MITIGATING THE EFFECT OF LOAD SHEDDING IN ELECTRICAL GRID USING HYBRID RENEWABLE ENERGY SYSTEM APPROACH

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DEDICATION

To my beloved parents, wife, sons, brother and sisters for their patience, support, motivation, and enduring love

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ABSTRACT

Load shedding is an operating condition whereby the electrical grid is temporarily disconnected or suspended from the load. The idea is to minimize the deficit between generation capacity and load demand, while ensuring a fair level of supply availability for all consumers. Load shedding is a prominent problem for many developing countries and thus, this thesis investigates the prospects of hybrid renewable energy system (HRES) to mitigate its effect at the distribution level. The proposed HRES in this work is configured using the photovoltaic (PV) array, wind turbine (WT), energy storage unit (ESU) and diesel generator (Gen). Despite the substantial amount of literatures on HRES, limited work is directly related to load shedding mitigation in grid-connected system. Furthermore, it is unclear what would be the cost of installing HRES and under what operating conditions the system would perform optimally. Thus, the main design objective of the proposed system is to ensure supply availability with minimum levelized cost of electricity (LCOE) and payback period (PBP). A small residential locality in Quetta, Pakistan is selected as a case study to test the system. The proposed HRES is equipped with the energy management scheme (EMS), which is designed in MATLAB/Stateflow. The sizes of HRES components (*i.e.*, PV, WT and ESU) are optimized by the grasshopper optimization algorithm (GOA) and the results are verified with particle swarm optimization algorithm (PSO). The objective function of the optimization is characterized by three variables: LCOE, PBP and the loss of power supply probability (LPSP). Scenario-based simulations are performed in MATLAB to validate the functionality of the EMS and the behaviour of optimized HRES for various load shedding and meteorological conditions. In addition, it is compared with the conventional solutions for load shedding, namely the diesel generator (only), uninterruptable power supply (UPS), and the combination of both. The results based on one-year climatic data shows that the LCOE for the HRES is 6.64 cents/kWh, with PBP of 7.4 years. The LCOE of HRES is 77.6% cheaper than the LCOE for generator (only), 49.8% for the UPS, and 66.7% for the combined solution. Accordingly, the PBP is also shorter compared to diesel generator (12.9 years), UPS (9.8 years) and the combined system (11.3 years). Furthermore, the integration of HRES alleviates the annual grid burden by 32.9, 47.2 and 42.3%, respectively. These results confirm the superiority of the HRES over the conventional solutions. Finally, sensitivity analysis is performed to observe the changes in the LCOE and PBP with respect to the variation in the components prices, feed-in-tariff rate, metrological conditions and load demand. It can be concluded that a well-designed and optimized HRES has the potential to effectively mitigate the problem of load shedding with reasonable cost.

ABSTRAK

Penyisihan beban ialah keadaan pengendalian di mana grid elektrik diputuskan sementara atau terampai daripada beban. Ideanya adalah untuk meminimumkan defisit antara kapasiti penjanaan dan permintaan beban, sambil memastikan tahap ketersediaan bekalan yang adil untuk semua pengguna. Penyisihan beban adalah masalah utama bagi kebanyakan negara membangun maka dengan itu, tesis ini menyiasat prospek sistem tenaga kacukan yang boleh diperbaharui (HRES) untuk mengurangkan kesannya pada peringkat agihan. HRES yang dicadangkan dalam kerja ini dikonfigurasi menggunakan tatasusunan fotovolta (PV), turbin angin (WT), unit simpanan tenaga (ESU) dan penjana diesel (Gen). Walaupun terdapat banyak literatur tentang HRES, kerja secara langsung berkaitan dengan pengurangan penyisihan beban dalam sistem yang disambungkan dengan grid adalah terhad. Tambahan pula, adalah tidak jelas berapakah kos pemasangan HRES dan dalam keadaan pengendalian yang mana sistem akan berfungsi secara optimum. Oleh itu, objektif reka bentuk utama sistem yang dicadangkan adalah untuk memastikan ketersediaan bekalan dengan meratakan kos elektrik (LCOE) dan tempoh bayaran balik (PBP) yang minimum. Kawasan kediaman kecil di Quetta, Pakistan dipilih sebagai sebuah kajian kes untuk menguji sistem tersebut. HRES yang dicadangkan dilengkapi dengan skim pengurusan tenaga (EMS), yang direka dengan menggunakan MATLAB/Stateflow. Saiz komponen HRES (iaitu, PV, WT, ESU dan Gen) dioptimumkan oleh algoritma pengoptimuman belalang (GOA) dan hasilnya disahkan menggunakan algoritma pengoptimuman kerumunan zarah (PSO). Fungsi objektif pengoptimuman dicirikan oleh tiga pembolehubah: LCOE, PBP dan kebarangkalian kehilangan bekalan kuasa (LPSP). Penyelakuan berasaskan senario dilakukan di MATLAB untuk mengesahkan fungsi EMS dan tingkah laku HRES yang dioptimumkan untuk pelbagai penyisihan beban dan keadaan meteorologi. Di samping itu, ia dibandingkan dengan penyelesaian konvensional untuk penumpahan beban, iaitu penjana diesel (sahaja), sistem bekalan kuasa tanpa gangguan (UPS), dan gabungan kedua-duanya. Keputusan berdasarkan data iklim setahun menunjukkan bahawa LCOE untuk HRES ialah 6.64 sen/kWj, dengan PBP selama 7.4 tahun. Ini adalah 77.6% lebih murah daripada LCOE untuk penjana (sahaja), 49.8%, untuk UPS dan 66.7% untuk penyelesaian gabungan. Selain itu, penyepaduan HRES mengurangkan beban grid tahunan masing-masing sebanyak 32.9, 47.2 dan 42.3%. Keputusan ini mengesahkan keunggulan HRES berbanding penyelesaian konvensional. Akhir sekali, analisis kepekaan dilakukan untuk melihat perubahan dalam LCOE dan PBP berkenaan dengan variasi dalam harga komponen, kadar tarif galakan, keadaan metrologi dan permintaan beban. Dapat disimpulkan bahawa HRES yang direka bentuk dengan baik serta dioptimumkan berpotensi untuk mengurangkan masalah penyisihan beban secara berkesan dengan kos yang berpatutan.

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LIST OF ABBREVIATIONS

AGC	-	Automatic generation control
AI	-	Artificial intelligence
ANN	-	Artificial Neural Network
Both Gen	-	Generator 1 and Generator 2
BTS	-	Base transceiver station
CA	-	Condition action
CC	-	Cycle charging
CFT	-	Condition for transition
COE	-	Cost of electricity
DSM	-	Demand side management
ESU	-	Energy storage unit
EMS	-	Energy management scheme
FiT	-	Feed in tariff
FSM	-	Finite state machine
GA	-	Genetic algorithm
Gen	-	Generator
Gen1	-	Generator 1
Gen2	-	Generator 2
GOA		Grasshopper optimization algorithm
HOMER	-	Hybrid optimization model for electric renewables
HRES	-	Hybrid renewable energy system
IHOGA	-	Improved hybrid optimization by genetic algorithms
kW	-	Kilowatt
kWh	-	Kilowatt hour
LCOE	-	Levelized cost of electricity
LF	-	Load following
LPS	-	Loss of power supply
LPSP	-	Loss of power supply probability
MPPT	-	Maximum power point tracking
NOCT	-	Nominal operating cell temperature

PBP	-	Payback period
PSO	-	Particle swarm optimization
PV	-	Photovoltaic
SOLCAST	-	Solar resource assessment and forecasting data
SOC	-	State of charge
TA	-	Transition action
ToU	-	Time of use
UPS	-	Uninterruptible power supply
WT	-	Wind turbine

LIST OF SYMBOLS

a	-	Ideality factor in single-diode model
α	-	Ground surface coefficient
A	-	Total area of solar panel
A_i	-	Wind advection for the grasshopper
B_{Grid}	-	State of the grid
C	-	GOA adaptive parameter
C_1, C_2		Coefficients of fuel consumption
C_{Bat}	-	Rated capacity of single battery in ESU
COE_{Grid}	-	Cost of electricity of grid
$Cost_{ESU}$	-	Total cost of ESU
$Cost_{Gen}$	-	Total cost of Gen
$Cost_{HRES}$	-	Total cost of HRES
$Cost_{PV}$	-	Total cost of PV
$Cost_{WT}$	-	Total cost of WT
DEG_{PV}	-	Degradation rate of PV
DEG_{WT}	-	Degradation rate of WT
d_{ij}	-	Distance of the grasshopper with the grasshopper
$\hat{e}_g$	-	Unit vector in the vertical direction of the surface
$\hat{e}_w$	-	Unit vector in the direction of the wind
$Energy_{GEN}$	-	Total energy of Gen
$Energy_{HRES}$	-	Total energy of HRES
$Energy_{PV}$	-	Total energy of PV
$Energy_{WT}$	-	Total energy of WT
ESU_supp_Load	-	ESU supplying load
η_{Bat}	-	Battery charging and discharging efficiency
η_{Gen}	-	Generator efficiency
η_{Inv}	-	Inverter efficiency
f	-	Intensity of attraction
FC_{Gen}		Diesel fuel cost per litre
FC_{Gen}	-	Fuel consumed by Gen

g	-	gravitational constant
G	-	Solar irradiance
G_{best}	-	Global best position
G_i	-	Gravity force for the grasshopper
G_{STC}	-	Solar irradiance at STC
Grid_ch_ESU	-	Grid charging ESU
Grid_supp_Load	-	Grid supplying load
h	-	Hour
h_{iu}	-	Functioning time of ith appliance of uth class
H	-	WT hub height
H_0	-	WT reference height
H	-	Annual average solar radiation on the tilted panels
H	-	History function
ith	-	Index for i$_{th}$ grasshopper
$iter_i$	-	Current iteration
$Iter_{max}$	-	Maximum iteration
I_0	-	Saturation or leakage current of diode
IC_{ESU}	-	Initial cost of ESU
IC_{Gen}	-	Initial cost of Gen
IC_{Inv}	-	Initial cost of inverter
IC_{PV}	-	Initial cost of PV
IC_{WT}	-	Initial cost of WT
I_{mp}	-	Maximum power current
I_{PV}	-	Photovoltaic current
I_{RS}	-	Reverse saturation current in diode
$I_{SC\text{-}STC}$	-	Reference short circuit current
J	-	Objective function
jth	-	Index for j$_{th}$ grasshopper
k	-	Boltzmann constant used in PV model
k_i	-	Short circuit current coefficient of PV module
k_v	-	Open circuit voltage coefficient of PV module
l	-	Attractive length scale
$Life_{Gen,\ year}$	-	Lifetime of generator in years

n_{iu}	-	Number of ith appliances in uth class
n_p	-	Sizing vector
n_p^{min}	-	Minimum bound of the decision variables
n_p^{max}	-	Maximum bound of the decision variables
n_s	-	Number of cells in single PV module
N_{Bat}	-	Optimal number of batteries in ESU
Ng	-	Number of grasshoppers
N_{PV}	-	Optimal number of modules in PV array
N_u	-	Number of users
N_{WT}	-	Optimal number of WTs
OC_{ESU}	-	Operational cost of ESU
OC_{Gen}	-	Operational cost of Gen
OC_{PV}	-	Operational cost of PV
OC_{WT}	-	Operational cost of WT
P_ESU	-	Power supplied by ESU
P_ESU_Req	-	Power required by ESU
P_Gen		Generated power of Gen
P_Gen_rated		Rated power of Gen
P_Grid	-	Power supplied by grid
P_Load	-	Power demanded by load
P_PV	-	Power supplied by PV
P_{Inv}	-	Power rating of inverter
P_{iu}	-	Nominal power rating of appliance i
P_{PV}	-	Maximum output power of single PV module
P_{Peak}	-	Peak load demand
PV_Surplus	-	PV surplus power
P_{WT}	-	Power produced by single WT
P_WT	-	Power supplied by total WT s
PV_ch_ESU	-	PV charging ESU
PV_inj_Grid	-	PV power injected to grid
PV_supp_Load	-	PV supplying load
PR	-	Performance ratio of PV

q	-	Electron charge
r	-	Total solar panel yield
r	-	Discount rate
r_1, r_2	-	Random numbers in PSO
RC_{ESU}	-	Replacement cost of ESU
RC_{Inv}	-	Replacement cost of inverter
RC_{Gen}	-	Replacement cost of Gen
R_{Grid}	-	Reserve capacity margin of the grid
R_P	-	Parallel resistance of PV module
R_S	-	Series resistance of PV module
s	-	Strength of social force
s_i	-	Social interaction for ith grasshopper
$SOCC$		Current SOC of ESU at time *t*
$SOCL$	-	Lower limit of SOC of ESU
$SOCU$	-	Upper limit of SOC of ESU
t	-	Current time step
T	-	Ambient temperature
T	-	Complete time horizon
T	-	GOA best fitness function
T_{STC}	-	Temperature at STC
u	-	User class
u_i	-	Weight assigned by designer for objective function *i*
ubd	-	Upper bound in d^{th} dimension
v	-	velocity of PSO particles
$v_{cut\ in}$	-	Cut in speed
$v_{cut\ out}$		Cut out speed
V_{mp}	-	Maximum power voltage of PV module
V_{OC}	-	Open circuit voltage
$V_{OC,STC}$	-	Reference open circuit voltage
v_0	-	Measured wind speed to anemometer height
v_{PV}	-	Photovoltaic voltage
v_{rated}	-	Rated speed of wind turbine
V_T	-	Thermal voltage of PV module

w	-	Inertia weight
w_i	-	Weight for objective function *i*
w_{max}, w_{min}	-	Inertial factor of velocity of PSO particles
$WH_{Gen, year}$	-	Generator working hours per year
WT_ch_ESU	-	WT charging ESU
WT_inj_Grid	-	WT power injected to grid
WT_supp_Load	-	Wind turbine supplying load
WT_surplus	-	WT surplus power
x_i	-	Position of ith particle in PSO
X_i	-	Position of ith grasshopper
θ_i	-	Normalization factor of objective function *i*

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CHAPTER 1

INTRODUCTION

1.1 Background

For decades, many developing countries are grappling with energy crisis that severely hindered their economic growth and social transformation programs [1]. Due to regular, long-term electric power shortages, consumers in these affected regions must rely on alternative source of power such as diesel generators and battery banks to meet their own energy needs. Often, electricity derived from these sources is insufficient to meet their needs and, in most cases, it is more expensive than the grid tariff. But since options are limited, they have to make do with these solutions. On the utility side, one of the most effective short-term measures to alleviate this problem is to impose load shedding—a regimented operating condition whereby the grid is disconnected from customers within a specified region for several hours per day. In essence, it removes or curtail certain amount of load when the demand for electricity exceeds the supply capability of the network [2]. The idea is to minimize the deficit between generation capacity and demand, while ensuring a fair level of supply availability for all consumers [3]. Although this constraint is undesirable, load shedding is necessary to prevent systemic power failure, which can be detrimental to the transmission and distribution infrastructures [4].

Normally, the supply disconnection is scheduled on a rotational basis *i.e.*, the electricity is made available (or conversely, unavailable) to different consumers during different window, within the 24 hours. Whilst load shedding is supposedly to be a temporary solution, unfortunately, for many developing countries, the inability of the utility operator (or the government) to build power generators results in no immediate prospect in sight [5]. Failure to provide continuous electricity supply has negative consequences on the economy, productivity, security and social well-being of the population [6]. Since the impact of the load shedding is adverse, the operator is left with little choice but to upgrade the generation capacity [7]. However, in countries where load shedding is in place, the projected supply-demand gap continues to rise exponentially—primarily due to the rapid growth and the changing lifestyles of the population. With little prospect of investment, it seems that the problem of supply availability will persist for a foreseeable future.

To many customers, the most practical mitigation method is to self-install their own uninterruptible power supply system (UPS), diesel generators, or a combination of both [8]. Although these conventional solutions are widely adopted, they inherit several drawbacks. For instance, the UPS must be charged from the grid electricity, which is already under stress from the insufficient generation and over-demand. Further, due to the crude infrastructure, the power wastage of UPS can be as high as 25% during the charging and discharging process [9]. On the other hand, the generators have numerous disadvantages: their running cost (in Dollar/Watt) is very high, while their economic viability is extremely vulnerable to the price of fossil fuel (diesel). Generators are also noisy, require regular maintenance and exhibit much lower efficiency. Furthermore, they contribute significantly to the greenhouse gas emission—thus, posing serious negative impact to the environment [10]. Despite these drawbacks, UPS and generators are still indispensable due to their rapid deployment and their ability to overcome load shedding at any time of the day.

In the wake of growing environmental concerns, the energy sector is urged to reduce the reliance on fossil fuel and is encouraged to utilize renewable sources for electricity generation [11][12]. Under these circumstances, the developing countries face two-fold energy challenges. They have to meet the need of their growing population that still lack access to basic electricity services, while simultaneously adhere to the pressure to participate in the global transition towards clean and sustainable, low-carbon energy production [13]. Nevertheless, most of these countries have numerous sources of renewable that can be tapped at a reasonable cost. Among them, solar and wind energy are recognized as the most promising due to their abundance and environment friendly nature [14]. These systems are simple to install, low in maintenance, and do not require fuel to sustain their operation. Furthermore, the energy harvesting technologies, which include photovoltaic module (PV), wind turbine (WT) and power electronic converters have reached high level of maturity and are readily available in the market. Despite these advantages, renewable sources still face obstacles to become fully dependable power generator. The sporadic behaviour of sun and wind, coupled with reliance on weather conditions and high capital costs are major barriers to their acceptance [15].

However, research has shown that if the system cost over the lifetime of the project are considered, PV or WT can be a serious competitor to the conventional energy systems [16]. This is coupled with the fact that the prices of PV modules and wind turbines have dropped significantly over the past decades. The concerns regarding intermittency can be addressed by integrating the renewables with other sources such as battery banks and diesel generator [17]. Against this background, the hybrid renewable energy system (HRES) incorporating PV, WT, ESU, and stand-by diesel generator is being proposed as an innovative concept to deal with the load shedding problem. The hybridization of the renewable sources in HRES improves the energy security by reducing the reliance on the grid uncertainty. Furthermore, the exploitation of the locally available renewable sources in the close proximity to the end users enable the HRES to offer potential environmental, economic, and societal benefits [18]. Thus, the installation of HRES represents a significant step towards the transition to more sustainable energy systems.

Although HRES is an attractive proposition, the interaction between the intermittent renewable sources and the interrupted grid (due to shedding) greatly increases the complexity of the plant. Inevitably, an energy management scheme (EMS) is needed to coordinate these sources and load to achieve an efficient and stable HRES operation during load shedding. The primary function of EMS is to manage the energy production, exchange, and utilization, such that uninterrupted power flow from the sources to the load is ensured. In addition, other objectives, such as minimizing operational cost and maximizing the usage of the renewables may be set according to the localized requirements [17].

Notwithstanding the number of research works on HRES and EMS, most of them focused on the off-grid systems [17][19][20]. There are fundamental differences between the off-grid and grid-connected with regard to load shedding. Since the former is stand-alone, *i.e.*, not connected to the grid, load shedding is never of any concern [21]. On the other hand, for grid-connected system—although it provides more flexibility, the load shedding results in system vulnerability as the grid is expected to fulfil the load demand in the absence of a sustainable source. Obviously, the conventional solution (diesel generator or UPS) can overcome this problem, but the cost of fuel and equipment maintenances might not be favourable. For HRES, the situation is more complicated because the grid must simultaneously cope with several constraints, namely the intermittency of renewables, the fluctuating power demand, the state of charge of the ESU, and the fuel consumption of the generators.

Numerous possible combinations of renewable technologies for HRES are reported in literature. For example, there are studies involving two energy sources: PV-WT [22][23][24][25], PV-ESU [26][27][28][29][30], PV-solar thermal [31][32], and WT-ESU [33][34]. In addition, several works on three sources of HRES are also reported: PV-WT-ESU [21], WT-PV-biomass [35], PV-ESU-Gen [36][37], PV-WT-fuel cell [38] and WT-PV-hydroelectricity system [39]. For comparative purposes, different grid and off-grid configurations have also been examined [40][41][42]. Furthermore, HRES are continually being applied in various regions of the world, for example in Hong Kong [43], Australia [44], France [45] and Iran [46]. Besides EMS, most of the works focuss on optimal system sizing to determine cost-effective combination of renewables and batteries system [47][48]. In recent years, heuristic algorithms such as particle swarm optimization (PSO) [49], cuckoo search (CS) [50], genetic algorithm (GA) [51], simulated annealing (SA) [52], bee algorithm (BA) [53] and grasshopper optimization (GOA) [54] are considered to solve the complex HRES sizing problems. In the light of the forgoing, this research intends to design and optimize HRES to address the load shedding problem.

1.2 Problem Statement

Despite many studies concerning HRES, limited research has been done on its application to mitigate the load shedding problem [9][55][56][57][58][59][60][61]. In particular, there is no published work that evaluates the performance of HRES compared to the conventional solution, namely the diesel generators and UPS. This is rather surprising, as the latter is very popular in countries where load shedding is an issue. Thus, it is of great interest to learn if the HRES is a more viable substitute to the diesel generation and UPS under this condition. Furthermore, it is unclear what would be the cost of installing HRES (in comparison with the conventional solution), and under what operating conditions the system would perform optimally. This is taken in the context of time of use (ToU) tariff structure and the impact of feed-in tariff (FiT) on the overall system design.

To investigate the effectiveness of HRES (in comparison to the conventional solutions), optimization of HRES should be performed from technical and economic perspective simultaneously. Indeed, optimizing the HRES under this condition is a complex task because the supply cut-offs must be synchronized with the intermittency of the renewables sources and varying load. In addition, the performance of HRES involves conflicting objectives namely minimizing the levelized cost of electricity (LCOE) and payback period (PBP), while fulfilling the dynamics of the load and weather conditions.

Due to the radically different variable types involved, plus the highly non-linear and non-convexities nature of the system, the deterministic method has never been a preferable choice to solve the component sizing problem. It has been concluded in literature that the exact mathematical formulation for such system is very complex and rarely leads to a manageable solution. Furthermore, the deterministic approach has high probability of non-convergence in polynomial computation time. It is widely believed that a good and stable sizing solution can be achieved using efficient optimization or metaheuristics algorithms. On the other hand, for the EMS, it is related to the sequential execution of the system operation; hence the deterministic method such as the rule-based [19][62] is more appropriate because it is more amenable for decision-making in real-time environment. Thus, this mixed approach, *i.e.*, metaheuristic (for sizing) and deterministic rule-based (for EMS) will be explored in this work.

1.3 Research Objectives

To address these challenges, the optimal design of HRES should consider techno-economic approach both in design and operation phases. To realize this, the following research objectives are proposed:

1. To propose a HRES of PV-WT-battery-diesel generator system such that uninterrupted power supply operation under varying weather and load shedding conditions is ensured.

2. To optimize the HRES, based on techno-economic aspects that include system sizing, LPSP, LCOE and PBP minimization within the constraints of shedding schedule, ToU and FiT incentive using grasshopper optimization algorithm.

3. To compare the performance of the HRES to the conventional solutions (UPS and generator) and to suggest recommendations on the best conditions to operate the former.

1.4 Research Scope

The scopes of the research to be carried out in this thesis is defined as follows:

1. The load shedding is categorized as planned and unplanned. This thesis only considers the former because the latter is rare and not relevant to the real power system operating condition. The planned load shedding is announced beforehand and its schedule is publicly available.

2. The research considers HRES that incorporates PV, WT, ESU, and diesel generators to fill the load energy deficit created by the load shedding. The PV and WT serve as the main energy sources; the ESU serves as the primary backup and the generators serve as a secondary backup supply during load shedding intervals. The performance of the HRES is assessed based on LPSP, LCOE and the PBP. The performance is then compared with the conventional

load shedding mitigation methods that include diesel generator, UPS, and the combination of both.

3. The proposed model is integrated with the existing grid at distribution feeder level. As case study, the HRES is intended to supply the electricity demand of a small residential community situated in the city of Quetta, Pakistan.

4. In principle, HRES operation can be viewed either as a power management or energy management strategy [63]. The concern of the former is the transients of such as voltage, current and frequency, while the latter is into system scheduling, cost, and the lifetime system performance. Due to the long-term evaluation of the proposed HRES, this work is limited to energy management only.

5. Due to the unavailability of actual systems of the appropriate size, the research is primarily based on the mathematical simulation model using MATLAB/Stateflow simulation package, and no hardware implementation is involved.

1.5 Research Significance

The renewed interest for power generation using renewables due to the global trends provide an opportunity to rethink the approach to address old yet existing load shedding problem. The problem requires intervention from the state-of-the-art as it is likely to remain significant for the near and medium term in the developing countries [64]. In this regard, proposed HRES incorporating the renewable and non-renewable energy sources (generators and batteries) considers optimized load scheduling of the sources to execute smooth power supply operation by taking into account the FiT incentive of RES and ToU grid electricity tariff. The GOA has been utilized for the very first time to optimize the size of HRES components according to the amount of load shedding. The potential application of the Stateflow in this thesis provides energy researchers an alternative to design event-driven systems. The research via a case study of Pakistan (a representative developing country) can help policy makers to ascertain the competitiveness of HRES in comparison to UPS and standalone diesel generator for regions with weak or inadequate power supply. In addition, it helps the investors to investigate the PBP of the project before its installation. On a practical level, HRES can be integrated with existing infrastructure and their installation can contribute to improve the performance of overall system in both technical and economic terms. Furthermore, this work supports the United Nation's Sustainable Development Goal (SDG) under Goal Number 7, *i.e.*, clean and affordable energy.

1.6 Research Methodology

In order to accomplish the proposed research, following methodology has been followed:

1. A comprehensive literature review on load shedding is performed focusing mainly on the root causes of the load shedding and its mitigation strategies. The renewable based hybrid system commonly known as HRES is selected as most feasible option to overcome the effect of load shedding. The literature review aims to highlight the strengths and limitations of the various aspects regarding HRES integration into the existing grid for further research. Moreover, the energy management schemes, energy management algorithms and optimal sizing methods used for HRES are analyzed.

2. A critical and strategic literature review of HRES application in several developing countries facing energy crisis is performed. The review focusses on observing the tight operational constraints of HRES components in the realistic scenario of shedding schedule, ToU and FiT structure. Several performance indicators for HRES based on technical (LPSP) and economic aspects (LCOE, PBP) are highlighted. Besides, the objective of the review is to look for a gap in the existing literature.

3. EMS for HRES is proposed to ensure continuity of power supply during load shedding. EMS is developed using rule-based algorithm and implemented in Stateflow. The optimal sizing of HRES is proposed using GOA based on multi decision criteria. The ultimate goal of the fitness function is to minimize the LCOE, PBP and LPSP. The optimal sizing results obtained by GOA are benchmarked with PSO for verification.

4. The performance of the HRES is examined via a long-term simulation study to ascertain its resiliency during extreme weather and load shedding conditions and to ensure the operating limit of the ESU is not violated. The performance of HRES is compared with conventional methods (generator, UPS, combined UPS-generator) used to mitigate the effect of load shedding. Analysis of the energy balance within the HRES, the dynamic payback period and breakdown of the cost analysis have also been performed in-depth.

5. Lastly, sensitivity analysis is performed to examine the effect of uncertainties on the system inputs that may arise in the future. The analysis is carried out by assuming variations in economic parameters, climatological parameters and demand profile. Several scenarios are generated from sensitivity analysis and the impact of each individual variation is observed on the LCOE and the PBP of the HRES.

1.7 Thesis Organization

This thesis is organized into five chapters. Chapter 1 encompasses the background of the study, problem statement, research objectives, research scope, research significance and a brief description of the methodology. The contents of the remaining chapters are outlined as follows.

Chapter 2 reviews the related research work in the literature and presents the research gap in the existing studies. Chapter is divided into two main parts. First part presents the essential background of the load shedding problem and various mitigation strategies to overcome its effect. This is followed by the introduction of the HRES, their classification, mode integration topology and the control structure. Accordingly, second part investigates the current energy management schemes applied in HRES up to date. Afterward, the criteria for HRES optimisation and the different sizing methods are discussed. Lastly, gap analysis of the existing HRES and justification to perform the ongoing research are discussed.

Chapter 3 presents the simulation model of HRES based on the components of the system, which are PV, WT, ESU, Gen and inverter along with utility grid. The model also integrates the economic modelling of these components based on the LCOE concept. Then, a brief description of the localized conditions (load shedding schedule, weather) of representative case study region along with load estimation to represent the demand profile for the simulation is given. Afterward, the development of proposed EMS for HRES is accomplished using Stateflow. Lastly, system sizing method using GOA and PSO to determine optimum size of PV modules, WT units and ESU batteries employing proposed EMS is discussed.

Chapter 4 commences by presenting the results of optimal size of the HRES for considered demand profile using GOA. Then, the sizing results are compared and validated with the help of PSO. Chapter goes on to demonstrating the resiliency of HRES in providing uninterrupted supply under different weather conditions and year-round operation. In the context of this work, resiliency is defined as the strength of the system to fulfil the demand under the given operating condition. Consequently, the comparison of HRES with diesel generator, UPS, and combined UPS-generator system is presented. At the end, sensitivity analysis is given to the test the impact of different economic, climate and demand data on the proposed HRES design.

Chapter 5 summarises the main findings derived from this research work and highlights the contributions of the proposed work. In addition, several suggestions are given for possible directions of future work.

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LIST OF PUBLICATIONS

1. **Bakht, Muhammad Paend,** Zainal Salam, Mehr Gul, Waqas Anjum, Mohamad Anuar Kamaruddin, Nuzhat Khan, and Abba Lawan Bukar. "The Potential Role of Hybrid Renewable Energy System for Grid Intermittency Problem: A Techno-Economic Optimisation and Comparative Analysis." Sustainability 14, no. 21 (2022): 14045. (Q2, IF: 3.889)

2. **Bakht, Muhammad Paend**, Zainal Salam, Abdul Rauf Bhatti, Usman Ullah Sheikh, Nuzhat Khan, and Waqas Anjum. "Techno-economic modelling of hybrid energy system to overcome the load shedding problem: A case study of Pakistan." *PloS one* 17, no. 4 (2022): e0266660. (Q2, IF: 3.752)

3. **Bakht, Muhammad Paend**, Zainal Salam, Abdul Rauf Bhatti, Waqas Anjum, Saifulnizam A. Khalid, and Nuzhat Khan. "Stateflow-Based Energy Management Strategy for Hybrid Energy System to Mitigate Load Shedding." *Applied Sciences* 11, no. 10 (2021): 4601. (Q2, IF: 2.838)

4. **Bakht, Muhammad Paend**, Zainal Salam, and Abdul Rauf Bhatti. Investigation and modelling of load shedding and its mitigation using hybrid renewable energy system. IEEE 7th International Conference on *Power and Energy (PECon)* (2018), Dec 3 (pp. 35-40). IEEE. (Indexed by SCOPUS)