

INTELLIGENT MODELLING FOR SOLAR ENERGY FORECASTING AND APPLICATIONS

A Thesis submitted to the
Delhi Technological University
for the award of Doctor of Philosophy
in
Electronics and Communication Engineering

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DECLARATION

I Gulnar Perveen, a Ph.D. scholar, Roll No. 2K14/Ph.D./ECE/08 hereby declare that the thesis titled **“Intelligent Modelling for Solar Energy Forecasting and Applications”** which is submitted by me to the Department of Electronics and Communication Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Doctor of Philosophy has not previously formed the basis for the award of any degree, diploma associateship, fellowship or other similar title or recognition.

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CERTIFICATE

On the basis of declaration submitted by Ms. Gulnar Perveen, a Ph.D. scholar, Roll No. 2K14/Ph.D./ECE/08. I hereby certify that the thesis titled “**Intelligent Modelling for Solar Energy Forecasting and Applications**” which is submitted to the Department of Electronics and Communication Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Doctor of Philosophy, is an original contribution with existing knowledge and faithful record of research carried out by her under my guidance and supervision.

To the best of my knowledge this work has not been submitted in part or full for any degree or diploma to this university or elsewhere.

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ACKNOWLEDGEMENT

This thesis may not have been in its present shape and content without the astute and continuous guidance of my supervisor Dr. Nidhi Goel and Jt. supervisor Dr. M. Rizwan. I extend my sincere gratitude to them for their persistent guidance, encouragement and motivation throughout the research work. Dr. M. Rizwan is an outstanding mentor and working with him helped me in supplementing my thoughts in the right direction for attaining the desired objectives. I consider it my proud privilege to have worked with him and I am forever thankful to him for all his wise words and inspiring thoughts.

I wish to express gratefulness to Prof. S. Indu, Head, Department of Electronics and Communication Engineering and Prof. Madhusudan Singh, Head, Department of Electrical Engineering, Delhi Technological University, Delhi, for all the help during my research.

I am also thankful to all faculty members of the Department of Electronics and Communication Engineering and Department of Electrical Engineering, Delhi Technological University for their encouragement and moral support for the completion of this thesis.

I would like to extend my special thanks to SRC members Prof. T. S. Bhatti, Professor, Centre for Energy Studies, IIT Delhi who has given me valuable guidance and advice to improve quality of my research work.

I wish to express my gratitude to all DRC members particularly Prof. M. T. Beg, Jamia Millia Islamia, New Delhi for giving his valuable suggestions to improve my Ph.D. thesis.

I extend my personal thanks to my friends and colleagues especially, Md. Tausif Ahmed, Shagufta Khan, Priyanka Chaudhary, Astitva Kumar, Priyanka Anand and Rahul Bansal for their valuable support and reminding me to complete my work at the earliest.

The assistance of the valuable staffs in Electrical Energy Utilization Laboratory of Delhi Technological University is gratefully acknowledged. I extend my gratitude to all my seniors and colleagues at National Institute of Solar Energy (NISE), Gurgaon for their substantial technical assistance and companionship during my research.

I want to take this opportunity to thank my parents, from the bottom of my heart for everything that they have done and continue to do for me. They have sacrificed a lot in their lives to help me come this far. Every bit of mine would always remain indebted to my loving parents whose blessing have been and will always be an inseparable part of every stride of my life. I also want to thank my brothers Gulzar, Ajaz and Niyaz for being a consistent source of motivation.

This acknowledgment would not be complete without mentioning my husband. He has been my core support system and words cannot articulate my admiration for him. He gave his unconditional love, support and continues to be a source of inspiration during my research.

I am wholly indebted to ALLAH who is the superpower of this universe.

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ABSTRACT

Due to the growing population of the world, there is a surge in the demand for energy – specifically element energy. The production of electricity contributes the largest share in the emission of greenhouse gases that emanate from the burning of fossil fuel. So, a need has arisen for a clean form of energy i.e. renewable energy that can contribute to the increasing demand for energy worldwide. For the accurate design and development of solar energy based systems, solar radiation resource data plays a significant role. Unfortunately, the measured data is rarely available for research purpose for these stations where measurement is already being done. Therefore, it is essential to develop modelling techniques that can forecast global solar energy for such locations where measurements have not been done with reasonable accuracy. The number of mathematical models has been developed for assessment of solar energy under cloudless skies. In fact, it is rather difficult to forecast accurately the behaviour of solar radiation by using these stochastic models, as they need the bases of the precise definition of problem domains and these stochastic models were found with relatively large errors and sometimes difficult to be adopted widely. These models developed, however, are not appropriate to forecast solar energy during cloudy sky. So, fuzzy logic based model have been developed in situations when deterministic or probabilistic models do not provide a realistic description of the phenomenon under study. A lot of research has been carried out and it is observed that for modelling complex systems involving large data sets, it is difficult to maintain accuracy with so much of data sets by employing fuzzy logic approach. So, an Artificial Neural Network (ANN) models were introduced, that employ artificial intelligence techniques and are data-driven which can subsequently simulate the structure. For complex function estimation, the prediction of a number of hidden layers and hidden neurons accurately using ANN is difficult as they are large in number. Also, the training time for the conventional neural network is too large, which results in a slower response of the system. The existing neural model performs only

the operation of summation of its weighted inputs; it does not perform the operation of products on its weighted inputs. Therefore, hybrid intelligent models have been introduced for forecasting solar energy which integrates the features of fuzzy logic approach and ANN. Further, the obtained results have been implemented for short-term power forecasting in solar photovoltaic (PV) system under composite climate zone.

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LIST OF ABBREVIATION, SYMBOLS AND NOMENCLATURE

a, b, c, d	regression coefficients of empirical models (dimensionless)
c_a	average calculated value (dimensionless)
c_i	i^{th} calculated value (dimensionless)
E	absolute error (%)
e_i	i^{th} estimated value (dimensionless)
e_h	hourly error (hours)
f_i	first order polynomial
G_{sc}	solar constant (W/m^2)
G_T	solar irradiance at Standard Test Condition (STC) (W/m^2)
GW_p	giga watt peak
H_d	diffuse solar energy (MJ/m^2)
H/H_g	global solar energy (MJ/m^2)
H_o	extraterrestrial solar radiation on horizontal surface (MJ/m^2)
I_{pmax}	maximum power point current of solar PV module (A)
I_{sc}	short circuit current of solar PV module at STC (A)
kWh/kW_p	kilowatt hours per kilowatt peak
$kWh/m^2/day$	kilowatt hour per meter square per day
$kWh/year$	kilowatt hour per year
L	measured data
L_{max}	highest value of relevant set of data
L_{min}	lowest value of relevant set of data
L_s	normalized/scaled data
m_a	average measured value (dimensionless)
MJ/m^2	mega joule per meter square

m_i	i^{th} measured value (dimensionless)
MW_p	mega watt peak
n	number of observations (dimensionless)
N_{OCT}	temperature of solar panel ($^{\circ}\text{C}$)
N_{PVP}	photovoltaic arrays in parallel (number)
N_{PVS}	photovoltaic arrays in series (number)
$O_{1,i}$	output function for fuzzy sets A_i
$O_{1,j}$	output function for fuzzy sets B_j
$O_{2,i}$	output of i^{th} node of layer 2
$O_{3,i}$	output of i^{th} node of layer 3
$O_{4,i}$	output of i^{th} node of layer 4
$O_{5,i}$	output of i^{th} node of layer 5
P_m	measured atmospheric pressure (hPa)
P_{max}	power of solar PV module at Maximum Power Point (MPP) (W)
$P_{m,h}$	hourly mean values of the measured power in the h -th hour
P_o	maximum possible atmospheric pressure (hPa)
$P_{p,h}$	hourly mean values of the forecasted power in the h -th hour
P_{PV}	power output of solar PV array at MPP (W)
$P_{PV,STC}$	rated power output of solar PV system of single array at MPP (W)
r	correlation coefficient (dimensionless)
R^2	coefficient of determination (dimensionless)
RF_m	measured rainfall (mm)
RF_o	maximum possible rainfall (mm)

RH_m	measured relative humidity (%)
RH_o	maximum possible relative humidity (%)
S	measured sunshine duration (hours)
S_o	maximum possible sunshine duration (hours)
T_j	ambient temperature around PV panels (°C)
T_{amb}/T_m	measured ambient temperature (°C)
T_o	maximum possible ambient temperature (°C)
V_{oc}	open circuit voltage of solar PV module at STC (V)
V_{pmax}	maximum power point voltage of solar PV module (V)
w_i	i^{th} rules strength
\overline{wi}	normalized firing rule strength
w_{ij}	connection weight directed from j neuron to i neuron
WS_m	measured wind speed (Km/hr)
WS_o	maximum possible wind speed (Km/hr)
x_{ij}	j^{th} neuron incoming signal
X_{max}	maximum limit of normalized range
X_{min}	minimum limit of normalized range

Greek Symbols

ϕ	latitude of the site (degree)
ω_s	mean sunrise hour angle (degree)
n_{day}	number of days in a year beginning from 1 st January (dimensionless)

δ	solar declination angle (degree)
η_o	optical efficiency (%)
γ	temperature parameter at MPP (dimensionless)
θ_i	bias of i neuron
$\mu_A(Y)$	membership function of subset A of universal set Y
$\mu_{A,i}(x)$	membership function degree of fuzzy sets A_i
$\mu_{A \cup B}(Y)$	union of fuzzy sets A and B of universal set Y
$\mu_{A \cap B}(Y)$	intersection of fuzzy sets A and B of universal set Y
$\mu_B(Y)$	membership function of subset B of universal set Y
$\mu_{B,j}(y)$	membership function degree of fuzzy sets B_j
μ_p	membership function
$\mu_p(Y)$	grade of membership function of universal set Y
N	normalization to the firing strength
Σ	summation function
U	union
\cap	intersection

Nomenclature

AC	Alternating Current
ANFIS	Adaptive Neural-Fuzzy Inference System
ANN	Artificial Neural Network
AR	Auto Regressive
ARMA	Auto Regressive Moving Average
CFNN	Cascade Forward Neural Network
CPCR2	Code for Physical Computation of Radiation, 2 bands
CWET	Centre for Wind Energy Technology

DNI	Direct Normal Irradiance
EMR	Eastern Mediterranean Region
EMS	Energy Management System
ENN	Elman Neural Network
FCS-MPC	Finite Control Set-Model Predictive Control
FFNN	Feed Forward Neural Network
FIS	Fuzzy Inference System
FY	Financial Year
GA	Genetic Algorithm
GBIs	Generation Based Incentives
GRNN	Generalized Regression Neural Network
GWO	Grey Wolf Optimization
H	High
HH	High-High
HIT	Heterojunction with Intrinsic Thin Layer
IMD	Indian Meteorological Department
INC	Incremental Conductance
ISA	International Solar Alliance
IST	Indian Standard Time
JNNSM	Jawaharlal Nehru National Solar Mission
L	Low
LAT	Local Apparent Time
LM	Low-Medium

LNN	Linear Neural Network
LRNN	Layered Recurrent Neural Network
LVQ	Learning Vector Quantization
M	Medium
MAPE	Mean Absolute Percentage Error
MBE	Mean Bias Error
MF	Membership Function
MH	Medium-High
MLFFNN	Multi-Layer Feed Forward Neural Network
MNRE	Ministry of New and Renewable Energy
MPC	Model Predictive Control
MPE	Mean Percentage Error
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
NAPCC	National Action Plan on Climatic Change
NISE	National Institute of Solar Energy
NIWE	National Institute of Wind Energy
NMAE	Normalized Mean Absolute Error
nRMSE	Normalized Root Mean Square Error
NWP	Numerical Weather Prediction
P&O	Perturb and Observe
PSO	Particle Swarm Optimization
PV	Photovoltaic

RBFNN	Radial Basis Function Neural Network
RES	Renewable Energy Sources
REST	Reference Evaluation of Solar Transmittance
REST2	Reference Evaluation of Solar Transmittance, 2 bands
RMSE	Root Mean Square Error
SEC	Solar Energy Centre
SOM	Self-Organizing Map
SPV	Solar Photovoltaic
SRRA	Solar Radiation Resource Assessment
STC	Standard Test Condition
SVM	Support Vector Machine
SVR	Support Vector Regression
SVR-RBF	Support Vector Regression -Radial Basis Function
TRAINLM	Levenberg-Marquardt Training algorithm
TSK	Takagi, Sugeno & Kang
VH	Very-High
VL	Very-Low