Design and Simulation of a Fuzzy Logic Controller for Adaptive Air Conditioning Systems

Harsh Pagare[1], Kushagra Mishra[2], Kanhaiya Sharma[3] ,Ketan Kotecha[4], Ambarish Kulkarni[5]

[1,2,3]Department of Computer Science & Engineering, Symbiosis Institute of Technology, constituent of Symbiosis International (Deemed University) Pune, Maharashtra, India
[4]Symbiosis Centre for Applied Artificial Intelligence, Symbiosis Institute of Technology, Symbiosis International University, Pune, 411045 India
[4]UCSI University, Kuala Lumpur 56000, Malaysia
[5]School of Engineering, Swinburne University of Technology, Hawthorn, Australia

Corresponding author email: sharmakanhaiya@gmail.com

Abstract- There is a mounting demand for energy-efficient air conditioning systems in the context of rising global temperatures and consumption cuts. Ensuring optimal indoor comfort levels is arduous when operating with rigid control mechanisms in conventional air conditioning systems, significantly when outdoor conditions change. In such systems, invariant control parameters have limited adaptivity to variations in temperature, humidity, or voltage swings and thus do not guarantee optimal operation as consumptions rise. This study deals with an FLC that is to be used in determining optimized values for some key parameters, namely the fan and compressor speed ratios in an air conditioner. Hence, the procedure enables the regulation of air conditioning performance in a resourceful way with specified inputs. In general, a system employing fuzzy logic shows much robustness when environmental conditions vary in nature and uncertainties. The approach focuses on providing a system that can adapt to dynamic circumstances without compromising user comfort or energy cost. Compared to traditional systems, quantitative analysis demonstrates 20–25% energy savings through fan speed modifications and optimum compressor usage. This paper builds the concept of climate control systems that are more intelligent and adaptive to the modern demands of technology.

Keywords: **Fuzzy Logic Controller, Air Conditioning Systems, Voltage, Temperature, Humidity.**

Article Highlights:

- **The simulation demonstrates how fuzzy logic's real-time adaptation improves air conditioning comfort and efficiency.**
- **Energy Savings are possible under a variety of conditions because the compressor is operated at different settings, and the fan speed is varied.**
- **It performs better, on average, than more conventional techniques because overall performance is better balanced with cooling requirements and energy usage.**

I. Introduction

Ensuring occupant comfort has become both a necessity and a prerequisite for sustaining residential, commercial, and industrial communities. Thus, air conditioning systems need to become part of every living space. While energy poverty remains unaddressed in large parts of the world, energy consumption in the rest of the globe continues to rise as natural global temperature increases. Consequently, to mitigate the high energy use of traditional air conditioning systems and sustain the growth in demand, it is becoming ever more essential to develop energy-efficient systems with optimum air conditioning operations that never fall out of balance with external conditions.

Conventional air conditioning systems, from simple thermostats to PID controllers, rely on pre-set control parameters that work optimally within narrow and relatively stable environmental conditions. Many of these methods cannot adapt to dynamic fluctuations in temperature, humidity, or voltage since they are designed for steady-state control. For instance, while a PID controller will work well for a setpoint temperature in predictably stable conditions, its traditional problem of overshooting or undershooting presents challenges when there are rapid changes. In the same vein, most simple thermostats will try to cycle the system based on a given threshold by using a simple on/off mechanism; this can lead to binary on/off control that may result in poor comfort levels, increased component wear and tear, and wasted energy consumption, especially when the external circumstances are not predictable. Fuzzy logic solves these problems by providing a control system that can handle uncertainties and variabilities under real situations.

Papers such as those of **Alshenaifi et al. [2**] cover designing an adaptive HVAC system that uses fuzzy logic to reduce energy use while retaining indoor thermal comfort by creating its own fuzzy rules automatically as input data (humidity, ambient rooms, indoor occupancy status, and so on) are fed into it. In the study's conclusion, the technology describes how it could potentially – under certain conditions – reduce energy use by half. However, given its complexity in integrating more input parameters, especially for applications in pre-existing infrastructure in older buildings, it may not be as easy to apply in real-world scenarios.

Ledesma [3] and his colleagues have a real-world case study of fuzzy logic controllers dealing with air conditioning and refrigeration systems. The fuzzy controllers' ability to preserve thermal comfort and provide energy saving are evaluated, and many diverse architectures in the controllers are considered, ranging from input-output variables, membership functions, and inference rules. It is a survey paper, and the mention of alternative cooling strategies is scarce because it concentrates on vapor compression. **Mohamed [4] et al.** propose a fuzzy logic-based control method for HVAC systems that emphasizes occupant thermal comfort and energy economy. The study reveals that fuzzy logic control performs better than conventional techniques such as PID, and the study compares time domain responses of real-time situations of state feedback versus fuzzy logic controllers in the same system. The shortcoming specific to this study is that the system's rule requires constant modification on-site as the building occupies the system, which will make it arduous for bigger and more complicated systems of control.

The fuzzy logic and neural networks designed **by Pooja et al. [5]** are applied in intelligent air conditioning to adapt to variations that result from use and fluctuations in environmental conditions. Their hybrid technique settles on a stable temperature because the knowledge base is adjusted by real-time learning, and the gradient correction enhances the effectiveness of the fuzzy model, resulting in a progressive autonomous increase of effectiveness. In addition, the results on comfort and energy savings presented in the paper are encouraging. Although it is much more complex, the neural network interface could be integrated into existing systems with minimal changes.

The creation of a fuzzy logic controller for air conditioning is developed with a bit more detail by the study by **Sobhy et al. [6].** In this application, Sobhy seeks the design for a system that would ensure not only thermal comfort – which is dictated by the setting desired by users – but also the best possible energy consumption, as these two goals often conflict under real-world and ever-changing environmental conditions, such as temperature variation. The study mentions the special benefit of fuzzy logic over conventional controllers, emphasizing its ability to handle uncertainty in the input variables for the controller. The air-conditioning system uses sensors for tracking temperature and humidity, and fuzzy logic is used to assess the data and make decisions on the settings of the air-conditioning unit. Sobhy admits, however, that adding fuzzy logic controllers to the current air conditioning systems will have some specific challenges. Implementing the system requires massive changes to the existing architecture, making it very difficult to be deployed across the globe. The study sheds light on the fact that there might be errors in the sensor data, which could hamper the performance of the fuzzy logic controller. Even with issues that might arise, the study contains valuable information regarding the benefits of fuzzy logic control in air conditioning systems.

M Abbas et al. designed an autonomous room air cooler system capable of improving energy efficiency and interior comfort using fuzzy logic control **[7].** The system integrates a fuzzy logic-based methodology that dynamically adjusts the cooling intensity (fan speed) regarding observed environment variables, humidity, and temperature. Results report significant gains in energy efficiency when compared with systems in which cooling intensity and fan speed are set to fixed thresholds; also, fuzzy controllers have fast responses that traditional techniques cannot cope with. The core contribution of this paper is based on the practical achievement of fuzzy logic applied in a real system. At the same time, it clearly demonstrates fuzzy-logic capabilities to adapt and withstand many circumstances.

Nevertheless, it also shows some drawbacks, such as difficulty configuring the fuzzy logic system or optimizing membership function and rule, which is not shown in this study. Also, this study only focused on a single-room air cooler. Extending the system to a more extensive area will also present more difficulties than this study. However, the study provides a good foundation for further studies in fuzzy logic-based intelligent air conditioning systems.

Fuzzy logic (and 'neuro-fuzzy' algorithms, i.e., fuzzy logic improved by elements of neural networks, such as a self-learning system able to gradually optimize the system states) was applied by **Rajani Kumari Poonia et al [8]** to enhance the efficacy and adaptability of air conditioning systems, by combining the 'best' aspects of a neural network (they can 'learn' from data) with the best aspects of fuzzy logic (suited to deal with uncertainty). Their result showed that 'the hybrid system performed better than conventional controllers as well as those of self-standing FL [fuzzy logic] systems in terms of energy saving in the [air-conditioning] system and user comfort.'

However, due to the complexity of the hybrid system, there are obstacles to this task. As it is difficult to filter in traditional air conditioning units, there are special requirements for large amounts of training data and processing power. The quality and quantity of the training data also significantly affect the performance of the system, and they might be informative sometimes. In my opinion, though there are problems and challenges with this study, it is still a feasible way of future research on intelligent air conditioning systems.

Kumar et al. [9] studied how to automate air-conditioning systems for humidity and temperature control using a fuzzy logic-based controller. The system was designed to adjust the cooling output autonomously based on real-time data to provide a more pleasant indoor environment while using less energy. The simulation results for various settings proved the effectiveness of the FLC against the conventional outdoor air controller in terms of user comfort and energy savings.

Despite that, the paper acknowledges possible obstacles to adapting the system for practical use. The scientists did not attempt modeling unexpected occurrences, such as sudden power outages or extreme weather, which might temper the simulated system's performance in real life. However, the fuzzy logic controller performed well in isolated simulations. Also, the system's complexity might preclude widespread adoption, particularly in older buildings with aging infrastructure.

An intelligent fuzzy logic controller (FLC) for an air conditioning system was developed by the team of **Nizam U. Ahamed, Zahari Bin Taha [10],** and colleagues based on the drawbacks of traditional air conditioners with constant control parameters that can cause frequent overuse of power. The proposed FLC consumes comparatively less power, owing to dynamically adjusting the speed of the fan and compressors in order to maintain desirable humidity and temperature ranges. In addition to the optimal maintenance of oxygen levels indoors, this recent technology not only makes air conditioning energy-saving but also comfortable for users by providing them with suitable indoor conditions while optimizing energy usage. Fuzzy logic enables the system to make more intricate sets of judgments considering the input values such as temperature, humidity, and oxygen levels. Unlike previous systems, this makes the system more flexible in capturing changing conditions in novel ways.

Although this paper presents a system design orientated primarily towards maintaining a healthy indoor environment rather than reducing energy use altogether, it suggests even more strongly that its application to practical systems would be slow and difficult. This is because performance could vary over time due to a variety of hypothetical constraints. These include issues related to sensor accuracy, as well as the necessity of performing regular maintenance. Another factor is that the model's complexity, brought about through the use of fuzzy logic, could, especially in older buildings, provide some useful information regarding how fuzzy logic could be applied to improving air-conditioning system performance with respect to environmental impact.

Safa Riyadh Waheed [11] and colleagues present a fuzzy logic controller (FLC) designed for air conditioning in classrooms. The abstract draws attention to some of the issues that can arise from standard air conditioning systems, which often require assistance with variable indoor comfort and energy efficiency. The authors hope to overcome these issues using fuzzy logic with the ability for the system to dynamically change the fan speed and air distribution according to changing conditions in real-time. The FLC is more adaptive and responsive as it does not depend on the precise mathematical models that older generation systems typically do. This will be especially useful in education facilities, as maintaining consistent and comfortable learning conditions is crucial.

The major contribution of this study is its practicality; the fuzzy logic controller is written to run on standard microcontrollers. Thus, its implementation, in reality, is easier. As shown through testing, the FLC performs better than traditional systems conservation overall (a major sustainable outcome). Some disadvantages, pointed out by the study's authors, include its requirements for precise sensor data, as well as the maintenance that needs to be performed continuously to reach peak functioning. There was also a set of negative-yield findings that while the FLC could work well in a constant system, like a regulated classroom, different, more complex, or variable environments needed more testing to determine how well it would function. The study's authors also suggested that this would be a focus of future studies, with the goal of further developing the system and integrating it into embedded devices to make it more effective and increase the range of its applications.

By knowing the weakness of the work that has been done before us, in this paper, we constructed and modeled a fuzzy logic controller (FLC) more efficiently to reach the objective, and it will operate more smoothly than before. The FLC will receive real-time inputs, such as temperature differential, humidity, and electric voltage, and adjust some of the most important parameters dynamically, such as compressor speed, fan speed, mode of operation, and fan direction. Due to the FLC continually watching these inputs, it is able to make the exact changes that ensure the highest energy economy and user satisfaction.

The basic goal is to connect simple, rigid 'rule controllers' at the primary level with complex, data-driven models like machine learning and deep learning. Since fuzzy logic can read and act on inaccurate inputs, it is useful in a context where conditions are less predictable and prone to catch changes. Due to its flexible and innovative design of the fuzzy rules together with the membership functions, the air conditioning system can judge how best to compromise energy efficiency and comfort. It relies on information and insight that has been encoded in the rule base and provided by the end-user or an expert.

From these simulation results, it is easy to see how the FLC minimizes energy usage even as it maintains a steady, comfortable indoor ambiance. Even at a challenging setpoint, the FLC has obvious energy usage efficiency gains over conventional control strategies. Today's air-conditioning requirements would really do well to incorporate such a technique. In this final study, we have brought the story of fuzzy logic to its most recent milestone. This paper showcases the advantages of the FLC in controlling air-conditioning systems in an actual application. However, this paper also points toward the future. Given the demonstrated benefits of control based on fuzzy logic, how can we further enhance the FLC for purposes such as HVAC control? More specifically, we demonstrate the viability of using fuzzy logic not only as a univariate controller but also as a major part of a hybrid controller with other modern control methods, such as genetic algorithm and machine learning, that we can incorporate into the FLC technique.

II. Air Conditioning Mechanics and the Superiority of Fuzzy Control Systems

The inner workings of an air conditioner are illustrated in detail in **Figure 01 and it at available at US department of Energy Saver 101: Home Cooling Infographic**, highlighting each component's function in the cooling process.

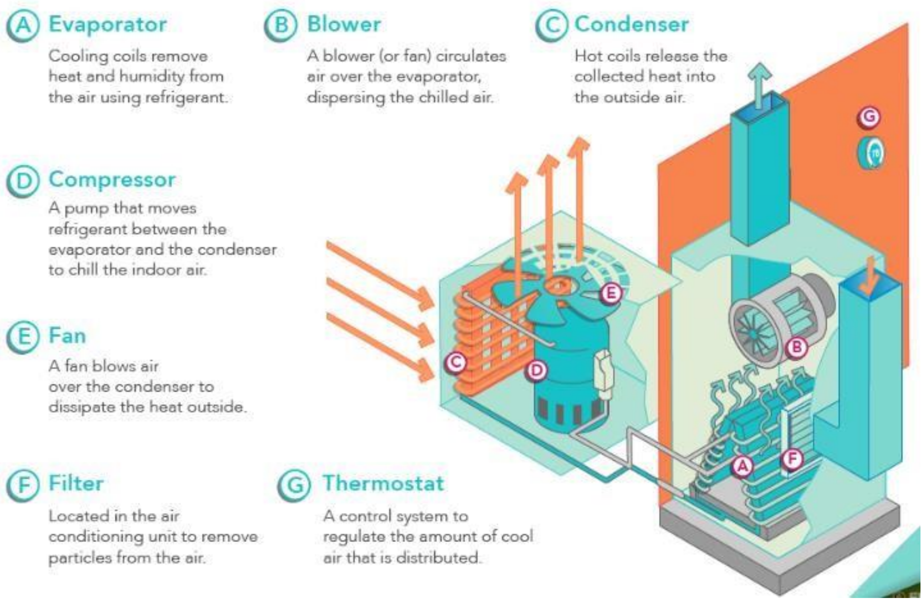


Fig 01: Working of an Air Conditioner

The illustration presents the main parts and working processes of an air-conditioning system: it moves heat from inside a building to the outside of the building, just like a fridge. Generally speaking, as is shown, an air-conditioning system operates by absorbing heat from inside a building and releasing it outside. Therefore, one can easily depict the process of why heat is absorbed. In the beginning, the **evaporator (A)** is engineered by cooling coils to remove heat and moisture from the inside air. A refrigerant is inside a fridge to take the heat from the air. Due to that, the air flowing over the cooling coils is warm, but the air that will be re-circulated to the room becomes cooler than before. The **blower (B)** is the fan that helps keep the inside of a building at the correct temperature by circulating cooled air wherever it is needed. The cooled air is moved around by this fan to make the temperature steady and comfortable **[12].**

As is shown at the top, the refrigerant inside advances to the next stage of the process as it takes all of the heat from the air. The refrigerant travels to the **condenser (C),** usually positioned outside of the building, from where it picks up the heat. This is the part in which the heat from the heated interior air is expelled to the exterior space that surrounds the outdoor condenser coils (which are open for the transfer of hot refrigerant exiting the condenser), causing the heat to be exited by the freon from the building. This is made possible by the condenser coils through which the gas suction is throttled to absorb the heat against the evaporator. The main component of this cycle is the **compressor (D)** that pumps the freon refrigerant from the condenser to the evaporator.

Compression in the compressor stage ensures that heat is removed efficiently in the condenser by increasing the temperature and pressure of the refrigerant. Also, it ensures the proper flow of refrigerant through the system **[13].**

The system also has an **external fan(E),** which cools the condenser coils to assist the condenser coils in dissipating heat from the system into the outdoor ambient. This component makes sure that the speed of refrigerant cooling is high with no restriction. This way, the system will always be able to run continuously, avoiding the occurrence of overheating.

First, as this reliably warm air goes through the system, it gets filtered by the **filter (F)** in the air conditioner. This cleans the air and makes it more pleasant to experience because it removes particles and pollutants. Additionally, it keeps dust and debris outside of the system, which can affect its functioning by reducing the ability of the air conditioner to move, heat, and cool.

Next, the single point of control for the system is the **thermostat (G).** This system keeps track of the temperature within and uses this information to determine whether or not to activate the air conditioner. It uses less energy by turning the system off when the preferred temperature is reached, and it turns the cooling on when the room temperature exceeds the desired point.

Together, these elements form a seamless cycle that ensures effective indoor air conditioning no matter how the outside temperatures change. None of these things can be left out if we want an efficient, cozy interior and guaranteed energy efficiency.

These are some of the limitations of conventional controllers: they are ill-suited to deal with the uncertainties of the real world as it is imperfect in many ways (for example, involving humidity, uneven power supply, and external temperatures that change) and do not behave reliably to the required accuracy **[14]**. As a result, in certain situations, conventional systems might be 'too early or too late to react,' either wasting energy or leaving us cold.

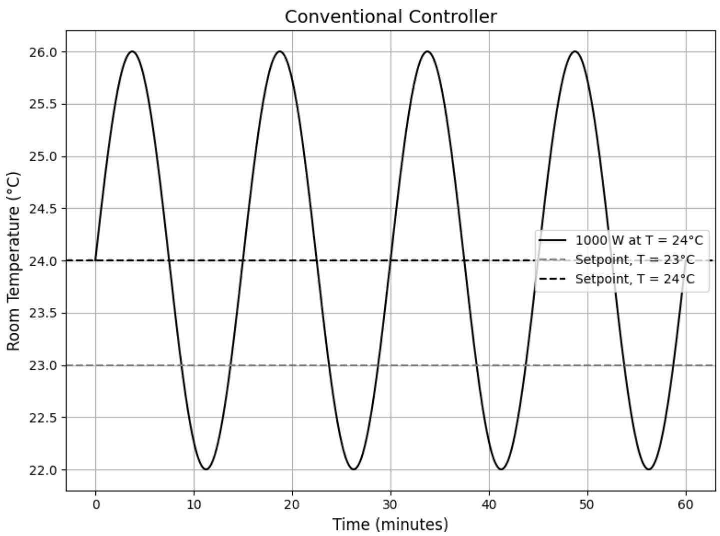
This paper explains how a fuzzy logic controller (FLC) can be used to control the repeated problems that arise with air conditioning systems. *Fuzzy logic* is a decision-making process that can overcome the uncertainty that traditional binary logic cannot. Fuzzy logic can help control changeable and ill-defined inputs. The new suggested controller will help the air conditioning system to improve by following the fuzzy logic rule; it can herd the system in seconds in case there is a change in the conditions in real-time, and this will save energy that is wasted.

Fuzzy's ability to accommodate vagueness surrounding environmental factors is the reason it is used here. Rather than fixed thresholds, an FLC can communicate in terms of data with inconclusive values, so its reaction to anything from temperature and humidity to voltage fluctuations will be more responsive, giving a smoother, continual adjustment process compared with conventional systems. The result is usually reduced energy consumption and increased comfort for the user.

Three input variables of the FLC are temperature difference, humidity, and electric voltage, and they were chosen because they can directly impact the user's comfort and the running effect of the air conditioning system. The air temperature changes can directly affect the total quantity of cooling; the humidity level can directly affect how people feel when they get out of an air-conditioned room since different people have different acceptable temperatures for their comfort; the electric voltage can be used to reflect the system response to fluctuation because the time of the air conditioning system makes the energy unit price vary.

These four output variables (compressor speed, fan speed, mode of operation, and fan direction) are determined based on the inputs cited above by the FLC. As outputs of the FLC, this system as a whole may prove to be effective at controlling by modifying these values in real-time to adapt to changes in environmental conditions (temperature). For instance, the FLC may respond to changes in temperature by changing the compressor to provide a comfortable inside atmosphere while not wasting excessive energy.

Figures 02 and 03 show the room temperature variations in an ordinary system and a Fuzzy Logic Controlled system as an example. These graphs were created through using the points given by several simulation studies **[16][17][18].**



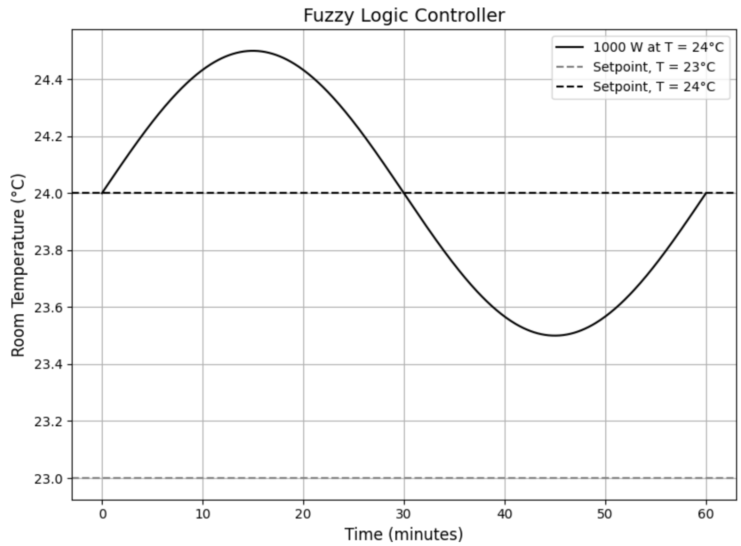


Fig 02: Temperature Fluctuations in a Conventional Controller

Fig 03: Temperature Fluctuations in a Fuzzy Logic Controller

The most user-friendly F.I.S. type, the **Mamdani** Fuzzy Inference System, serves as the basic architecture of the FLC in this project. All the membership functions for input and output spaces were carefully chosen in order to represent the operational ranges of the system accurately. For example, the temperature difference can be represented as five levels: "Too Cold," "Cold," "Warm," "Hot," and "Too Hot." Then, humidity and voltage levels are also divided into suitable categories to ensure accurate control. So, fuzzy control is accurate enough to carry out such a task. After the careful analysis of various air conditioner manuals and **"ASHRAE" (American Society of Heating, Refrigerating, and Air-Conditioning Engineers)** Standards, fuzzy rules were obtained. The FLC avoids the problems of standard air-conditioning systems and paves the way towards new, smarter, active climate-control technologies that not only use less energy but can also help preserve comfortable indoor climates.

III. Methodology

A) Overview of Fuzzy Control System

Rather than being based on binary logic such as true/false and yes/no, fuzzy logic (F.L.) is a computational technique based on how humans reason and make decisions, and it accounts for the notion of a 'variable degree of truth,' unlike classical logic whereby propositions may be either true or false but not both **[19].** In particular, whereas in classical logic, propositions are always either 100 percent true or false (0 percent), fuzzy logic works with the concept of 'partial truth,' and, therefore, the values involved may be anywhere between 0 and 1. One advantage of F.L. is its ability to operate on imprecise or unpredictable input data, which, since this is a common feature of real-world systems – e.g., air conditioning, where external variables may be the difference in temperature and humidity, and they can change rapidly – applying a fuzzy approach can often lead to better results than a conventional mathematical model.

The object being made in this project is an air conditioning system controller with fuzzy logic. According to inputs such as voltage level, temperature difference, and level of humidity, the operation mode of the system, its fan speed, and the compressor speed will have to be adjusted. Traditional methods for controlling a system could have been used only with numerical inputs and outputs. However, those methods tend to be both stiff and inflexible, and in many cases, the control system will need additional input to 'help' it deal with changes. The air conditioning system was more fluid and more effective, being based on fuzzy logic, as the system could interpret all those values and judge what was needed according to that interpretation.

The first step of fuzzy logic is **fuzzification,** in which the input variables are transformed into fuzzy sets by the predetermined membership functions **[20]**. These fuzzy sets represent the fuzzy levels of the input variables, such as 'Cold,' 'Warm,' or 'Hot' for the temperature difference degrees. The fuzzy sets of the input variables will be compromised with other input variables' fuzzy levels and then converted into a fuzzy output during the rule evaluation stage. A set of fuzzy rules, just the IF-THEN statement, is applied at this stage. For example, 'IF Temperature Difference is Hot AND Humidity is High, THEN Fan Speed should be High.' The fuzzy output from the rule evaluation becomes an exact value that can be fed back into the air conditioning system for control during defuzzification.

Figure 04 gives a detailed, illustrated, finalized diagram of how the fuzzy logic controller (FLC) works in air conditioning by dividing the stages it uses into capsule form. The figure shows that a fuzzy logic controller (FLC) starts with input variables such as temperature difference, humidity, and voltage on its left side. In the first stage of the process, fuzzification-specific membership functions help turn the sharp value of variables into fuzzy sets, which represent weather conditions like 'warm,' 'cold', or 'hot.'

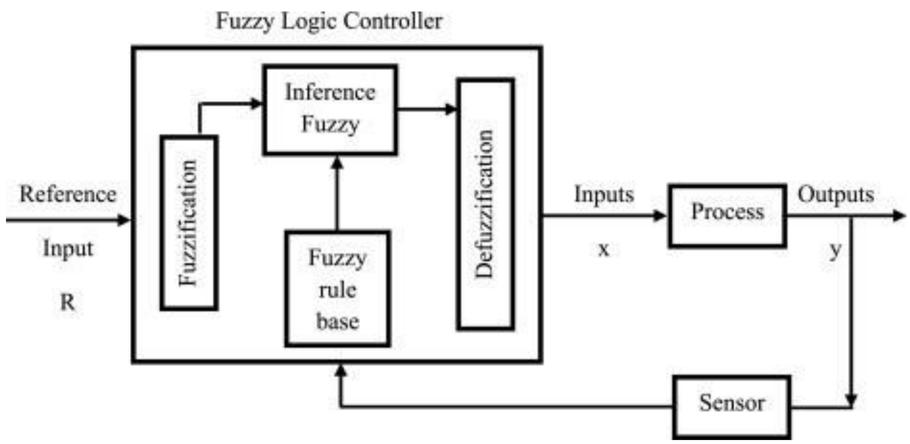


Fig 04: Working of a Fuzzy Logic Controller

After fuzzification, the input data is fed into the fuzzy rule base, containing predefined fuzzy IF-THEN rules defining the relationships between the input and output variables. The fuzzy inference step evaluates the fuzzy rules, producing outputs that fuse the fuzzy inputs using logical connectives (AND, OR).

The final step in the process, known as defuzzification, describes the transformation of the fuzzy output to a crisp value that the system can then use to signal the air conditioning system parameters, such as compressor speed, fan speed, and operating mode **[21].** This process acts as a surrogate for the natural air conditioning system and adjusts itself following the recommendations from the fuzzy logic controller.

Fuzzy logic was chosen for this application due to its extraordinary ability to handle uncertainties and provide smooth transitions between states. Therefore, this makes fuzzy controllers perfect for fine-tuned processing of air conditioning to ensure that the system operates smoothly. When the surrounding conditions are altered, traditional controllers often struggle to maintain the best performance possible. This can then result in many more on / off cycles. This translates into inefficient energy usage and a decrease in comfort. Alternatively, a fuzzy logic controller can gradually modify the system's parameters in small incremental steps, creating fewer abrupt changes when a set point is crossed and improving overall performance. In conclusion, fuzzy logic is reliable and can have a high adaptability in an air conditioning system. This is thanks to the fact that the system has a human-like approach in analogic computing, taking into consideration partial truths that enable adjusting the outputs improving system performance

B) Defining System Variables

The principal inputs are the temperature difference, humidity, and electric voltage, with the outputs being the compressor speed, fan speed, the mode of operation, and the fan direction. They were chosen because they directly impact user comfort, and part of the objective is to maximize energy efficiency by responding to them dynamically, including changing directions when needed.

Input Variables

1) **Temperature Difference:** This project calculates the temperature difference between what the room temperature needs to be and what the actual room temperature is right now. This is also fuzzified into five fuzzy sets: "Too Cold,"

"Cold," "Comfortable," "Warm," and "Too Hot." The temperature difference is fuzzified using the Triangular Membership Function (trimf) because it is usually a smooth curvature without sharp edges, which is a good way to model the gradual transformation of the temperature difference between "Too Cold" and "Too Hot." It is well-known that the difference between the room temperature readers and the set point temperature is directly related to the required cooling capacity for the air conditioner. That is why it was chosen to be one of the two main inputs for this project.

2) **Humidity:** This is the next critical FLC variable that has a profound impact on the comfort level of humans. The lowest limit of 0% and the highest limit of 100% encompass all probable situations, from extreme dryness to too much humidity. There are five murky categories that express humidity: Dry, Refreshing, Comfortable, Humid, and Sticky. It is also measured using the triangular membership function (trimf). We must simulate sequential changes in comfort levels as humidity changes, so we choose this function type. This is a good application for the triangle function, as we can fine-tune the system behavior by precisely determining the center of the comfort region.

3) **Electric Voltage:** Steady operation of the air conditioning system relies on the stability of the voltage. The input membership range between 180V to 240V is chosen for common fluctuations that might arise in home or business power sources. The two sets that separate this input are 'Regular' and 'Low.' Since the fluctuations in voltage are of a particular type, the trapezoidal membership function (trapmf) was chosen because trapezoidal functions work well to handle voltage variations. The trapezoidal shape functions well with such systems because if the voltage is stable between specific points, those points define a flat top on the trapezoid, which means that the system can conveniently consider a range of voltages as 'Regular,' so in effect, the system does not need to make needless changes for small variations.

Clustering ranges for all input variables can be seen in **Tables 01 to 03** below. For every variable, each membership function has its own defined parameters.

Table 01: Temperature Difference Clustering Range

Input Variable	Too Cold	Cold	Warm	Hot	Too Hot
Temperature Difference (℃)	-20 to 0	-10 to 10	0 to 20	10 to 30	20 to 40

Table 02: Humidity Clustering Range

Input Variable	Dry	Refreshing	Comfortable	Humid	Sticky
Humidity (%)	-30 to 30	20 to 50	40 to 70	60 to 90	80 to 160

Table 03: Electric Voltage Clustering Range

Input Variable	Low	Regular
Electric Voltage (V)	180 to 215	200 to 240

Output Variables

1) **Compressor Speed:** In the thermostat ideology, the speed of the compressor is directly related to the level of cooling power achieved by the system. The five-level quantization is as follows: off, very low, low, medium, and fast. This quantization helps the trimf (triangular membership function) place the compressor speed to minimum energy inefficiency so the compressor speed can make smooth adjustments as the condition changes.
Since the compressor speed's triangular membership function has a mathematical structure that is analogous to humidity and a temperature difference, the system can adjust the compressor speed relative to it.

2) **Fan Speed:** The other major output to control the airflow in the room is the fan speed, again with five levels-"Off," "Very Low," "Low," "Medium," and "Fast"- within which the fan speed is also controlled by a triangular membership function (trimf) that ensures a proportional response to any changes in the input variable so as to deliver a congenial ambiance.

3) **Mode of Operation:** A triangular membership function (trimf) is also used in this project to capture the air conditioning Mode of Operation variable. There are two operational states for the air conditioning system: "Dehumidifier" and "AC," and the trimf function allows smooth transitions between these two operational states.

   Under certain circumstances inside an ambient controlled space, triangular membership in the Mode of Operation cylinder can be more effective in balancing cooling and dehumidification.

4) **Fan Direction:** For fan direction, there are two choices, 'Away' and 'Towards.' This output defines the direction of airflow and, therefore, has a big impact on user comfort. A trapezoidal membership function (trapmf) is used for this output, which allows us to define the borders between the two directions accurately and ensures a smooth response should we change direction. It is possible for the technology to keep airflow direction within a predefined boundary since the trapezoidal membership function for the fan direction inherits the same mathematical structure of the voltage.

Tables **04 to 07** depict the clustering ranges for all the output variables. The parameters of each membership function are defined for every variable.

Table 04: Compressor Speed Clustering Range

Input Variable	Off	Very Low	Low	Medium	Fast
Compressor Speed (% of rated rpm)	-25 to 25	0 to 50	25 to 75	50 to 100	75 to 125

Table 05: Fan Speed Clustering Range

Input Variable	Off	Very Low	Low	Medium	Fast
Fan Speed (rpm)	-350 to 350	0 to 700	350 to 1050	700 to 1400	1050 to 1750

Table 06: Mode of Operation Clustering Range

Input Variable	Dehumidifier	AC
Mode of Operation	-1 to 1	0 to 2

Table 07: Fan Direction Clustering Range

Input Variable	Towards	AC
Fan Direction (°)	-90 to 80	30 to 190

In **Tables 01 to 03,** the ranges for clustering of input variables like humidity and temperature difference are deliberately designed with overlapping regions to meet the principles of fuzzy logic. Overlapping ranges are one of the features of fuzzy logic systems that allow smooth transitions among states and help the controller cope with ambiguities and uncertainties.
The overlapping ranges of our fuzzy sets are tuned precisely to ensure suitable system responses in case of changeable input circumstances. This is due to the intrinsic variety of real-world situations when gradual changes take place in environmental conditions rather than abrupt ones. Overlapping zones add flexibility to the fuzzy logic controller by allowing smooth interpolation between various control modes.
Besides, fuzzy logic inference techniques naturally handle the case of overlapping membership functions, such as the centroid defuzzification method used in our paper. It ensures that, for any set of input values, the resultant control actions are a weighted average of contributions from each relevant fuzzy set, even when the input values fall within overlapping regions. This approach removes ambiguity and ensures that the controller yields consistent and reliable operations.

The ranges of the membership functions are also deliberately designed to be out of the normal range of the variables they represent. This approach enhances the overall stability and dependability of the system while serving a specific function within the fuzzy logic framework.

For instance, allowing for smoother crossing at the ranges of variation, membership function shapes such as the trapezoidal (trapmf) and triangular (trimf) may exceed both the minimum and maximum values of a variable. In practice, and because of oscillations or measuring noise, environmental quantities such as thermal gradient or relative humidity may deviate from their usual or common operating/working ranges by wide margins. The fuzzy logic controller can, therefore, achieve stability and reliably provide control at or beyond these limits if the membership function parameters, most especially the lower and upper bounds, are allowed to extend outside their conventional bounds. This smooths the output and prevents the system from overacting to sudden changes, thus destabilizing control operations.

The larger ranges allow the system to handle unexpected situations, such as loud or erroneous input data. For instance, the inclusion of slightly negative humidity values in the design of the membership function creates a buffer zone that helps the controller deal with unexpected input anomalies, even though negative humidity values are physically impossible. Even when the input circumstances become close to or surpass anticipated limitations, this design decision guarantees that the air conditioning system will continue to run smoothly and without pauses or inefficiencies. It also prevents sudden changes in output.

Therefore, the extension of the membership function parameters beyond the common operating range of the variable is reasonable and intentionally performed. It enhances the power of the fuzzy logic controller due to its ability to handle different uncertainties and variabilities in the real world efficiently. Thereby, this flexibility allows for consistent performance and reliable control actions under dynamic and complicated contexts where the input conditions may be different from the usual ones.

C) Mathematical Foundations of Membership Functions and Fuzzy Logic Operators

- **Triangular Membership Function (trimf)**

Our first example of a fuzzy membership function is an example of one of the simplest types: the triangle membership function. A triangle membership function takes three parameters from the set R: a, b, and c as arguments. The triangle's height reaches one at b, then tapers off to zero at a and c. The increase and decrease are linear.

Mathematically, the triangular membership function is defined as:

$$\mu(x;a,b,c) = \begin{cases} 0 & \text{if } x \le a \text{ or } x \ge c, \\ \dfrac{x-a}{b-a} & \text{if } a \le x < b, \\ \dfrac{c-x}{c-b} & \text{if } b \le x < c. \end{cases}$$

Since the triangle function is linear on both sides of the peak, it is simple and compact in how it is applied and, thus, cheap to compute. Since it is easy, it is ideal for systems with performance limitations, where computational or processing resources are scarce, especially when decisions need to be made quickly.

- **Trapezoidal Membership Function (trapmf)**

The trapezoidal membership function is a generalization of the triangular one where a plateau (with a constant membership value of 1) is introduced over an interval of values. It is defined by four parameters that specify the trapezoid position and shape: a, b, c, d.

Mathematically, the trapezoidal membership function is defined as:

$$\mu(x;a,b,c,d) = \begin{cases} 0 & \text{if } x \le a \text{ or } x \ge d, \\ \frac{x-a}{b-a} & \text{if } a \le x < b, \\ 1 & \text{if } b \le x < c, \\ \frac{d-x}{d-c} & \text{if } c \le x < d. \end{cases}$$

The trapezoidal function will be useful when several values are considered indicative of the same condition. Its flat top (between b and c) ensures that small changes in that interval will not influence the system's decisions.

- **AND(min):**

The minimum function selects the smallest membership value from the relevant fuzzy sets. In other words, the AND operator is implemented by the minimum function. In the IF-THEN rule, the THEN part cannot be true unless all of the IF parts are true. That is the logic of the AND operator. In terms of math, it is stated as:

$$\mu_{AND} = \min(\mu_A(x), \mu_B(x))$$

The minimum operator makes sense as it ensures that the output is valid only when it reflects the weakest of the inputs – that is, that the system reacts strongly only if all of the inputs do.

- **OR(max):**

The maximum function selects the highest membership degree from among the relevant fuzzy sets and applies the OR operator. This operator is used when it is sufficient for the rule to hold any time at least one of the conditions is true.

The mathematical expression is as follows

$$\mu_{OR} = \max(\mu_A(x), \mu_B(x))$$

In so doing, it allows the system to respond to the strongest trip wire, meaning the system will respond only if any of the inputs merit it. This additional restriction is called the maximum operator.

- **Implication(min):**

The minimum function – analogous to the AND logic operator – is typically used in fuzzy logic to manage implication, ensuring that a rule's output is confined by its weakest condition – preventing overreaction when only some of the requirements are met.

$$\mu_{Implication} = \min(\mu_{Premise}, \mu_{Conclusion})$$

- **Aggregation(max):**

Aggregation is the process of combining several fuzzy rule results. It is customary to use the maximal operator in order for the strictest rule fired to appear in the final result. This allows the system to specify the most important factors when making decisions. The expression looks something like this:

$$\mu_{Aggregation} = \max(\mu_{Rule1}, \mu_{Rule2}, \ldots, \mu_{RuleN})$$

With these fuzzy logic operators, in conjunction with the membership functions, the system can make complex decisions based on all the relevant factors and ensure that whatever output it achieves is a reasonable response to the input information in a balanced way.

D) Design and Structure of Fuzzy Rules

Fuzzy rules are the decision-making basis for an FLC, as they define the relationship between the input and output fuzzy variables. These rules are commonly written in the IF-THEN form: IF the firing condition is α, THEN do some action/respond by acting β. Here, the THEN section specifies the outputs or actions to be performed in response to the condition specified in the IF part, which in turn defines those conditions in terms of its input variables **[22].**

Every fuzzy rule codifies an expert view of what the system should do under a specific set of environmental conditions. Each rule individually takes care of an entire subset of different combinations of input conditions in which the system should react in a specific way.

By aggregating the input conditions and computing the output, the rules and their defuzzification are performed through fuzzy logic operators (for example, the max operator for the OR circumstances of each rule and the min operator for the AND conditions), and the final judgment is averaged out by the outputs generated from all applicable rules.

The fuzzy rules in the project have been designed to allow the air conditioning system to deal with foggy, humid, and hot times of the year and to be energy-saving in mild weather. These fuzzy rules vary their compressor speed and fan speed, modify the mode of operation, and set the direction of the fan according to actual input data in real time in order to save on energy and create a level of comfort for the user.

Because of the adaptability and broadness of the fuzzy rule base, it can make changes on its own in response to changing circumstances without needing continuing changes by humans. It can mimic the way humans reason about the problem – using fuzzy rules to decide what is best, balancing many elements in the best possible way to produce the desired result. With this fuzzy logic, the air-conditioning system can become more sensitive and intelligent and can continue to work at its most efficient level in any environmental conditions. Fifty fuzzy rules were created using the MATLAB Fuzzy Rule Editor to account for every combination of input variables. Since every rule has equal priority, the rule weight in each case is set to one.

All the rules have been listed below for the reader's reference.

1) "If (TemperatureDifference is TooCold) and (Humidity is Dry) and (ElectricVoltage is Regular) then (CompressorSpeed is Off)(FanSpeed is Off)(ModeOfOperation is AC)(FanDirection is Away) (1)"

2) "If (TemperatureDifference is TooCold) and (Humidity is Refreshing) and (ElectricVoltage is Regular) then (CompressorSpeed is Off)(FanSpeed is Off)(ModeOfOperation is AC)(FanDirection is Away) (1)"

3) "If (TemperatureDifference is TooCold) and (Humidity is Comfortable) and (ElectricVoltage is Regular) then (CompressorSpeed is Off)(FanSpeed is Off)(ModeOfOperation is AC)(FanDirection is Away) (1)"

4) "If (TemperatureDifference is TooCold) and (Humidity is Humid) and (ElectricVoltage is Regular) then (CompressorSpeed is Off)(FanSpeed is VeryLow)(ModeOfOperation is AC)(FanDirection is Away) (1)"

5) "If (TemperatureDifference is TooCold) and (Humidity is Sticky) and (ElectricVoltage is Regular) then (CompressorSpeed is VeryLow)(FanSpeed is Low)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

6) "If (TemperatureDifference is Cold) and (Humidity is Dry) and (ElectricVoltage is Regular) then (CompressorSpeed is Off)(FanSpeed is Off)(ModeOfOperation is AC)(FanDirection is Away) (1)"

7) "If (TemperatureDifference is Cold) and (Humidity is Refreshing) and (ElectricVoltage is Regular) then (CompressorSpeed is Off)(FanSpeed is Off)(ModeOfOperation is AC)(FanDirection is Away) (1)"

8) "If (TemperatureDifference is Cold) and (Humidity is Comfortable) and (ElectricVoltage is Regular) then (CompressorSpeed is VeryLow)(FanSpeed is VeryLow)(ModeOfOperation is AC)(FanDirection is Away) (1)"

9) "If (TemperatureDifference is Cold) and (Humidity is Humid) and (ElectricVoltage is Regular) then (CompressorSpeed is VeryLow)(FanSpeed is Low)(ModeOfOperation is AC)(FanDirection is Towards) (1)"

10) "If (TemperatureDifference is Cold) and (Humidity is Sticky) and (ElectricVoltage is Regular) then (CompressorSpeed is Low)(FanSpeed is Low)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

11) "If (TemperatureDifference is Warm) and (Humidity is Dry) and (ElectricVoltage is Regular) then (CompressorSpeed is VeryLow)(FanSpeed is VeryLow)(ModeOfOperation is AC)(FanDirection is Away) (1)"

12) "If (TemperatureDifference is Warm) and (Humidity is Refreshing) and (ElectricVoltage is Regular) then (CompressorSpeed is VeryLow)(FanSpeed is VeryLow)(ModeOfOperation is AC)(FanDirection is Away) (1)"

13) "If (TemperatureDifference is Warm) and (Humidity is Comfortable) and (ElectricVoltage is Regular) then (CompressorSpeed is Low)(FanSpeed is Low)(ModeOfOperation is AC)(FanDirection is Away) (1)"

14) "If (TemperatureDifference is Warm) and (Humidity is Humid) and (ElectricVoltage is Regular) then (CompressorSpeed is Medium)(FanSpeed is Medium)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

15) "If (TemperatureDifference is Warm) and (Humidity is Sticky) and (ElectricVoltage is Regular) then (CompressorSpeed is Medium)(FanSpeed is Medium)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

16) "If (TemperatureDifference is Hot) and (Humidity is Dry) and (ElectricVoltage is Regular) then (CompressorSpeed is Low)(FanSpeed is Low)(ModeOfOperation is AC)(FanDirection is Away) (1)"

17) "If (TemperatureDifference is Hot) and (Humidity is Refreshing) and (ElectricVoltage is Regular) then (CompressorSpeed is Medium)(FanSpeed is Medium)(ModeOfOperation is AC)(FanDirection is Away) (1)"

18) "If (TemperatureDifference is Hot) and (Humidity is Comfortable) and (ElectricVoltage is Regular) then (CompressorSpeed is Medium)(FanSpeed is Medium)(ModeOfOperation is AC)(FanDirection is Towards) (1)"

19) "If (TemperatureDifference is Hot) and (Humidity is Humid) and (ElectricVoltage is Regular) then (CompressorSpeed is Fast)(FanSpeed is Fast)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

20) "If (TemperatureDifference is Hot) and (Humidity is Sticky) and (ElectricVoltage is Regular) then (CompressorSpeed is Fast)(FanSpeed is Fast)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

21) "If (TemperatureDifference is TooHot) and (Humidity is Dry) and (ElectricVoltage is Regular) then (CompressorSpeed is Medium)(FanSpeed is Medium)(ModeOfOperation is AC)(FanDirection is Away) (1)"

22) "If (TemperatureDifference is TooHot) and (Humidity is Refreshing) and (ElectricVoltage is Regular) then (CompressorSpeed is Medium)(FanSpeed is Medium)(ModeOfOperation is AC)(FanDirection is Towards) (1)"

23) "If (TemperatureDifference is TooHot) and (Humidity is Comfortable) and (ElectricVoltage is Regular) then (CompressorSpeed is Fast)(FanSpeed is Fast)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

24) "If (TemperatureDifference is TooHot) and (Humidity is Humid) and (ElectricVoltage is Regular) then (CompressorSpeed is Fast)(FanSpeed is Fast)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

25) "If (TemperatureDifference is TooHot) and (Humidity is Sticky) and (ElectricVoltage is Regular) then (CompressorSpeed is Fast)(FanSpeed is Fast)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

26) "If (TemperatureDifference is TooCold) and (Humidity is Dry) and (ElectricVoltage is Low) then (CompressorSpeed is Off)(FanSpeed is Off)(ModeOfOperation is AC)(FanDirection is Away) (1)"

27) "If (TemperatureDifference is TooCold) and (Humidity is Refreshing) and (ElectricVoltage is Low) then (CompressorSpeed is Off)(FanSpeed is Off)(ModeOfOperation is AC)(FanDirection is Away) (1)"

28) "If (TemperatureDifference is TooCold) and (Humidity is Comfortable) and (ElectricVoltage is Low) then (CompressorSpeed is Off)(FanSpeed is Off)(ModeOfOperation is AC)(FanDirection is Away) (1)"

29) "If (TemperatureDifference is TooCold) and (Humidity is Humid) and (ElectricVoltage is Low) then (CompressorSpeed is Off)(FanSpeed is Off)(ModeOfOperation is AC)(FanDirection is Away) (1)"

30) "If (TemperatureDifference is TooCold) and (Humidity is Sticky) and (ElectricVoltage is Low) then (CompressorSpeed is Off)(FanSpeed is Off)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

31) "If (TemperatureDifference is Cold) and (Humidity is Dry) and (ElectricVoltage is Low) then (CompressorSpeed is Off)(FanSpeed is Off)(ModeOfOperation is AC)(FanDirection is Away) (1)"

32) "If (TemperatureDifference is Cold) and (Humidity is Refreshing) and (ElectricVoltage is Low) then (CompressorSpeed is VeryLow)(FanSpeed is VeryLow)(ModeOfOperation is AC)(FanDirection is Towards) (1)"

33) "If (TemperatureDifference is Cold) and (Humidity is Comfortable) and (ElectricVoltage is Low) then (CompressorSpeed is Off)(FanSpeed is Off)(ModeOfOperation is AC)(FanDirection is Away) (1)"

34) "If (TemperatureDifference is Cold) and (Humidity is Humid) and (ElectricVoltage is Low) then (CompressorSpeed is VeryLow)(FanSpeed is VeryLow)(ModeOfOperation is AC)(FanDirection is Towards) (1)"

35) "If (TemperatureDifference is Cold) and (Humidity is Sticky) and (ElectricVoltage is Low) then (CompressorSpeed is VeryLow)(FanSpeed is Low)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

36) "If (TemperatureDifference is Warm) and (Humidity is Dry) and (ElectricVoltage is Low) then (CompressorSpeed is VeryLow)(FanSpeed is VeryLow)(ModeOfOperation is AC)(FanDirection is Away) (1)"

37) "If (TemperatureDifference is Warm) and (Humidity is Refreshing) and (ElectricVoltage is Low) then (CompressorSpeed is VeryLow)(FanSpeed is VeryLow)(ModeOfOperation is AC)(FanDirection is Towards) (1)"

38) "If (TemperatureDifference is Warm) and (Humidity is Comfortable) and (ElectricVoltage is Low) then (CompressorSpeed is VeryLow)(FanSpeed is VeryLow)(ModeOfOperation is AC)(FanDirection is Towards) (1)"

39) "If (TemperatureDifference is Warm) and (Humidity is Humid) and (ElectricVoltage is Low) then (CompressorSpeed is Low)(FanSpeed is Low)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

40) "If (TemperatureDifference is Warm) and (Humidity is Sticky) and (ElectricVoltage is Low) then (CompressorSpeed is Low)(FanSpeed is Low)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

41) "If (TemperatureDifference is Hot) and (Humidity is Dry) and (ElectricVoltage is Low) then (CompressorSpeed is Low)(FanSpeed is Low)(ModeOfOperation is AC)(FanDirection is Away) (1)"

42) "If (TemperatureDifference is Hot) and (Humidity is Refreshing) and (ElectricVoltage is Low) then (CompressorSpeed is Low)(FanSpeed is Low)(ModeOfOperation is AC)(FanDirection is Towards) (1)"

43) "If (TemperatureDifference is Hot) and (Humidity is Comfortable) and (ElectricVoltage is Low) then (CompressorSpeed is Medium)(FanSpeed is Medium)(ModeOfOperation is AC)(FanDirection is Towards) (1)"

44) "If (TemperatureDifference is Hot) and (Humidity is Humid) and (ElectricVoltage is Low) then (CompressorSpeed is Medium)(FanSpeed is Medium)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

45) "If (TemperatureDifference is Hot) and (Humidity is Sticky) and (ElectricVoltage is Low) then (CompressorSpeed is Fast)(FanSpeed is Fast)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

46) "If (TemperatureDifference is TooHot) and (Humidity is Dry) and (ElectricVoltage is Low) then (CompressorSpeed is Medium)(FanSpeed is Medium)(ModeOfOperation is AC)(FanDirection is Towards) (1)"

47) "If (TemperatureDifference is TooHot) and (Humidity is Refreshing) and (ElectricVoltage is Low) then (CompressorSpeed is Medium)(FanSpeed is Medium)(ModeOfOperation is AC)(FanDirection is Towards) (1)"

48) "If (TemperatureDifference is TooHot) and (Humidity is Comfortable) and (ElectricVoltage is Low) then (CompressorSpeed is Medium)(FanSpeed is Medium)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

49) "If (TemperatureDifference is TooHot) and (Humidity is Humid) and (ElectricVoltage is Low) then (CompressorSpeed is Fast)(FanSpeed is Fast)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

50) "If (TemperatureDifference is TooHot) and (Humidity is Sticky) and (ElectricVoltage is Low) then (CompressorSpeed is Fast)(FanSpeed is Fast)(ModeOfOperation is Dehumidifier)(FanDirection is Towards) (1)"

E) Configuration and Analysis Membership Functions

The particular membership functions for the input and output variables that were used in the air conditioning system are presented in the graphs in this section. The visual representation of the degree of membership for every state within the variable range, provided by each graph, could explain the way in which the system understands the situation.

With the help of these figures, looking at the internal operation of the fuzzy logic controller and how it interprets the measured data to come to decision-making becomes evident. To further this aim and understand details, the paper will take a closer look into the design of each membership function in this section. This section explain in reasoning terms of how each function contributes to the system's behavior, and, in the end, a better understanding would be expected to come along.

Figure 05 represents the membership functions for an input variable named "Electric Voltage," which has two fuzzy sets - "Low" and "Regular." The "Low" voltage range is clearly shown in the figure, with its membership value 1 for voltages below 200V and gradually decreasing to 0 at 215V. So, the "Low" voltage range is 180V to 215V, and the voltage range assigned to set "Regular" starts at 200V, and its membership value at that voltage is minimum. It reaches its maximum membership at 220V, and from there on, it stays constant above that point. That is how we get a gradual transition from "Low" to "Regular" for estimating the electric voltage using the F.I.S. When the power supply fluctuates, it is essential for the system not to have any sudden changes in behavior, and this is when the discussed architecture can effectively enable it.

Membership functions for one of the input variables named "Humidity," which is split into five fuzzy sets, "Dry," "Refreshing," "Comfortable," "Humid," and "Sticky," are shown in **Figure 06.** Membership functions of these sets are made using a triangular structure, and each category has different peaks that show the range of humidity where membership becomes the highest. For instance, "Dry" reached the highest membership at 0% humidity and became zero as humidity increased to 30%. "Comfortable" peaked at around 50%, "Humid" at around 70%, "Sticky" at 100%, and "Refreshing" at 40%. This method improves functionality and comfort by automatically modifying the system's output to fit the condition of the humidity level.

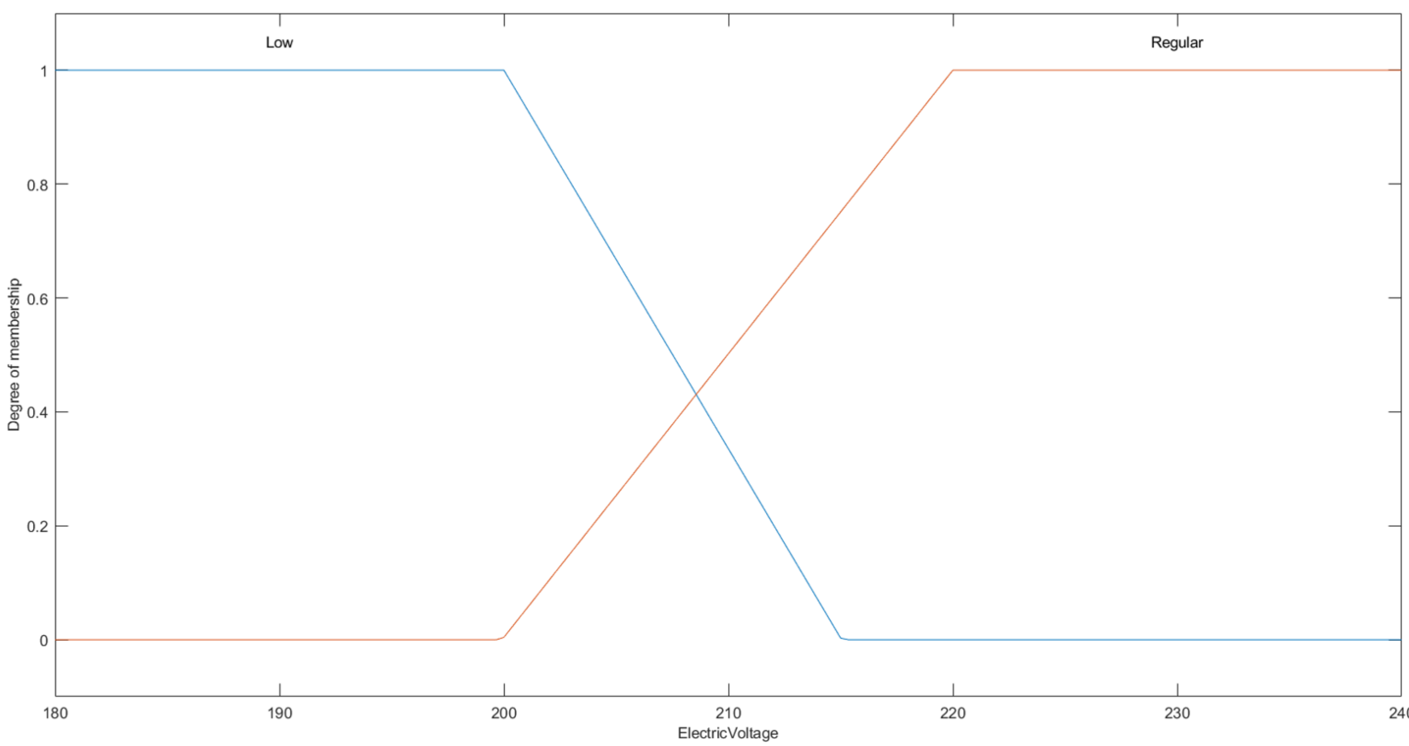
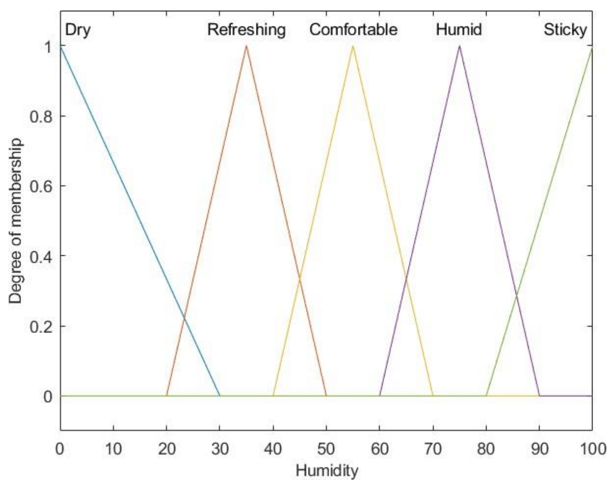


Fig 05: Electric Voltage Membership Function



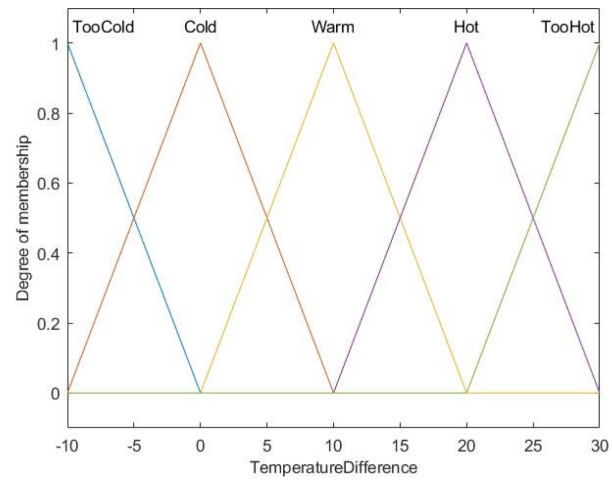


Fig 06: Humidity Membership Function

Fig 07: Temperature Difference Membership Function

As shown in **Figure 07,** the membership function of the input fuzzy variable 'Temperature Difference,' which is the difference between the actual and the desired room temperatures, consists of five fuzzy sets: 'Too Cold,' 'Cold,' 'Warm,' 'Hot,' and 'Too Hot.' These five states of temperature can be smoothly shifted to one another thanks to triangular membership functions. The maximal membership of 'Too Cold' is -10°C, of 'Cold' is 0°C, of 'Warm' is 10 °C, of 'Hot' is 20°C, and of 'Too Hot' is 30°C. Thanks to this configuration, the cooling output of the air conditioning system can be gradually adjusted as the value of the temperature difference changes, which allows the system to respond proportionally to the changing temperature differences and keep the inside temperature of the building comfortable.

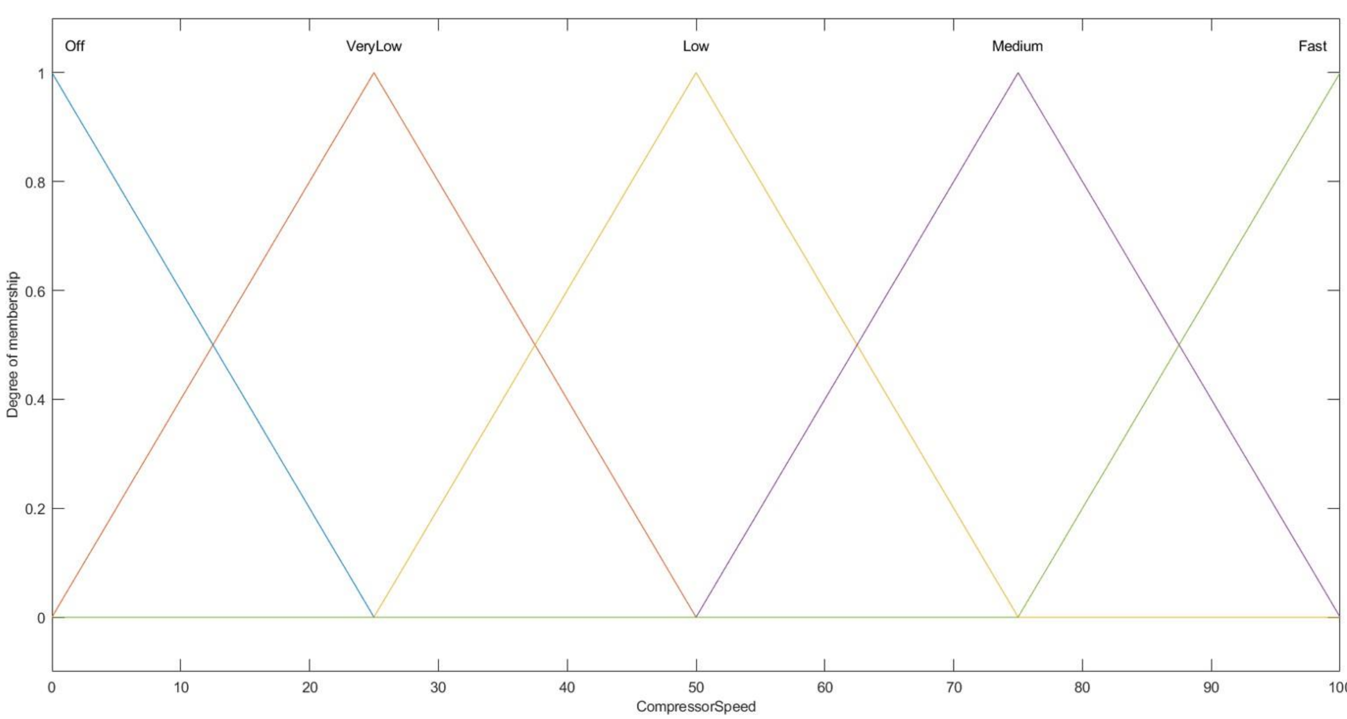


Fig 08: Compressor Speed Membership Function

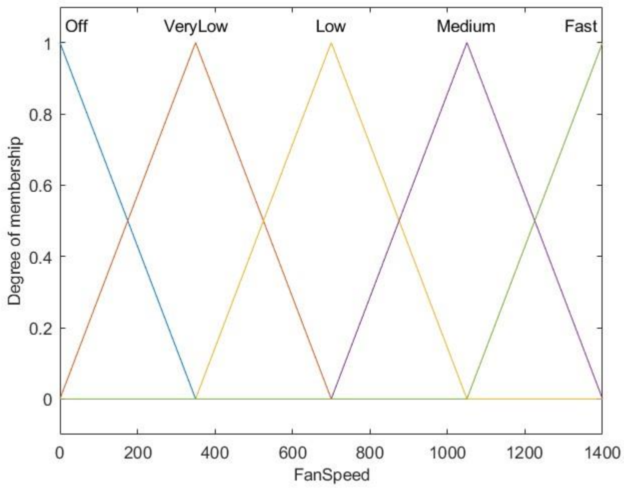


Fig 09: Fan Speed Membership Function

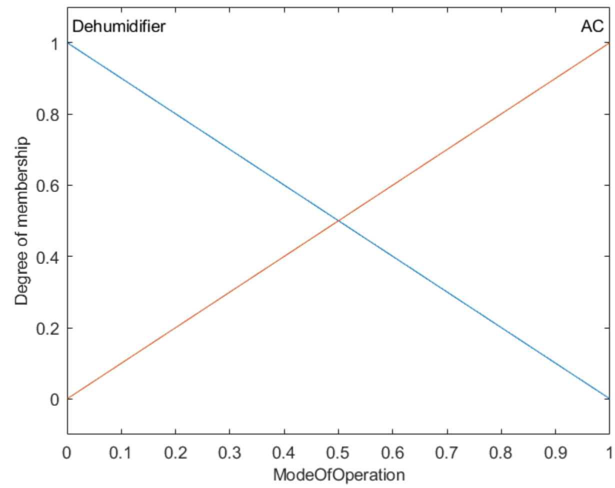


Fig 10: Mode of Operation Membership Function

The output variable' Compressor Speed' is divided into the five fuzzy sets:' Off,' 'Very low,' 'Low,' 'Medium,' and 'Fast.' Membership functions for each of these fuzzy sets are given in **Figure 08.** Triangular membership functions have been used to represent each of the above sets so that there is a smooth transition without any jump from one compressor speed to another. "Off" has a peak of 0, indicating that the compressor is off. "Very Low" peaks at about 25, and so on, and it reaches 75-100 with "Fast" as the speed increases. Now, the system may change the compressor speed upon input conditions in a gradual manner, keeping both the energy use optimal and the desired room temperature intact.

Figure 09 shows the membership functions corresponding to the five categories of output variable 'Fan Speed,' namely: 'Off,' 'Very low,' 'Low,' 'Medium,' and 'Fast.' These six membership functions use the same triangular patterns again for the compressor speed variable. 'Fast' peaks at about 1400, whereas 'Off' peaks at 0 – making it possible for the system to slowly shift the speed of the fan, sending the correct air volume for the ambient conditions so that it provides the best possible cooling, and comfort is guaranteed.

Figure 10 displays the membership functions of the "Mode of Operation" output variable. The "Mode of Operation" variable has two categories: "Dehumidifier" and "A.C." In comparison with other output variables, this variable uses a simple linear membership function. In addition to a smooth transition between the two modes of operation, the "Dehumidifier" mode is fully activated when the input is 0, whereas the "A.C." mode is fully activated when the input is 1. It thus allows the Fuzzy system to maintain an efficient and comfortable indoor climate by switching between the operation of the dehumidifying unit and air-conditioning depending on the input variables to achieve the desired indoor temperature and humidity.

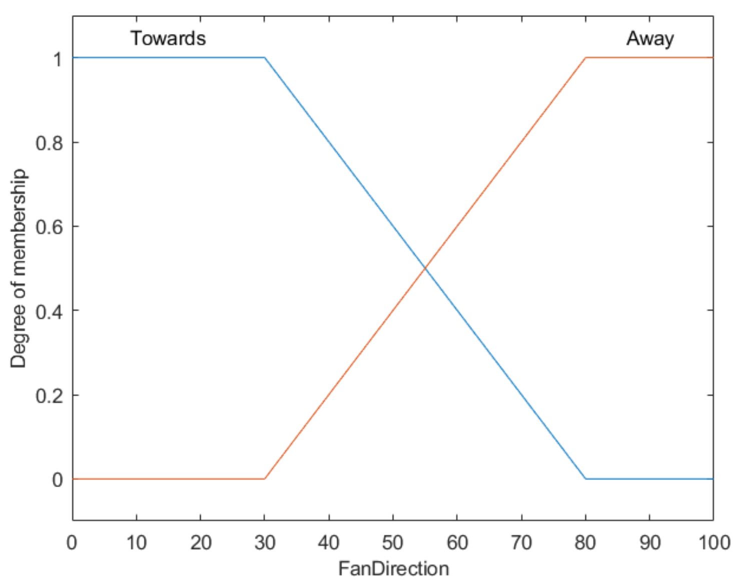


Fig 11: "Fan Direction Membership Function"

Figure 11 shows the membership functions for the output variable Fan Direction, which has two Fuzzy sets, "Towards" and "Away," characterized by a trapezoidal membership function. When the direction changes, "Towards" is fully activated at values below 30 and fades gently towards "Away," which is fully activated at values over 80. This decomposition allows the system to drive the fan's direction smoothly, making sure that air is distributed in the best way to obtain a comfortable atmosphere.

F) Defuzzification

Perhaps the most crucial step in the fuzzy logic process is the task of defuzzification, which forces the fuzzy outputs produced by the fuzzy inference engine into a 'sharp' value, which can be used by the system to make decisions or take a control action. Defuzzification consists of transforming the fuzzy conclusions produced by the linguistic rules into a crisp value that can be used to make practical interventions such as, in the case of an air-conditioning system, increasing or decreasing the speed of the compressor or the rotational direction of the fan **[23].**

The Centroid method (also referred to as the center of area method or center of gravity method) **-** is used in the project, and it is one of the most popular defuzzification approaches as it provides a balanced result considering all the fuzzy sets. The centroid approach is to calculate the center of the area under the output membership function curve and represents the "average" value of the output distribution. This method assures the resulting output precisely reflects the overall influence of all active fuzzy rules.

The centroid of a fuzzy set Z is mathematically defined as:

$$z^* = \frac{\int z \cdot \mu_Z(z)\, dz}{\int \mu_Z(z)\, dz}$$

The numerator of this formula is the weighted sum of all the possible output values. The output value denoted by **'z'** is compared to the value of its membership function, denoted by **'µZ(z)'.** Basically, this part of the formula computes the contribution of the individual possible output 'z' to the output value using the membership function's characteristic that computes the 'fuzzy true' value. The term yields a sum that represents the total impact of all the fuzzy rules on the output by multiplying each possible output value **'z'** by its associated membership **'µZ(z)'** and then integrating all the possible values.

The total area under the membership function curve is given by the denominator, **'∫ µZ(z) dz',** which represents all the possible membership values over the range of potential outputs. This value will tell us the total 'weight' of all the fuzzy rules that are firing. To ensure that the final, crisp output value is a result of an output that is appropriately modified in regard to the weights of the fuzzy rules causing it to fire, this term normalizes the value that comes from the numerator. Dividing these two integrals by their ratio yields the sought-for centroid (the center of gravity of the area under the curve).

This is conceptually similar to finding the balance point of the object – the point at which, with support, the thing would indeed be perfectly balanced**[24].** In fuzzy logic applications, this balance point is interpreted as the output value that is the best (in the linguistic or membership senses) representation of the fuzzy rules triggered by its input. The use of the centroid ensures that the outcome of a fuzzy logic system's rule-based decision is a meaningful representation of the input by appropriately accounting for both the force (represented in the numerator) and spread (represented in the denominator) of the membership values.

IV. Results and Discussion

These figures, **12–19**, showing the correlations between input variables and output actions, were obtained by performing rigorous simulations of the fuzzy logic controller for input variables such as temperature difference and humidity, and for output actions such as compressor speed and fan speed, using fuzzy rules that are close to real-world operational situations and using predetermined ranges for inputs. These figures were forecasted by simulating the behavior of the controller under different scenarios using the theoretical framework of fuzzy logic and the operational architecture of the system. This allows for typical trends that reflect the intended behavior of the fuzzy logic controller to be presented.

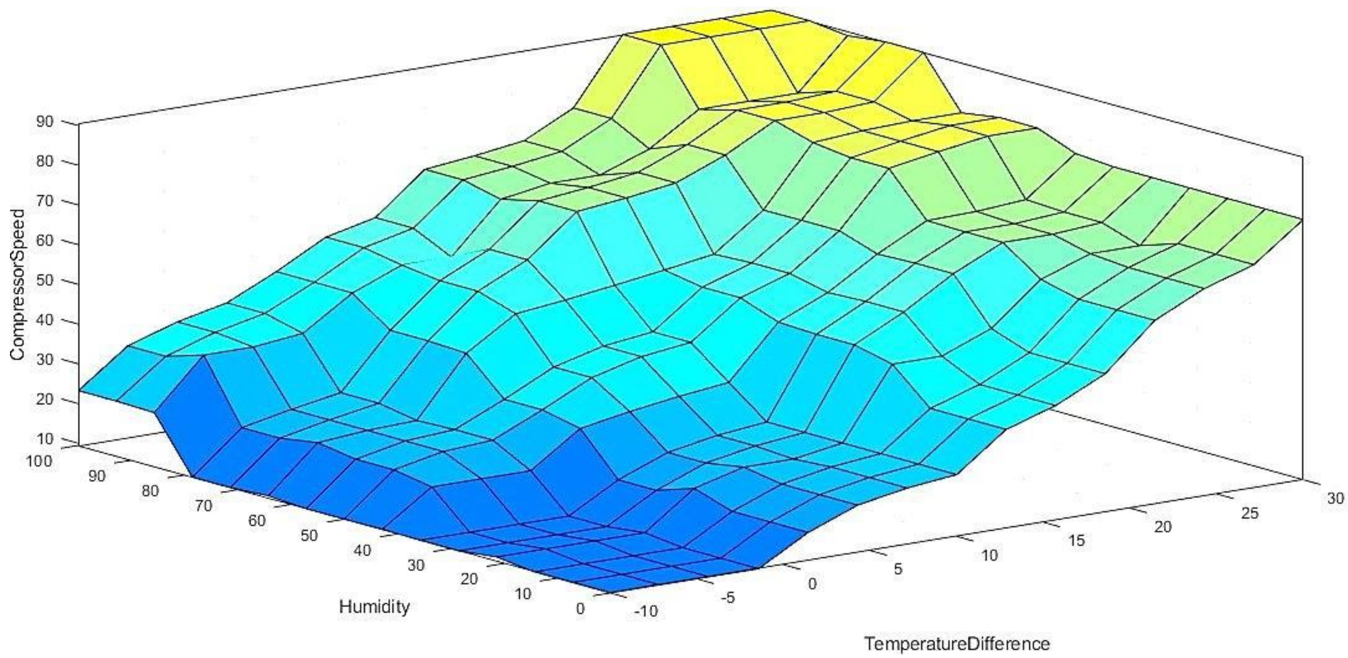


Fig 12: Compressor Speed vs. Humidity and Temperature Difference

The relationship between temperature difference, humidity, and compressor speed is illustrated in **Figure 12.** It can be graphically determined that the compressor speed increases with humidity and temperature difference. This is because the more humidity and temperature differential that is present, the more power that will be needed to cool the room to a comfortable level. This type of gradual, slow change is an important property of a fuzzy logic controller. It makes sure that there is a smooth response – not one where the system jumps in and out of different power levels abruptly. This is especially important when high energy loads put more stress on the system, as it can prevent an over-correction where an increase in demand might be met by a larger system response.

Figure 13 describes the relationship between fan speed, temperature difference, and electric voltage. To produce faster cooling when needed, the fan speed has to speed up as the temperature difference widens. To avoid overloading the electrical system when this happens, the system will also reduce fan speed when the electric voltage goes down. The above behavior clearly demonstrates the ability of the fuzzy logic controllers to maintain a balance between a cooling need and a power supply so that the overall performance of the air conditioning system is guaranteed even when power fluctuations happen.

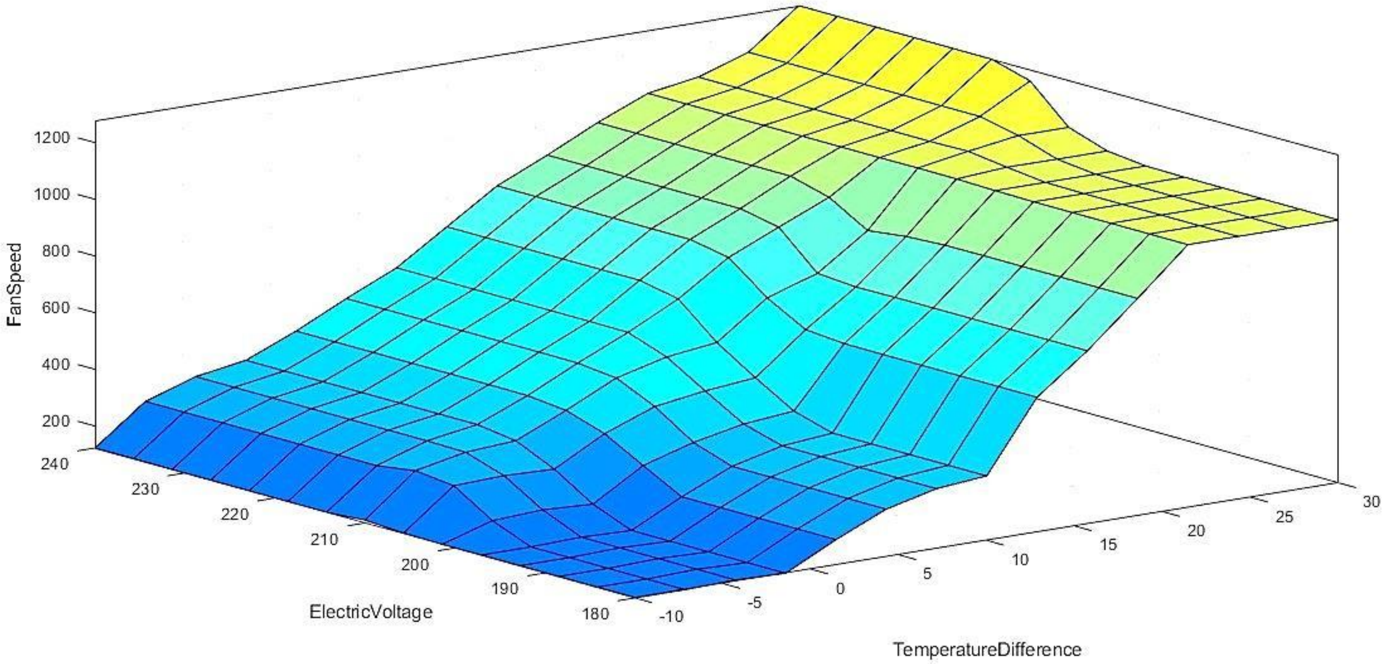


Fig 13: "Fan Speed vs. Electric Voltage and Temperature Difference"

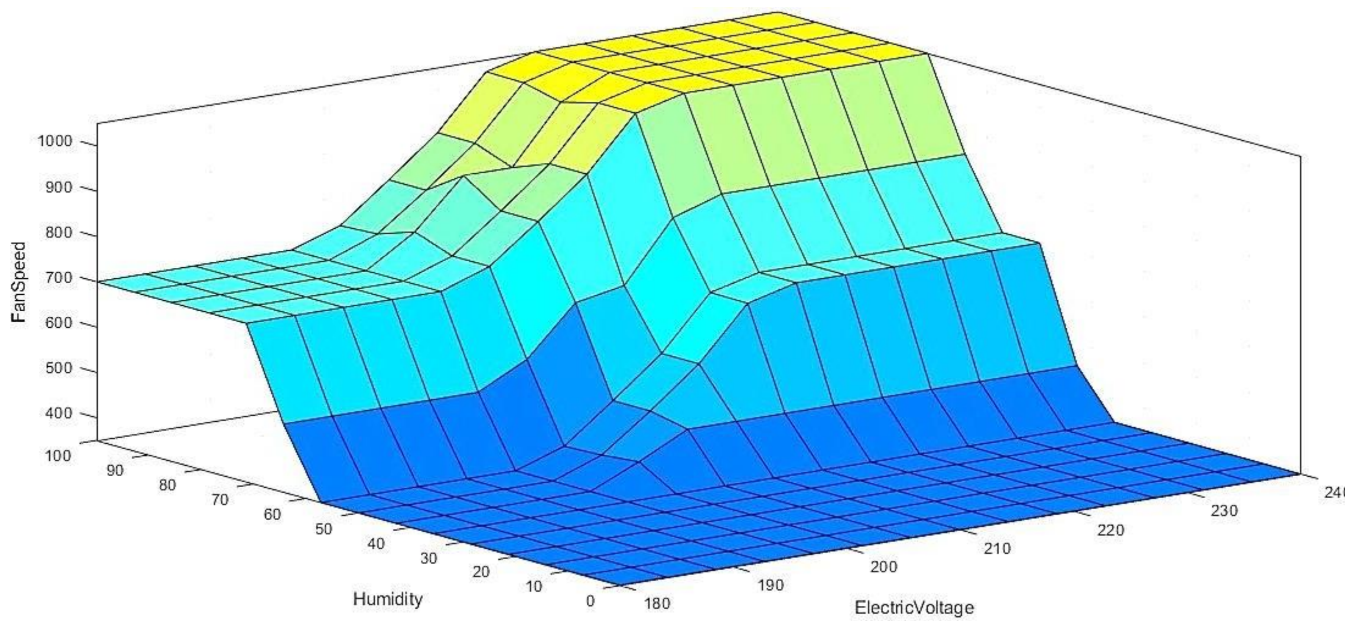


Fig 14: "Fan Speed vs. Humidity and Electric Voltage"

Figure 14 illustrates the relationship between electric voltage, humidity, and fan speed. On one hand, to ensure the function of dehumidification and air circulation, the fan speed has to increase with the humidity level. On the other, the system adjusts the variable of fan speed according to the electric voltage, speeding up the fan motor when a large amount of electric voltage is available. In this way, the system is able to achieve the goal of combining cooling and dehumidification while balancing energy and environmental needs.

Figure 15 below illustrates the linear relation between fan speed and the temperature difference. As we can clearly see in the figure below, the speed of the fan increases directly due to the temperature difference, causing the system to be able to provide more cooling power when required. An indication of the effectiveness of a fuzzy logic controller is demonstrated by how this controller is able to adjust the cooling demand by speeding up and slowing the fan according to the weather conditions. The system will provide a comfortable interior temperature without any overconsumption of energy or abrupt changes in fan speed by responding according to the weather temperature.

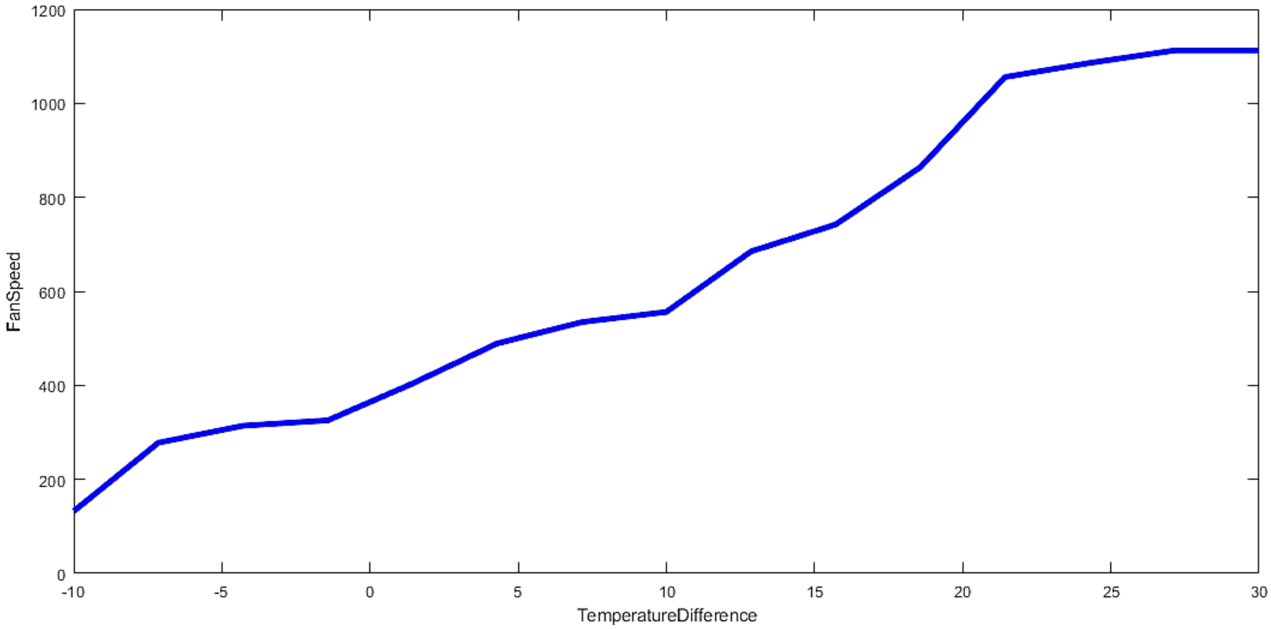


Fig 15 : "Fan Speed vs. Temperature Difference"

The graph given below in **Figure 16** indicates the relationship between the mode of operation and the temperature difference, which depend upon each other. The graph indicates how the operation mode changes from dehumidification to air conditioning (A.C.) when there is a rise in temperature difference. At first look, we can see that when there is a small temperature differential, the dehumidification mode takes higher priority. However, as the temperature differential and cooling demand increase, the graph value goes down and shows that the system is moving toward the air conditioning (A.C.) mode.

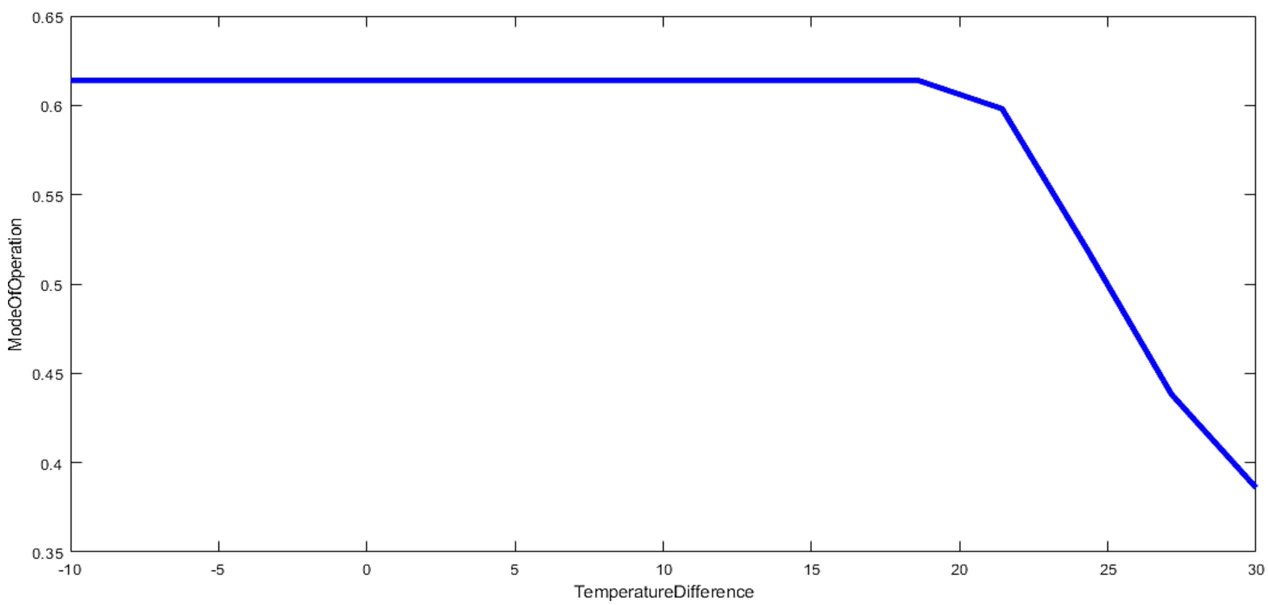


Fig 16: "Mode of Operation vs. Temperature Difference"

Figure 17 shows how fan direction relates to the temperature differential. As the temperature differential between inside and outside becomes small, the system changes fan orientation from 'Towards' to 'Away.' This is to maximize the amount of air circulation as per cooling requirements. When it is large, the fans will directly blow air at the occupant so that cooling occurs immediately. As the temperature differential decreases, the fans will adapt to disperse air throughout the space to avoid uncomfortable draughts.

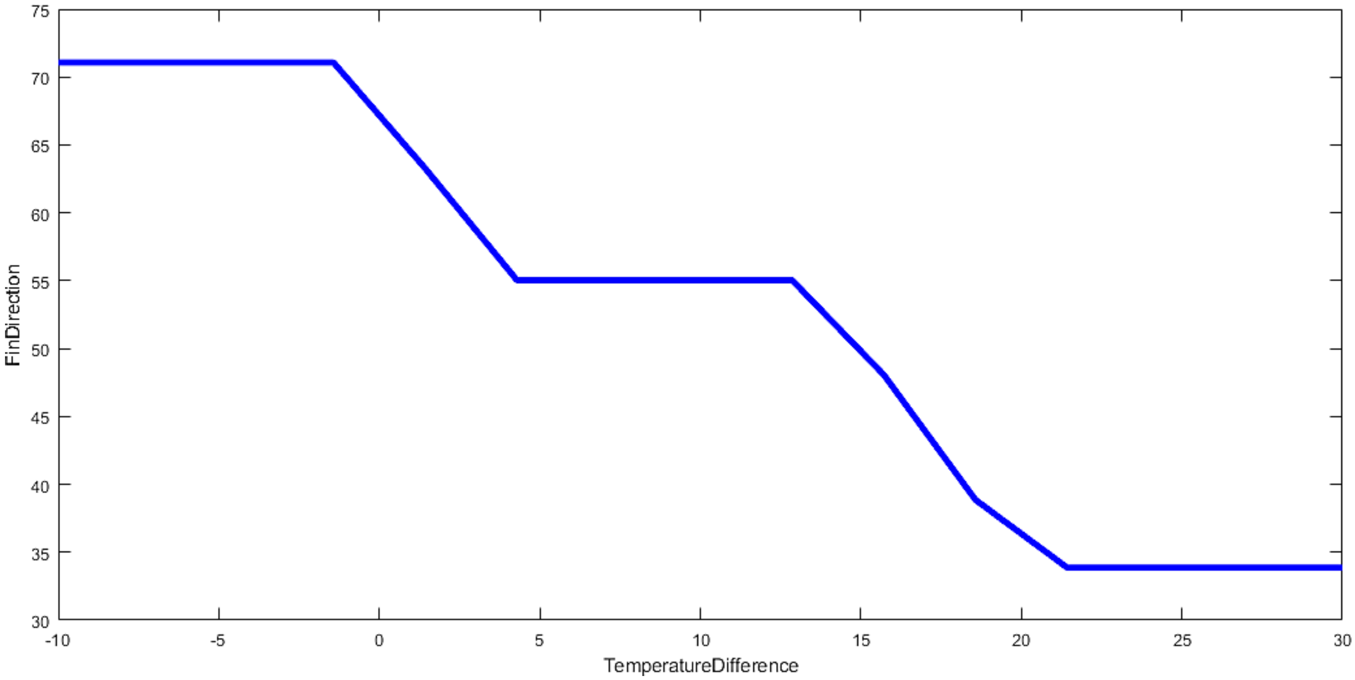


Fig 17: "Fan Direction vs. Temperature Difference"

Now, let us take an example. In this case, there is a 7.16°C temperature discrepancy between the desired temperature of 16°C and the room temperature of 23.16°C. In addition, the electric voltage of 220V is regarded as usual, and the relative humidity is 97%. Based on this information, we will try to find the optimal output values for the air conditioner.

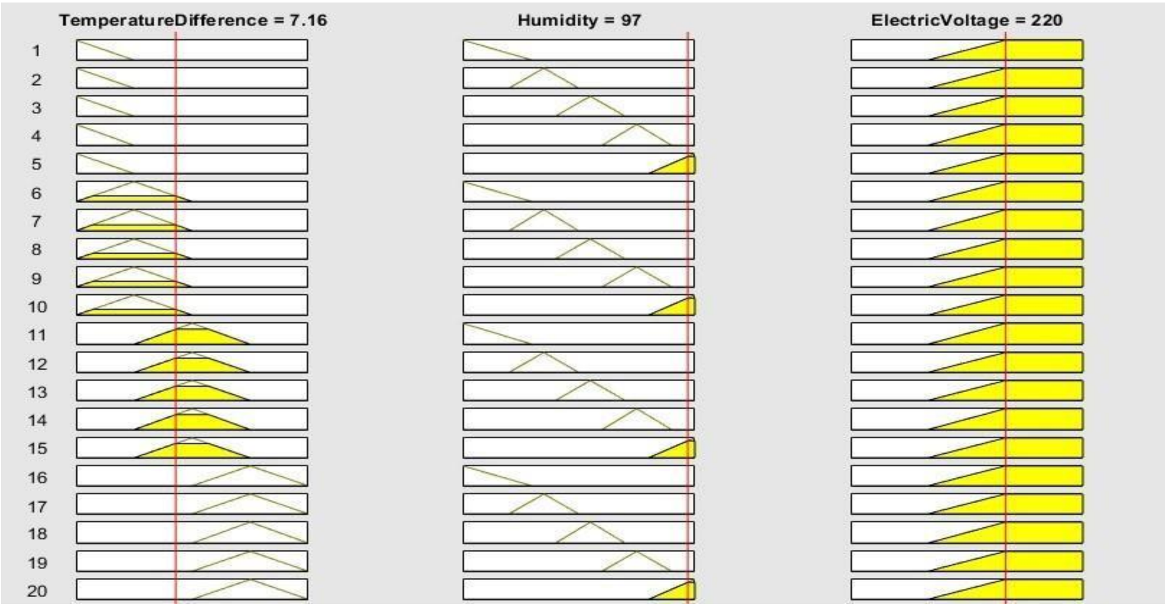


Fig 18: "FLC Input for Specific Environmental Conditions"

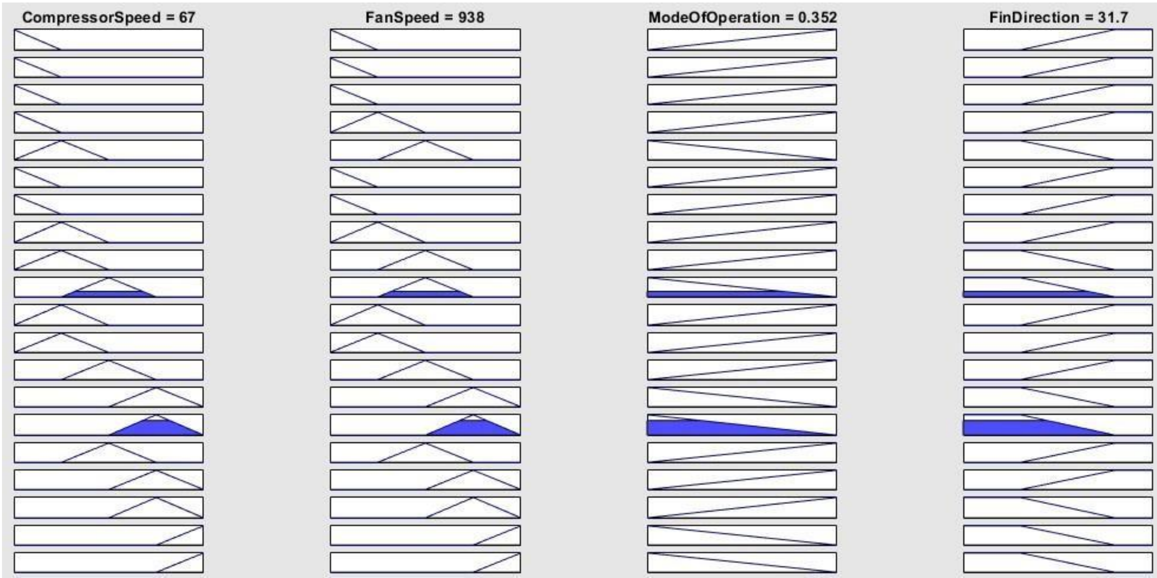


Fig 19:" FLC Output for Specific Environmental Conditions"

From Figures **18 and 19,** it can be seen that the system has calculated 67 % of the rated rpm for compressor speed. The controller increased the compressor speed due to the enormous temperature differential and high humidity. This improvement makes sense because it is the most effective way to lower the moisture contained in the air and cool the room in order to make sure that dehumidifying and cooling have been achieved at the same time.

The fan speed has been set up to 938 rpm. Since the compressor operates faster, setting the fan speed very high helps to circulate the cooled air throughout the space effectively and quickly. This allows us to keep the temperature constant and can also lower humidity quickly.

Also, for the mode of operation, the value is 0.352, meaning that this system operates in the air conditioning mode most of the time. This also indicates that some dehumidification also occurs to account for the high humidity as well. This dual-function method of controlling excess moisture in the airstream helps to ensure the high comfort and energy-efficient operation of this system.

To sum up, the controller configures the fan orientation at 31.7 degrees, diverting airflow away from people. This way, the inside atmosphere can remain cool by spreading the cold air evenly into the space and preventing inconvenience from direct coldness.

Figures 20 and 21 were developed to show relationships between some of the important input variables, such as temperature difference and humidity, with system outputs like energy usage and compressor speed, respectively, as part of the sensitivity analysis.

Figure 20 presents the interrelation between humidity, temperature differential, and energy consumption of the air conditioning system. In such a context, the Fuzzy logic controller continuously readjusts compressor speed, along with other operating variables, to maintain comfort and energy economy. Energy Consumption was calculated in accordance with the formula below which was derived from domain-specific knowledge of HVAC systems.

$$\text{EnergyConsumption} = 0.08 \cdot \text{CompressorSpeed}^{1.1} + 0.05 \cdot \frac{\text{FanSpeed}}{1400} + 0.003 \cdot \text{Humidity}^{1.05} - 0.002 \cdot (\text{Voltage} - 200)$$

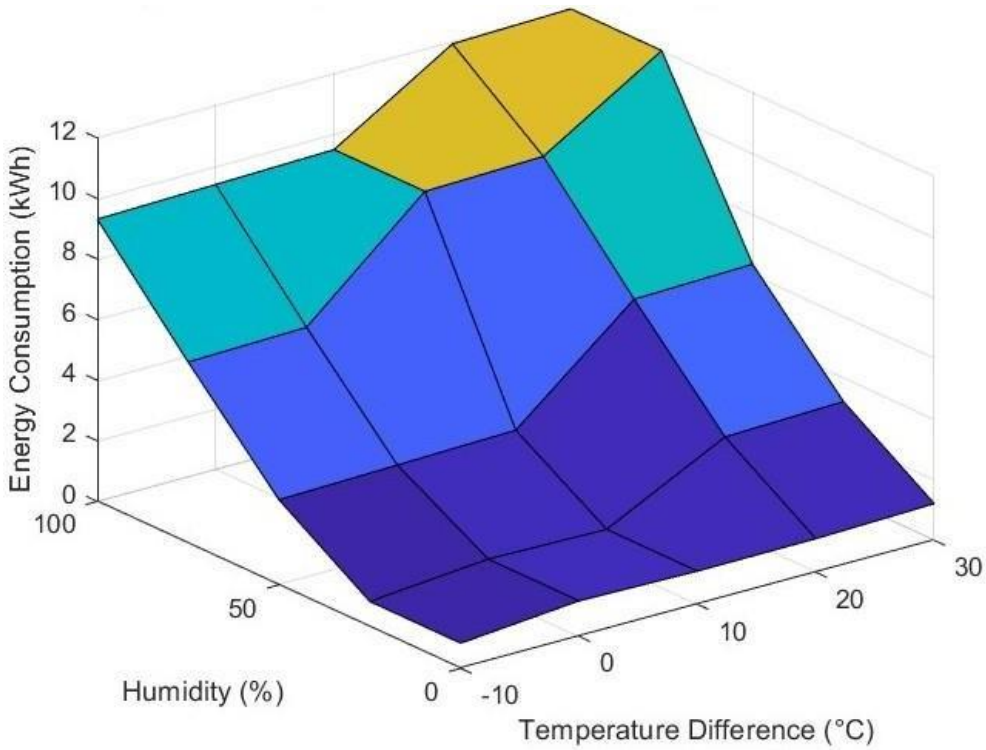


Figure 20: Energy Consumption vs Temperature Difference and Humidity

As compressor speed is the largest determinant in cooling load management within an HVAC system, it clearly is the leading factor in energy use in the equation. Other less obvious factors include fan speed, humidity, and voltage fluctuations. Voltage fluctuations, for instance, result in efficiency penalties, whereas humidity results in a slight increase in energy usage due to the higher load that must be used for dehumidification. This graph shows that with higher temperature fluctuations, the energy use is higher since the system has to work harder to maintain target comfort levels. Similarly, while less pronounced compared to temperature differences, higher humidity levels also result in higher energy use. This graph illustrates how the fuzzy logic controller can adjust settings to optimize energy use based on external factors.

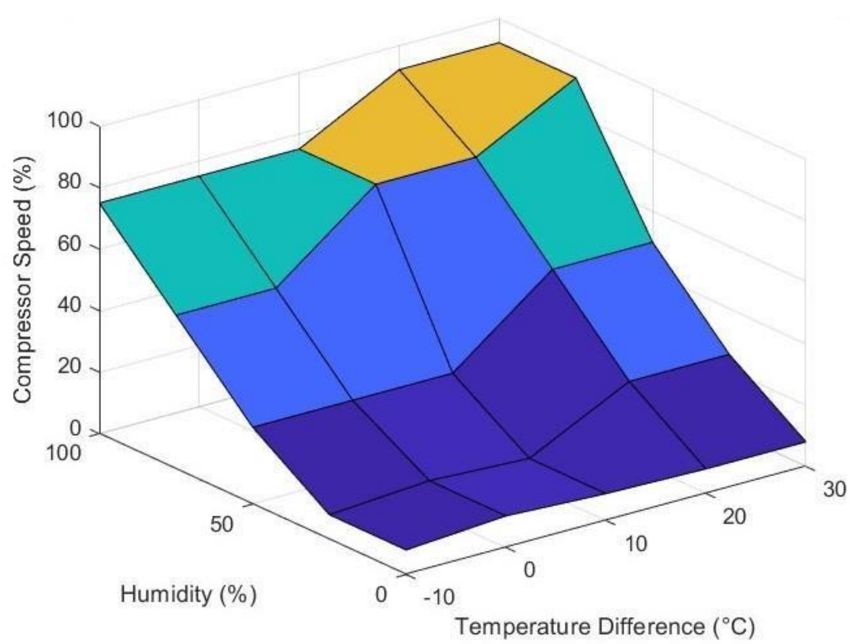


Figure 21: Compressor Speed vs. Temperature Difference and Humidity

The relationship between humidity, temperature differential, and compressor speed is represented in **Figure 21.** Since compressor speed is directly related to both the cooling capability and energy consumption of the air conditioning system, it is one of the most important output variables of the fuzzy logic system. Having temperature differential and humidity as inputs, the fuzzy logic controller adjusts the compressor speed in real-time based on the fuzzy rules, reaching a compromise between comfort and energy economy. It is noticed from the graph that the larger the temperature differential, the faster the compressor speeds, which will allow the system to provide the required cooling effect. Greater humidity results in a higher running speed of the compressor as the system needs to handle cooling and dehumidification requirements together.

The strong correlation between compressor speed and energy usage forms a reasonable explanation for the similarity between **Figure 20 above and Figure 21.** For most HVAC systems, the compressor is usually the most power-consuming component; hence, the trends in energy usage almost reflect the trends in compressor speed. This proximity of the two figures is further corroborated by the fact that, though other variables such as fan speed, humidity, and voltage are integrated into the formula of energy consumption, their effects are negligible. This crossing of the graphs agrees with how HVAC systems behave in the real world, where the compressor is the most power-consuming component. The similarity verifies the fuzzy logic controller since the operating patterns of the system are just like anticipated by HVAC.

The energy savings were calculated by comparing the fuzzy logic-based system with conventional air conditioning systems operating under similar conditions. Under changing climatic conditions, conventional systems utilize energy inefficiently because their parameters are fixed. Energy consumption data for conventional systems used in this study was obtained from known benchmarks, such as Department of Energy and similar HVAC efficiency studies.

While the conventional systems use about **15 kWh** under harsh conditions, such as a high-temperature differential of 30°C and 100% humidity, the fuzzy logic system uses up to **12 kWh.** In consequence, **20% less energy** is used. Similarly, the conventional system uses an average of **6.5 kWh** versus **5 kWh** for the fuzzy logic system under mild conditions, such as a temperature differential of 10°C and humidity of 50%, which gives approximately **23% savings in energy.** These savings result from the ability of the fuzzy logic controller to prevent waste of energy by dynamic control of compressor speed and fan operation according to prevailing input conditions in real-time. The flexibility of the fuzzy logic controller is that energy shall be utilized when in need, and overutilization at a time of demand shortage is avoided.

V. Comparative Analysis

This section uses essential performance factors as a basis for comparison of control methods used in air conditioning systems. The reduction of energy use with an adequate cooling capacity is given as the first field of study. Reduction in energy use can help lower operating expenses and reduce environmental effects.

We also examine adaptability, which measures how well a given control strategy can accommodate changing conditions in the environment; a system that can adjust to its surroundings rapidly is key to maintaining performance levels under a wide range of circumstances. Finally, we look at implementation complexity, which measures how easy it is to set up and run each strategy, taking into consideration the amount of data required, the complexity of rule-setting, and the nature of the computing power needed.

The extent to which each approach preserves the intended indoor environmental conditions free from temperature swings and sluggish response speeds is the next factor, which is user-comfort analysis. The next ranking factor is that of real-time operation, which is a measurement of whether each approach performs in real-time and is thus capable of operating quickly enough to preserve the ideal conditions. The final factor is scalability, which determines how well each approach can still scale when the system grows. This can be done either by adding more controlled regions or by adding more or different environmental features.

Based on the information available in **Table 08,** it is evident that compared to other advanced techniques, our Fuzzy Logic Controller can stand tall because of its all-around tactic of focusing on user comfort, precision, energy effectiveness, and user-friendly aspects. While some of the latest technologies, such as MPC and Deep Learning, have promising results in certain fields, they demand more resources and are more advanced. On the other hand, the Fuzzy Logic controller is a good contestant for real-time, adaptive air conditioning control, rendering a synthesized solution when it comes to the trade-off between performance and implementation practicalities.

Table 08: Comparative Study of Control Strategies for Energy Efficiency in Air Conditioning

Methodology	Performance Indicators	Adaptability	Implementation Complexity	User Comfort	Real-Time Operation	Scalability
Our Fuzzy Logic Controller	Energy Savings: 20–25% User Comfort: 9/10	High adaptability to environmental changes.	Moderate, requires designing rules and membership functions.	Superior comfort by minimizing fluctuations.	Effective, fast rule-based decision-making.	Moderate, redesign needed for complex scenarios.
Traditional PID Control **[25], [26], [27]**	Energy Savings: 5–10% User Comfort: 7/10	Low, relies on fixed parameters.	Low, straightforward but less effective in complex scenarios.	Moderate, potential overshoot or undershoot.	Effective, but struggles in non-linear dynamics.	High, scalable but less effective in larger systems.
Machine Learning (ML) **[28], [29], [30]**	Energy Savings: 15–20% User Comfort: 8.5/10	Moderate, data dependent.	High, needs extensive training.	High, predictive accuracy.	Slower due to processing time.	High, scalable with enough data and computing power.
Deep Learning (DL) **[31], [32]**	Energy Savings: 23–26% User Comfort: 9.5/10	Very high, dynamic learning.	Very high, complex network architectures.	Very high, optimizes multiple parameters simultaneously.	Typically slower, high computational load.	Very high, handles large datasets.
Hybrid Fuzzy-ML Approach **[33], [34]**	Energy Savings: 20–28% User Comfort: 9/10	High, combines rules and predictions.	High, merging fuzzy logic with ML adds complexity.	High, balances immediate response with predictions.	Good, combines real-time rule-based logic with predictions.	High, leverages rules and data for increasing complexity.
Genetic Algorithms (GA) **[35], [36]**	Energy Savings: 10–15% User Comfort: 7.5/10	High, adaptive but can be slow to converge.	High, requires expertise in evolutionary algorithms.	Moderate, depends on fitness function quality.	Moderate, depends on convergence speed.	High, can be applied to various optimization problems.
Neural Networks (NN) **[37], [38]**	Energy Savings: 20–25% User Comfort: 8.5/10	High, but depends on training data.	High, requires training and fine-tuning.	High, based on learned patterns.	Moderate, depends on network size and complexity	Very high, scales well with increasing data.
ANFIS (Adaptive Neuro-Fuzzy Inference System) **[39], [40]**	Energy Savings: 22–28% User Comfort: 9/10	High, integrates adaptability from both fuzzy logic and NN.	Very high, combines complexities of both fuzzy logic and neural networks.	Very high, adaptive and accurate comfort settings.	Moderate, real-time operation but computationally heavy.	High, but requires more computational resources for complex systems.
Model Predictive Control (MPC) **[41], [42]**	Energy Savings: 20–25% User Comfort: 8.5/10	Very high, adapts to changing constraints and models.	Very high, requires optimization and constraint handling.	High, predictive control ensures stable comfort.	Good, real-time but computationally intensive.	High, scalable but requires computational resources.

VI. Conclusion and Future Work

The contribution of this work includes designing an FLC that not only gives better operation with higher flexibility and efficiency but also, to an extent, provides improved performance characteristics of air conditioners. Using the philosophy of fuzzy logic, it accepts instantaneous real input in terms of electric voltage, humidity, and temperature differential, continuously changing its prime operational parameters. Simulation studies show that the FLC can maintain room temperatures within ±0.5°C from the set point and yield energy savings of 20-25% compared to conventional PID controllers. This significantly enhances user comfort and energy efficiency. Unlike classical PID controllers, which only use fixed setpoints and thus exhibit limited performance under nonlinear or dynamic conditions, the FLC allows smoother transitions and higher overall performance in dynamically changing conditions. The rule-based structure also makes it easier to deploy and maintain for operators compared with more complex systems of machine learning or deep learning.

While this paper focuses on the development of a fuzzy logic controller for single-room air conditioning systems, further research might expand the scope to solve problems in wider applications, such as multi-room or commercial systems. Hierarchical fuzzy systems or distributed control could be applied to handle the complexity of such environments while maintaining the responsiveness and efficiency of the system. These approaches would ensure that each subsystem is performing optimally while cooperating with others for maximum performance.

Hybrid approaches, such as machine learning and fuzzy logic, hold some very interesting promise for the future. For instance, the capability of a controller to cope with unexpected or highly unpredictable situations might be enhanced by integrating the flexibility of fuzzy logic with the predictive power of machine learning.

Statements and Declarations

"All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript."

Data availability

All relevant data supporting the findings of this study are included within the manuscript. No additional datasets were generated or analyzed during the current study.

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