PROGRESS IN ENGINEERING APPLICATION AND TECHNOLOGY
e-ISSN: 2773-5303

PEAT

Vol. 6 No. 2 (2025) 412-418
https://publisher.uthm.edu.my/periodicals/index.php/peat

Optimization Train Auxiliary Power Converters Using Fuzzy Control Techniques

Muhammad Ilias Roslin[1], Siti Idzura Yusuf[1]*, Norazman Abu Hassan[2]

[1] *Department of Transportation Engineering Technology Faculty of Engineering Technology,*
Universiti Tun Hussein Onn Malaysia, Kampus Pagoh, 84600 Johor, Malaysia
[2] *ERL Maintenance Support Sdn Bhd,*
Kompleks Rel Udara, Bandar Baru Salak Tinggi, 43900 Sepang, Selangor

*Corresponding Author: idzura@uthm.edu.my
DOI: https://doi.org/10.30880/peat.2025.06.02.044

Keywords

Received: 26 June 2025
Accepted: 11 August 2025
Available online: 30 October 2025

Keywords

Fuzzy logic control, auxiliary power converters, electric trains, energy efficiency, overshoot, transient response, PID control, MATLAB/Simulink, voltage and current stablization, railway power systems

Abstract

This research investigates fuzzy logic control (FLC) as a potential solution to improve the performance of auxiliary power converters (APCs) in electric trains, particularly during start-up, a period in which significant overshoot and undershoot may occur. In order to operate under realistic train auxiliary loads and generate a 400-volt root-mean- square (RMS) output at 50 hertz, a comparison simulation was conducted in MATLAB/Simulink with a 670-volt direct current (DC) input inverter. The results indicated that the FLC performed significantly better than a conventional PID controller. In contrast to the 15.8% overshoot and 3.45 seconds settling time that were characteristic of PID control, the FLC achieved a settling time of just 0.1 seconds and virtually no voltage overshoot, as indicated by the data. Furthermore, FLC guaranteed a more rapid and consistent control, while concurrently minimizing current overshoot to a mere 2.7%. Fuzzy logic has been demonstrated to be particularly effective in improving both energy efficiency and system stability as a consequence of these discoveries, rendering it a potentially beneficial approach for the development of future railway auxiliary power systems.

1. Introduction

A significant quantity of research has been conducted into novel technologies for energy management and optimization, particularly for electric trains, as a consequence of the emphasis placed on energy efficiency within the transportation industry [1]. Despite the fact that electric trains are more environmentally favorable than conventional alternatives that are powered by fossil fuels, they necessitate a significant amount of electrical energy. The potential for advancement in energy efficiency is suggested by the development of auxiliary power converters (APCs) for railroads [2]. APCs are critical onboard systems that support the train's ventilation, air conditioning, illumination, and communication apparatus. In recent years, research has concentrated on a variety of strategies that are designed to enhance the energy efficiency of APCs. It has been demonstrated that fuzzy logic control (FLC) methods are a practical method for improving the performance of automatic passenger cars (APCs) on trains [3].

Despite the fact that these advancements have been achieved, there are still substantial challenges to be surmounted in order to conserve energy in railway systems. For instance, the synchronization of auxiliary converters during the train's start-up phase can lead to substantial voltage fluctuations, identified by overshoot and undershoot events. There is a substantial risk of train components and onboard systems being compromised as a result of these oscillations, which exhibit substantial deviations from the anticipated operational levels. Overshoot can result in overvoltage stress, which can reduce the lifespan of electrical

components and increase the probability of their failure under specific conditions. However, undershoot may lead to insufficient power availability, which can negatively affect the performance and stability of auxiliary systems, such as illumination, heating, ventilation, and air conditioning (HVAC), as well as control electronics.

This study is motivated by the necessity of creating more advanced control algorithms to improve the stability of voltage-current and energy savings in auxiliary converters. The objective of this investigation is to evaluate the current and voltage stabilization of auxiliary converters during train start-up while the Pulse Width Modulator Inverter (PWMI) is in operation. Furthermore, it will encompass the development of a simulation framework to facilitate the implementation of flexible control algorithms, thereby enhancing the stability of voltage and current. As a final stage, this investigation will evaluate the influence of fuzzy control methodologies on the overall performance of auxiliary converters during train startup. The results of this assessment will offer a substantial understanding of the potential advantages of fuzzy control in railway auxiliary power systems.

2. Methodology

2.1 Data Collection

The issue of energy efficiency in train APCs was identified at the outset of the project, and specific objectives were established to design, simulate, and evaluate FLC solutions for PWMI. The data collection necessitated the use of an RS232 communication connection cable, which was connected between the controller board and the COM terminals of the Service PC. In order to evaluate the APC's condition, SIBMON was implemented to access previously preserved data and monitor variables in real time. Figure 1 illustrates a sequence of diagrams that may be located within the graphics function.

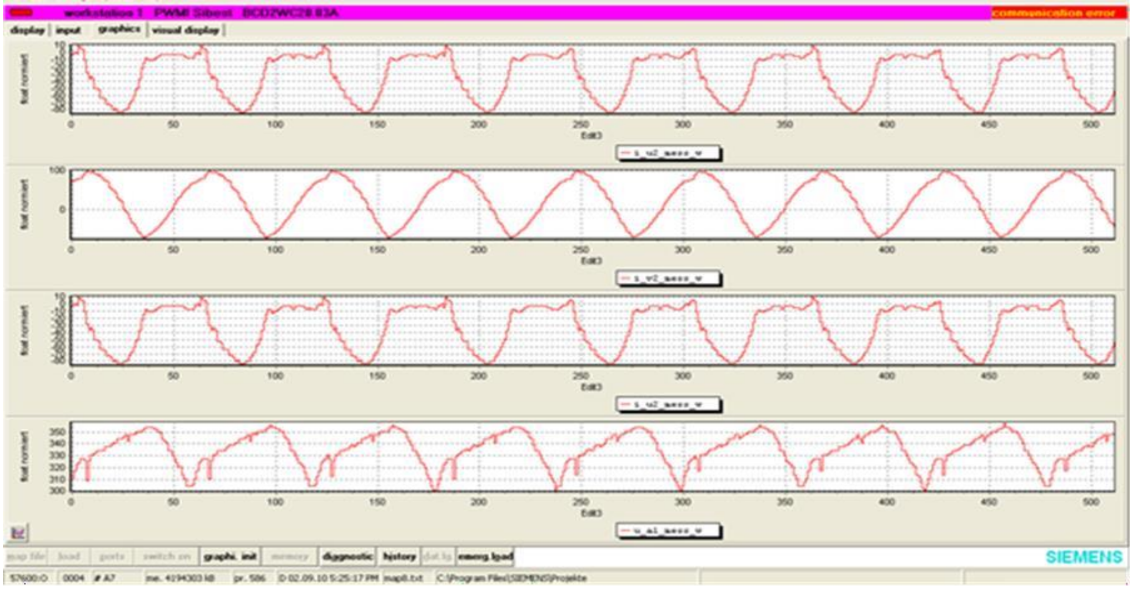


Fig. 1 Set of graphs in graphics function

2.2 Simulation Framework Development

The simulation framework was effectively implemented by leveraging the robust capabilities of MATLAB/Simulink to model power electronic circuits, control algorithms, and signal processing. The inverter topology, pulse-width modulation (PWM) approach, control structures, and load dynamics were all accurately depicted under actual operating conditions with the assistance of this platform. The system was designed to integrate both traditional proportional–integral–derivative (PID) controllers and fuzzy logic controllers in order to regulate the output of the inverter.

The initial phase in the model development process was to explicitly define the simulation objectives. The primary objective was to develop a DC–AC inverter that is capable of serving common railway auxiliary loads, including resistive–inductive (RL) loads and induction motors. This inverter is capable of transforming a fixed 670-volt DC input into a consistent 400-volt RMS, 50-hertz three-phase output. One of the primary objectives was to evaluate the comparative performance of the two control methods in order to ensure output voltage stability during initialization and load-transient settings.

The system's specifications, which encompass the input voltage, output voltage and frequency, load design, and inverter toggling frequency, were specified to ensure that they accurately reflect the practical requirements on auxiliary power. In order to achieve a balance between the efficacy of the computation and the quality of the output power, the switching frequency was selected at 10 kHz. The power stage of the inverter was implemented using a conventional six-switch, IGBT-based bridge inverter. Simulink's Universal Bridge block was employed to execute this specific implementation. A balanced three-phase load was connected at the output, and the DC input was supplied by a source that was set at 670 volts, as illustrated in Figure 2.

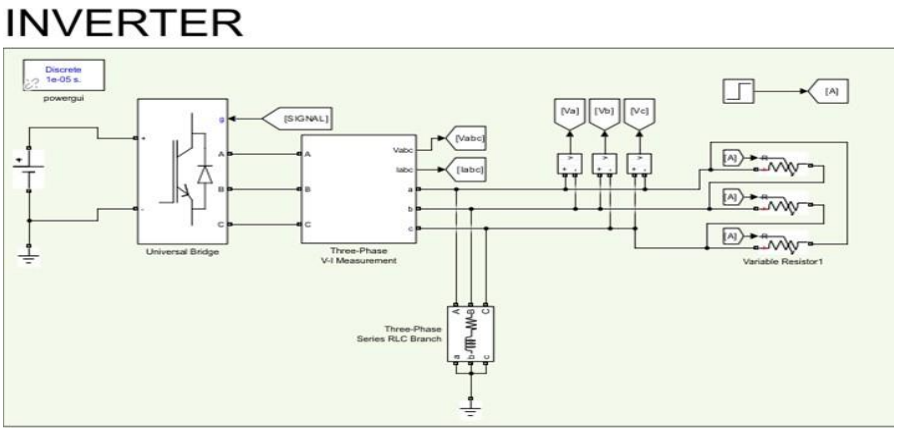


Fig. 2 Inverter setup in MATLAB/Simulink

A sinusoidal pulse width modulation (SPWM) generator was employed to generate gate pulses for the IGBT switches. The PWM unit regulated the amplitude and frequency of the output voltage by modulating the control signal transmitted from the appropriate controller, as illustrated in Figure 3. Subsequently, the control algorithms were implemented in parallel: one branch implemented a conventional PID controller, while the other branch employed a fuzzy inference system to regulate the output voltage, as illustrated in Figure 4.

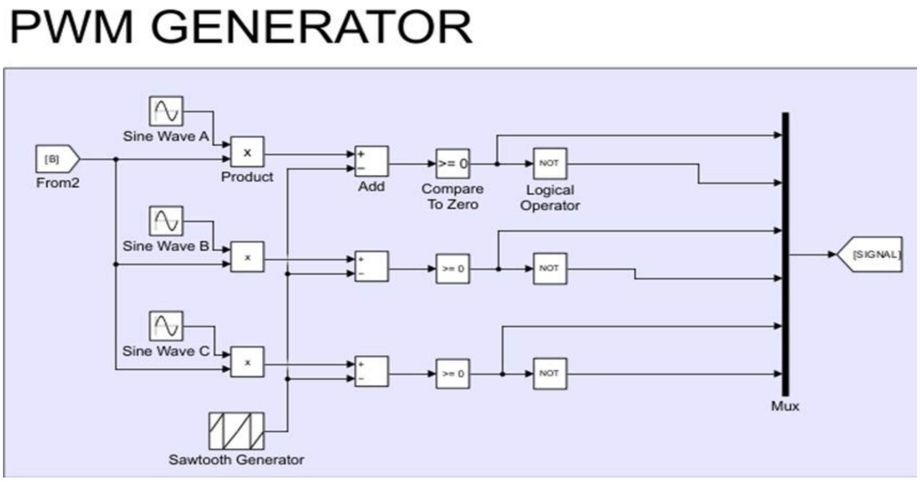


Fig. 3 PWM generator setup in MATLAB/Simulink

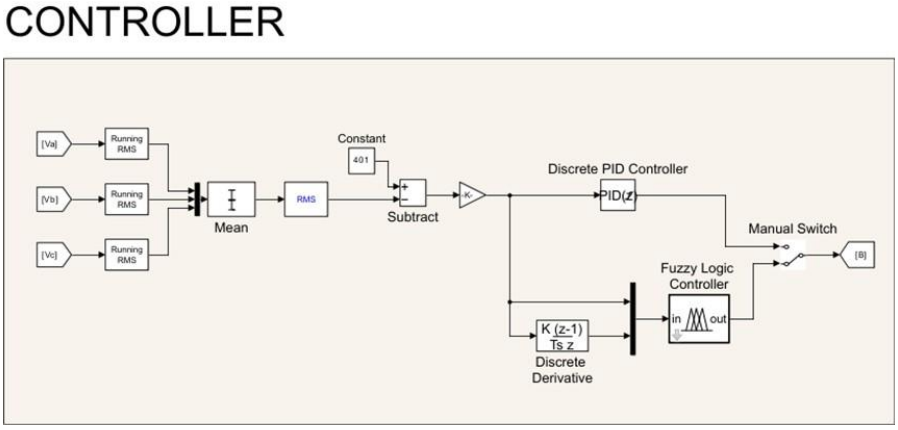


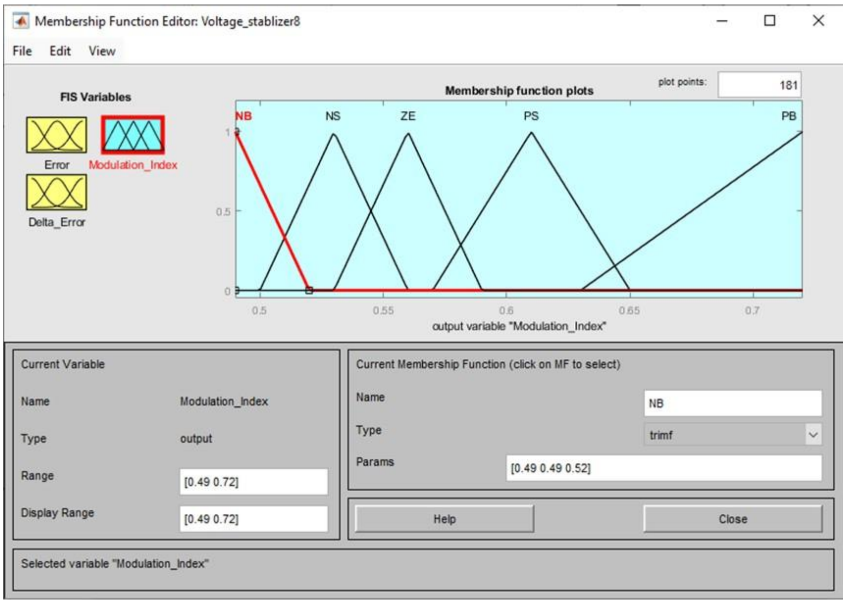
Fig. 4 Controllers setup in MATLAB/Simulink

2.3 Controller Design

The control method is a critical factor in determining the regulation of voltage in DC–AC inverters. In order to ensure consistent output, it is imperative to have a controller that is both responsive and robust, as loads in railway auxiliary power systems are susceptible to rapid fluctuations. Fuzzy logic control (FLC) and conventional PID control are two fundamental methodologies that are frequently encountered.

The PID controller adjusts its output by considering the proportional, integral, and derivative components of the voltage error. The implementation is well-known and straightforward; however, it frequently encounters difficulties when dealing with nonlinear or highly varying loads and requires precise adjustment. This investigation employed a PID that was initially calibrated using the Ziegler–Nichols method and subsequently refined through simulation. The PID was supplied the error signal, which was the discrepancy between the 400-volt reference and the output that was measured.

FLC, in contrast, employs heuristic knowledge to address nonlinearities in the absence of explicit system models. The fuzzy controller was defined with one output, the modulation index, and two inputs, error and change of error. Additionally, the fuzzy controller had a single output. Each input was partitioned into five distinct linguistic terms using triangular and trapezoidal membership functions, as demonstrated in Figure 5. The following terms are used: negative big (NB), negative small (NS), zero (ZE), positive small (PS), and positive big (PB).



plot points: 181

Current Variable
Name Modulation_Index
Type output
Range [0.49 0.72]
Display Range [0.49 0.72]

Current Membership Function (click on MF to select)
Name NB
Type trimf
Params [0.49 0.49 0.52]

Selected variable "Modulation_Index"

Fig. 5 Input and Output of Fuzzy Logic Control

In Table 3.1, each of the 25 fuzzy IF–THEN rules that are part of the 5×5 rule base encodes control actions that are pertinent to all operating circumstances. Situations that could potentially lead to oscillations or overshoot were given particular attention.

A control output that was precise for the PWM generator was generated by utilizing a Mamdani type inference engine and a centroid defuzzification method. The PWM block, which was responsible for regulating the six-switch inverter, was subjected to both fuzzy control signals and PID signals in the subsequent phase.

The output voltage regulation, transient behavior, total harmonic distortion (THD), and reaction time of each control approach could be directly compared by utilizing simulation data generated under comparable operating conditions. The fuzzy controller demonstrated enhanced adaptability to load changes and nonlinearities, thereby reducing overshoot and settling time without the necessity for human re-tuning. The final calibrated parameters, response graphs, and comparison data were organized into tables and figures for the purpose of evaluation.

Table 3.1 *5x5 Rule matrix*

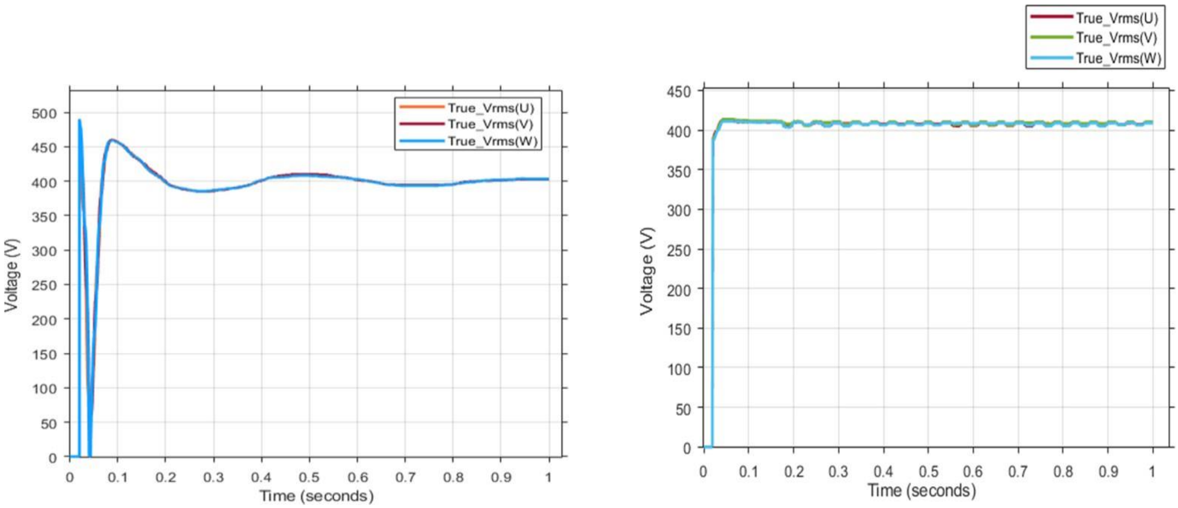
ΔError \ Error	NB	NS	ZE	PS	PB
NB	PB	PB	PB	PS	ZE
NS	PB	PB	PS	ZE	ZE
ZE	PS	PS	ZE	NS	NS
PS	ZE	NS	NS	NB	NB
PB	NS	NB	NB	NB	NB

The initial phase of the process involved the establishment of critical performance measures to enable a direct comparison between the fuzzy logic controllers and the PID controllers in the absence of demand. Various examples of these were the output waveform quality, the steady-state error, the overshoot, the settling time, and the rising time. These criteria, when combined, enabled the quantitative and qualitative assessment of each controller's steady-state and dynamic behaviour.

Subsequently, the data from the simulation were collected and transformed into graphical representations to facilitate a clear understanding of the system's response. These plots enabled a fundamental assessment of each controller's performance, which encompassed overshoot and stabilization speed. Minor variations between the two control schemes were observed, even in the absence of load. These discrepancies offered a glimpse into the system's general stability and the efficacy of the control during its operation in open-circuit conditions. Finally, a concise summary of the most significant discoveries was provided to underscore the controller that achieved the most effective regulation of the inverter outcome.

3. Result and Discussion

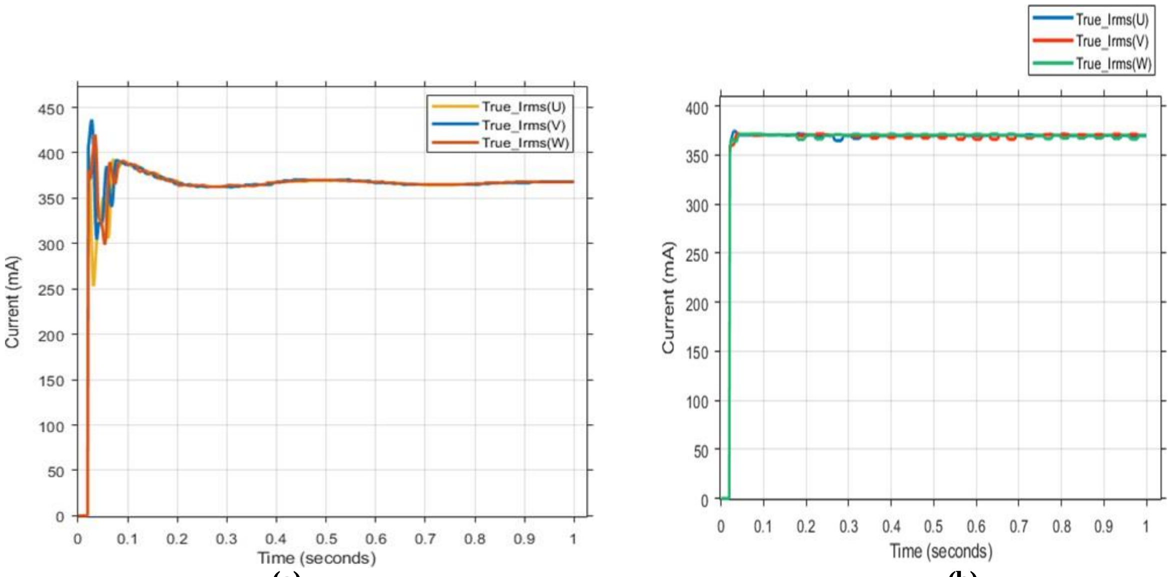
The voltage responses that were simulated under PID control and fuzzy logic control are depicted in Figure 6. Fuzzy logic controllers can be employed to accomplish transient behavior that is more stable and fluid. It has a rise time of approximately 0.05 seconds, which is substantially longer than that of the PID controller. Nevertheless, it leads to a substantial reduction in overshoot, which is nearly nonexistent, in contrast to the approximately 25% that occurs when PID control is employed. The steady-state inaccuracy of both controllers is minimal at 400 volts, and the settling time is also considerably improved, averaging approximately 0.1 seconds compared to 0.3 seconds with PID. The fuzzy-controlled output exhibits a clean and steady waveform and fewer oscillations, which is indicative of enhanced damping and overall system stability.



(a) **(b)**

Fig. 6 *Voltage responses (a) PID control; (b) Fuzzy logic controller*

Figure 7 illustrates comparable instances of contemporary reactions. With a rising time of approximately 0.03 seconds and a stabilization time of approximately 0.05 seconds, the fuzzy logic controller provides a substantial reduction in overshoot, which is approximately 2.7% compared to 18% when using the PID controller. Nevertheless, the current waveform that is controlled by fuzzy logic is significantly more balanced and smoother across all phases. The steady-state error of both controllers is nearly nil. The fuzzy logic controller generates a system that is more responsive, precise, and stable than the PID-controlled system. This illustrates that the fuzzy logic controller exhibits superior performance in both constant state and dynamic scenarios.



(a) **(b)**

Fig. 7 *Current responses (a) PID control; (b) Fuzzy logic controller*

4. Conclusion

This research examined the similarities and differences between classic PID control and fuzzy logic control (FLC) in order to regulate voltage and current in train auxiliary power systems. The simulation results demonstrated that FLC outperformed PID control in both transient and steady state performance. The FLC was capable of generating a steady response that was free of overshoot and had a settling time of approximately 0.1 seconds in the context of voltage control. This was a significant advance over the 0.3 seconds that the PID controller required, which also resulted in up to 25% overshoot. FLC was able to eliminate oscillations in current control, reduce overshoot to approximately 2.7%, and minimize the settling time to 0.05 seconds in a similar manner. This is substantially less than the 0.2 seconds that PID required. This enhanced control responsiveness promptly contributes to an improvement in energy efficiency by reducing transient losses and ensuring precise power delivery to auxiliary systems. Furthermore, the FLC's consistent output enhances the system's dependability, reduces the stress on the components, and contributes to a longer service life. FLC is an extremely effective method for regulating auxiliary power, particularly in dynamic railway situations where a swift and steady reaction is of the uttermost importance, due to these benefits. In summary, fuzzy logic control provides substantial improvements in operational stability, power quality, and energy efficiency when contrasted with conventional PID methods. It is feasible that additional research can be conducted in the future to assess its viability across a diverse array of transportation scenarios and to investigate its integration with other advanced energy management strategies.

Acknowledgement

I am grateful to University Tun Hussein Onn Malaysia especially Faculty of Enginering Technology for providing guidance to complete my project.

References

[1] Davoodi, M., Jafari Kaleybar, H., Brenna, M., & Zaninelli, D. (2023). Energy Management Systems for Smart Electric Railway Networks: A Methodological Review. Sustainability. DOI:10.3390/su151612204

[2] Istomin, S., & Shatohin, A. (2024). Development of a method for determining the parameters of energy storage devices to ensure uninterrupted power supply for auxiliary needs of an electric train. Journal of Applied Engineering Science. DOI:10.5937/jaes0-42009

[3] Yu, Q., & Hou, Z. (2021). Adaptive Fuzzy Iterative Learning Control for High-Speed Trains With Both Randomly Varying Operation Lengths and System Constraints. IEEE Transactions on Fuzzy Systems, 29, 2408–2418. DOI:10.1109/tfuzz.2020.2999958

[4] Das, D. and Rahaman, H. (2011). Crosstalk overshoot/undershoot analysis and its impact on gate oxide reliability in multi-wall carbon nanotube interconnects. Journal of Computational Electronics, 10(4), 360-372. https://doi.org/10.1007/s10825-011-0371-x

[5] Cheng, L., Tang, K., Ki, W. H., & Su, F. (2020). Fast-transient techniques for high-frequency dc–dc converters. Journal of Semiconductors, 41(11), 112402. https://doi.org/10.1088/1674-4926/41/11/112402