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Graduation Project

Optimization and Application of Fuzzy Logic Controller in HOMER Software

ENHANCING SYSTEM PERFORMANCE IN ENERGY MODELING

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Introduction:

Background

Integrating energy sources into power systems poses challenges that require advanced control strategies to ensure stability and efficiency. Traditional control methods often struggle with the variability and unpredictability of sources such, as solar and wind. Fuzzy Logic Controllers (FLC) emerge as a solution due to their capacity to manage imprecision and partial truths associated with real world inputs making them well suited for environments like renewable energy management. The global acceleration of energy integration into power grids in years brings forth distinct hurdles especially in handling the fluctuating nature of sources like wind and solar. Sophisticated control systems like Fuzzy Logic Controllers (FLC) play a role, in overcoming these obstacles by offering dependable and effective energy management solutions.

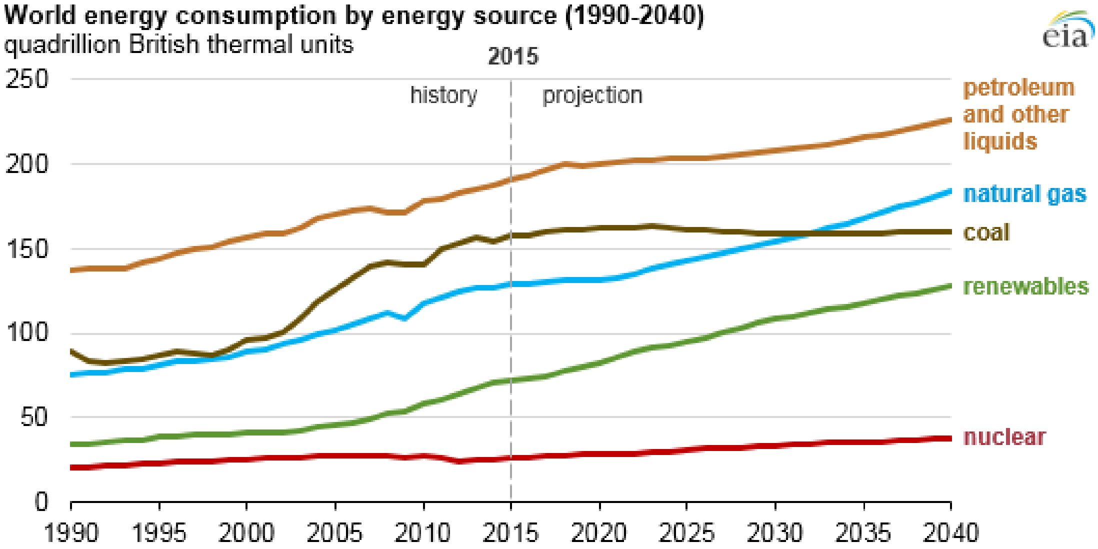

Fig.1: World energy consumption by energy source

Problem Statement

The increasing use of energy highlights the importance of improving the effectiveness of energy management systems especially when it comes to reducing costs. Conventional systems face challenges, because of the nature of energy sources. Fuzzy Logic Controllers, fine tuned with algorithms such, as Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) offer a solution to boost cost efficiency while adjusting to fluctuating energy scenarios.

Objectives

The main goal of this project is to create and improve a Fuzzy Logic Controller by utilizing Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) to manage energy in an energy system. The focus of this optimization is to reduce expenses while ensuring energy efficiency and reliability are upheld. Some of the objectives are:

1. Develop FLC for managing energy distribution in renewable energy systems.
2. Utilize PSO and GA to enhance the cost-effectiveness of the FLC.
3. Compare the cost efficiency of the optimized FLC against traditional controllers used in HOMER software, such as load flow and cycle-by-cycle controllers, to establish the most cost-effective control strategy.

Scope

This research study delves into developing, refining and assessing a Fuzzy Logic Controller using the HOMER software with a focus on minimizing operational expenses. It investigates how various optimization methods, particularly PSO and GA influence the cost effectiveness of FLCs in overseeing energy setups. The project extensively employs MATLAB for crafting the Fuzzy Logic Controller implementing optimization algorithms and establishing connectivity, with HOMER software via a customized MATLAB Link script. This integration facilitates management and optimization of energy systems allowing for real time simulations and thorough evaluations of cost effectiveness.

Overview of Fuzzy Logic Controllers (FLC):

Definition and Principles of Fuzzy Logic

Fuzzy Logic extends classical Boolean logic to handle the concept of partial truth — truths that can exist between completely true and completely false. Developed by Lotfi Zadeh in the 1960s, fuzzy logic introduces degrees of truth as a way to mimic human reasoning in decision-making processes under uncertainty. This logic is particularly useful in systems where information is imprecise or incomplete, making it ideal for complex and dynamic environments like renewable energy management.

Architecture of Fuzzy Logic Controllers

A Fuzzy Logic Controller (FLC) operates on the principles of fuzzy logic to transform a set of input data into desired output actions through a process of fuzzification, rule application, and defuzzification:

- **Fuzzifier:** Converts crisp input values into degrees of match with linguistic terms by applying membership functions.
- **Rules Base:** Contains a set of fuzzy rules which are linguistic rule statements that describe how the FLC should make decisions.
- **Inference Engine:** Processes the rules in the context of the current input conditions to derive fuzzy output distributions.
- **Defuzzifier:** Converts the fuzzy outputs into a crisp output, typically using methods like the centroid or the mean of maximum.

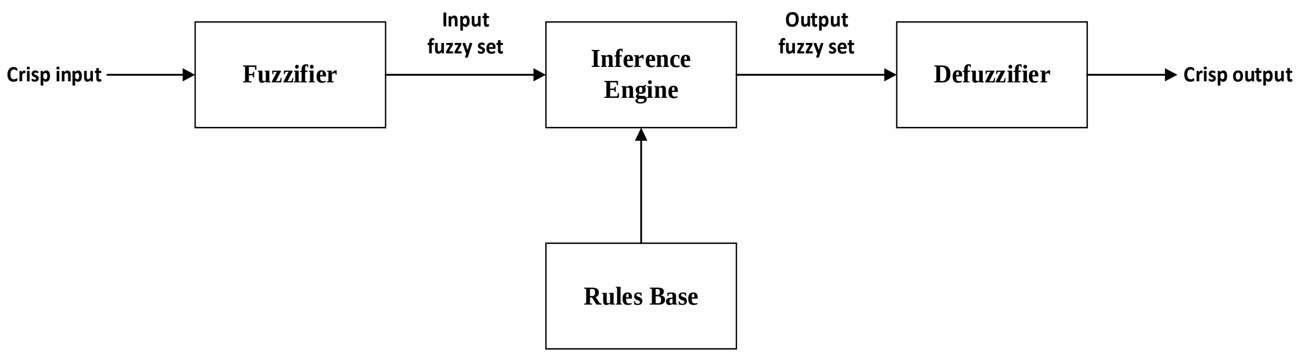

Fig.2: Fuzzy Logic Controller block diagram

Applications in Energy Management

Fuzzy logic controllers (FLCs) are commonly used in energy management to optimize and regulate systems like solar power plants, wind turbines and smart grids. Their effectiveness, in dealing with changing and environmental factors makes them well suited for renewable energy purposes especially when the availability of resources varies greatly. FLCs excel in handling nonlinear systems without the need for precise mathematical models. This flexibility allows them to adapt quickly to changing system inputs and maintain high performance without extensive recalibration.

Challenges and Limitations

While FLCs offer significant benefits, they also come with challenges:

- **Design Complexity:** The design of an effective FLC depends heavily on the knowledge and expertise of the designer in crafting the rule base and choosing appropriate membership functions.
- **Scalability Issues:** When more inputs and rules are added the fuzzy logic controller can become more complex. Require higher computational resources, which might result in delays, in response times.
- **Research Gaps:** Further research is needed to automate the design of FLCs, enhance their scalability, and integrate machine learning techniques for dynamic rule adjustment.

Overview of Particle swarm optimization (PSO):

Introduction to PSO

Particle Swarm Optimization (PSO) is a method for optimizing processes that relies on the collective movement and intelligence of groups. In PSO a group of solutions called particles navigates through the search area adjusting their paths based on individual experiences and interactions, with neighboring particles. This collaborative approach enables the swarm to progress towards solutions effectively..

Mechanism of PSO

PSO simulates the behaviors of bird flocking or fish schooling, where all individuals adjust their positions using the following two "best" values:

- **Personal Best (pBest):** Each particle keeps track of its personal best position in the search space where it experienced the highest performance measured by the fitness function.
- **Global Best (gBest):** The best position found by any particle in the entire swarm is shared among all particles, influencing their next position.

The position and velocity of each particle are updated using the following formulas:

- **Velocity Update:** $vi(t+1) = w \cdot vi(t) + c1 \cdot r1 \cdot (pBesti - xi(t)) + c2 \cdot r2 \cdot (gBest - xi(t))$
- **Position Update:** $xi(t+1) = xi(t) + vi(t+1)$

Here, vi and xi represent the velocity and position of the particle, w is the inertia weight, $c1$ and $c2$ are the cognitive and social parameters, respectively, and $r1, r2$ are random numbers between 0 and 1.

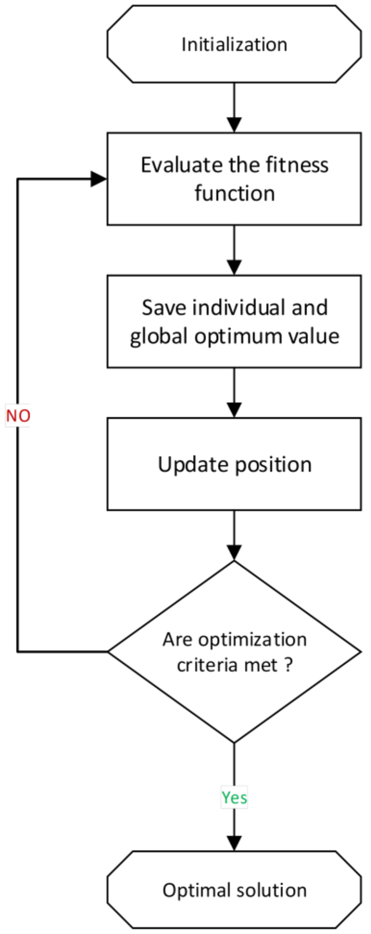

Fig.3: Basic structure of PSO algorithm

PSO in Controller Optimization

When it comes to optimizing controllers PSO is used to discover the configurations that enhance the performance of controllers such, as Fuzzy Logic Controllers (FLCs). For instance, PSO can be used to tune the membership functions or the rule base of an FLC, effectively adapting the controller to various operational conditions without human intervention.

Benefits and Challenges

- **Advantages:** PSO is favored for its simplicity and effectiveness, particularly in high-dimensional spaces. It does not require gradient information and can escape local optima, which is advantageous for non-linear problem spaces like controller design.
- **Challenges:** Despite its benefits, PSO can suffer from convergence issues in complex landscapes and is sensitive to the settings of its parameters (e.g., swarm size, $c1$, $c2$, and w).

Connection to Project

In this project, PSO is strategically used to enhance the performance of a Fuzzy Logic Controller managing a renewable energy system within the HOMER environment. By optimizing the parameters of the FLC, like membership functions and rule bases, PSO notably reduces operational costs.

Overview of Genetic Algorithm (GA):

Introduction to GA

Genetic Algorithms (GA) are a type of optimization technique that takes inspiration from the natural selection process observed in evolution. These algorithms mimic how the strongest solutions survive and evolve over generations to solve complex problems. GAs are known for their success in scenarios with difficult solution spaces making them applicable to various optimization challenges, such, as refining controllers.

Mechanism of GA

The Genetic Algorithm works through several stages, each mimicking natural evolutionary processes:

- **Encoding:** Solutions in a GA are represented as chromosomes, which are typically strings of bits, characters, or numbers. Each chromosome encodes a potential solution to the problem.
- **Selection:** GA begins with a randomly generated population of chromosomes. The algorithm then selects individuals at random to reproduce, with a higher selection probability assigned to those with better fitness scores.
- **Crossover (Recombination):** Selected chromosomes pair and exchange segments of their encoding, creating offspring that inherit features from both parents. This process helps to explore new parts of the solution space.

- **Mutation:** With a small probability, random changes are introduced to the offspring chromosomes to maintain genetic diversity within the population and to explore new areas of the solution space.

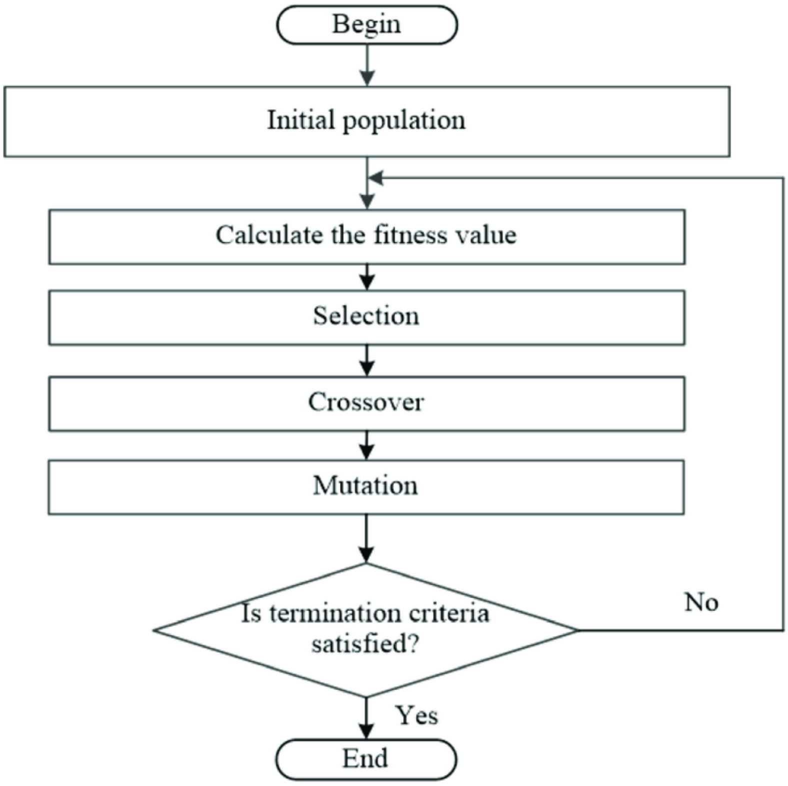

Fig.4: Basic structure of GA algorithm

GA in Controller Optimization

In the context of optimizing Fuzzy Logic Controllers (FLCs):

FLC Optimization: Genetic algorithms play a role in enhancing the effectiveness of Fuzzy Logic Controllers (FLCs) by adjusting their rule base and membership functions. Each parameter setting in the FLC is represented as a gene in a chromosome allowing genetic algorithms to systematically explore configurations. This structured search process helps pinpoint the setup for managing energy systems. By starting with an population of solutions each represented by a unique chromosome genetic algorithms refine these solutions through cycles of selection, crossover and mutation. Through these operations superior traits are. Combined in new ways to continuously improve system performance. This strategic approach effectively tackles the challenges, in energy system management ultimately boosting FLC adaptability and efficiency.

Benefits and Challenges

- **Advantages:** GA is powerful in solving problems with multiple local optima, as it is less likely to get stuck in suboptimal solutions compared to other optimization methods. It is also flexible enough to handle different types of data and constraints.
- **Challenges:** One of the main challenges with GA is the risk of premature convergence, where the population loses diversity and converges to a suboptimal solution. Additionally, GAs can be computationally expensive, especially as the size of the problem increases.

Connection to Project

In this research we utilized a Genetic Algorithm (GA) to tune the settings of a Fuzzy Logic Controller (FLC) for enhancing an energy system. This optimization led to reduced expenses improved dependability and effectiveness. The GA demonstrated effectiveness in developing control strategies that can adapt to the changing environment often encountered in energy setups.

Preliminary Project: Motor Controller Using Fuzzy Logic Optimized by PSO and GA:

Introduction to the Preliminary Project:

before implementing optimization methods on the energy management system a preliminary project was initiated to confirm the feasibility and efficiency of these techniques. The goal was to create a motor controller utilizing a Fuzzy Logic Controller (FLC) enhanced through Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). This initial project focused on regulating motor speed to align with the desired speed serving as a demonstration of concept.

Implementation Details

The motor controller was created using MATLAB Simulink. Combined with a Fuzzy Logic Controller, for the primary control logic. PSO and GA were included to tune the controller membership functions guaranteeing efficient adjustments to the motor speed. The main goal of the optimization was to reduce the gap between the desired speed and the actual speed and see how well the controller responds and maintains accuracy. The diagram below in (figure 6) is from the Simulink model used in this project offering an overview of the control systems structure.

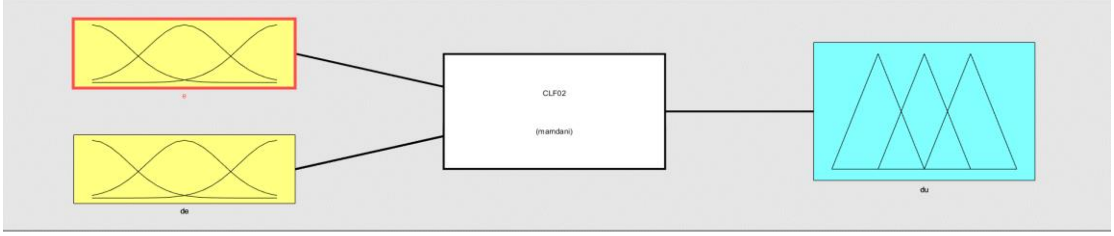

Fig.5: FLC model

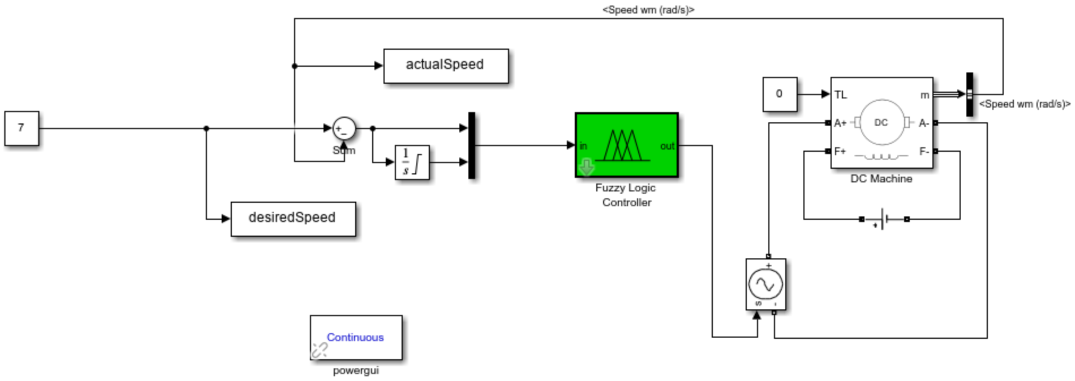

Fig.6: Simulink model for motor control

Optimization Techniques Applied

The motor controller was optimized using Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) to refine the membership functions of the Fuzzy Logic Controller (FLC). The graphs (figure 7 - 8) below provided showcase how each technique showing the fitness value across iterations and highlighting the best value for each method.

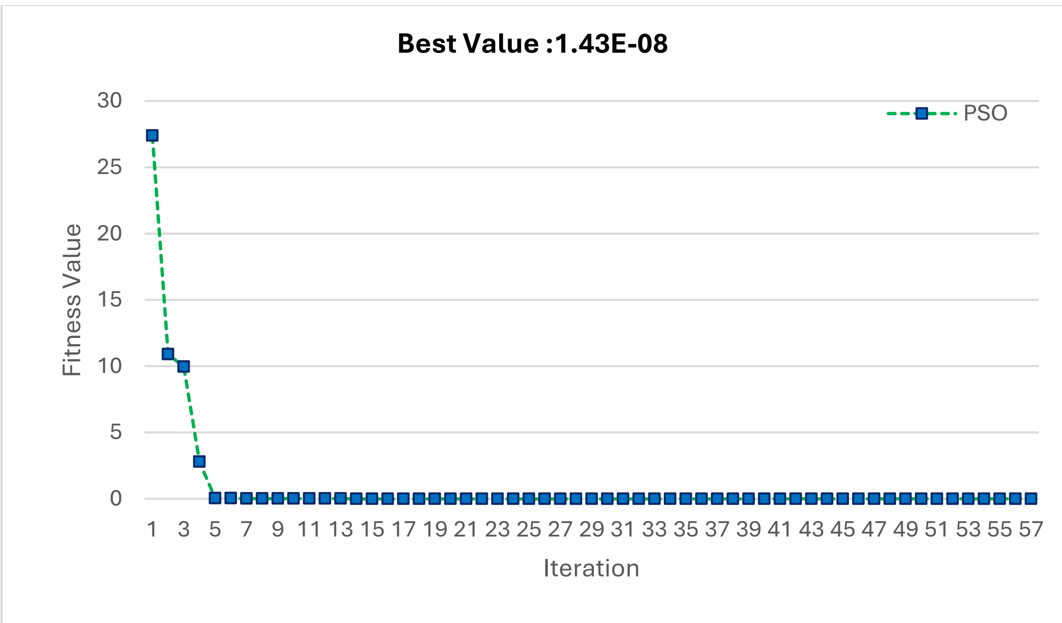

Fig.7: Optimization process for PSO

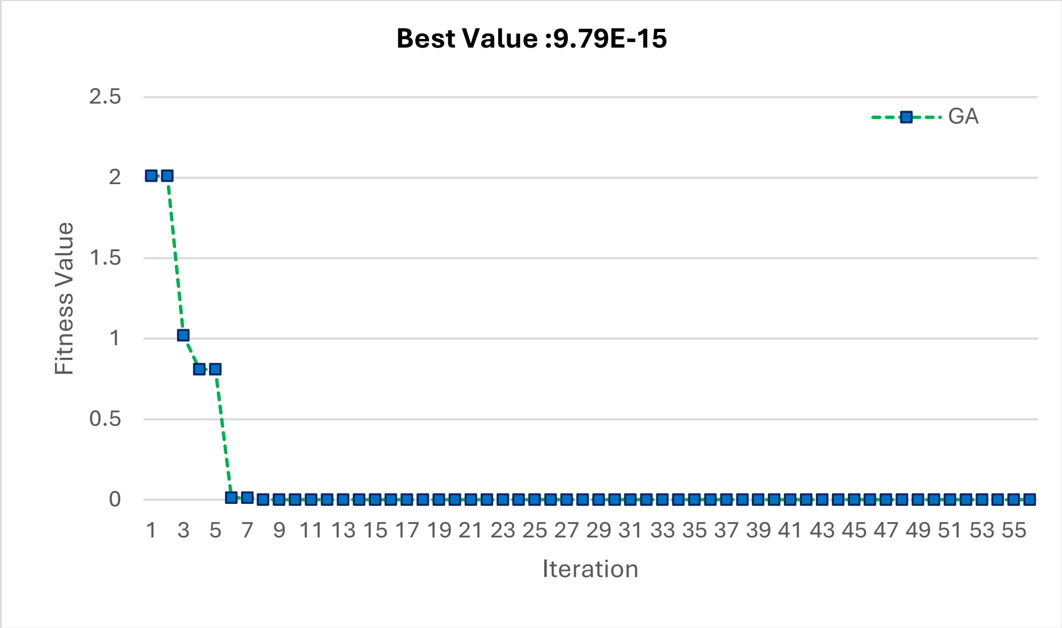

Fig.8: Optimization process for GA

Results of the Preliminary Project

The preliminary project outcomes were very promising and showing a match between the targeted and achieved motor speeds.

Lessons Learned and Transition to Main Project

The initial use of PSO and GA to enhance a FLC offered perspectives on how to apply these methods. The positive outcome of the motor controller initiative validated the effectiveness of employing optimization techniques for systems and paving the way for their utilization in the primary project.

Main Project Overview:

Introduction to the Main Project

The primary project builds on the understanding acquired in the preliminary project to create a complex energy management system. This system aims to improve the distribution and storage of energy generated from panels (PV) and wind turbines. By using a Fuzzy Logic Controller the system smartly controls the electricity generated by these sources and control the battery charge level and power consumption to boost effectiveness and dependability.

System Design and Setup

The energy management system combines MATLAB and HOMER software to develop an adaptive energy management solution. It consists of three scripts; an start script for setting up system parameters, a dispatch script to utilizes the FLC to regulate real time energy distribution based on data and a end script for ending operations. This configuration ensures that the FLC plays a role in decision making effectively adapting to changes in energy supply and demand. The diagram below in (figure 9) outlines the process from design to implementation and assessment in the project. Each phase is carefully organized to ensure development and enhancement of the FLC ultimately integrating it with HOMER.

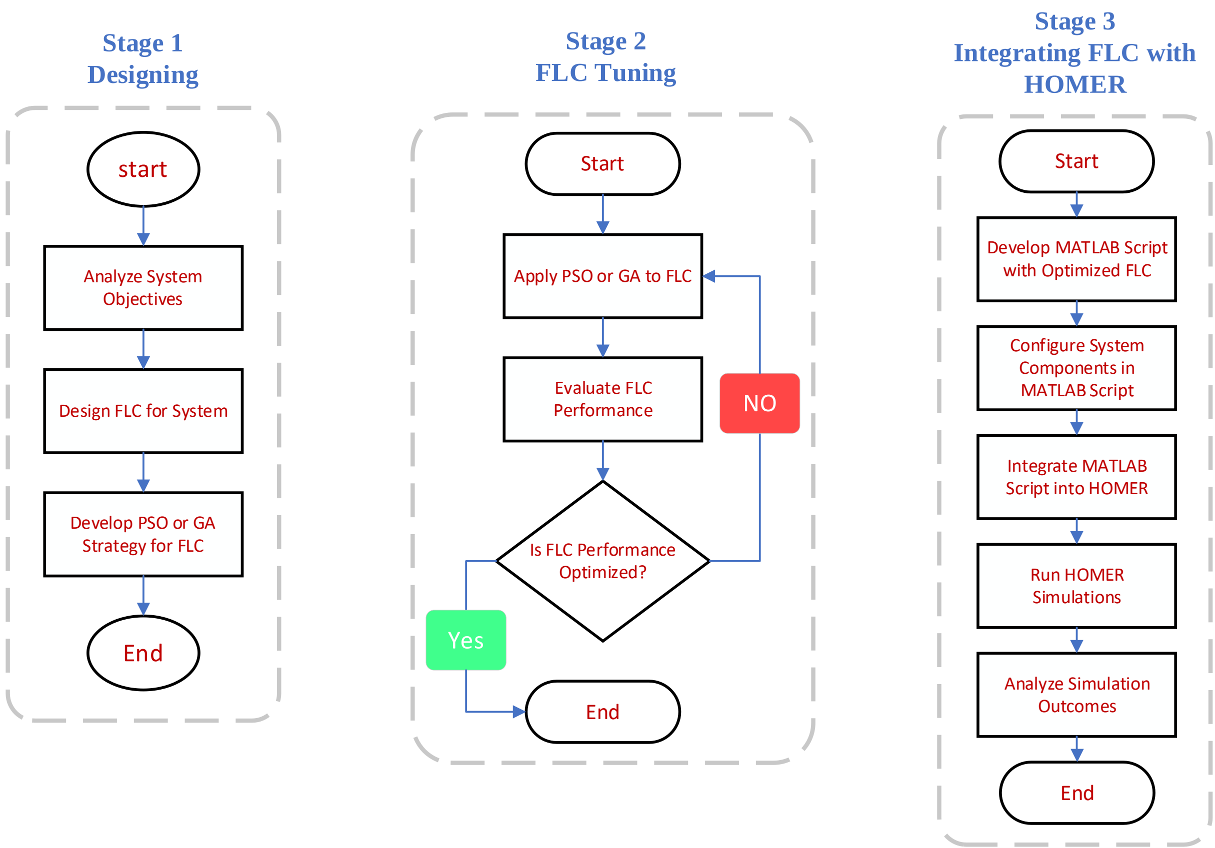

Fig.9: Flow chart of integrating FLC with HOMER software

The energy management system aims to optimize the distribution and storage of energy derived from PV and wind sources. In the center of this system is the Fuzzy Logic Controller (FLC) for managing the relationships among power generation, storage and loa demands. The configuration of the system combines MATLAB and HOMER software to establish an adaptable solution.

Fuzzy Logic Controller (FLC) Integration:

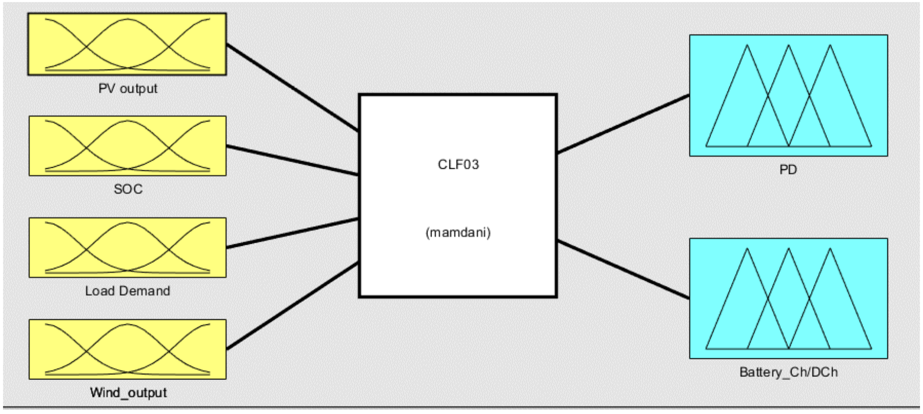

Fig.10: FLC model

- **Model Implementation:** The FLC model, as described in the section 'Overview of Fuzzy Logic Controllers' is put into action using MATLAB. This setup includes adjusting the membership functions of the controller to effectively manage inputs, like PV output, wind output, state of charge (SOC) and load demand.
- **FLC Inputs:** The inputs for the FLC are PV output, wind output, SOC, and load demand. These inputs are important for making real time decisions and energy distribution and storage.
- **Decision-Making Process:** The FLC evaluates the energy need to be provided and manages the energy flow by either storing it (charging the battery) or meet the load demands (consumption). This process of decision making plays a role in keeping system stability and effectiveness particularly when facing changing environmental conditions.

The diagram shown in (figure 10) can be used to show how the FLC manages energy sources to enhance system efficiency. FLCs output are designed to interact with HOMER software. This integration enables the simulation of scenarios and assessment of how the FLC affects system performance with a focus on lowering operational cost and improving energy efficiency.

Implementation of Optimization Techniques

To improve the decision making accuracy of the Fuzzy Logic Controller (FLC) we utilized Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) to tune the controllers membership functions. These methods systematically adjust the FLCs outputs through parameter optimization. This strategy improve FLC and boosts system sensitivity and efficiency. Both PSO and GA are reliable tools for complex optimization and they are customized to enhance control precision and overall system effectiveness.

Parameters and Values of Optimization Techniques

In Particle Swarm Optimization (PSO) important factors to consider are the number of particles, inertia weight (w) cognitive (c1) and social (c2) coefficients and the maximum velocity of particles which is set at 1.49. Initially the swarm consisted of 1000 particles with an inertia weight of 0.7 to achieve a balance between local exploration abilities. Both cognitive and social coefficients were set at 2 to ensure a mix of collective particle knowledge.

As for Genetic Algorithm (GA) the population started with 1000 individuals. Utilized a crossover probability of 0.8. These configurations aimed at exploring the solution space while preserving diversity within the population to prevent local optimum which is extreme value of an objective function, representing the best possible solution under certain circumstances, pinpointing the exact optimum value may pose a challenge. In such instances, when the objective function attains a value greater than its neighboring points, it is identified as a local optimum.

Optimization Process

Both Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) were utilized in a sequence of loops, where each loop involved assessing the effectiveness of every solution, by its capability to minimize the difference between predicted and actual system results. The evaluation function was created to penalize deviations from desired outcomes.

Adjustments of the parameters were implemented based on outcomes for example the inertia weight in PSO was gradually reduced from 1.6 to 0.6 to transition the focus from exploration to more concentrated local exploitation as the optimization process advanced. Likewise in GA the mutation probability was adapted according to the diversity within the population slightly increased if genetic diversity within the population decreased, aiming to stimulate exploration of solutions.

Evaluation and Adaptation

During the optimization stages I kept an eye on how the FLC was doing compared to specific standards I had set. I made changes to the PSO and GA settings in a way taking into account this feedback on performance. This helped me make sure that the optimization procedure stayed in tune with the changing aspects of the energy management system. By using this method I could make improvements to the FLC making it more responsive and dependable when it came to managing the system.

Results and Analysis:

Overview of Results

The findings of this study support the effectiveness of the enhanced FLC in managing the energy system. Important targets examined like system cost and energy generation statistics from panels and wind turbines which are essential, for determining the financial and efficiency of the enhancements.

Optimization Results

The graphs shown in the (figure 11-12) describes how the fitness function optimization progresses over iterations, for both PSO and GA. This visual representation showcases how effective each method is in tuning the parameters of the FLC with a reduction in fitness value indicating enhanced controller performance.

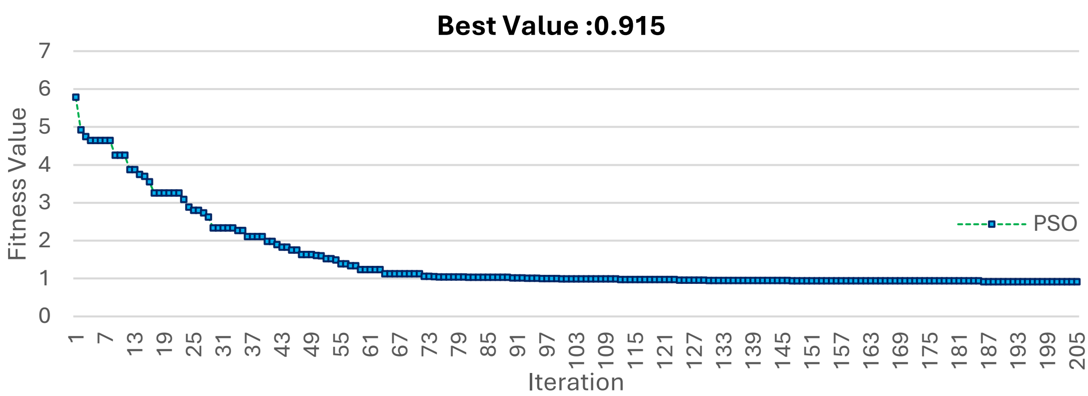

Fig.11: Optimization process for PSO

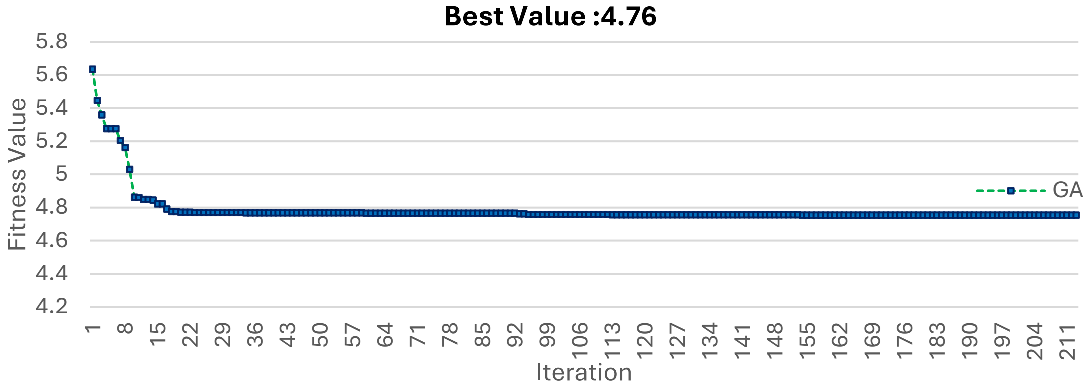

Fig.12: Optimization process for GA

Detailed Comparative Results

The table below provide compression of the outcomes of using control methods (CC+LF) versus the FLC enhanced by PSO and GA. These findings showcase variations in cos, power generation and grid interactions offering a offering a clear quantitative basis for evaluating the benefits of each control strategy.

Table1: comparison between controllers

Controller	sys cost	Battery cost	PV production KWh/yr	Wind production KWh/yr	Grid purchases KWh/yr	Grid Sales KWh/yr	Load KWh/yr
(CC+LF)	$25,341.07	$229.93	7,794	4,760	3,215	7,087	8,136
FLC_PSO	$25,274.32	$229.93	6,572	4,760	4,535	3,549	8,136
FLC_GA	$38,740.13	$13,459.82	5,202	4,760	4,771	2,888	8,136

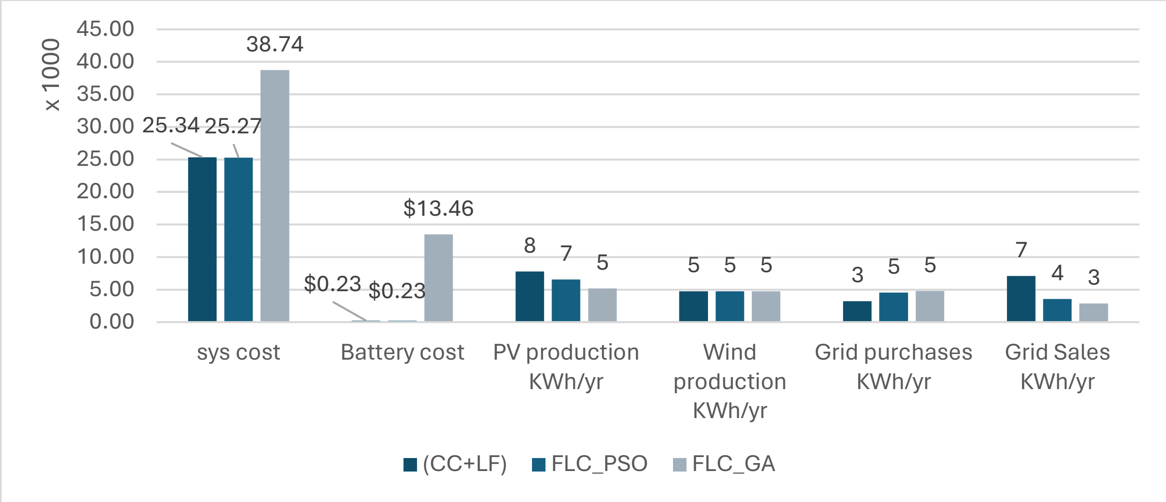

Fig.13: comparison chart

Analysis the results

Analyzing the data from the table and the optimization graph show major insights into the benefits of the optimized FLC. Lower system costs and more efficient energy production prove the advantage of implementing advanced optimization techniques in real-world energy management systems.

Limitations:

Although the project has made progress in improving energy management using FLC. It encounters challenges in scalability and adaptability. The current FLC setup needs a overhaul to incorporate new energy sources, which can be cumbersome and inefficient in fast changing energy markets. Moreover, the inflexibility of the existing rule base limits the systems ability to adapt independently to scenarios without manual adjustment . To adjust these issues potential solutions could include exploring FLC structures or integrating machine learning methods to allow for rule adjustments based on real time data. This approach could enhance the systems flexibility and reduce the need for redesigns.

Conclusion:

In conclusion this project showcases how using PSO GA can improve the performance of FLCs, in energy systems. The enhancements in efficiency and cost effectiveness are in line with the project's goals. And Open up opportunities for technological advancements. Subsequent efforts could dive into combining a range of energy sources and utilizing adaptive optimization methods in real time to enhance energy management strategies and sustainability further.

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