportunity to work with him and for his guidance, encouragement, continual guidance and simulate discussion on all aspects concerning this thesis.

I would like to give my heartfelt appreciation to my parents, who brought me up with their love and encouragement me to pursue advanced degrees.

Also, I would like to give my heartfelt appreciation to my wife, who has accompanied me with her love, unlimited patience, understanding, helping and encouragement. Without her support, I would never be able to accomplish this work. So, I want to dedicate this thesis to my wife.

Finally, I’d like to thank the staff of the Electrical Engineering Department, Faculty of Engineering, El-Minia University.

Author

Adel Abd Elbaset Mohammed
Abstract

The overall objective of photovoltaic and wind energy system is to obtain electricity from the sun and wind that are cost competitive and even advantageous with respect to other energy sources. Design of photovoltaic Wind Energy System Hybrid Electric Power System (PV/WES HEPS) has many issues if we take all economical and technical parameters into account. This thesis presents a complete design and simulation of a PV/WES HEPS to be interconnected with utility grid, UG.

The proposed design of PV/WES HEPS is based on energy balance, minimum price of generated kilo watt hour (kWh), maximum power point tracking for PV and WES by using an artificial intelligence technique. In this thesis, novel computer programs are proposed to design a Photovoltaic system, wind energy system and PV/WES HEPS.

These novel computer programs determine hourly system parameters such as optimum solar cells area, optimum number of inverter unit, total number of modules /subsystem, total number of parallel panel /string, total number of series module/panel , total number of modules, total number of WTGs, price of kWh (ECF) produced form PV system and WES and reliability of the system. This thesis presents also a possible circuit topology and controller design for a grid-connected DC-AC power converter. In this thesis we present a study, describe a control strategy for interconnection of hybrid system with electric utility accompanied with or without battery storage using artificial intelligence techniques and also a fuzzy logic technique to calculate and assess the reliability index for each HEPS configuration under study.

The computer programs can be applied to any site of the world. The development proposed package has been applied to Zafarâna site, Egypt as a case study. The thesis contains eight chapters which are summarized as follows:
Chapter 1 presents the role and important need of renewable energies for todays and future, especially PV and wind energies. It presents also an introduction for renewable energies and previous work in the filed of the thesis.

Chapter 2 introduces a proposed computer program for optimal design of a PV system to be interconnected with UG at M.P.P using neural network. It presents also methodologies for calculating the hourly solar radiation on tilted surfaces and design of each component of PV system.

Chapter 3 presents an application of an artificial neural network on the strategy of the operation control of the PV/UG to improve system efficiency and reliability. It introduces also a complete computer simulation program of PV system interconnected with UG.

Chapter 4 introduces a proposed computer program for optimal design of a WES to be interconnected with UG at M. P. P using neural network. It presents also a complete methodology to obtain an optimum design of WES interconnected with UG to supply a load at any site in the world.

Chapter 5 introduces an application of an artificial neural network on the operation control of the WES/UG to improve system efficiency and reliability. It presents also a computer modeling, simulation, analysis of a variable speed WTG interconnected with UG. The computer simulation program is confirmed on a realistic circuit model which implemented in the Simulink environment of Matlab and works as if on line.

Chapter 6 introduces a proposed computer program for optimal design of a PV system, WES and PV/WES HEPS to be interconnected with UG to feed a load demand at any site in the world. It presents an application of an artificial neural network (ANN) on the operation control and interconnection of the PV/WES interconnected with UG. Also it introduces a computer modeling, simulation, analysis of a HEPS interconnected with UG.
Chapter 7 presents a complete study, from reliability point of view, to determine the impact of interconnecting PV, WES and PV/WES HEPS into UG. It also presents a Fuzzy logic technique to calculate and assess the reliability index for each HEPS configuration under study.

Chapter 8 presents the conclusions and suggestions for future work.
TABLE OF CONTENTS

ACKNOWLEDGMENTS I
ABSTRACT III
TABLE OF CONTENTS VI
LIST OF FIGURES XI
LIST OF TABLES XVIII
LIST OF SYMBOLS XX
LIST OF ABBREVIATIONS XXIII

Chapter 1
INTRODUCTION AND PREVIOUS WORK

1-1 INTRODUCTION 1
  1-1-1 Biomass Energy 2
  1-1-2 Geothermal Energy 3
  1-1-3 Hydropower 3
  1-1-4 Ocean Energy 4
  1-1-5 Fuel Cell 5
  1-1-6 Photovoltaic 7
  1-1-7 Wind Energy 9
1-2 REVIEW OF RELATED RESEARCHES 12
  1-2-1 PV Design, Interconnection and Simulation 13
  1-2-2 WES Design, Interconnection and Simulation 17
  1-2-3 Hybrid PV/WES Design, Interconnection and Simulation 20
1-3 OUTLINE OF THE THESIS 23
1-4 THESIS OBJECTIVES 28

Chapter 2
DESIGN OF PV SYSTEM CONNECTED WITH UG

2-1 INTRODUCTION 30
2-2 METHODOLOGY 31
  2-2-1 Estimation of Hourly Radiation on the Tilted Surfaces 31
3-6 CONCLUSIONS

Chapter 4

DESIGN OF WES CONNECTED WITH UG

4-1 INTRODUCTION

4-2 DESIGN METHODOLOGY OF WES AT MPPs

4-2-1 Modification of Average Wind Speed to Hub Height

4-2-2 Estimation of Weibull Parameters, C and K

4-2-3 Calculation of Capacity Factor, CF and ANWTG

4-2-4 Output power form WTG at MPPs

4-2-5 Design Issue of the NN for MPPs

4-3 CALCULATION OF OPTIMUM NUMBER OF WTG's

4-4 METHODOLOGY OF ECF [62], [114]

4-5 APPLICATIONS AND RESULTS

4-5-1 Design of WES

4-5-2 Design of NN for Optimum Operating Speed of WTG

4-6 CONCLUSIONS

Chapter 5

OPERATION CONTROL STRATEGY AND SIMULATION OF WTG CONNECTED WITH UG

5-1 INTRODUCTION

5-2 METHODOLOGY OF CONTROL STRATEGY

5-2-1 Control Strategy Issue of WES Connected with UG without BS

5-2-2 Control Strategy Issue for WES/BS Connected to UG.

5-3 METHODOLOGY OF WES OPERATION ISSUE WITH UG

5-3-1 Modeling of WTG Interconnected With UG

5-3-2 The Proposed Control System

5-4 APPLICATIONS AND RESULTS

5-4-1 Operation Control of WES CONNECTED TO UG

5-4-2 Operation Control of WES/BS Interconnected with UG
5-5 CONCLUSIONS

Chapter 6

DESIGN AND CONTROL STRATEGY OF PV/WES HEPS CONNECTED WITH UG

6-1 INTRODUCTION
6-2 DESIGN METHODOLOGY OF PV/WES HEPS at MPP's.
   6-2-1 Modeling PV Module
   6-2-2 Modeling of WTG
   6-2-3 PV/Wind Energy System Sizing
6-3 METHODOLOGY OF CONTROL STRATEGY ISSUE OF PV/WES
6-4 Applications and Results of PV/WES HEPS
   6-4-1 Design Issue of PV/WES HEPS Interconnected with UG
   6-4-2 Operation control strategy Issue of PV/WES Interconnected With UG
   6-4-3 Simulation Results for PV/WTG HEPS Interconnected with UG
6-5 CONCLUSIONS

Chapter 7

IMPACT OF CONNECTING ISSUE PV/WES WITH UG ON THEIR RELIABILITY USING A FUZZY SCHEME

7-1 INTRODUCTION
7-2 METHODOLOGY
   7-2-1 Probabilistic Modeling and Reliability Index
   7-2-2 FL Application on Reliability Study of Renewable Energy
7-3 APPLICATIONS AND RESULTS OF PROBABILISTIC MODELING
   7-3-1 Capacity Outage Table for the Configuration of UG Only.
   7-3-2 Capacity Outage Table for the Configuration of PV/UG HEPS.
Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

8-1 DISCUSSIONS AND CONCLUSIONS 213
8-2 RECOMMENDATIONS FOR FUTURE WORK 219

References 222
List of Publications 233
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 1-1</td>
<td>A scheme of a Fuel Cell [8].</td>
<td>6</td>
</tr>
<tr>
<td>Fig. 1-2</td>
<td>PV Array Connected with UG without Battery Storage</td>
<td>8</td>
</tr>
<tr>
<td>Fig. 1-3</td>
<td>PV Array Connected with UG Accompanied with Battery Storage.</td>
<td>9</td>
</tr>
<tr>
<td>Fig. 1-4</td>
<td>WTG Connected to UG</td>
<td>12</td>
</tr>
<tr>
<td>Fig. 2-1</td>
<td>Equivalent Circuit of PV Solar Cells Module.</td>
<td>34</td>
</tr>
<tr>
<td>Fig. 2-2</td>
<td>Circuit Schematic of Step-up DC/DC Converter [85]</td>
<td>38</td>
</tr>
<tr>
<td>Fig. 2-3</td>
<td>Equivalent Circuit for Boost Converter in CCM [85]</td>
<td>39</td>
</tr>
<tr>
<td>Fig. 2-4</td>
<td>Equivalent Circuit for Boost Converter in DCM</td>
<td>41</td>
</tr>
<tr>
<td>Fig. 2-5</td>
<td>Multi Layer Network [89].</td>
<td>45</td>
</tr>
<tr>
<td>Fig. 2-6</td>
<td>The Block Diagram for Tracking MPPs.</td>
<td>46</td>
</tr>
<tr>
<td>Fig. 2-7</td>
<td>Flowchart of the Proposed Computer Program.</td>
<td>49</td>
</tr>
<tr>
<td>Fig. 2-8</td>
<td>The Radiation on Horizontal Surfaces of Zafarâna Site</td>
<td>50</td>
</tr>
<tr>
<td>Fig. 2-9</td>
<td>Daily Load Curve for January, April, July and October.</td>
<td>51</td>
</tr>
<tr>
<td>Fig. 2-10</td>
<td>ECF for each Selected Module Type for the year 2005.</td>
<td>53</td>
</tr>
<tr>
<td>Fig. 2-11</td>
<td>The Total Surplus and Deficit Power for each Month.</td>
<td>55</td>
</tr>
<tr>
<td>Fig. 2-12</td>
<td>The Total Energy Generated and Energy Demand for each Month.</td>
<td>55</td>
</tr>
<tr>
<td>Fig. 2-13</td>
<td>Relation between Output Current and Duty Cycle at the Boundary of CCM-DCM</td>
<td>58</td>
</tr>
<tr>
<td>Fig. 2-14</td>
<td>Relation between Output Current and Input Voltage at the Boundary of CCM-DCM</td>
<td>58</td>
</tr>
<tr>
<td>Fig. 2-15</td>
<td>Relation between Critical Inductance and Duty Cycle for Variations of Switching Frequency.</td>
<td>59</td>
</tr>
<tr>
<td>Fig. 2-16</td>
<td>Relation between Capacitance and Duty Cycle for Variations of Switching Frequency.</td>
<td>60</td>
</tr>
<tr>
<td>Fig. 2-17</td>
<td>Proposed NN for MPPT</td>
<td>61</td>
</tr>
<tr>
<td>Fig. 2-18</td>
<td>The Training process (Error versus Epochs) with Configuration 3+10+2 NN</td>
<td>62</td>
</tr>
<tr>
<td>Fig. 2-19</td>
<td>Results of Testing a Trained 3+10+2 FFNN for Voptimum</td>
<td>63</td>
</tr>
</tbody>
</table>
Fig. 2-20 Results of Testing a Trained 3+10+2 FFNN for $P_{\text{optimum}}$  64
Fig. 3-1 PV/Load/UG System Block Diagram.  67
Fig. 3-2 Single-Line Diagram for the Control Strategy of the PV/UG System  68
Fig. 3-3 Single-line Diagram for the control strategy of the PV/UG/BS System  71
Fig. 3-4 Modeling Diagram of one Subsystem.  74
Fig. 3-5 Circuit Diagram of the Three-Phase Voltage Source Inverter  76
Fig. 3-6 Generation of Switching Pulses by Hysteresis Band Control  77
Fig. 3-7 Modeling of LC Filter  77
Fig. 3-8 Block Diagram of Three-phase AC Voltage Source  78
Fig. 3-9 Schematic Diagram of the PV System Connected with UG.  79
Fig. 3-10 Active and Reactive Power Regulation  82
Fig. 3-11 Structure of the Proposed Three Layers NN used for Control Strategy of PV/UG.  83
Fig. 3-12 Relation Between Error and Epoch 3+6+3 NN  84
Fig. 3-13 Optimal Operation of the PV/UG to Feed the Load Demand during January (winter)  85
Fig. 3-14 Optimal Operation of the PV/ UG to Feed the Load Demand during July (summer).  85
Fig. 3-15 Relation Between Outputs and Target for Five Months  86
Fig. 3-16 Outputs of Neural Network for Month of January.  87
Fig. 3-17 Outputs of Neural Network for Month of July.  87
Fig. 3-18 Flowchart of the Proposed Computer Program for PV/UG Accompanied with BS.  89
Fig. 3-19 Structure of the Proposed Three Layers NN used for Control Strategy of PV/UG Accompanied with BS.  90
Fig. 3-20 Relation Between Error and Epoch For 5+9+4 ANN  91
Fig. 3-21 Optimal Operation of the PV/BS with UG to Feed the Load Demand during January (winter)  92
Fig. 3-22 Optimal Operation of the PV/BS with UG to Feed the
Load Demand during July (summer).

Fig. 3-23 State of Charge of PV/BS with UG during January (winter) and July (summer)

Fig. 3-24 Relation Between Outputs and Target for Five Months

Fig. 3-25 Outputs of Neural Network for January

Fig. 3-26 Outputs of Neural Network for July

Fig. 3-27 Simulated of Generated Power from PV, Load Demand and UG Power from/to UG.

Fig. 3-28 Simulated Phase Voltage of the Inverter Leg

Fig. 3-29 Simulated Phase-to-Phase Voltage of the Inverter Leg, $V_{ab}$

Fig. 3-30a Simulated Switch Current in IGBT's

Fig. 3-30b Simulated Switch Current in IGBT's

Fig. 3-30c Simulated Switch Current in IGBT's

Fig. 3-31 Simulated of Inverter Current Injected to the Load/UG.

Fig. 3-32 Simulated of Load Current.

Fig. 3-33 Simulated Current From/to UG.

Fig. 3-34 Simulated Power Factor of the Grid.

Fig. 3-35 Simulated Load Current $i_a(t)$ and $i_\beta(t)$.

Fig. 3-36 Simulated Load Voltage $v_a(t)$ and $v_\beta(t)$.

Fig. 3-37 Simulated of the Inverter Power Factor.

Fig. 4-1 Coefficient of Performance Versus tip speed ratio

Fig. 4-2 Shaft Power Output Versus Generator Speed

Fig. 4-3 Flowchart of the Proposed Computer Program.

Fig. 4-4 Wind Speed during January, April, July and October for Zafarâna site, Egypt.

Fig. 4-5 The Capacity Factor of the Selected WTG's for Zafarâna site, Egypt.

Fig. 4-6 Energy Cost Figure of the Selected WTG's for Zafarâna site, Egypt.

Fig. 4-7 The Total Power Surplus and Deficit Power for each Month for T600-48 Wind Turbine Type for Zafarâna site, Egypt.
Fig. 4-8 The Total Energy Generated and Energy Demand for each Month for T600-48 Wind Turbine Type. 123
Fig. 4-9 Variations of Wind Speed and Rotor Speed with time 125
Fig. 4-10 Relation between Error and Epoch for the NN 2+10+1 126
Fig. 4-11 Proposed NN for Optimum Operating Speed. 126
Fig. 4-12 The Performance of 2+10+1 NN for Period Five Months 127
Fig. 5-1 Single-Line Diagram for the Control Strategy of WTG/UG System 131
Fig. 5-2 Single-line Diagram for the control strategy of WES/UG/BS system 134
Fig. 5-3 WTG Equipped with Back-to-Back Converter 136
Fig. 5-4a. Per Phase Equivalent Circuit 137
Fig. 5-4b The per Phase Equivalent Circuit and Phasor Diagram 138
Fig. 5-5 Circuit Diagram of the Three-Phase Voltage Source Inverter. 139
Fig. 5-6 Schematic Diagram of the WTG Connected to the UG 141
Fig. 5-7 Structure of the proposed three layers NN used to Interconnect WES with UG. 142
Fig. 5-8 Relation between Error and Epoch 4+5+3 NN 142
Fig. 5-9 Optimal Operation of the WES/UG to Feed the Load Demand during January (winter) 144
Fig. 5-10 Optimal Operation of the WES/UG to feed the Load Demand during July (summer). 144
Fig. 5-11 Relation between outputs and target for five months 145
Fig. 5-12 Outputs of Neural Network for Month of January. 146
Fig. 5-13 Outputs of Neural Network for month of July. 146
Fig. 5-14 Flowchart of the Proposed Computer Program For WES/UG accompanied with BS. 148
Fig. 5-15 Structure of the proposed three layers NN used to Interconnect WES/BS HEPS with UG. 149
Fig. 5-16 Relation between error and Epoch for 4+7+4 ANN 149
Fig. 5-17 Optimal Operation of the WES/UG Accompanied with BS
Fig. 5-18 Optimal Operation of the WES/UG Accompanied with BS to feed the Load Demand during January (winter)  151
Fig. 5-19 State of charge of WES/BS HEPS with UG during January (winter) and July (summer)  152
Fig. 5-20 Relation between outputs and target for five months  153
Fig. 5-21 Outputs of Neural Network for January  154
Fig. 5-22 Outputs of Neural Network for July  154
Fig. 5-23 Overview of the Power Circuit and Control System of the Three-Phase DC/AC Converter  155
Fig. 5-24 Simulated of the Generated Power from WTG, Load Demand and Grid Power.  156
Fig. 5-25 Waveform of the Switch Current in IGBT's  157
Fig. 5-26 Waveform of the Inverter Line current to the Load/Grid  158
Fig. 5-27 waveform of the Load Line Current  158
Fig. 5-28 Waveform of the Grid Line Current  159
Fig. 5-29 Waveform of the Power Factor of the Grid  159
Fig. 5-30 Waveform of the Power Factor of the Inverter  160
Fig. 6-1 Single-Line Diagram for the Control Strategy of the PV/WTG/UG System  164
Fig 6-2 Flowchart of the Proposed Computer Program.  168
Fig. 6-3 The Total Surplus and Deficit Power for each Month for PV/WES HEPS for penetration ratio =0.3  171
Fig. 6-4 The Total Energy Generated and Energy Demand for each Month for PV/WES for penetration ration =0.3  172
Fig. 6-5 Structure of the Proposed Three-layer NN used to Interconnect PV/WES/UG.  173
Fig. 6-6 Relation Between Error and Epoch 4+10+5 NN  173
Fig. 6-7 Optimal Operation of the PV/WES/UG to Feed the Load
Demand during March 175
Fig. 6-8 Optimal Operation of the PV/WES/UG to feed the
Load Demand during December 175
Fig. 6-9 Relation between outputs and target for five months 176
Fig. 6-10 Outputs of Neural Network for month of March 177
Fig. 6-11 Outputs of Neural Network for month of December 178
Fig. 6-12 Modeling of PV/WTG HEPS Interconnected with UG 180
Fig. 6-13 Overview of the Power Circuit and Control System of
the Hybrid PV/WTG system Interconnected with UG 181
Fig. 6-14 Simulated of the Generated Power from PV/WTG,
Load Demand and Grid Power. 182
Fig. 6-15 Simulated of the Inverter Line current from WTG
to the Load/Grid. 183
Fig. 6-16 Simulated of the Inverter Line current from PV to the
Load/Grid. 184
Fig. 6-17 Simulated of the Load Line Current. 184
Fig. 6-18 Simulated of the Grid Line Current. 185
Fig. 6-19 Simulated of the Power Factor of the Grid for the
Hybrid PV/WTG System 185
Fig. 6-20 Simulated of the Power Factor of the WTG Inverter 186
Fig. 6-21 Simulated of the Power Factor of the PV Inverter 186
Fig. 7-1 Elements of generation reliability evaluation [118] 189
Fig. 7-2 FIS under study a general structure 193
Fig. 7-3 Flowchart of the proposed computer program 194
Fig. 7-4 Total hourly LOLP values for all Months during the Year. 197
Fig. 7-5 Monthly Effective force outage rate values during the Year 198
Fig. 7-6 Total yearly LOLP value for each Penetration Ratio 200
Fig. 7-7 Membership Function for Input 1 (Hourly Load) 201
Fig. 7-8 Membership Function for Input 2 (Hourly PV power) 202
Fig. 7-9 Output of LOLP value using ANFIS for the configuration PV/UG HEPS. 203

Fig. 7-10 The difference between ANFIS and Probabilistic Model for the Configuration PV/UG HEPS 204

Fig. 7-11 Output of LOLP value using ANFIS for the Configuration WES/UG HEPS. 207

Fig. 7-12 The Difference between ANFIS and Probabilistic Model for the Configuration WES/UG HEPS. 207

Fig. 7-13 Output of LOLP Value Using FL. 210

Fig. 7-14 The Difference Between FL and Probabilistic Model. 210
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table (2-1)</th>
<th>Monthly Average of Maximum and Minimum Temperature of Zafarâna Site, C°</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table (2-2)</td>
<td>The Characteristics of the Different PV Solar Cells Module</td>
<td>50</td>
</tr>
<tr>
<td>Table (2-3)</td>
<td>The Construction of the Designed PV system Under Using Different Selected Types of Solar Cells Module</td>
<td>52</td>
</tr>
<tr>
<td>Table (2-4)</td>
<td>The Price of Each Components of PV system [95-100]</td>
<td>52</td>
</tr>
<tr>
<td>Table (2-5)</td>
<td>ECF for each Selected Module Type</td>
<td>53</td>
</tr>
<tr>
<td>Table (2-6)</td>
<td>Surplus and Deficit Power from PV System</td>
<td>54</td>
</tr>
<tr>
<td>Table (2-7)</td>
<td>The Total Energy Generated and Energy Demand for each Month</td>
<td>56</td>
</tr>
<tr>
<td>Table (2-8)</td>
<td>Parameter Values for DC/DC boost converter</td>
<td>60</td>
</tr>
<tr>
<td>Table (2-9a)</td>
<td>Weights W1 and Biases for 3+10+2 NN for MPPs for PV</td>
<td>63</td>
</tr>
<tr>
<td>Table (2-9b)</td>
<td>Weights W2 and Biases for 3+10+2 NN for MPPs for PV</td>
<td>63</td>
</tr>
<tr>
<td>Table (3-1)</td>
<td>Operational modes of PV System Interconnected with UG</td>
<td>70</td>
</tr>
<tr>
<td>Table (3-2)</td>
<td>Operational Modes of PV System Connected to UG Accompanied with BS</td>
<td>74</td>
</tr>
<tr>
<td>Table (3-3a)</td>
<td>Weights W1 and Biases for 3+6+3 NN for PV Interconnected with UG</td>
<td>84</td>
</tr>
<tr>
<td>Table (3-3b)</td>
<td>Weights W(2) and Biases for 3+6+3 NN for PV Interconnected with UG</td>
<td>84</td>
</tr>
<tr>
<td>Table (3-4a)</td>
<td>Weights W(1) and Biases for 5+9+4 NN for PV Interconnected with UG Accompanied with BS</td>
<td>91</td>
</tr>
<tr>
<td>Table (3-4b)</td>
<td>Weights W(2) and Biases for 5+9+4 NN for PV Interconnected with UG Accompanied with BS</td>
<td>91</td>
</tr>
<tr>
<td>Table (3-5)</td>
<td>System Parameters</td>
<td>97</td>
</tr>
<tr>
<td>Table (4-1)</td>
<td>Characteristics of the selected WTG's</td>
<td>118</td>
</tr>
<tr>
<td>Table (4-2)</td>
<td>The Price of Each Component of WTG's [72]</td>
<td>119</td>
</tr>
<tr>
<td>Table (4-3)</td>
<td>Parameter of Selected WTG's</td>
<td>120</td>
</tr>
<tr>
<td>Table (4-4)</td>
<td>Surplus Power and Deficit Power for WES</td>
<td>122</td>
</tr>
</tbody>
</table>
Table (4-5) The Total Energy Generated from WTG's and Energy Demand for Each Month for T600-48 Wind Turbine Type. 124
Table (4-6a) Weights W1 and Biases for 2+10+1 NN for MPPs of WTG 127
Table (4-6b) Weights W2 and Biases for 2+10+1 NN for MPPs of WTG 129
Table (5-1) Operational modes of WES interconnected with UG 132
Table (5-2) Operational Modes of WES Connected to UG Accompanied With BS 134
Table (5-3a) Weights W1 and Biases for 3+5+3 NN for WES interconnected with UG 143
Table (5-3b) Weights W2 and Biases for 3+5+3 NN for WES interconnected with UG 143
Table (5-4a) Weights W1 and Biases for 5+7+4 NN for WES interconnected with UG accompanied with BS 150
Table (5-4b) Weights W2 and Biases for 5+7+4 NN for WES interconnected with UG accompanied with BS 150
Table (6-1) Operational modes of PV/WES HEPS 166
Table (6-2) The Impact of Penetration Level on the Optimum Design of PV/WES HEPS 169
Table (6-3) Surplus Power and Deficit Power 170
Table (6-4) The Total Energy Generated from PV/WES and Energy Demand for Each Month for penetration ratio =0.3 171
Table (6-5a) Weights and Biases for 4+10+5 NN for PV/WES Interconnected with UG 174
Table (6-5b) Weights W2 and Biases for 4+10+5 NN for PV/WES Interconnected with UG 174
Table (7-1) Twenty Units System Capacity Outage Table 196
### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi$</td>
<td>The site latitude for the location, degrees.</td>
</tr>
<tr>
<td>$\delta$</td>
<td>The declination angle, degrees.</td>
</tr>
<tr>
<td>$\bar{R}$</td>
<td>The ratio between the radiation on the tilted surfaces to the radiation on the horizontal surfaces.</td>
</tr>
<tr>
<td>$\rho_g$</td>
<td>The ground reflectance.</td>
</tr>
<tr>
<td>$\bar{H}_d$</td>
<td>The monthly average daily diffuse radiation.</td>
</tr>
<tr>
<td>$\eta_{in}$</td>
<td>The inverter efficiency.</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>The penetration ratio</td>
</tr>
<tr>
<td>$\rho$</td>
<td>The air density, kg/m$^3$.</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>The percentage of ripple current to load output current.</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Forced Outage Rate.</td>
</tr>
<tr>
<td>$\omega_r$</td>
<td>The mechanical angular velocity of the turbine, radians/sec.</td>
</tr>
<tr>
<td>$\bar{H}_r(t)$</td>
<td>The average hourly radiation on the tilted surface, kW/m$^2$.</td>
</tr>
<tr>
<td>$A$</td>
<td>The ideality factor for p-n junction.</td>
</tr>
<tr>
<td>$A_w$</td>
<td>The swept area of the turbine, m$^2$.</td>
</tr>
<tr>
<td>$C$</td>
<td>The scale parameter, m/s.</td>
</tr>
<tr>
<td>CF</td>
<td>The capacity factor.</td>
</tr>
<tr>
<td>$C_p$</td>
<td>The coefficient of performance.</td>
</tr>
<tr>
<td>$D$</td>
<td>The duty cycle.</td>
</tr>
<tr>
<td>$E_{go}$</td>
<td>The band-gap energy of the semiconductor used in solar cells module.</td>
</tr>
<tr>
<td>$F(u)$</td>
<td>The cumulative distribution function.</td>
</tr>
<tr>
<td>$F_s$</td>
<td>The switching frequency, Hz</td>
</tr>
<tr>
<td>$H$</td>
<td>The height from ground, m.</td>
</tr>
<tr>
<td>$I(t)$</td>
<td>The hourly output current, Amp.</td>
</tr>
<tr>
<td>$I_{fa}$, $I_{fb}$, $I_{fc}$</td>
<td>inverter filter output currents</td>
</tr>
</tbody>
</table>
Ia, Ib, Ic       load phase currents
Io(t)  The hourly reverse saturation current, Amp.
IoR       The saturation current at Tr, Amp.
Iph(t)  The hourly generated current of solar cells module.
IPV       solar cells array current
Is
c       PV cell short-circuit current at 25°C and 100 mW/cm².
K       The shape parameter.
KB       The Boltzmann's constant in Joules per Kelvin, 1.38*10⁻²³ J/k.
K1       The short circuit current temperature coefficient.
MC       The cost of module, $/Wp.
Ninv      The total number of inverter.
Nw       The life period of WTG.
ONpv      Optimum number of PV system.
ONw       The optimum number of WTG's.
Pbat(t)    The output/input power from/to BS, kW.
PC       The price of inverter, $/kW.
Pg(t)      The power to/from UG, kW.
Pin,max    The maximum output power from PV array which it is the input to boost converter.
Pinv      The rated power of inverter.
P(t)       The Load demand, kW.
PM      The nominal power of module, W.
Ppv(t)      The power from PV system, kW.
Ppv,out(t)      The hourly generated power from PV module, kW.
PTL      The price of transmission, $/kW.
PWES(t)      The power from WES system, kW.
PWTG,out(t)      The hourly generated power from one WTG (see chapter 4).
Q       The charge of the electron in Coulombs, 1.6*10⁻¹⁹C.
R  The equivalent load, Ω.

r  The interest rate.

r_m  The radius of swept area, m.

S  The tilt angle of solar cell modules, degrees.

S_{in}  The inverter rating power, kVA.

t  The hourly time over one year.

T(t)  The hourly temperature, Kelvin.

T_r  The reference temperature, °K.

u  The wind speed, m/s.

U_c  The cut-in speed, m/s.

U_f  The cut-off speed, m/s.

U_h  The wind speed at height H-m, m/s.

U_{ho}  The wind speed at height H_0-m, m/s, (H_0 is usually 10-m)

U_r  The rated wind speed, m/s.

V(t)  The hourly output voltage, Volt.

V_a, V_b, V_c  UG phase voltages

V_{dc}  DC link voltage

V_{in}  The inverter rating voltage, V.

V_{PV}  solar cells array voltage

W_{1_q}^{(1)}  The weights of the hidden layer.

W_{1_q}^{(2)}  The weights of the output layer.

Z_q  The output from hidden layer.
### LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANFIS</td>
<td>Adaptive-network-based fuzzy inference system,</td>
</tr>
<tr>
<td>CCM</td>
<td>continues conduction mode</td>
</tr>
<tr>
<td>DC</td>
<td>direct current</td>
</tr>
<tr>
<td>DCM</td>
<td>discontinuous conduction mode</td>
</tr>
<tr>
<td>ECF</td>
<td>energy cost figure</td>
</tr>
<tr>
<td>EFORpv</td>
<td>Effective Forced Outage Rate for photovoltaic system,</td>
</tr>
<tr>
<td>EFORpvw</td>
<td>Effective Forced Outage Rate for photovoltaic/wind system.</td>
</tr>
<tr>
<td>EFORw</td>
<td>Effective Forced Outage Rate for wind system,</td>
</tr>
<tr>
<td>ESR</td>
<td>equivalent series resistance</td>
</tr>
<tr>
<td>EU</td>
<td>Electric Utility</td>
</tr>
<tr>
<td>FIS</td>
<td>Fuzzy Inference System,</td>
</tr>
<tr>
<td>FL</td>
<td>Fuzzy logic,</td>
</tr>
<tr>
<td>G. B.</td>
<td>gear box</td>
</tr>
<tr>
<td>HEPS</td>
<td>Hybrid Electric Power System</td>
</tr>
<tr>
<td>IG</td>
<td>Induction Generator</td>
</tr>
<tr>
<td>IRPT</td>
<td>Instantaneous Reactive Power Theory</td>
</tr>
<tr>
<td>kWh</td>
<td>kilo-watt hour</td>
</tr>
<tr>
<td>LOLP</td>
<td>Loss of Load Probability,</td>
</tr>
<tr>
<td>MPPT</td>
<td>maximum power point tracker</td>
</tr>
<tr>
<td>PCU</td>
<td>power conditioning unit</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PVPS</td>
<td>Photovoltaic Power system</td>
</tr>
<tr>
<td>THD&lt;sub&gt;i&lt;/sub&gt;</td>
<td>total harmonic distortion for current</td>
</tr>
<tr>
<td>UG</td>
<td>utility grid</td>
</tr>
<tr>
<td>VSI</td>
<td>voltage source inverter</td>
</tr>
<tr>
<td>WES</td>
<td>wind energy system</td>
</tr>
<tr>
<td>WTG</td>
<td>Wind Turbine Generator</td>
</tr>
</tbody>
</table>