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Preface

Conference Proceedings Message
Neil Bose, PhD, FCAE
President and Vice-Chancellor *pro tempore*
Memorial University
Newfoundland and Labrador

I have been proud to be closely involved with ICMCR (3rd International Conference on Mechatronics, Control and Robotics) conferences over the past few years and equally proud that Memorial University was a co-sponsor of the event. The 2025 conference once again delivered on charting the course for an advanced and interconnected future by bringing together brilliant minds to discuss new technologies and groundbreaking research.

As technology continues to evolve, the integration of mechatronics, control systems, robotics, information and electronics plays a crucial role in revolutionizing industries, from automation and healthcare to transportation and manufacturing. The event provided a unique opportunity to explore cutting-edge research, foster collaboration and discuss practical applications that push the boundaries of engineering and automation.

The conferences brought together several impressive keynote speakers on robot swarms, industrial and everyday robots, antenna design, analog computing, brain-computer interfaces and an invited speech on underwater robotics for oil spill detection. The presentations included presentations from many early career researchers on topics as diverse as language models, prosthetics, automated vehicles, a smart walking stick, air quality monitoring, sugar cane harvesting and much more.

I extend my sincere gratitude to all speakers, researchers and attendees who contributed to making the joint conferences a success. Your participation and engagement were invaluable in driving forward the progress of these dynamic fields.

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Industrial AHU Control Improvements using Fuzzy Logic for Energy Efficiency and Comfort

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***Abstract*—This study focuses on how fuzzy logic control can improve the efficiency and performance of Air Handling Unit (AHU) systems. Traditional methods of controlling AHUs, like fixed-frequency operation, often waste energy, cause unstable temperatures, and wear out equipment faster. To solve these problems, a fuzzy logic controller was designed to regulate motor frequency and motorized valve positions based on real-time inputs from Supply Air Temperature (SAT) and Return Air Temperature (RAT). The controller used Modbus communication to exchange data between Variable Frequency Drive (VFD). The system was tested over 21 days at a commercial building, comparing its performance to fixed-frequency settings between 40 Hz to 50 Hz configuration. The results showed that fuzzy logic control could reduce energy usage by up to 38% and stable temperatures. This research shows that fuzzy logic can improve energy efficiency and comfort in HVAC systems, making it a useful solution for modern building management.**

Keywords*—*fuzzy logic control, air handling unit (AHU), energy efficiency, variable frequency drive (VFD), HVAC system

I. Introduction

Air Handling Units (AHUs) are vital components of Heating, Ventilation and Air Conditioning (HVAC) systems, responsible for maintaining indoor air quality and thermal comfort in various building types [1]. However, traditional methods of controlling AHUs, such as fixed-frequency operation, present significant challenges. Operating at full frequency often results in excessive cooling, leading to energy waste and higher operational costs [2]. On the other hand, maintaining a constant lower frequency compromises temperature stability, which can lead to discomfort for building occupants [3]. Furthermore, fixed-speed operations accelerate wear and tear on motors and components, reducing equipment lifespan [4].

To address these inefficiencies, this study proposes the implementation of a fuzzy logic controller to optimize AHU operations. The fuzzy logic controller dynamically adjusts Variable Frequency Drive (VFD) and Motorized Valve (MV) positions based on real-time inputs from Supply Air Temperature (SAT) and Return Air Temperature (RAT) [5]. Modbus communication facilitates reliable data exchange between system components, that enables the controller to adapt to varying cooling demands effectively [6]. This research evaluates the performance of fuzzy logic control by comparing its energy efficiency and temperature stabilization capabilities to traditional fixed-frequency control methods. The findings aim to demonstrate the potential of fuzzy logic in reducing energy consumption while maintaining occupant comfort in modern building management systems [7].

A. Air Handling Unit (AHU)

AHUs are essential components of HVAC systems that regulate temperature, humidity and air quality across residential, commercial, and industrial environments [6, 8–10]. AHUs consist of critical components such as dampers, filters, fans and heating or cooling coils, all working together to ensure proper ventilation and indoor climate regulation [9, 11]. Given their significant contribution to building energy consumption, often exceeding 40%, optimizing AHU operations is crucial for achieving energy efficiency [9, 11-12]. Advanced control strategies have been developed to address inefficiencies in traditional fixed-frequency operations, such as energy waste, unstable temperatures and increased wear on components [8, 13]. VFDs have revolutionized airflow control by enabling precise fan speed regulation, which significantly reduces energy consumption compared to damper-based systems [9, 12]. Heat recovery systems, such as rotating heat wheels, further enhance

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Tier 1 (vot Q522).

energy efficiency by recovering up to 80% of exhaust air heat, reducing the load on heating and cooling systems [11, 14].

Control strategies like Proportional-Integral-Derivative (PID) controllers provide reliable temperature and humidity control under steady-state conditions, while advanced techniques such as Model Predictive Control (MPC) and fuzzy logic control adapt to dynamic environments and nonlinear system behaviours [8, 13, 15-16]. Fuzzy logic, in particular, has proven effective in managing uncertainties and optimizing AHU performance through adaptive control of motorized valves and supply air temperature settings [8, 10, 13]. Additionally, predictive models that incorporate real-time sensor data and learning frameworks, such as associative learning, allow AHUs to anticipate operational needs and respond proactively, further improving energy savings and performance [14, 17]. These innovations not only reduce energy consumption but also maintain occupant comfort and align AHUs with global sustainability goals [11, 14].

B. *Fuzzy Logic Controller*

Fuzzy logic is a computational approach that uses fuzzy sets, allowing partial membership values rather than binary true or false decisions, making it ideal for systems dealing with uncertainty and approximate reasoning [18]. Widely applied in control systems such as air conditioners, AHUs and greenhouses, fuzzy logic offers robust solutions for complex environments [18, 19]. In AHUs, adaptive fuzzy controllers estimate time-varying parameters like humidity sources and heat loads, improving the control of indoor air temperature and humidity while enhancing energy efficiency [20]. The system operates through key components which are pre-processing to convert sensor measurements, fuzzification to transform inputs into linguistic variables, an inference engine applying IF-THEN rules from the rule base and defuzzification to generate explicit control signals [18]. Membership functions, such as triangular, trapezoidal or Gaussian, define the degree of input belonging to a fuzzy set, while fuzzy rules enable the controller to interpret imprecise data and make decisions effectively under uncertainty [18, 21]. Fuzzy logic's advantages include robustness, simplicity, and adaptability, as it can mimic human reasoning and work alongside traditional controllers like PID to dynamically adjust parameters in real time, ensuring improved performance in applications such as AHUs and greenhouses [18, 19, 21].

C. *Affinity Law*

The Affinity Law is a key mathematical principle used to predict the performance of pumps and fans under varying operating conditions, such as changes in impeller speed or motor frequency. It is widely applied in HVAC systems, particularly in AHUs and chiller plants, where optimizing energy efficiency is critical [22]. The Affinity Law highlights the relationships between flow rate (Q), head (H), power (P), and speed (N), demonstrating that flow is proportional to speed, the head is proportional to the square of speed and the power is proportional to the cube of speed [22]. These relationships are summarized in Table I.

TABLE I. RELATIONSHIP OF AFFINITY LAW

Variable & Equation	Description
Flow: $\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$	Flow rate is proportional to the shaft speed.
Pressure (Head): $\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2$	Pressure (Head) is proportional to the square of the speed.
Power: $\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$	Power is proportional to the cube of the speed

These proportionalities demonstrate how even small reductions in speed can result in significant energy savings, as power consumption decreases cubically with speed. For example, reducing motor speed from 100% to 80% leads to a 20% frequency reduction, which translates to a 48.8% reduction in power consumption [29]. Additionally, the relationship between power, speed, and frequency is defined in (1):

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 = \left(\frac{f_1}{f_2}\right)^3 \tag{1}$$

Note that, P_1 and P_2 represent power consumption before and after the speed adjustment, N_1 and N_2 are the motor speeds, and f_1 and f_2 are the corresponding frequencies. For example, reducing the frequency from 50Hz to 25Hz decreases the motor frequency by half, resulting in an eighth of the original power consumption. This cubic relationship forms the foundation for energy-efficient design and operation in systems utilizing pumps and fans [22]. By applying these principles, this study demonstrates the potential for significant energy savings through frequency control, particularly in HVAC systems where motor speed and power consumption are key variables.

II. METHODOLOGY

A. *System Setup*

The research setup included key components, as shown in Fig. 1, which outlines the full process from developing the fuzzy logic controller to installing the Sauter controller, collecting data and evaluating the system's performance. The Sauter controller acted as the main control unit, which communicates in real-time with the VFD using the Modbus RTU protocol. Important inputs like SAT and RAT were collected using PT1000 sensors. These inputs were crucial for monitoring the system and making decisions in real-time.

The project started with designing a fuzzy logic controller using the Sauter Logic Designer software. This controller was created to adjust motor frequency and the MV positions automatically to save energy and keep temperatures stable. The fuzzy logic program was tested against MATLAB's fuzzy logic tool to ensure the rules worked correctly. Once the controller showed over 99% similarity to the MATLAB's tool, it was ready to be used.

After validating the fuzzy logic controller , the Sauter controller was installed and connected to the AHU system. All the input output which are SAT, RAT, motor frequency and MV positions were linked to the controller. The system also logged all data into the Sauter ModuWeb platform for data collection. Baseline data was first collected during 50 Hz configuration, followed by testing at 40 Hz to compare the performance of static control settings.

Finally, the system's performance was evaluated by comparing three control strategies: 50 Hz configuration, 40 Hz configuration and fuzzy logic control. Each method was tested for energy consumption and temperature stability. The fuzzy logic controller showed the best performance, automatically adjusting motor frequency between 40 Hz and 50 Hz and modulate the MV based on real-time SAT and RAT data. This led to noticeable energy savings while keeping temperatures stable.

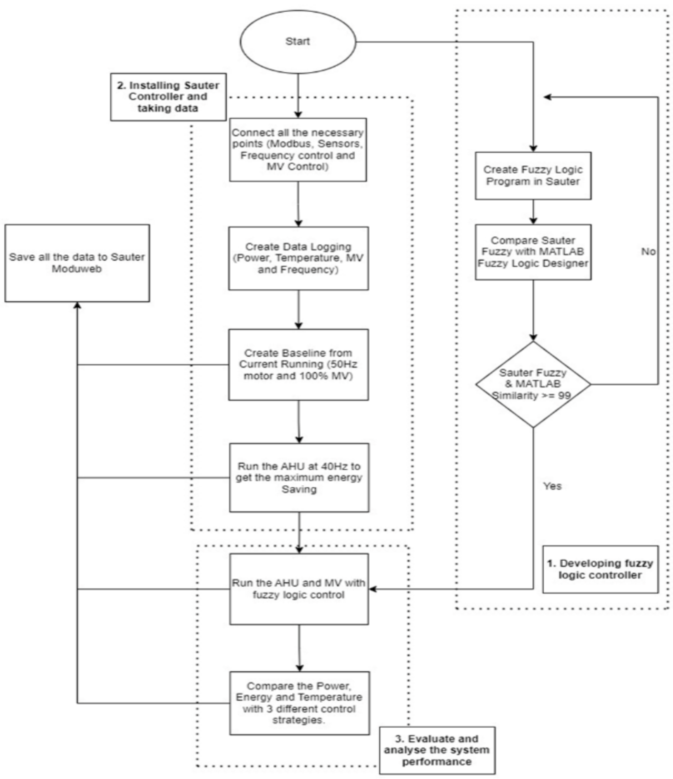

Fig. 1. System architecture

B. Control strategy

The fuzzy logic control system implemented in this research aimed to dynamically adjust motor frequency and MV positions to optimize AHU performance. The control logic was designed using Mamdani fuzzy inference, which applied triangular membership functions for inputs, which are SAT and RAT and for outputs are motor frequency and MV position. The control process is illustrated in Fig.2, that shows the flow of inputs through fuzzification, rule evaluation and defuzzification before generating control outputs. This flowchart highlights integrating fuzzy rules with real-time system feedback to achieve precise and adaptive control. The defuzzification process employed the Weighted Average Method (WAM), a robust approach for converting fuzzy outputs into actionable numerical values. The WAM equation is expressed in (2).

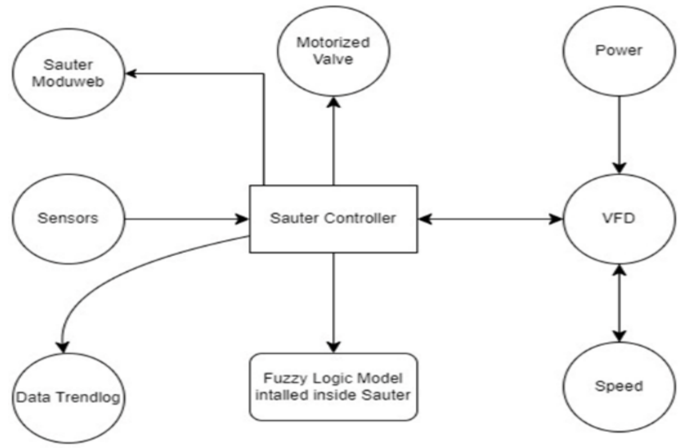

Fig. 2. Full system fuzzy logic control

$$W = \frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i} \tag{2}$$

In (2), W represents the crisp output, w_i is the degree of membership for the i^{th} rule and X_i is the corresponding output value. This method ensured smooth transitions in control actions, reduces mechanical stress and enhances energy efficiency. The fuzzy logic controller dynamically adjusted motor speeds between 40 Hz and 50 Hz and modulated the MV opening between 30% and 100% based on real-time cooling demands, ensuring optimized energy use while maintaining thermal comfort.

C. Baseline and Comparative Analysis

The system performance was evaluated across three configurations to determine energy efficiency and operational effectiveness. The first configuration involved fixed frequency configuration at 50 Hz, where the motor operated continuously at full speed with the MV is fully open. This served as the baseline for energy consumption and temperature stability. The second configuration reduced the frequency to 40 Hz, aiming to assess the impact of operating at the constant lower frequency on energy consumption and cooling performance. Lastly, the fuzzy logic control system dynamically adjusted AHU motor frequency between 40 Hz and 50 Hz and modulated the MV opening based on real-time inputs from SAT and RAT. This approach enabled the system to respond adaptively to cooling demands, optimizing energy use and maintaining thermal comfort. To quantify energy savings, the Affinity Law was applied, as power consumption (P) is proportional to the cube of motor speed (N) and frequency (f), as shown in (3).

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 = \left(\frac{f_1}{f_2}\right)^3 \tag{3}$$

In this study, energy consumption was measured for all configurations using on-site VFD and the results were compared to theoretical calculations derived from the Affinity Law. For example, reducing motor frequency from 50 Hz to 40 Hz achieved a theoretical power reduction of 48.8%. By combining real-time data collection with the predictive capabilities of fuzzy logic control, this methodology provided accurate assessments of energy efficiency and system performance.

D. *Controller Implementation*

This study utilized one main controller and one input-output (I/O) module to effectively manage the AHU system's operations. The Sauter EY-AS680F021 works as the primary controller and the Sauter EY-EM510 as the I/O controller. These controllers were integral to the implementation of fuzzy logic control and real-time system management.

The Sauter EY-AS680F021 served as the main controller, processing the fuzzy logic control algorithms to regulate motor frequency and MV position dynamically. Equipped with Modbus communication capabilities, this controller ensured seamless data exchange between the VFD, temperature sensors and other system components. It also handled complex control strategies such as defuzzification using the WAM, enabling precise and adaptive adjustments to the AHU operations.

The Sauter EY-EM510 acted as the I/O interface, facilitating connections between the main controller and field devices such as temperature sensors, VFD and the MV. This controller provided analog and digital input and output capabilities, ensuring accurate data acquisition and reliable control signal transmission. The EY-EM510 played a crucial role in integrating real-time feedback from sensors which are SAT and RAT, into the fuzzy logic system for optimized performance.

III. Results And Discussion

This study evaluated the performance of fuzzy logic control in optimizing AHU energy consumption and maintaining temperature stability. Baseline tests were conducted at fixed frequency configuration of 50 Hz and 40 Hz to establish reference energy consumption and temperature stability. The fixed 50 Hz configuration demonstrated the highest energy consumption, averaging 78.85 kWh per day, whereas the 40 Hz setup reduced energy consumption to 41.76 kWh per day but resulted in slower temperature stabilization and reduced cooling capacity. In contrast, the fuzzy logic controller dynamically adjusted motor frequency between 40 Hz and 50 Hz and modulated MV positions between 30% and 100% based on real-time inputs from SAT and RAT. This adaptive approach reduced average daily energy consumption to 48.83 kWh, representing a 38% reduction compared to the 50Hz baseline while maintaining stable temperature conditions. Fig.3 presents daily energy consumption for the three configurations which are 50 Hz, 40 Hz and fuzzy logic control. It visually demonstrates how fuzzy logic achieves significant energy savings compared to fixed-frequency operations.

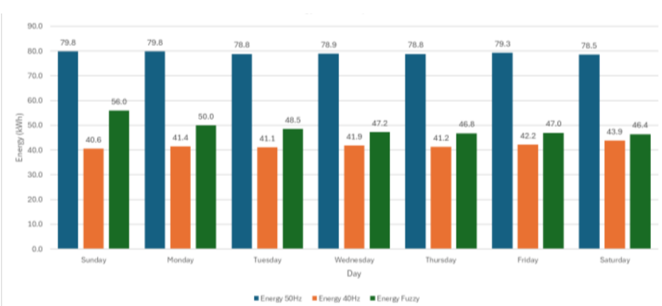

Fig. 3. Comparison of energy consumption between 50 Hz, 40 Hz and fuzzy logic control.

Temperature stability was assessed using SAT and RAT ranges, as summarized in Table II. The results indicate that fixed-frequency configurations exhibited wider temperature fluctuations. The 50 Hz setup had a SAT range of 0.15C° whereas the 40 Hz configuration showed a range of 2.16°C. In comparison, the fuzzy logic controller maintained a narrow SAT range of 0.47°C. This demonstrates that even the fixed frequency configuration at 50 Hz offers a smaller temperature range, but this configuration consumes more energy, whereas the 40Hz configuration has a wider temperature. Hence, fuzzy logic control offers better control not only by having a narrow temperature range but also by offering energy savings.

TABLE II. Table of Temperature Range

Configuration	Median, °C	Minimum, °C	Temperature range, °C
50 Hz	7.00	6.85	0.15
40 Hz	8.48	6.33	2.16
Fuzzy Logic Control	8.08	7.61	0.47

Fig. 4 illustrates the difference in power usage between the 50 Hz and 40 Hz configurations, demonstrating the impact of frequency reduction on energy savings. The observed energy savings align with predictions based on the Affinity Law, which states that power consumption is proportional to the cube of motor speed. The graph clearly follows the Affinity Law, which states that power consumption decreases cubically with frequency. For example, reducing motor frequency from 50 Hz to 40 Hz resulted in a theoretical power reduction of approximately 48.8%, closely matching the measured results. At a frequency of 50 Hz, the AHU motor operates at its full speed, N_1, with a power consumption of 7.14 kW. When the frequency is reduced to 40 Hz, the motor speed, N_2, decreases proportionally, resulting in a power consumption of 3.75 kW. This represents a reduction in power consumption of 48.8%. By leveraging the Affinity Law, fuzzy logic controls the frequency modulation to achieve substantial energy savings while maintaining occupant comfort. This result shows that by reducing the motor frequency by just 10 Hz can lead to substantial power savings, making it a crucial strategy for energy-efficient AHU operation. The ability to modulate frequency based on demand not only reduces power consumption but also minimizes wear and tear on system components, extending equipment lifespan while maintaining effective cooling performance.

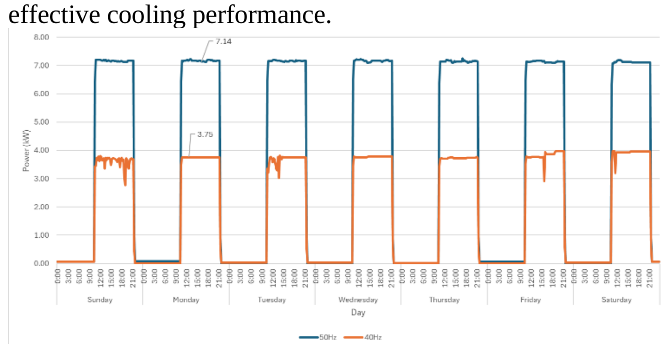

Fig. 4. AHU power usage during 5 0Hz and 40 Hz configurations.

In summary, the fuzzy logic controller outperformed fixed-frequency configurations by achieving a balance between energy efficiency and temperature stability. This demonstrates the practical application of fuzzy logic in optimizing AHU operations, reducing energy consumption, and enhancing thermal comfort.

IV. Conclusion

This study successfully developed and implemented a fuzzy logic controller to optimize the operation of AHU, focusing on energy efficiency and occupant comfort. From the study, the fuzzy logic controller was able to dynamically adjust motor frequencies between 40 Hz and 50 Hz and modulate the MV positions based on real-time inputs from SAT and RAT. This adaptive approach enhanced energy efficiency while maintaining indoor thermal comfort. The results showed that the fuzzy logic system reduced energy consumption by 38% compared to the baseline 50 Hz operation, achieving significant savings while ensuring stable temperature conditions. As reflected in narrower temperature ranges, the SAT and RAT stability achieved through the fuzzy logic controller outperformed traditional fixed-frequency configurations.

Integrating the fuzzy logic controller into the Sauter Logic Program demonstrated significant improvement in the AHU system’s operational reliability and energy efficiency. The controller optimized motor frequency and motorized valve by providing real-time responses to fluctuating cooling demands, achieving substantial energy savings while maintaining consistent comfort levels for occupants. The study leveraged the principles of the Affinity Law to showcase how precise control of motor frequency and valve positions can result in efficient energy use without compromising system performance. These results validate the effectiveness of fuzzy logic as a practical and intelligent solution for modern HVAC systems, offering a reliable approach to balancing energy efficiency with operational requirements. Additionally, the findings highlight the potential of fuzzy logic to support sustainable building practices, emphasizing its role in reducing energy consumption and improving system reliability. Future research could explore the scalability of this approach to larger and more complex systems, as well as investigate the inclusion of additional control parameters to enhance performance and adaptability further.

References

[1] H. M. N. B. Herath, P. Paranamana and D. C. N. Chandrasena, "Development of A Demand Control Algorithm for HVAC Systems to Conserve Energy in Office Buildings," *IEEE International Conference on Energy Technologies for Future Grids (ETFG)*, pp. 1-6, 2023.

[2] U.S Energy Information Administration, "Use of energy explained," 2023. [Online]. Available: https://www.eia.gov/energyexplained/use-of-energy/homes.php. [Accessed 6 September 2024].

[3] U.S Energy Information Administration, "Residential Energy Consumption Survey (RECS)," 2023. [Online]. Available: https://www.eia.gov/consumption/residential/. [Accessed 6 Sept 2024].

[4] H. Ritchie, "Air conditioning causes around 3% of greenhouse gas emissions. How will this change in the future?," OurWorldinData.org, 2024. [Online]. Available: https://ourworldindata.org/air-conditioning-causes-around-greenhouse-gas-emissions-will-change-future. [Accessed 6 September 2024].

[5] F. Al Qahtani and M. Muaafa, "Chiller Plant Management Optimization By Artificial Intelligence," *Saudi Arabia Smart Grid*, pp. 1-2, 2022.

[6] O. Asvadi-Kermani et al., "Energy Optimization of Air Handling Units Using Constrained Predictive Controllers Based on Dynamic Neural Networks," *IEEE Access,* vol. 10, pp. 5-6, 2022.

[7] Mohamed Adel Esmaeel Salama, Nada Mohamed El-Naggar & Salama Abu-Zaid, "Energy saving analysis for pump-motor set in water purification plant using variable speed drive," *Scientific Reports,* vol. 14, no. 1, pp. 1-15, 2024.

[8] Y. Sun, N. Liu and C. Liu, "A Backstepping-Based Temperature and Humidity Nonlinear Tracking Control Scheme for a Class of Air-Handling Units," in *International Annual Conference on Complex Systems and Intelligent Science (CSIS-IAC)*, pp. 129-134, 2023.

[9] F. Ghawash, M. Hovd, B. Schofield and D. Monteiro, "Model Predictive Control of Air Handling Unit for a Single Zone Setup," in *IEEE International Symposium on Advanced Control of Industrial Processes (AdCONIP)*, pp. 158-163, 2022.

[10] F. B. Liavoli, R. Shadi and A. Fakharian, "Multivariable Nonlinear Model Predictive Controller Design for Air-Handling Unit with Single Zone in Variable Air Volume," in *7th International Conference on Control, Instrumentation and Automation (ICCIA)*, pp. 1-6, 2021.

[11] Kassai, Miklos, Al-Hyari, Laith, "Monitoring the heating energy performance of a heat wheel in a direct expansion air handling unit," *International Journal of Refrigeration,* vol. 169, pp. 115-123, 2025.

[12] G. Balasubramanian, P. Chandrasekar and S. A. Alexandar, "Variable Frequency Drive operated Air Blower in Air Handling Unit of Heating, Ventilation and Air Conditioning Systems," in *IEEE Delhi Section Conference (DELCON)*, pp. 1-7, 2022.

[13] F. Shang, Y. Yin, J. Duan and W. Peng, "Temperature Regulation for a Single Zone with Air Handling Units," in *China Automation Congress (CAC)*, pp. 202-207, 2023.

[14] M. Eik, H. N. Hokmabad, A. Kose, O. Husev, J. Belikov, "Supply Air Temperature Control in Air Handling Unit based on Federated Learning," in *2024 IEEE Power & Energy Society General Meeting (PESGM)*, pp. 1-5, 2024.

[15] Naveed, P. V. Patil and S. A., "Implementation of VFD Application for Speed Control of Induction Motor," in *International Conference on Smart Innovations in Design, Environment, Management, Planning and Computing (ICSIDEMPC)*, pp. 168-170, 2020.

[16] Peter A. Lindahl, Muhammad Tauha Ali, Peter Armstrong, Andre Aboulian, John Donnal, Les Norford and Steven B. Leeb, "Nonintrusive Load Monitoring of Variable Speed Drive Cooling Systems," *IEEE Access,* vol. 8, pp. 211451- 211463, 2020.

[17] Johansson, Dennis, Daugela, Marius, Wahlström, Åsa, Bagge, Hans, "Modelling an air handling unit, building and occupant variation regarding energy, moisture and frost protection based on measurements of an air handling unit and occupants’ moisture supply," *SN Applied Sciences,* vol. 5, no. 3, pp. 74, 2023.

[18] Abubakar Unguwanrimi Yakubu, Shusheng Xiong, Qi Jiang, Jiahao Zhao, Zhankuan Wu, Haixuan Wang, Xuanhong Ye, Huang Wangsen, "Fuzzy-based thermal management control analysis of vehicle air conditioning system," *International Journal of Hydrogen Energy,* vol. 77, pp. 834-843, 2024.

[19] Chaowanan Jamroen, Ploylin Jirayus, Pooreepong Saneseepon, Thitiporn Suttikul, "Toward sustainable greenhouses: Self-tuning adaptive temperature control and its renewable energy potential," *Energy Reports,* vol. 12, pp. 1608-1622, 2024.

[20] Jihua Liu, Jingyu Li, Xiaoping Liu, Cungen Liu, Guangxu Liu, Zhen Xu, "Adaptive fuzzy controller design for an air handling unit," *European Journal of Control,* vol. 79, pp. 101085, 2024.

[21] Jun-Hong Chen, Pu He, Sai-Jie Cai, Ze-Hong He, Hao-Ning Zhu, Zi-Yan Yu, Lu-Zheng Yang, Wen-Quan Tao, "Modeling and temperature control of a water-cooled PEMFC system using intelligent algorithms," *Applied Energy,* vol. 372, pp. 123790, 2024.

[22] J. Simpson, N. Binesh, M. Rivera and C. Monroy, "Energy Efficiency Using a VSD in a Mining Installation, Analysis, and Measured Results," in *IEEE IAS Petroleum and Chemical Industry Technical Conference (PCIC)*, pp. 489-499, 2023.