Chapter 1

Introduction

The global demand for energy is rising, driven by population growth, urbanization, and industrialization. However, traditional fossil fuel-based power generation is not only limited in availability but also contributes to environmental pollution, notably through increased (CO_2) emissions [120]. This has spurred a search for sustainable alternatives, leading to the widespread exploration of sustainable energy resources such as solar and wind energy. Photovoltaic (PV) power, in particular, has seen rapid expansion due to factors like dwindling fossil fuel reserves, environmental concerns, and advancements in manufacturing technologies associated with PV systems. Renewable energy systems, particularly photovoltaic (PV) cells, heavily rely on fluctuating external factors like solar radiation and temperature[230]. This variability leads to non-linearity in the current-voltage (I-V) characteristic curve of PV cells, resulting in time-varying maximum power outputs. Without tracking systems, the rated power stated in PV module data-sheets remains underutilized, diminishing the cost-effectiveness of PV systems[260]. This limitation, coupled with low power output capacity and high associated costs, drives the investigation into developing efficient PV converters and controllers to maximize power extraction while ensuring cost and energy efficiency.

DC-DC Power Processing Units (PPUs), equipped with power point tracking, play a vital role in optimizing the operational state of PV systems by regulating voltage and current to approach the maximum power point (MPP) in response to varying atmospheric conditions [61]. The Maximum Power Point Tracker (MPPT) ensures efficient energy transfer by balancing incoming and outgoing power based on the equality principle [97]. The functioning is based on the equality of power, i.e. power input P_{in} is equal to the power output P_{out} [97]. Moreover, during nighttime or low solar irradiance conditions, the MPPT prevents reverse power flow from the batteries to solar panels , enhancing system reliability and performance[44, 186, 275].

The importance of the DC-DC converters is further highlighted in their use in renewable energy applications [28, 165, 209, 236], in speed control of DC motor drives [175] and BLDC motor drive control [126], in fuel cell applications [117] making them a very efficient power conversion device. Implementing optimization techniques in the development of power electronic converters presents a compelling research challenge [161]. Traditional manual design processes for DC-DC converters are labor-intensive and costly, involving meticulous selection of components like inductors and capacitors, as well as consideration of factors such as electromagnetic interference (EMI) and load variations. Designers must ensure efficiency across diverse loads while meeting stringent EMI criteria. This complexity often necessitates iterative design processes. Consequently, the application of optimization algorithms has emerged as a promising approach to streamline converter design, tailor topologies to specific utility needs, and reduce computational time[214].

Electronics breakthroughs have improved DC-DC converter production, particularly energy storage elements [85, 212]. Size and losses have been reduced, and power electronic switches have improved blocking voltage, transient stress withstand, and operational efficiency. Even though significant advances have been made, the difficulty of choosing ideal size design parameters to enable effective functioning under certain constraints persists[129, 214].

Solar, wind, biomass, and other renewable sources are combined in a hybrid renewable energy system (HRES) to generate power reliably and cheaply[142]. These systems can be grid-connected or isolated and use diesel generators for storage and backup. HRES can supply energy needs in remote places where traditional power sources are inaccessible or impracticable, minimizing grid dependence [207]. Efficient HRES control requires assessing primary resource availability, determining load demands, and optimizing system design and sizing with or without storage. To ensure dependable transmission of electricity to consumers or distributed generation, researchers optimize system size[25, 38, 62, 76, 81, 141, 163, 168, 174, 179, 179, 182, 223, 245, 259], economic operation [25, 33, 49, 80, 103, 164, 218, 256], controller design [26, 29, 30, 39, 110, 218],real and reactive power control [29,67,251,269] voltage and frequency control [162] and for grid connected HRES, evaluation of performance based on reliability is conducted [251]. An investigation of concept of the complementarity of the time for hydro and PV system based generating power plants is covered in [24,32,119,132].

Results indicated that solar and hydro power in the long term are complementary with each other, and if complementarity in the time index increases, failure index decreases.

Figure 1.1 illustrates the schematic representation of a HRES using solar energy and wind energy as the primary sources.

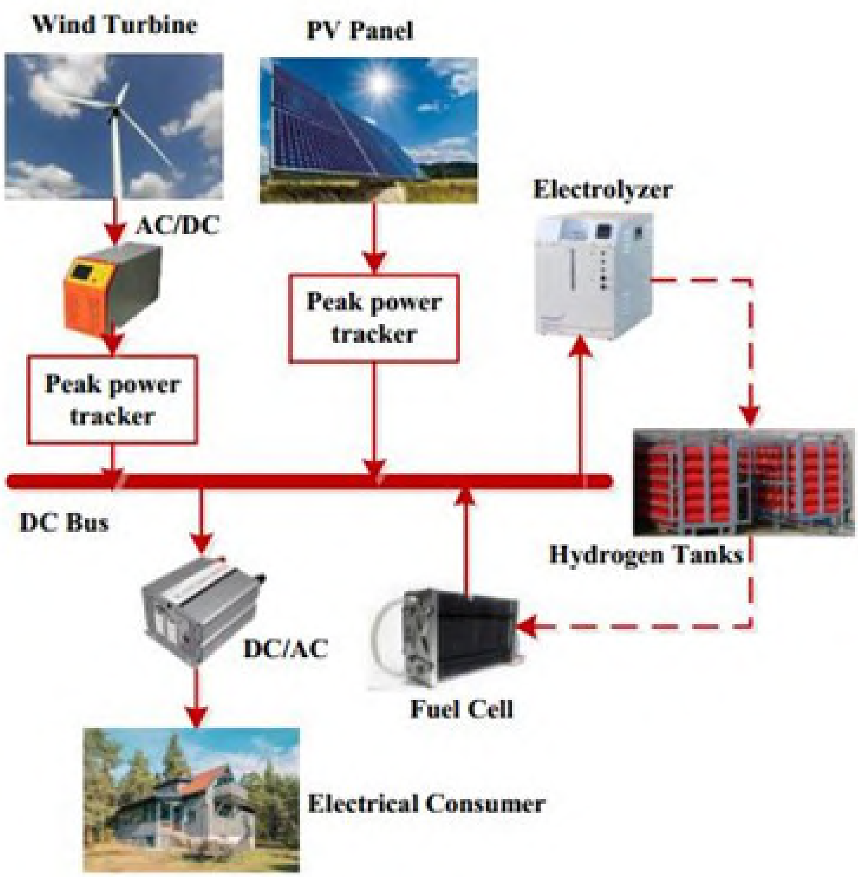

Figure. 1.1: Architecture of a HRES based on PV and wind power [102]

Metaheuristics are popular optimization algorithms because they solve nonlinear problems realistically in an acceptable period[41, 74, 253]. Metaheuristics improve convergence to optimal solutions and reduce processing costs over derivative-based methods like Steepest Descent and Newton's Method [147, 177]. Exploration and exploitation are the two search phases that metaheuristic optimization algorithms employ. Exploration thoroughly searches the search space to identify solutions without local optima. In the exploitation phase, algorithms use recognized solutions to improve local solutions[88, 229]. These approaches are effective in real-time assessment, however their convergence rate, iteration rate, and optimal solution speed are limitations.

1.1 Motivation

The objective of scientific investigation is to offer the optimal solution to an identified problem. The answer to the problem should have two primary aspects: firstly, it should fill the gap in the existing literature by contributing new insights, and secondly, it should include a comprehensive description of the technique used to acquire the solution within the specific area of the research challenge.

Based on the comprehension of examined literature, DC-DC converters as power interfaces are crucial to MPPT PV systems. Fast-responding algorithms which track solar irradiance and ambient temperature changes can match shifting load demand and source potential. Power converters have switching and operational losses. Under a rated voltage and current, an optimized converter topology improves performance. Selecting the right switching frequency, inductor and capacitor sizes helps meet the required performance criteria. Thus, an optimal power converter will increase tracking efficiency for MPPT applications for standalone PV systems, which is the goal of every MPPT algorithm. Similarly, the ideal design of a hybrid PV-hydro Renewable Energy System for rural North East India has not been examined. The complimentary nature of renewable sources is well recognized, but demand response should be considered when designing a hybrid system when grid electrification is problematic or uneconomical. Metaheuristic algorithms have become popular in the last decade because they find optimal solutions with cheap computing cost. Their gradient-free method offers advantages, but their stochastic character makes them susceptible to local optima. This also requires improving an algorithm's exploration and exploitation capacity to explore the search space to maximize both features for an optimization challenge.

This thesis aims to fill the gap in current literature by conducting a thorough examination into the areas of design optimization in renewable energy systems. This involves selecting the most suitable converter architecture for standalone photovoltaic (PV) systems that integrate MPPT to improve the system's performance. Next, we examine the most efficient way to determine the optimum sizing for a hybrid renewable energy system that combines PV and hydro-power technologies, designed for remote areas applications based on load demand and lowest possible cost configuration. Furthermore, a novel hybrid algorithm is introduced that possesses superior capabilities in both exploration and exploitation by integrating the principles of Grey Wolf Optimizer (GWO), Sine Cosine Algorithm (SCA) and Particle Swarm Optimization (PSO) algorithms. This algorithm is specifically designed for optimizing renewable energy systems, with a particular focus on addressing the aforementioned challenges and improving the overall performance in the application for solving engineering design optimization problems. The overall workflow adopted in the thesis is presented in figure 1.2.

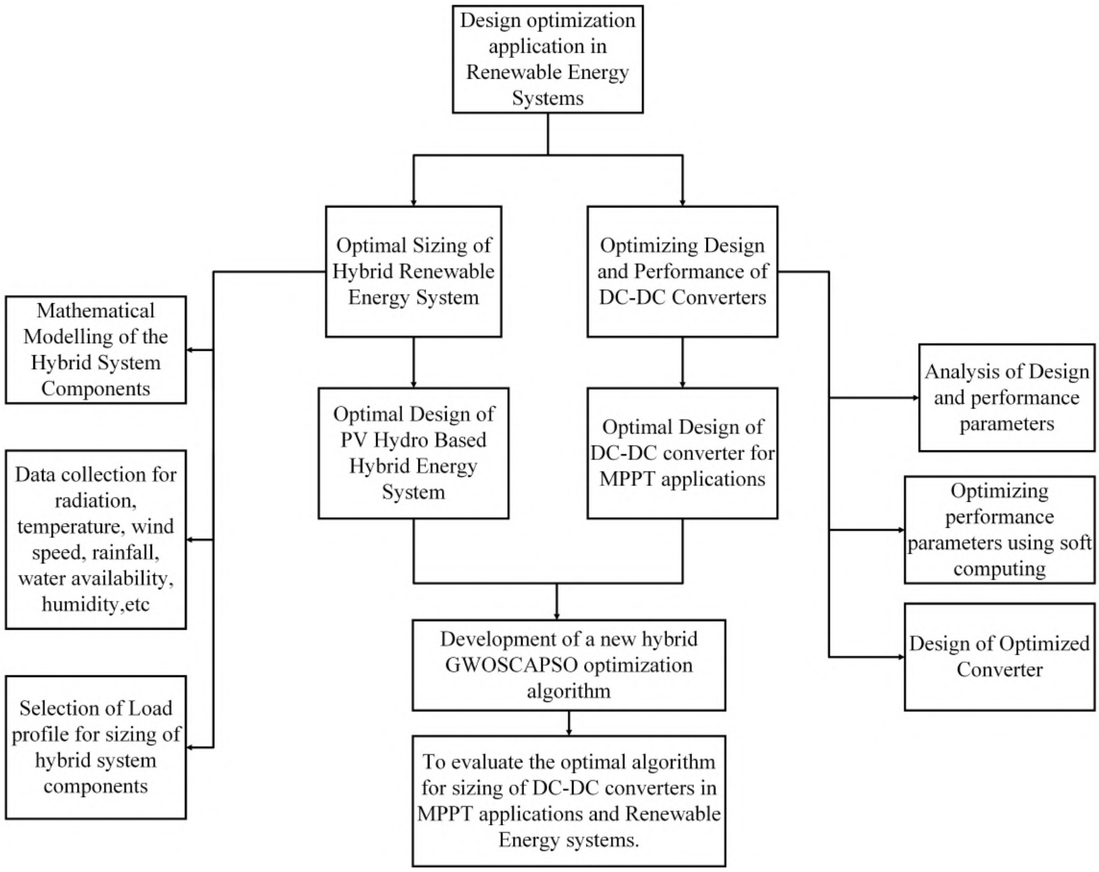

Figure. 1.2: A flowchart of overall workflow of the research work

1.2 Objectives

The research work presented in this thesis will delve into reviewing and finding the best configuration of dc-dc converter topology that can be implemented for MPPT applications with PV source in a standalone system configuration. Steady state system modeling along with the design optimization at reduced converter loss will be explored. The study will focus on finding and assessing the performance of an optimal power converter design configuration, together with the appropriate chosen tracking algorithm, for power point tracking application in a standalone PV system.

The thesis will also focus on developing a mathematical model of PV Hydro HRES. Proper system sizing with respect to the individual components of the hybrid system based on predicted or anticipated energy generation (based on weather data) from the primary energy sources of PV and Hydro with options for storage along with the ability to meet the load demand will be explored. A class of most recent algorithms implemented with respect to this objective will be referred and comparative assessment will be reported on the efficacy of the selected algorithms with popular and widely used optimization algorithms which find inspiration in nature.

The use of a hybrid optimization algorithm to solve the design optimization problems associated with renewable energy systems will also be addressed in the current study. In order to improve the performance of the Grey Wolf Optimizer (GWO), it is hybridized with the Sine Cosine Algorithm (SCA) and the Particle Swarm Optimization (PSO) Algorithm to produce the hybrid GWOSCAPSO algorithm. The breakup of the proposed work can be classified under the following heads:

I To optimize the design and performance parameters of the dc-dc converter interface for Maximum Power Point Tracking (MPPT) applications.

II To optimize the component sizing of a hybrid renewable energy system based on the load demand.

III To develop a novel hybrid optimization algorithm for the optimal sizing of renewable energy systems.

IV To evaluate the optimal algorithm for sizing of DC-DC converters in MPPT applications and renewable energy systems.

1.3 Materials and Methods

This thesis attempts to bridge the gap between the application of soft computing approaches with comparative assessment and analysis of individual algorithms for the control and design optimization of HRES. This is planned to be achieved as per the following objectives:

1. **To optimize the design and performance parameters of the DC-DC converter interface for Maximum Power Point Tracking (MPPT) applications.** The choice of correct converter topology to implement the MPPT algorithm is a critical deciding factor that enables harnessing the

maximum energy potential from the sun. The intelligent tracking algorithm ensures that the maximum available energy is utilized for power generation in the hybrid system.

2. **To optimize the component sizing of a hybrid renewable energy system based on the load demand:** Optimum sizing of the system components of a HRES on the basis of available data for radiation, temperature, wind speed, availability of water to match the demand load profile ensures proper utilization of the available resources for clean power generation. Improper design of the system will lead to mismatch due to an ineffective co-generation from the sources, which will result in a decrease in the overall performance efficiency of the HRES.

3. **To develop a novel hybrid optimization algorithm for the optimal sizing of renewable energy systems:** The growing interest in design and development of new metaheuristic algorithms for the solution of engineering design optimization problems is a research dimension with potential wide-scale application. The hybridization of well known popular algorithms have given improved results and have been successfully implemented in signal processing, power system optimization studies, microwave and antennas, to name a few. An hybrid algorithm to tackle the above listed problems under consideration in the current work will be addressed.

4. **To evaluate the optimal algorithm for sizing of DC-DC converters in MPPT applications and renewable energy systems:** Validation of the developed hybrid algorithm and comparative analysis of the results obtained from the solution of the optimization problem of sizing of DC-DC converters and a hybrid PV-Hydro based RES is essential. Intelligent algorithms need to be evaluated on the basis of their performance in achieving near optimum result without premature convergence, minimal computation effort and ability to handle the constraints of the optimization problem along with the robustness of the algorithm.

1.3.1 Computational Methods

I **To optimize the design and performance parameters of the DC-DC converter interface for Maximum Power Point Tracking (MPPT) applications:** This step includes the identification of performance parameters and the design constraints of the DC-DC converters. The steady state space model of a non-isolated converter topology (boost converter considered in this thesis) and formulation of the design optimization problem is developed. Furthermore, optimizing the design of the converter will reflect a long way in the development and implementation of the MPPT algorithm. MATLAB simulation software is used to implement this step. The work is further divided into the following stages:

(a) A state space based approach for the design optimization problem for minimized power loss subject to constraints for a reference DC-DC boost power converter topology.

(b) A comparative assessment of 23 metaheuristic algorithms inspired from nature which are categorized to be swarm based, physics based and others to be applied for the optimal design and sizing of dc-dc converter.

(c) Finally for a PV system with MPPT applications, an optimized DC-DC boost converter is designed such that the configuration will enable the converter to be utilized to track the solar PV MPP operation condition.

II **To optimize the component sizing of a hybrid renewable energy system based on the load demand:** The optimized component sizing of the hybrid PV/Hydro system is divided into the following tasks:

(a) Mathematical Modeling of the hybrid system components. This includes modeling the PV subsystem along with hydro subsystem along with the constraints for the optimization problem.

(b) Evaluation of available local resources for renewable power generation estimation. This task encompasses the data collection on the availability of the solar irradiation data, temperature and humidity data, along with the potential use of mini or micro hydel power plants, i.e. the availability of rainfall data and reserve water storage. To accomplish this goal data from a previous study conducted by Pandey [181] has been taken into account.

(c) A selected load profile for a remote location in Dimapur, Nagaland, North East India for optimal sizing of the hybrid PV/Hydro based renewable energy system.

(d) The system development and integration in MATLAB environment to accomplish the aforementioned tasks. Similar to objective I, 23 metaheuristic algorithms are also implemented for the optimization problem.

III **To develop a novel hybrid optimization algorithm for the optimal sizing of renewable energy systems:** The design and development of a hybrid metaheuristic optimization algorithm for solving engineering optimization problems with special application for optimizing RES is presented. The GWO algorithm is hybridized with SCA and PSO algorithms to improve its exploration and exploitation capabilities. The algorithm is evaluated first on 23 benchmarks problems which include Unimodal, multimodal and fixed dimension multimodal functions. The hybrid GWOSCAPSO algorithms performance is investigated using statistical parameters like standard deviation, mean value, worst value and best value obtained. The performance indicators illustrate the effectiveness of the algorithm developed and its potential scope of application in design optimization problems considered in the current study and the field of engineering optimization in general.

IV **To evaluate the optimal algorithm for sizing of DC-DC converters in MPPT applications and renewable energy systems:** This involves the comparative study of the algorithms used for the optimization of the power converter topology, the optimal design of the DC-DC Converter for MPPT applications of PV systems and for the optimal sizing of the HRES. To study the efficacy of the developed hybrid algorithm, comparative assessment is made with GWO,SCA, PSO, WOA, ALO and MFO algorithms which have proved their worth in major areas of optimization and engineering applications. The comparisons are made on the basis of performance criterion like convergence speed, computational effort, and statistical analysis to evaluate the best algorithm.

1.4 Major Contribution of the thesis

The study conducted in this thesis resulted in the following contributions:

- A comparative investigation of 23 optimization algorithms, both new and popular for solving design optimization problems involving DC-DC power converters and optimal sizing of a hybrid renewable energy based system with PV and hydro power as the primary sources.
- An optimized DC-DC boost converter for application in MPPT for standalone PV systems.
- A framework for size optimization of PV-Hydro based Hybrid Renewable Energy System for rural electrification of isolated hamlets for regions with

similar demographic, geographic and load profiles as compared to the study region under consideration, i.e. Dimapur, Nagaland, North East, India.

- A novel hybrid GWOSCAPSO metaheuristic optimization algorithm for solution of engineering optimization problems.

1.5 Organization of the Thesis

The thesis is organized into six chapters. A brief introduction to each chapter is given as follows:

Chapter 1: Introduction : The chapter gives a brief overview of the work presented in the thesis. The major points of note includes the motivation behind the current work, the objectives of the study, the methodology and contribution of the thesis.

Chapter 2: Literature Review: The chapter introduces the classification of metaheuristic algorithms based on swarm intelligence, physics-based methods, and other approaches, highlighting their natural inspirations and governing philosophies. The philosophy of hybridization of algorithms to improve the performance of algorithms will also be briefly discussed. These algorithms are used in the thesis for comparative investigations in design optimization problems. The challenges of design optimization of DC-DC converters and various solution approaches reported though literature are briefly highlighted. The chapter also covers an overview of the literature on Maximum Power Point Tracking (MPPT) using various power converter topologies. It presents a detailed analysis of both isolated and non-isolated DC-DC converters, emphasizing the advantages of non-isolated converters in MPPT applications. The literature review also covers optimization techniques for hybrid renewable energy systems, focusing on the application of Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and other metaheuristic algorithms.

Chapter 3: Optimal design of DC-DC converter for MPPT applications: The chapter outlines the criteria for designing an optimal DC-DC converter. It uses state space model of the boost converter to optimize configurations for frequency, capacitance, and inductance while minimizing losses for a given load. The design optimization problem is formulated with an objective function, decision variables, governing equations, and constraints. The chapter also covers the optimally designed boost converter's role in MPPT applications for standalone PV systems, analyzing various atmospheric conditions. It investigates standalone PV system integrated with optimally designed DC-DC boost converter using tracking algorithms such as Perturb and Observe, Fuzzy Logic, Artificial Neural Network, Particle Swarm Optimization, and Cuckoo Search Algorithm. The optimally designed converter shows improved tracking performance, and a comparative analysis of 23 selected algorithms is presented for the design optimization problem.

Chapter 4: Optimal sizing of the Hybrid Renewable Energy System (HRES): The chapter details the design optimization methodology for hybrid renewable energy systems, focusing on rural electrification using PV and hydro power. It highlights the complementary nature of these energy sources and presents a mathematical model of the system. The feasibility and cost analysis for a region near Hazadisa Village in Nagaland, North East India, based on a specific demand load profile, is examined. The chapter also outlines the mathematical formulation for using metaheuristic algorithms to optimally size the hybrid system for the levelized cost of electricity (LCOE). This sizing approach is applied using 23 selected algorithms.

Chapter 5: Development and comparative assessment of a hybrid optimization algorithm: The chapter introduces the hybrid GWOSCAPSO algorithm, which combines the Grey Wolf Optimizer (GWO), Sine Cosine Algorithm (SCA), and Particle Swarm Optimization (PSO) to improve the exploration and exploitation capabilities of the GWO algorithm. This hybrid approach leverages the strengths of each algorithm: GWO's ability to balance exploration and exploitation, SCA's mathematical functions for exploration, and PSO's social and cognitive learning mechanisms as well as exploitation. The performance of the GWOSCAPSO algorithm is evaluated based on computational complexity of the algorithm and on 23 established benchmark functions covering unimodal, multimodal and fixed dimension multimodal operators. To test the efficacy of the proposed algorithm against established algorithms, the optimization problem involving renewable energy systems considered in the study is detailed. Additionally, the chapter emphasizes the importance of statistical tests in validating the performance enhancements offered by the hybrid algorithm.

Chapter 6: Conclusion and Future Directions: The chapter draws a conclusion to the thesis work. The limitation of the study are highlighted and discussed. The follow up work related to hybrid metaheuristic algorithms is presented along with some of the possible future research directions in the same area.