

**NEURAL NETWORK MODEL FOR FORECASTING SOLAR
ENERGY GENERATION AND ANALYSIS OF POWER
OUTPUT CONTROLLING BY ENERGY STORAGE
SCHEMES**

Weerasekera W.B.M.U.T

(148367F)

Degree of Master of Engineering

Department of Mechanical Engineering

University of Moratuwa

Sri Lanka

May 2019

**NEURAL NETWORK MODEL FOR FORECASTING SOLAR
ENERGY GENERATION AND ANALYSIS OF POWER
OUTPUT CONTROLLING BY ENERGY STORAGE
SCHEMES**

Weerasekera W.B.M.U.T

(148367F)

Thesis submitted in partial fulfillment of the requirements for the degree
Master of Engineering

Department of Mechanical Engineering

University of Moratuwa
Sri Lanka

May 2019

Declaration

I declare that this is my own work and that this thesis doesn't include material from a previous submission of a third-party for a diploma or degree of any University or institute. This thesis does not contain previously published material from books, articles or research papers except where proper acknowledgement is made in the text.

Further, I hereby grant the University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or part in print, electronic or other medium while retaining the right to use this content for my future endeavors.

Signature:

Date:

W.B M U T Weerasekera

The above candidate has carried out research for the Masters Thesis under my supervision

Signature:

Date:

Prof. R.A Attalage

Abstract

Modeling of power fluctuations in a solar PV power plant using an Artificial Neural Network (ANN) was carried out in the study. The resulting model was used to evaluate the energy storage requirement to control fluctuations of the power output. The ANN was trained to model the output of a 300kW solar PV system installed in Colombo with an average hourly energy output of 90.55kWh and an average daily energy production of 1177 kWh. The ANN model proved to deliver forecasts with significant accuracy and generalizability. Correlation coefficients for training, validation and testing were 0.945 0.948 and 0.939 respectively. Further validation was done using an isolated data set of a time period of a month for which model was able to achieve a correlation coefficient of 0.93. Residual analysis confirmed the error was random and free of autocorrelation. Error terms had a normal distribution with mean 1.09kWh and standard deviation of 20.06kWh. A direct mapping was established between meteorological parameters and power output of a solar PV system, as oppose to estimating solar irradiance. Energy storage requirement was evaluated for two power output control schemes. First scheme specifies a ramp up, ramp down rate, and a continuous power delivery period. By means of an optimizing algorithm the combination of parameters corresponding to the least energy storage requirement was established and the result for energy requirement was approximately 15% of the average daily energy generation of the PV system. Variation of energy storage requirement under different operating conditions was analyzed further. The second output control scheme uses moving average smoothening to control power output. The calculated energy storage requirement for moving average scheme was approximately 8% of the average daily energy generation. The effect of imposing restriction on operating parameters of the schemes were examined in detail.

Acknowledgement

This research was carried out under the supervision of senior professor R.A Attalage, Department of Mechanical Engineering, University of Morata. I am very much grateful to Prof. R.A Attalage for providing me with the guidance, motivation and support throughout the research. I admire his kind hearted co-operation and encouragement extended at every stage of the study. I wish to thank Dr. Himan Punchihewa for the continuous engagement with the students to successfully complete the research. Finally, I would like to acknowledge all lecturers and teachers that imparted values and knowledge to us.

Table of Contents

Declaration.....	i
Abstract.....	ii
Acknowledgement	iii
List of figures.....	vi
List of Tables	viii
Chapter 1 Introduction	1
1.1 Background of study	1
1.1.1 Solar Energy Potential in Sri Lanka.....	2
1.1.2 Sri Lankan context of Solar Energy Applications	6
1.2 Problem Statement	7
1.2.1 Aim	8
1.2.2 Objectives	8
1.2.3 Scope.....	8
1.2.4 Outcomes of the study	9
1.2.5 Outline of the Study	9
Chapter 2 Review of Literature.....	10
2.1 Fundamentals of Solar Radiation	10
2.1.1 Introduction to the solar radiation.....	10
2.1.2 Solar geometry	11
2.2 Introduction to the solar irradiation fluctuations.....	17
2.2.1 Weather seasons of Sri Lanka and climatic patterns	20
2.2.2 Effect of clouds on solar irradiation.....	24
2.3 Mathematical models for solar irradiation and PV power forecasting.....	35
2.3.1 Physical methods of forecast	35
2.3.2 Statistical methods of forecast	37
2.4 Artificial Neural Networks (ANN)	40
2.4.1 Introduction.....	40
2.4.2 Fundamentals of Neural Networks	41
2.4.3 Solution of a single hidden layer ANN.....	43
2.4.4 Training validation and testing an artificial neural network.....	49
2.4.5 Applications of neural networks in similar scope.....	51
2.4.6 Methods of evaluating model performance	52
Chapter 3 Research Approach.....	56
3.1 Introduction	56

3.2	Development and training of a neural network.....	56
3.2.1	Identification of input parameters.....	56
3.2.2	Establishing time span for neural network.....	64
3.2.3	Design of the artificial neural networks.....	66
3.2.4	Training neural network with data from existing solar PV project	69
3.2.5	Validation of model	73
3.2.6	Evaluation of adequacy and significance of the predictive model	75
3.3	Calculate energy storage requirement under different operating schemes	79
3.3.1	Operation under controlled ramp rate	79
3.3.2	Operation under moving average smoothening	83
Chapter 4	Results and Discussion	84
4.1	Evaluation of energy storage requirement.	87
Chapter 5	Conclusion and future work	93
References	96

List of figures

Figure 1-1 : Direct Normal Irradiation (DNI) data for horizontal plane.....	3
Figure 1-2: Annual average daily total solar irradiance at surface tilted at latitude angle	4
Figure 1-3 Monthly average hourly global horizontal irradiation (W/m^2) of Colombo for the duration from year 2000 to 2003	6
Figure 1-4 installed Solar PV capacity of Sri Lanka and projected growth	7
Figure 1-5 Periodic change of Solar caused by relative motion of the sun	7
Figure 1-6 Short term random variation caused by weather.....	7
Figure 1-7 Hourly variation of PV power.....	9
Figure 2-1 Exaggerated depiction of the angle subtended on Earth by the sun due to the placement.....	10
Figure 2-2 Earth's orbit relative to the sun.....	12
Figure 2-3 Variation of solar declination.....	12
Figure 2-4 Variation of the solar declination angle throughout the year.....	13
Figure 2-5 The Latitude angle (ϕ) and Hour angle (ω).....	14
Figure 2-6: Altitude angle (α), Zenith angle (θ_z), and Azimuth angle (A_z).....	15
Figure 2-7 : The position of the sun relative to a tilted plane.....	16
Figure 2-8 Solar PV power curves under three sky conditions	17
Figure 2-9 Geographical smoothening of collective solar power curve	18
Figure 2-10 Effect of sky condition change on PV power within a day.....	19
Figure 2-11 Rainfall of NE monsoon 1200mm-200mm.....	20
Figure 2-12 Rainfall distribution of first inter-monsoon 700mm -100mm.....	21
Figure 2-13 Rainfall distribution of SW monsoon 300mm-2000mm.....	22
Figure 2-14 Rainfall distribution of inter-monsoon 1000mm-200mm	22
Figure 2-15 Variation of monthly average solar irradiance over the year.....	23
Figure 2-16 Cirrus clouds with fibrous texture source www.metoffice.gov.uk	24
Figure 2-17 Cirrocumulus clouds www.metoffice.gov.uk	25
Figure 2-18 Cirrostratus clouds www.metoffice.gov.uk	25
Figure 2-19 Altocumulus clouds www.metoffice.gov.uk	26
Figure 2-20 Altostratus clouds www.metoffice.gov.uk	27
Figure 2-21 Stratus Clouds www.metoffice.gov.uk	27
Figure 2-22 Stratocumulus Clouds www.metoffice.gov.uk	28
Figure 2-23 Nimbostratus Clouds www.metoffice.gov.uk	28
Figure 2-24 Cumulus Clouds www.metoffice.gov.uk	29
Figure 2-25 Cumulonimbus clouds www.metoffice.gov.uk	30
Figure 2-26 Visual evaluation of cloud types, International Cloud Atlas WMO	31
Figure 2-27 Variation of irradiance with cloud cover and solar altitude angle	33
Figure 2-28 Image of the complete sky take from a TSI system	36
Figure 2-29 Single neuron of an artificial neural network.....	41
Figure 2-30 Single hidden layer neural network structure.....	43
Figure 2-31 Nomenclature of synaptic weights of a neural network.....	43
Figure 2-32 Total sum of squares and regression sum of squares comparison	53
Figure 2-33 Linear model fit with $R^2 > 99\%$	53
Figure 2-34 Residuals appear random without a pattern	54

Figure 2-35 Histogram of errors with peak frequency at zero.....	55
Figure 3-1 Monthly solar PV energy output with monthly rainfall.....	57
Figure 3-2 Solar PV energy output with monthly average irradiation.....	59
Figure 3-3 Comparison of actual monthly average energy output with multivariable linear model.....	64
Figure 3-4 comparison of correlation coefficient of monthly models to annual model	65
Figure 3-5 comparison of mean error of monthly models to annual model	65
Figure 3-6 Correlation coefficient of training validation testing and overall model with number of hidden neurons	67
Figure 3-7 Structure of the artificial neural network for each month.....	68
Figure 3-8 Synaptic weights nomenclature of the monthly neural network models	69
Figure 3-9 Overall correlation coefficient variation with number of hidden layer neurons for annual model.....	70
Figure 3-10 Convergence of mean square error with training iterations.....	71
Figure 3-11 Error Histogram	71
Figure 3-12 Regression of Training Validation and Testing	72
Figure 3-13 Predicted power cycles to target cycles	73
Figure 3-14 Comparison of prediction to target data.....	73
Figure 3-15 Random distribution of error terms.....	74
Figure 3-16 Histogram of residuals for February	74
Figure 3-17 Normalized distribution of error	76
Figure 3-18 Comparison of error distribution to standard normal curve.....	77
Figure 3-19 Predicted monthly total energy comparison with actual monthly total energy and error percentage	78
Figure 3-20: Ramp rate control scheme.....	79
Figure 3-21 Ramp rate control compared to uncontrolled PV power output for an day	80
Figure 3-22 Potential ramp rate controlled paths identified in the optimization program.....	81
Figure 3-23 Optimum ramp rate controlled path and variation of SOC of the storage system.....	82
Figure 3-24 Operation under moving average output control scheme	83
Figure 4-1 Monthly energy output successfully modeled by identified variables.....	85
Figure 4-2 Comparison of model agreement to the training, validation, testing and overall data sets.....	86
Figure 4-3 Energy storage requirement variation with time for ramp rate controlled scheme and moving average control scheme part 1.....	88
Figure 4-4 Energy storage requirement variation with time for ramp rate controlled scheme and moving average control scheme part 2.....	88
Figure 4-5 Mean energy storage requirement variation with averaging window size.....	89
Figure 4-6 Histogram of energy storage requirement for ramp rate controlled scheme.....	89
Figure 4-7 Variation of energy storage requirement.....	90
Figure 4-8 Cumulative probability of energy storage requirement under $t_2 > 0$ and $R_{max} = 40$ condition	91
Figure 4-9 Variation of energy storage requirement for 95% of the days.....	92

List of Tables

Table 1-1 Monthly averaged insolation of Colombo -----	5
Table 2-1 Analysis of variation of solar radiation on degree of cloud cover and altitude angle by Dorota Matuszko in Krakow, Poland 2004-2007 -----	32
Table 2-2 Percentage of radiation intensity variation with cloud type and solar altitude angle for Krakow- Poland 2004-2007 -----	33
Table 2-3 Transmission of solar radiation by cloud genre analysis by Dorota Matuszko for Krakow poland 2004-2007-----	34
Table 3-1 Monthly total energy variation with monthly rainfall average cloud cover and monthly insolation-----	56
Table 3-2 Correlation coefficient and mean error of monthly neural network models-----	64
Table 3-3 Correlation coefficient and mean error of annual neural network model-----	65
Table 3-4 Variation of number of hidden layer neurons with alpha -----	67
Table 3-5 Correlation coefficient of training validation testing and overall model with number of hidden neurons -----	67
Table 3-6 Allocation of data Training Validation and Testing sets -----	70
Table 3-7 Mean square error and coefficient of correlation for training, validation and testing data sets -----	72
Table 3-8 Outlier data points -----	75
Table 3-9 Classed error terms -----	75
Table 3-10 Descriptive statistics of error term distribution -----	76
Table 3-11 Actual and predicted monthly total energy error percentage-----	78