OPTIMAL PLANNING AND SIZING OF AN AUTONOMOUS HYBRID ENERGY SYSTEM USING MULTI STAGE GREY WOLF OPTIMIZATION

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DEDICATION

I would like to dedicate this thesis to my beloved father, dearest mum, lovely children and my darling wife, whom without their enthusiasm and encouragement; I would never have been able to complete this journey to fruition.

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ABSTRACT

The continuous increase in energy demand and the perpetual dwindling of fossil fuel coupled with its environmental impact have recently attracted research focus in harnessing renewable energy sources (RES) across the globe. Representing the largest RES, solar and wind energy systems are expanding due to the growing evidence of global warming phenomena. However, variability and intermittency are some of the main features that characterize these RES as a result of fluctuation in weather conditions. Hybridization of multiple sources improves the system's efficiency and reliability of supply due to the varying nature of the RES. Also, the unavailability of solar radiation (SR) and wind speed (WS) measuring equipment in the meteorological stations necessitates the development of prediction algorithms based on Artificial Intelligent (AI) techniques. This thesis presents an autonomous hybrid renewable energy system for a remote community. The hybrid energy system comprises of a photovoltaic module and wind turbine as the main source of energy. Batteries are used as the energy storage devices and diesel generator as a backup energy supply. A new hybrid Wavelet Transform and Adaptive Neuro-Fuzzy Inference System (WT-ANFIS) is developed for the SR prediction, while a hybrid Particle Swarm Optimization (PSO) and ANFIS (PSO-ANFIS) algorithm is developed for the WS prediction. The prediction accuracy of the proposed WT-ANFIS model was validated by comparison with the conventional ANFIS model, Genetic Algorithm (GA) and ANFIS (GA-ANFIS), and PSO-ANFIS models. The proposed PSO-ANFIS for the WS prediction is also compared with ANFIS and GA-ANFIS models. Also, Root Mean Square Error (RMSE), Correlation Coefficient (r) and Coefficient of Determination (R^2) are used as statistical indicators to evaluate the performance of the developed prediction models. Additionally, a techno-economic feasibility analysis is carried out using the SR and WS data predicted to assess the viability of the hybrid solar-wind-battery-diesel system for electricity generation in the selected study area. Finally, a new cost-effective Multi Stage – Grey Wolf Optimization (MS-GWO) algorithm is applied to optimally size the different system components. This is aimed at minimizing the net present cost (NPC) while considering reliability and satisfying the load demand. MS-GWO is evaluated by comparison with PSO, GWO and PSO-GWO algorithms. From the results obtained, the statistical evaluators used for model performance assessment of the SR prediction shows that the hybrid WT-ANFIS model's accuracy outperforms the PSO-ANFIS model by 65% RMSE and 9% R^2. Also, from the simulation results, the optimal configuration has an NPC of $1.01 million and cost of energy (COE) $0.110/kWh, with an operating cost of $4,723. The system is environmentally friendly with a renewable fraction of 98.3% and greenhouse gas emission reduction of 65%. Finally, a comparison is done between the proposed MS-GWO algorithm with the PSO, GWO and PSO-GWO algorithms. Based on this comparison, the proposed hybrid MS-GWO algorithm outperforms the individual PSO, GWO and PSO-GWO by 3.17%, 2.53% and 2.11% in terms of NPC and reduces the computational time by 53%, 46% and 36% respectively. Therefore, it can be concluded that the proposed MS-GWO technique can be applied for optimal sizing application globally.

ABSTRAK

Peningkatan berterusan terhadap permintaan tenaga dan kemerosotan bahan api fosil serta kesan alam sekitar baru-baru ini telah menarik tumpuan penyelidikan dalam memanfaatkan sumber tenaga boleh diperbaharui (RES) di seluruh dunia. Sistem tenaga solar dan angin yang mewakili sistem tenaga RES terbesar, kian berkembang kerana terdapat bukti fenomena pemanasan global yang kian meningkat. Walau bagaimanapun, kebolehubahan dan sifat keputus-putusan merupakan beberapa sifat utama yang mencirikan RES akibat daripada ketidaktentuan keadaan cuaca. Penghibridan pelbagai sumber meningkatkan kecekapan dan kebolehpercayaan bekalan sistem kerana kepelbagaian sifat RES. Selain itu, ketiadaan alat pengukuran sinaran solar (SR) dan kelajuan angin (WS) di stesen-stesen kaji cuaca memerlukan pembangunan algoritma ramalan berasaskan teknik Kecerdasan Buatan (AI). Tesis ini membentangkan satu sistem tenaga boleh diperbaharui hibrid berdiri sendiri untuk masyarakat terpencil. Sistem tenaga hibrid ini terdiri daripada modul fotovolta dan turbin angin sebagai sumber tenaga utama. Bateri digunakan sebagai peranti simpanan tenaga dan penjana diesel digunakan sebagai bekalan tenaga sandaran. Sistem Jelmaan Gelombang Kecil dan Inferens Mudah Suai Neuro-Kabur (WT-ANFIS) yang baharu dibangunkan untuk ramalan SR, manakala algoritma hibrid Pengoptimuman Kerumunan Zarah (PSO) dan ANFIS (PSO-ANFIS) dibangunkan untuk ramalan WS. Ketepatan ramalan model cadangan WT-ANFIS telah ditentusahkan oleh perbandingan dengan model ANFIS konvensional, Algoritma Genetik (GA) dan model ANFIS (GA-ANFIS) dan PSO-ANFIS. PSO-ANFIS yang dicadangkan untuk ramalan WS juga dibandingkan dengan model ANFIS dan GA-ANFIS. Malahan. Punca Min Ralat Kuasa Dua (RMSE), Pekali Korelasi (r) dan Pekali Penentuan (R^2) juga digunakan sebagai penunjuk statistik untuk menilai prestasi model ramalan yang dibangunkan. Selain itu, analisis kebolehlaksanaan tekno-ekonomi dijalankan menggunakan data SR dan WS yang diramalkan untuk menilai kebolehjayaan sistem hibrid solar-angin-bateri-diesel ini untuk penjanaan elektrik di kawasan kajian yang dipilih. Akhir sekali, satu algoritma baharu Berbilang Peringkat - Pengoptimuman Serigala Kelabu (MS-GWO) yang kos efektif digunakan untuk mengoptimumkan saiz komponen sistem berbeza. Ini bertujuan untuk meminimumkan kos kini bersih (NPC) dengan mengambil kira kebolehpercayaan dan memuaskan permintaan beban. MS-GWO dinilai melalui perbandingan dengan algoritma PSO, GWO dan PSO-GWO. Berdasarkan keputusan yang diperoleh, penilai statistik yang digunakan untuk penilaian prestasi model ramalan SR menunjukkan bahawa ketepatan model hibrid WT-ANFIS mengatasi model PSO-ANFIS sebanyak 65% RMSE dan 9% R^2. Keputusan simulasi itu juga menunjukkan konfigurasi optimum mempunyai NPC sebanyak \$1.01 juta dan kos tenaga (COE) \$0.110/kWj, dengan kos operasi sebanyak \$4,723. Sistem ini adalah mesra alam dengan pecahan boleh diperbaharui sebanyak 98.3% dan pengurangan pelepasan gas rumah hijau sebanyak 65%. Akhir sekali, perbandingan dilakukan antara algoritma MS-GWO cadangan dengan algoritma PSO, GWO dan PSO-GWO. Berdasarkan perbandingan ini, algoritma hibrid MS-GWO cadangan mengatasi algoritma individu PSO, GWO dan PSO-GWO masing-masing sebanyak 3.17%, 2.53% dan 2.11% dari segi NPC dan mengurangkan masa pengiraan masing-masing sebanyak 53%, 46% dan 36%. Oleh itu, dapat disimpulkan bahawa teknik MS-GWO yang dicadangkan boleh digunakan untuk penggunaan pensaizan optimum secara global.

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LIST OF ABBREVIATIONS

ABC	-	Artificial Bee Colony
ABSO	-	Artificial Bee Swarm Optimization
AC	-	Alternating current
ACO	-	Ant colony Optimization
AGA	-	Adaptive Genetic Algorithm
AI	-	Artificial Intelligence
ANFIS	-	Adaptive Neuro Fuzzy Inference System
ARMA	-	Autoregressive and Moving Average
ASC	-	Annual system cost
BBO	-	Biography Based Optimization
BFPSO	-	Butterfly Particle Swarm Optimization
BPNN	-	Back Propagation Neural Network
BS	-	Battery storage
CARDS	-	Coupled Autoregressive and Dynamic System
CC	-	Cycle charging
CCP	-	Chaosed constrained programming
COE	-	Cost of energy
CRF	-	Capital recovery factor
CSA	-	Cuckoo Search Algorithm
DC	-	Direct current
DFID	-	Doubly fed induction generator
DG	-	Diesel generator
DHS	-	Discrete Harmony Search
DOD	-	Depth of discharge
DPSP	-	Deficiency of power supply probability
DSA	-	Discrete Simulated Annealing
ECN	-	Energy commission of Nigeria
EENS	-	Expected energy not supplied
ELM	-	Extreme Learning Machine
ENS	-	Energy not supplied

FCT	-	Federal Capital Territory
FFA	-	Firefly Algorithm
GA	-	Genetic Algorithm
GA-ANFIS	-	Genetic Algorithm- Adaptive Neuro Fuzzy Inference System
GA-ES	-	Genetic Algorithm and Exhaustive Search
GANN	-	Genetic Algorithm Neural Network
GAPSO	-	Genetic Algorithm Particle Swarm Optimization
GC	-	Graphical Construction
GD	-	Gradient Decent
GHG	-	Greenhouse gas
GP	-	Genetic Programming
GRNN	-	Generalized Regression Neural Network
GUI	-	Graphical user interface
GWO	-	Grey Wolf Optimization
HBB-BC	-	Hybrid Big Bang - Big Crunch
HOMER	-	Hybrid optimization model for electric renewable
HRES	-	Hybrid renewable energy system
HSBCS	-	Harmony Search Algorithm Based Chaotic Search
HT	-	Hydrogen tank
HYBRID2	-	Hybrid system simulation model
ICA	-	Imperative Competitive Algorithm
iHOGA	-	Improved Hybrid Optimization by Genetic Algorithm
IPF	-	Pareto Iterative and Fuzzy
LA	-	Level of autonomy
LCOE	-	Levelized cost of energy
LCC	-	Life cycle cost
LF	-	Load following
LOEE	-	Loss of energy expectation
LOLE	-	Loss of load expectation
LOLP	-	Loss of load probability
LP	-	Linear programming
LPSP	-	Loss of power supply probability
MBA	-	Mine Blast Algorithm

MCS	-	Monte Carlo Simulation
MOPSO	-	Multi objective Particle Swarm Optimization
MSDF	-	Modified sun duration fraction
MW	-	Megawatt
NBS	-	National Bureau of statistics
NERL	-	National renewable energy laboratory
NPC	-	Net present cost
NSD	-	Non sunshine duration
NSGA- II	-	Non-Dominated Sorting Genetic Algorithm
O&M	-	Operation and maintenance
OPEC	-	Organization of petroleum exporting countries
PMSG	-	Permanent magnet synchronous generator
PSO	-	Particle Swarm Optimization
PSO-ANFIS	-	Particle Swarm Optimization - Adaptive Neuro Fuzzy Inference System
PSO-MCS	-	Particle Swarm Optimization - Monte Carlo Simulation
PV	-	Photovoltaic
RES	-	Renewable energy sources
RMSE	-	Root mean square error
SA	-	Simulated Annealing
SAM	-	System Advisor Model
SAPSO	-	Simulated Annealing – Particle Swarm Optimization
SA-TS	-	Simulated Annealing – Tabu Search
SC	-	Super capacitor
SCC	-	Social cost of carbon
SDF	-	Sunshine duration fraction
SECS	-	Solar energy conversion systems
SOC	-	State of charge
SVM	-	Support Vector Machine
SVM-FFA	-	Support Vector Machine – Firefly Algorithm
SVM-poly	-	Support Vector Machine Polynomial
SVM-rbf	-	Support Vector Machine Radial Basic Function
SVM-WT	-	Support Vector Machine – Wavelet Transform

TAC	-	Total annual cost
TC	-	Total cost
TDNN	-	Time Delay Neural Network
TIC	-	Total investment cost
TLBO	-	Teaching Learning Based Optimization
WECS	-	Wind energy conversion systems
WT	-	Wavelet Transform
WT-ANFIS	-	Wavelet Transform – Adaptive Neuro Fuzzy Inference System
DGPS	-	Differential Global Positioning System

LIST OF SYMBOLS

$C_{ann.tot}$	-	Total annual cost
i	-	Real interest rate
$Rproj$	-	Project lifetime
i_0	-	nominal interest rate
f	-	Annual inflation rate
N	-	Project lifetime
$E_{prim.AC}$	-	AC primary load served
$E_{prim.DC}$	-	DC primary load served
$E_{grid.sales}$	-	Total grid sales
CC_i	-	Capital cost
RC_i	-	Replacement cost of components i
OMC_i	-	Operation and maintenance cost of components i.
A_{CC}	-	Capital cost per annum
A_{MC}	-	Annual maintenance cost
A_{RC}	-	Annual replacement cost
$LPS(t)$	-	loss of power supply at time (t)
$P_L(t)$	-	Load demand at time (t)
$P_{PV}(t)$	-	Solar PV power output at time (t)
$P_{WT}(t)$	-	wind turbine power output at time (t)
$P_{DG}(t)$	-	Diesel generator power at time (t)
$P_{BATT}(t)$	-	Battery discharge capacity at time (t)
T_{LNS}	-	Total load not served
$T_{Operation}$	-	Operation time
L	-	Annual average load demand
D	-	Duration in which the load cannot be met
A	-	Swept area of wind turbine
ρ	-	Air density
v	-	Wind speed
k	-	Shape parameters

c	-	Scale parameters
v_0	-	Wind speed at reference height
v	-	Wind speed at required hub height
h_0	-	Reference height
h	-	Required hub height
$\propto$	-	Site surface roughness coefficient
I	-	PV output current
I_L	-	solar generated current
I_D	-	diode current
I_{sh}	-	shunt leakage current
μ_{Ai}	-	Membership function of node A
μ_{Bi}	-	Membership function of node B
w_i	-	Firing strength of node *i*
$\overline{w_i}$	-	Normalized signal of node *i*
f_i	-	Linear combination of the consequent parameters of the fourth layer
a_i, b_i, c_i	-	Variable sets
p_i, q_i, r_1	-	Consequent parameters
$O_{j,i}$	-	Membership grade of a fuzzy sets A and B
$v_i(t)$	-	Agent velocity at iteration
x	-	Inertia weight
w	-	Weighing factor of inertia
ρ_1 and ρ_2	-	Random variables
A_n	-	approximate component
$D_n(t)$	-	Detail component
$\psi(t)$	-	Mother wavelet
a	-	Time-shift parameter
b	-	Scale factor
O_i and P_i	-	Estimated and experimental values
$\bar{O}_i$ and $\bar{P}_i$	-	Mean values of O_i and P_i
n	-	The entire amount of test data
I_{oc}	-	Open circuit current
V_{oc}	-	Open circuit voltage

η_{MPPT}	-	Maximum power point tracking factor efficiency
f_{PV}	-	Derating factor
$I_{sc(STC)}$	-	Short circuit current at a standard test condition
$V_{oc(STC)}$	-	Open circuit voltage at standard test condition
K_i	-	Temperature coefficient of the PV module current
K_V	-	Temperature coefficient of the PV module voltage
G_{STC}	-	PV module reference solar radiation
T_{STC}	-	PV module reference ambient temperature under standard test condition
T	-	PV module temperature
G	-	PV module solar radiation
C_p	-	Power coefficient,
N_w	-	Number of wind turbines
N_{pv}	-	Number of PV panels
N_B	-	Number of batteries
N_{DG}	-	Number of diesel generators
P_{rate}	-	Rated power of the wind turbine
V	-	Hourly wind speed
$V_{cut-in,}$	-	Rated cut-in wind speed
$V_{cut-out}$	-	Rated cut-out wind speed
P_{Rdg}	-	Rated DG power
$P_{DG}(t)$	-	Actual power generated by the DG at a time t
a and b	-	Constants for the DG
$P_T(t)$	-	Total power generated by the RES at time t
σ	-	Self-discharge rate of the battery
η_{Batt}	-	Battery efficiency
η_{inv}	-	Inverter efficiency
$P_L(t)$	-	Load demand at time t
P_{wt}	-	Wind turbine output power
P_{pv}	-	PV module output power
SOC_{min}	-	Minimum battery state of charge
SOC_{max}	-	Maximum battery state of charge

C_a	-	Total capital cost
C_{OM}	-	Operation and maintenance cost
C_r	-	Replacement cost
C_{WT}	-	Wind turbine cost
C_{PV}	-	PV module cost
C_B	-	Battery cost
C_i	-	Inverter cost
C_{uPV}	-	Unit cost of solar PV
C_{uWT}	-	Unit cost of wind turbine
C_{uB}	-	Unit cost of battery storage
C_{uDG}	-	Unit cost of diesel generator
C_{ci}	-	Inverter investment cost
$C_{OM.PV}$,	-	Operational and maintenance cost of the solar PV
$C_{OM.WT}$	-	Operational and maintenance cost of the wind turbine
$C_{OM.B}$	-	Operational and maintenance cost of the battery storage
$C_{OM.DG}$	-	Operational and maintenance cost of the diesel generator
$C_{OM.i}$	-	Operational and maintenance cost of the inverter
$C_{R.B}$	-	Replacement cost of battery storage
$C_{R.DG}$	-	Replacement cost of diesel generator
$C_{R.WT}$	-	Replacement cost of wind turbine
$C_{R.i}$	-	Replacement cost of inverter
$N_{WT.min}$	-	Minimum number of wind turbines
$N_{WT.max}$	-	Maximum number of wind turbines
$N_{PV.min}$	-	Minimum number of solar PV
$N_{PV.max}$	-	Maximum number of solar PV
$N_{DG.min}$	-	Minimum number of diesel generator
$N_{DG.max}$	-	Maximum number of diesel generator
$N_{B.min}$	-	Minimum number of batteries
$N_{B.max}$	-	Maximum number of batteries
t	-	Current iteration
$\vec{A}$ and $\vec{C}$	-	Coefficient vectors
$\vec{X}$	-	Grey wolf position

$\overrightarrow{X_p}$	-	The prey position
r_1 and r_2	-	Random vectors
$\overrightarrow{X_\alpha}$	-	Alpha wolf position
$\overrightarrow{X_\beta}$	-	Beta wolf position
$\overrightarrow{X_\delta}$	-	Delta wolf position
$\overrightarrow{A_1}, \overrightarrow{A_2}, \overrightarrow{A_3}$	-	Random vectors

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CHAPTER 1

INTRODUCTION

1.1 Background

In the present day world, adequate supply of electricity serves as an index for measuring sustainable economic development of any nation and the wellbeing of its citizens. Without access to substantial energy supply, no country can grow to its expected level [1]. The perpetual increase in population growth and technological advancement has also contributed to the increase in electricity demand, thereby creating a wide gap between demand and supply [2]. According to Ahiduzzaman and Islam [3], about 75% of the world's total energy is from fossil fuels, the use of fossil fuels results in many problems such as environmental degradation and global warming as a result of CO_2 emission. Additionally, the gradual depletion of these fossil fuels that accounts for about 75% of world's total energy has given rise to other sources of energy from renewable energy sources (RES) for clean and sustainable energy production to meet the desired load demand [4-6]. RES integration and deployment has increased and has been given tremendous attention globally [7, 8]. There are still over half a million people of European residents without access to the national grid and about 45% of people living in sub-Saharan Africa, East, South, and Central Asia, South America and the Middle East living in darkness [9].

For remote areas where access to large transmission network is not economically viable and technically feasible, autonomous systems are considered in providing lasting solutions to these areas. This system can be used to provide electricity to rural areas with no access to national grid especially in the developing countries and can range from a few watts (W) to hundreds of megawatts (MW) [10]. The most promising RES technologies that can meet the demand of these remote areas are the photovoltaic (PV) technologies and wind turbine technologies [11]. These RESs are pollution free sources with zero environmental effect. They are freely available and free of greenhouse gas (GHG) emission [2, 12-14]. Several studies have suggested the deployment of solar PVs, wind turbines, and other RES for electricity generation [15-17]. The main challenge of relying on a single source of energy (solar or wind) is their intermittent nature due to fluctuation in solar radiation and wind speed which may affect the time distribution of the desired load demand. For this reason, there is a serious concern on the system's reliability.

To enhance the reliability of such system, a hybrid system consisting of two or more energy sources is used to implement the characteristics of the selected energy sources (e.g solar and wind) in the system design. While many studies employed the use of single RES for electricity generation, others considered the use of hybrid systems by combining two or more RESs and in some cases, diesel generators are used as backup power supply for more efficiency and reliability [18-22]. Hybrid systems with a diesel generator as backup power supply are mostly applicable to villages with no access to the national grid. The hybrid renewable energy system (HRES) is preferred because total reliance on a single energy source can result in system oversizing which may eventually increase the capital cost of the system [18, 23, 24]. Due to the current scenario on the global environmental regulations, hybrid energy systems planning utilizes the advantage of the available resources to present an environmentally friendly and a more economical system. This calls for more RES penetration by properly planning the hybrid systems efficiently and effectively.

Optimal sizing is a very important characteristic of every hybrid system design. Although, oversizing has the advantage of eliminating the fear of reliability, however, it has a tremendous effect on the cost of the system. In order to obtain a cost effective hybrid energy system, there is need to optimally size the system. The term optimum sizing can be referred to as the ability to determine the exact number of components that can efficiently and reliably satisfy the desired load at a minimized total cost [11]. Optimal sizing can be attained using optimization techniques with the aim of minimizing the system cost while complying with the technical constraints. The complexity of hybrid system optimal sizing problem makes it necessary to employ a powerful optimization method. Several optimization methods have so far been employed for hybrid system optimal sizing. The hybrid optimization model for electric renewables (HOMER) employed by [25, 26], Hybrid Optimization by Genetic Algorithm (HOGA) [27, 28], Genetic Algorithm (GA) [29], Grey Wolf Optimization (GWO) [30, 31], Ant Colony Optimization (ACO) [32], Linear Programming (LP) [33, 34], Bat Algorithm (BA) [35, 36], Particle Swarm Optimization (PSO) [37-39], Cuckoo Search Algorithm (CSA) [40]. Also, hybrid algorithms are used for solving more complex hybrid system optimization problems [41-43].

To optimally size the hybrid energy system, good record of meteorological data of temperature, solar radiation and wind speed is required. In most developing countries, most of these data records especially solar radiation and wind speed are not readily available. In this regard, weather forecasting models are developed to predict the data needed to effectively and efficiently size the HRES. Also, assessment of technical and economic feasibility for a hybrid PV/wind/diesel/battery system in a chosen community is performed. Furthermore, a cost effective optimal design of the system is achieved by developing a new Multi Stage Grey Wolf Optimization (MS-GWO) algorithm to minimize the Net Present Cost (NPC) while considering the Deficiency of Power Supply Probability (DPSP) subject to constraints.

This research presents new significant innovations. Firstly, development of new algorithms for solar radiation and wind speed prediction for effective optimal sizing application. Additionally, assessment and techno-economic feasibility analysis of the proposed hybrid system is performed using the predicted solar radiation and wind speed data. Finally, a new cost effective hybrid algorithm is developed to optimally size the PV/wind/diesel/battery system to satisfy the desired load demand while considering reliability (DPSP). The developed algorithms can be applied for optimal sizing applications globally.

1.2 Problem Statement

About 70% of rural communities in developing nations have no access to grid or electricity. Some of these nations established some reforms that includes grid extension to these rural communities but unfortunately, grid extension to rural communities attracts high cost of transmission and dangers of transmitting to rural communities having bushes as constraints. Also, the governments only looked at the possibility of grid extension without considering new generation solutions. The electricity challenges faced by these rural communities led to the total dependent on biomass for their day to day activities for the purpose of both domestic cooking and heating. The biomass resources used by the rural communities include charcoal, dried crops residue, dry wood and in some cases animal residue. Burning of these biomass energy sources used for cooking expose the community to air pollution, which leads to global warming. Due to the fact that these rural communities have no access to electricity and extension to grid seems practically not attainable, there is need for the establishment of an alternative way to solving this problem for the betterment of these communities. This will help in providing a conducive environment for learning and a good health care system for the rural communities. The best possible solution to these problems is the establishment of a renewable energy based off grid/standalone system for electrifying the rural communities.

Meteorological data and load demand are major factors considered while designing any off-grid energy system. In developing countries like Nigeria where the meteorological data like solar irradiance and wind speed are not readily available. Lack of modern equipment to calculate the solar radiation are expensive and are not available in the meteorological centers. This necessitates the need to develop algorithms that can predict the solar radiation/wind speed data of the specified study area to be used for the optimal design of the RES using the available meteorological data in those stations. Additionally, there is need to also predict the wind speed of the area of study in order to have a cost effective design.

Technically, a system that depends solely on a single RES cannot always be considered reliable and efficient due to the uncertainty on the availability of those RES. The intermittent nature of these RES due to fluctuation of weather condition makes it impossible to be solely dependent on. Hence, there is need to combine two or more RESs in hybrid form for a reliable and efficient power generation. In choosing these RESs for hybrid system design, a techno-economic feasibility study need to be carried out using the solar radiation and wind speed data developed to access the viability of the selected RESs based their availability in the study area. The hybrid RES is preferred because total reliance on a single energy source can result in system oversizing which may eventually increase the capital cost of the system.

Due to the complexity of optimal system design and planning, conventional optimization methods failed to either be efficient or accurate. Several single stochastic algorithms have in some ways offer efficient and accurate optimum solutions in RES sizing, planning and design, with fast convergence and best computational time. However, with the rapid growth of RES utilization, there is need for highly advanced and accurate optimization approaches. According to the no free lunch theorem, there is no single algorithm that can solve every engineering problem, every algorithm has its own merits and drawbacks. The PSO algorithm, for example, has the merit of fast convergence and good in exploitation, the GA algorithm is known for its low convergence but has high accuracy, the GWO is known for its simplicity and superiority in reaching global optimum, and it is also good in exploration, unlike the PSO algorithm. Therefore, methods combining two algorithms in hybrid form by combining two stochastic algorithms has upper hand in solving engineering problems. These algorithms will assume the merits of complementary characteristics between two methods to solve the optimal sizing problem.

Therefore this research aims to develop new algorithms for solar radiation and wind speed prediction. The predicted solar radiation and wind speed data will be used to perform the technical and feasibility analysis of the proposed hybrid RES system in providing electricity access to the rural area using HOMER. Also, a new hybrid cost-effective optimization model will be developed for sizing the solar-wind-diesel-battery system.

1.3 Motivation

It is believed that the economic development of any nation highly depends on high access to an efficient and reliable electricity supply. More so, with good and reliable electricity access in our remote areas, life in rural communities become easier and thus leads to the development of such communities. Additional concern is the issue of providing clean and environmentally friendly energy which can only be done employing the RES. This perhaps motivated and encouraged this research, with an effort to implement a hybrid solar-wind-battery energy system with a diesel generator as a backup to supply electricity at minimum cost. A case study is chosen, which led to the formation of various research questions stated below.

i. Will the methods employed in developing the meteorological data prediction models be suitable to perform such task?

ii. Are the RES chosen for this purpose technically and economically feasible for performing such task?

iii. Can a cost-effective system be achieved using the proposed hybrid algorithm?

These research questions are asked to properly design and size the proposed HRES. For this purpose, there is a need to optimally design and plan a cost-effective HRES that will supply electricity for the betterment of such communities. This can only be achieved by answering the research questions listed above, which can only be answered if the following research objectives are achieved.

1.4 Research Objectives

The objectives of the research are:

i. To develop a new algorithm for solar radiation prediction using a hybrid Wavelet Transform and Adaptive Neuro-Fuzzy Inference System (WT-ANFIS)

ii. To develop a new algorithm for wind speed prediction using hybrid Particle Swarm Optimization and Adaptive Neuro-Fuzzy Inference System (PSO-ANFIS)

iii. To assess the economic and technical feasibility of the proposed hybrid RES system in providing electricity access to the rural area using HOMER Pro.

iv. To develop a new cost-effective optimization model for sizing the solar-wind-diesel-battery hybrid system using Multi-Stage Grey Wolf Optimization algorithm (MS-GWO)

1.5 Research Scope and Limitations

Electrical power system is basically categorized into system planning and system operation and management. The system planning normally concentrates on the pre-design analysis with detailed engineering design of energy system, while the system operation and management focus on the implementation of the project. The focal aspects of this study are highlighted below

i. This research is limited to the use of solar and wind sources without considering other RESs. The limitation of solar and wind energy sources is as a result of the availability of the two sources in abundant quantity in the study location.

ii. The research also considers the use of battery as a storage device and a diesel generator as backup power supply to supply the load when the RES fails to supply the load and the battery storage is below the minimum state of charge.

iii. A study location is needed for optimal sizing application due to the use of meteorological data for the proposed RES used. In this regard, the study location for this research is a village in north central Nigeria.

iv. Minimum temperature, maximum temperature, relative humidity, and sunshine hours are the only meteorological data used to predict the solar radiation in the study location.

v. For the optimal sizing technique used, the objective of the study aims to minimize the system NPC with a reliability index DPSP as a constraint.

1.6 Research Significance

The significance of this research can be highlighted as follows

i. The developed prediction models will help in predicting the desired solar radiation and wind speed that could be used to achieve an optimum HRES design. The algorithms developed can be applied for weather forecasting globally and not limited to the study location.

ii. Implementing the developed solar radiation and wind speed data in the optimal design results in providing efficient and reliable HRES design.

iii. The technical and economic assessment of the hybrid energy system is to examine the feasibility of providing electricity access to the remote communities using the available RESs.

iv. The development of the new hybrid optimal sizing algorithm has significant impact on improving the system reliability at a minimized cost. This makes it significant to energy system design.

v. The developed algorithms in this research will help in renewable energy systems design. It will help the stakeholders to have a better picture of a HRES design in terms of system reliability and cost. The algorithms can be applied for optimal sizing applications globally.

1.7 Thesis Outline

The present chapter provides a brief background of the study, problem statement, objectives, research hypothesis, scopes and limitations, and research significance.

Chapter 2 presents a comprehensive and critical literature review of the theoretical background of renewable energy sources, hybrid renewable energy sources, hybrid system architectures, solar radiation prediction models, wind and solar energy conversion systems, optimal sizing methodologies, and optimal sizing problem formulations.

Chapter 3 explains the overall methodology employed to carry out the desired thesis objectives. This includes the methodology employed in developing the solar radiation and wind speed prediction models, the methodology employed in carrying out the technical and economic assessment of the RES for electrifying the remote communities, the mathematical models of the components used for the optimal sizing, and the methodology employed for optimally sizing the HRES for a reliable and cost effective system.

Chapter 4 outlines and discusses the results obtained after implementing the methodologies in Chapter 3. This includes the results of the solar radiation prediction model, the wind speed prediction model, the solar and wind energy models, the result of the economic assessment of the optimal configuration in the study area, and finally, the result of the developed hybrid algorithm used to optimally size the HRES at a minimized cost (NPC) while considering reliability (DPSP)

Finally, Chapter 5 concludes the thesis with novelty, contributions of the research, and recommendation for future outlook.

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APPENDICES A-C

Appendix A List of Publications

Journal Articles

i. **S Salisu**, MW Mustafa, and M Mustapha. "A Wavelet Based Solar Radiation Prediction in Nigeria Using Adaptive Neuro-Fuzzy Approach" Indonesian Journal of Electrical Engineering and Computer Science 2018; 12(3): 907-915. (**Scopus Indexed**).

ii. **S Salisu,** MW Mustafa, OO Mohammed, M Mustapha, and TA Jumani. "Techno-Economic Feasibility Analysis of an Off-Grid Hybrid Energy System for Rural Electrification in Nigeria" International Journal of Renewable Energy Research (IJRER) 2019; 9(1): 261-270. (**ESCI and Scopus Indexed**)

iii. **S Salisu** MW Mustafa, OO Mohammed, and M Mustapha. "Solar radiation forecasting in Nigeria based on hybrid PSO-ANFIS and WT-ANFIS approach" International Journal of Electrical and Computer Engineering 2019; 9(5): 3916-3926. (**Scopus Indexed**).

iv. **S Salisu**, MW Mustafa, OO Mohammed and M Mustapha. "A Hybrid PSO-ANFIS Approach for Horizontal Solar Radiation Prediction in Nigeria" ELEKTRIKA Journal of Electrical Engineering 2019; 18(2): 23-32.

v. **S Salisu,** MW Mustafa, OO Mohammed, L Olatomiwa. "Assessment of technical and economic feasibility for a hybrid PV-wind-diesel-battery energy system in a remote community of north central Nigeria" Alexandria Engineering Journal, Elsevier, 2019; 58(4): 1103-1118 **(ISI Indexed (Q1)).**

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