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CONTROL RESPONSE PERFORMANCE OF POWER ELECTRONICS CONVERTERS USING A COMBINED CASCADED PID-FUZZY LOGIC METHOD

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ABSTRACT

The fast and nonlinear dynamics associated with these converters; various difficulties have to be dealt with while controlling them. Thus, designing a controller with high response speed and robust capability is critical to guarantee efficient operation for power electronic converter. In this work, performance response improvement of power electronic converter using cascade controllers has been presented. The transient response characteristics of the system in the open-loop showed that it has a rise time of 0.000405 s, settling time of 0.00443 s, and overshoot of 42.3%. The high overshoot can be associated with the inability of the buck converter to handle nonlinearity in system dynamic process hence the outrageous oscillation and extremely peaking in output voltage. Therefore, a cascade control system based on combined Fuzzy-PID and PID controllers was designed and applied into the buck converter. The simulation results showed that the cascade control scheme offered enhanced rise time of 1.88e-05 s, settling time of 3.02e-05 s, and overshoot of 1.36%. Further analysis of the design controller to test for robustness proved that it was capable of handling change in operational parameters with fast tracking, stable and smooth response. When compared to the open-loop and PID controller, the cascade controller largely improved the overall system performance. With this outstanding performance, practical application of the designed control will be worthwhile to further ascertain its effectiveness.

KEYWORDS: Fuzzy-PID, PID-controllers, converters, enhanced response, power electronics.

I. Background of the Study

A power electronic converter basically consists of different sub-systems such as capacitors, power modules, control units, gate drivers, and a cooling system [1]. Though none of these sub-systems are perfect and can fail over time, and therefore affect system operation [2]. The two most fragile components are the power modules and electrolytic capacitors, which are also prone to wear-out failure [3p,8-9]*)*. There are different factors on which the reliability of these components depends on such as the mechanical strength of the device, applied electric load, climate conditions control, and switching techniques. The material composition of these components is degraded by these factors during long-term operation of the converter, eventually causing a potential failure.

II. Statement of the Problem

The fact that the static and dynamic characteristics of power converters become highly nonlinear due to the time variation and switching nature, has led to the implementation of different control techniques in literature to ensure stability in the system operating condition. However, in most system of practical interest, the problem is to minimise the deviation of actual output voltage from desired voltage while maintaining satisfactory transient response and efficient voltage/power transfer. Though in some cases where desired performance has been achieved, integral winding and nonlinearity effects associated with classical controllers have persisted. It is therefore desired to develop a system with improved transient response performance.

III. Literature Review

There are different types of DC-to-DC converters that have been presented in literature and are already implemented for use in certain applications. The well-known Pulse Width Modulation (PWM) based DC to DC converter technique accomplishes its control by varying the duty cycle of an external fixed frequency clock through one or more feedback loops at any time a parameter varies [4]. Presently, modern electronic systems require power with high reliability, low weight with high quality, and easy control capacity and are largely employed as switch mode power supply (SMPS) systems in electric vehicles[8-9].

[5], designed an Adaptive PD Controller for Microsatellite Yaw Axis Attitude Control System, in this recent research work, the control was based on the adaptive or dynamic PD controller but as some inherent error which needed to be improved on. However, it gave a clear adaptive PD strategy on the altitude Yaw Axis control system.

[6], presented a Performance Response Improvement of Automatic Voltage Regulator Using Linear Quadratic Gaussian Tuned Controller, which improved response time and faster action and information relay in terms of voltage and current. It gave a clear concept of performance response strategy in curbing delay time, settling time, overshoot and overall voltage management.

The State Variable Feedback Control of Data Centre Temperature by [7p4-7], addressed the response variable feedback control using temperature variables as data base information. It showcased that the feedback control has clearer response compared to direct system control.

In future hybrid and fuel cell vehicles, there is a possibility of electrical power systems using a total of three voltages (14V, 42V and high voltage, HV) [8]. There is a need to have high step-up DC to DC converters for many applications such as computers, industrial, and medical equipment. According to (Jayachandran *et al.*, 2015), "one of the key blocks inside hybrid electric vehicles is the DC-DC converter for auxiliary power supply of electric loads. The nominal voltage at the low voltage side of one input is 12 V and can vary from 8 to 16 V during charging and discharging. The nominal high-side voltage is 288 V, with an operating range from 255-425V. Nominal charging and discharging power is 1.5 kW. Switching frequency is 70-100 kHz. Battery power systems often stack cells in series to achieve higher voltage. However, sufficient stacking of cells is not possible in many high-voltage applications due to a lack of space. Boost converters can increase the voltage and reduce the number of cells. The NHW20 model Toyota Prius HEV uses a 500 V motor. Without a boost converter, the Prius would need nearly 417 cells to power the motor. However, a Prius actually uses only 168 cells and boosts the battery voltage from 202 to 500 V. Further, with the use of a re-lift converter, use of 3 batteries is enough to power up to 500V." A popular method widely used in electronic circuit design for DC-to-DC converters is the voltage lift technique. Its technology has achieved enormous acceptance and has been successfully used in DC-to-DC converter applications in recent times. It has also opened the way for improvement on existing design so as to achieve high voltage gain and efficient power transfer converters.

[9p5-8], simulated a Model Reference Adaptive Control-Based PID Controller for Hard Disk Drive Read/Write Head Servo Positioning System, in which the PID created a better control system for the hard disk Drive and it led to near-accuracy servo system positioning. However, this position control could be improved by using an entirely different method of control.

In recent times, the design of a Robust PID Controller for Improved Transient Response Performance of a Linearized Engine Idle Speed Model.by [10] was x-rayed and seen to have a control impact on the problem being created by dynamic systems. It created a design that is large enough to counter system inefficiencies by robustness inclusivity which made the system outstanding compared to others.

1V. Importance of DC-to-DC Conversion

One major area of application of DC-to-DC converters is in motor drives. A DC-to-DC converter converts a source of direct current (DC) from one voltage level to another. Most DC-to-DC converters also adjust the output voltage. Some exceptions include high-efficiency drive sources, which are a type of DC-to-DC converter that control the current during the drive, and easy-acquire pumps that twice or triple the crop voltage. Electronic switch-mode DC to DC converters change one DC voltage stage to one additional, by storing the input energy in the short term and then releasing that energy to the output of a dissimilar voltage. The storage can also be in magnetic field storage elements, such as inductors, transformers or electric field storage elements, capacitors [11]. This conversion method is more power efficacy, often 75% to 98% than linear voltage imperative, which dissipates surplus power as heat. DC-to-DC converters, energy is occasionally stored into and free from a magnetic field in an inductor or a transformer, classically in the range from 300 kHz to 10 MHz (Gunasekaran, 2015). By regulating the duty cycle of the charging voltage, that is, the relation of on/off time, the quantity of power transfer can be controlled.

[12] developed a cascade system with two control loops for a DC-DC Buck-Boost converter that was a right half-plane zero (RHPZ) structure called a non-minimum phase system. The concept presented several challenging constraints for designing well-behaved control techniques. The strategy assumed the system as a black-box structure without the need for a mathematical model of the system. The authors stated that the approach offers the benefit of decreasing the computational burden and provides faster dynamics along with ease of implementation. The technique consisted of an outer Fractional-order PID voltage controller tuned with the Ant-lion Optimizer (ALO) algorithm, which provides a reference current for

the inner control loop of the Neural Network-based LQR (NN-LQR) controller. The inner loop NN-LQR strategy was used to optimize and tune the gains of the LQR controller and showed faster dynamics and higher robustness. It should be mentioned that the number of neurons was limited to 2 and 4 in each layer to decrease the computational burden with lower complexity. Also, the ALO algorithm is a modern nature-inspired algorithm used to tune the PID gains with better results for under-constrained problems with diverse search spaces. Considering the negative impacts of various disturbances on a power converter, a Fractional-order-based PID (FO-PID) control technique was implemented as a proper alternative since it showed higher robustness in load uncertainties along with better dynamical responses based on its extra degree of freedom. Moreover, to evaluate the superiority of this controller, two other controllers were designed using the PSO algorithm for PID and FO-PID controllers. Finally, the presented cascade controller was tested in various working conditions through simulation and experiment results proved it effectiveness.

[13] investigated the performance of a boost converter regulating its output voltage using two control methods: Proportional-Integral (PI) control and neural control. Both methods were implemented on a simulation platform (MATLAB/Simulink) and evaluated in terms of accuracy, response speed, and robustness to disturbances. The output voltage of converters exhibited imperfections that required a control method to optimize efficiency when applying a variable load [7-8]. Results showed that neural control offered superior performance in terms of accuracy and response time, with faster and more precise regulation of the output voltage. On the other hand, PI control proved to be more robust against disturbances.

[14] carried out a comprehensive evaluation of bio-inspired optimization algorithms in enhancing the dynamic performance of a unity power factor AC-DC boost converter. In achieving constant output voltage and unity power factor at the supply mains, the Sliding Mode controller was cascaded with PID voltage loop controller used to control these converters and it was highly evident that the performance of these converters was highly influenced by PID controller gains. The feasibility of using bio-inspired optimization algorithms to find an optimal PID gain that enhanced the dynamic and static performance of the converter was implemented. The objective function formed for the optimization problem was framed from time domain performance parameters [3-9]. From simulation results, it was deduced that the bio-inspired optimization-based PID gain resulted in an enhanced converter performance compared to its traditional counterpart.

[15] introduced a filtering circuit design integrated with the DC-link of a medium power variable speed drive (VSD) system. The designed filtering circuit employed modern power electronic circuits to improve time response characteristics in both the grid and the dc-link sides. Depending on the widely used multi-level converters, a conventional three-level H-bridge four-quadrant chopper scheme was developed into a cascade five-level H-bridge four-quadrant chopper scheme [4-6] The time response of the proposed system was performed with both choppers, and results showed that the voltage drop on cascade chopper transistors was reduced to half in comparison with the voltage drop on conventional four-quadrant chopper transistors. Moreover, the sharp fluctuations in the system's waves were mitigated; consequently, time response characteristics in both steady and transient states were remarkably improved. The total harmonic distortion factor THD% of the input current and voltage was reduced to 26.2% and 2.43% respectively and the ripple factor RF for DC-link current was reduced to 0.196.

V. Proportional plus Integral plus Derivative Controller

The basic idea behind the operation of all DC-to-DC converters is the fact that voltage level is increased and maintained for a given output value. A DC-to-DC converter takes in an unregulated DC voltage and outputs a specific or constant regulated voltage. DC to DC converters (also called regulators) can be classified into linear and switching regulators [4]. Regulators are known to have a power transfer stage and a control circuitry to monitor the output voltage and adjust the power transfer stage to maintain a constant output voltage. In order to do this, a feedback loop is necessary, and certain types of compensation or control action are needed to maintain stability. such as MATLAB. Figure 1.1 is the block diagram representation of a PID control algorithm. Table 1.0 summarizes the functions of the three elements that make up a PID controller.

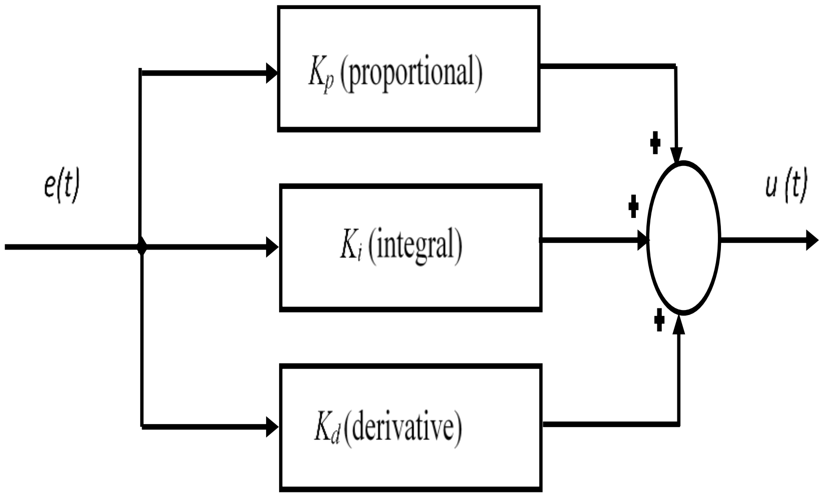

Figure 1.1: Block diagram of PID controller.

Table 1.0: Summary of the Elements of PID Controller.

Control Action	Symbol	Function
Proportional Control	P	It implements the typical operation of increasing the control variable when the control error is large
Integral Control	I	It momentarily tracks the control error. It does this by relating to the past values of the control error and allows the reduction to zero of the steady state error when a desired step input is applied
Derivative Control	D	It predicts the future values of the control error and has a great potential in improving the control performance as it can anticipate an incorrect trend of the control error and counteract it.

VI. Fuzzy Logic Intelligent Framework

Having identified the problem of uncertainty among variables posed on PID controller in most Industrial chemical plant designs, fuzzy logic is an intelligent technique that makes use of human expertise to monitor and control engineering and industrial processes. Fuzzy logic involves simple rule based that takes the form: "IF A and B then C" approach. Figure 1.2 shows the elements of a fuzzy logic system.

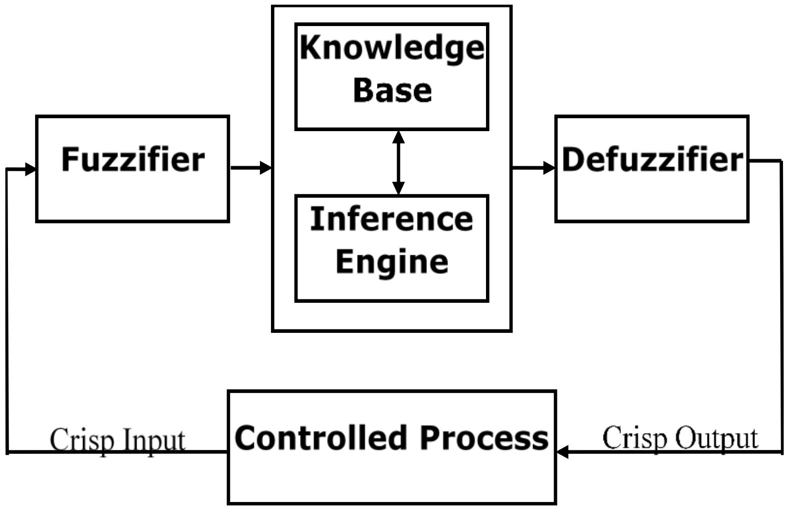

Figure 1.2: Elements of a Fuzzy Logic Control Algorithm.

The specific elements (or components) of a fuzzy logic controller consist of Fuzzifier, DE fuzzifier, Knowledge base and Inference Engine (Decision making unit). The representation of the parameters involved in fuzzy logic is known as linguistic variables.

Fuzzification: Fuzzification is the process of transforming a crisp value into a fuzzy set, so that it can be processed by fuzzy inference mechanism. The linguistic variables used be described as NL = Negative Large, NM = Negative Medium, NS = Negative Small, ZE = Zero Error, PS = Positive Small, PM = Positive Medium and PL = Positive Large.

Defuzzification: The transformation from a fuzzy set to a crisp value is known as defuzzification. Then the Crisp Output is obtained from the {Sum (Membership Degree*Singleton Position)}/Membership degree. The defuzzification strategy is aimed at producing a non fuzzy control action that best represents the possibility of an inferred fuzzy control action.

Fuzzifier: The inputs real-life data or crisp measurement from linguistic variables; the Fuzzifier converts the crisp input to degrees of membership using membership functions. This process is called fuzzification. The fuzzification block matches the input data with the conditions of the rule to determine.

Defuzzifier: The process by which the defuzzifier converts linguistic variables into crisp values that can be understood by a controlled system is known as defuzzification. This is achieved in the fuzzy set crisps sets.

Knowledge Base: The knowledge base consists of a database and the rule base is used for defining set of rules. The collection of rules in a fuzzy logic system is called a knowledge base. The rules consist of two "IF" sides and the "THEN" side is known as the conclusion. Using a larger number of rules is recommended for achieving a very accurate system.

Inference Engine: Decision making unit is responsible for taking decision based on given inputs and set of rules. The fuzzy set and crisps sets: It has been observed that the main objective behind fuzzy logic is to represent and reason with some particular form knowledge expressed in linguistic form.

VII. Summary of Literature Review

In most of the control systems for power electronic converters reviewed, the classical PI and PID controllers are the most widely implemented as shown from the review. This can be attributed to simplicity in design and the ability to provide a control solution to a system with dynamic complexity, usually in many process control operations in the industry, due to its simplified structure. Another obvious trend is the use of cascade controllers to provide more stable, robust and highly reliable power electronic converters in practical applications. These performance qualities are not offered by a single-loop control approach. In the study carried out by [16], a single-loop controller based on the PID algorithm was implemented for a power electronic (buck) converter. The body of work examined in this review spans a range of DC‑DC converter topologies and control approaches, with a particular focus on Luo‑type converters and their application to renewable‑energy systems, electric vehicles, and power‑quality improvement.

[17] proposed a robust nonlinear controller based on the uncertainty and disturbance estimator (UDE). By lumping system uncertainties and external disturbances into a single signal estimated through a low‑pass filter, the controller cancelled their effect. Comparative simulations with sliding‑mode control (SMC) indicated superior robustness to parameter variations and large load disturbances, suggesting that UDE‑based approaches merit further experimental investigation but still lack stability characteristics.

VIII. Key Findings

1 Fuzzy‑logic control offers effective disturbance rejection for Luo converters, yet pure fuzzy approaches can introduce steady‑state error, prompting hybrid solutions.

2. Cascade control architectures are widely adopted for both boost and buck‑boost converters to manage inner current and outer voltage loops, improving stability and performance, but automatic control is needed.

I X. Research Gaps

Despite the breadth of research, several gaps remain:

i. Limited experimental validation – Most studies present only simulation results of a single loop, but prototype testing is scarce, leaving real‑world performance under component tolerances and electromagnetic interference uncertain.

ii. Hybrid fuzzy‑PID implementations – Although fuzzy logic has been applied to Luo converters, a combined fuzzy‑PID architecture that exploits both interpretability and integral action has not been thoroughly investigated, hence the aim of this project work.

CONCLUSION

The literature demonstrates that cascade architectures that can offer clear advantages in disturbance rejection, transient response, and robustness is needed. Hence, the development of a hybrid control scheme, such as fuzzy‑PID that can address steady‑state errors while preserving the benefits of adaptive fuzzy logic. Addressing these gaps will facilitate the deployment of high‑performance DC‑DC conversion systems in renewable‑energy integration, electric transportation, and modern power‑electronics applications.

Hence, in this work, cascade controllers based on fuzzy-PID and PID techniques will be developed instead of using a single controller for a buck converter.

XII. MATERIAL AND METHODS

Material

The tools used in this work to realise the main objective of this are presented in this section below. The tools are listed as follows: MATLAB m-file environment, Graphical user interface (GUI) of PID-Tuning Compensator, Simulink and Fuzzy logic embedded block.

Methods

The existing type of control loop for buck converter based on single-loop control technique using PID controller is shown in Figure 3.1. In the figure, the entire control is provided by a single loop based on the account of the error between the output voltage and the referenced voltage without taking into account the state of the other electrical quantity (current) at the output. This control model does not guarantee stable, robust and reliable operation for power electronic system. Therefore, an approach that addresses the performance limitation of single-loop control by means of multi-loop strategy is developed in this work for buck converter. The cascade control system developed in this work is shown in Figure 1.4. The steps taken in modelling the cascade control system are presented in the subsequent subsections.

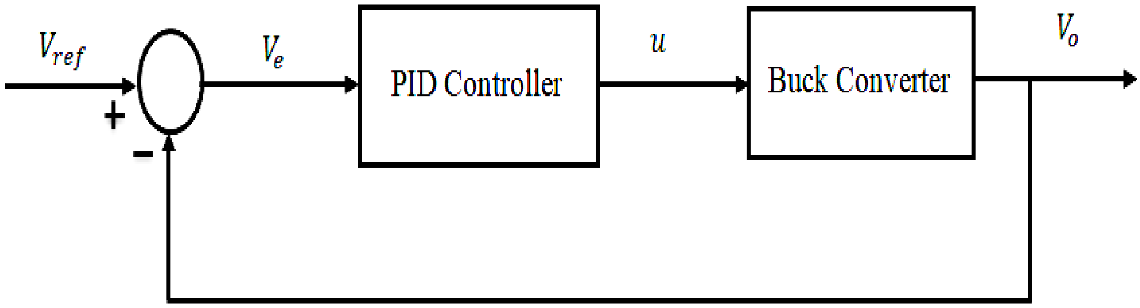

Figure 1.3: Single-loop PID control buck converter

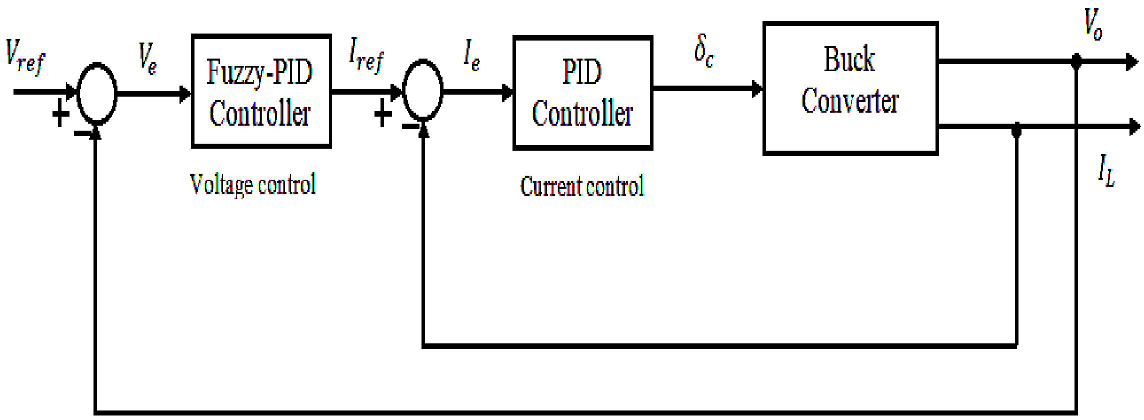

Figure 1.4: Cascade control system for buck converter.

As a power electronic converter, a buck converter can supply a load with a direct current (DC) voltage that is lower than the DC supply voltage. In this work, a switch-mode buck converter model designed to give a voltage regulation from 48 V to 12 V. The buck converter switching frequency is taken as 100 kHz. The cascade control system is designed in a manner that the inductor current, I_L is controlled by inner loop controller while the outer loop controller controls the output voltage, V_o. The current reference signal to the inner current loop is the output of the outer voltage loop. The duty cycle signal δ_c to the pulse width modulation (PWM) block is then provided by the inner current loop.

XIII. Mathematical Model of DC-DC Buck Converter

Design of PID Controller

Figure 1.5 shows the control system configuration of PID controller. The mathematical representation of linear relationship existing between the controller output, u(t) and the error, e(t) with respect to three term constants for the three components of the system given in Equation (1.1).

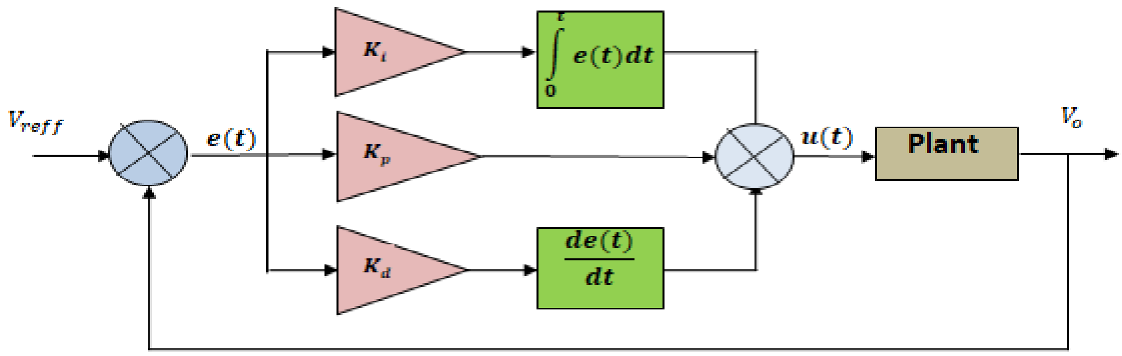

Figure 1.5: PID Control system Configuration.

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (1.11)$$

where $e(t)$ is the error signal, which is the deviation of the output voltage of the converter from the supply input voltage given by:

$$e(t) = V_{reff} - V_o \quad (1.12)$$

The Laplace transform of Equation (3.8), assuming zero initial conditions, gives:

$$U(s) = K_p E(s) + K_i \frac{E(s)}{s} + K_d sE(s) \quad (1.13)$$

Taking the ratio of the control variable, $U(s)$ to the error signal, $E(s)$ gives the PID controller:

$$C_{pid}(s) = \frac{U(s)}{E(s)} = K_p + K_i \frac{1}{s} + K_d \quad (1.14)$$

The tuned parameters of the PID are proportional gain, K_p = 4.83, integral gain, K_i = 1.34e+04, and derivative gain, K_d = 0.000436.

The aim of the controller is to track a set-point with a rise time of less than 0.5 s, an overshoot below 10 % and a steady-state error of essentially zero or close to zero.

The parameters were obtained using a two-step approach:

First, a coarse Ziegler-Nichols's tuning gave an initial proportional gain of $Kp_0 = 3.5$.

Then a systematic search (grid-search on the simulation model) was performed, varying Kp, Ki and Kd simultaneously to minimize a weighted cost function $J = w_1 \cdot t_r + w_2 \cdot OS + w_3 \cdot ISE$, where t_r is rise time, OS is overshoot and ISE is the integral of squared error. The optimum that satisfied the design specifications on the turning was $Kp = 4.83$, $Ki = 1.34 \times 10^4$ and $Kd = 4.36 \times 10^{-4}$.

The cost function shows the turning method;

Explanations: Proportional gain ($Kp = 4.83$). This is the primary source of speed. Raising Kp from the Ziegler-Nichols's value of 3.5 reduced the rise time from 0.62 s to 0.0044 s while keeping the phase margin above 45°(standard from Nichols turning method).

Integral gain ($Ki = 1.34e0^4$): Expressed in the discrete-time form $Ki = Kp \cdot Ts / Ti$, > $Ti = Kp / Ki \approx 4.83 / 1.34 \times 10^4 \approx 3.6 \times 10^{-4}$ s, the large value reflects a very short integral time ($Ti \approx 3.6 \times 10^{-4}$ s). It eliminates steady-state error quickly, which is essential for the temperature/heat control application where even a few degrees of offset are unacceptable.

The resulting output voltage of the buck converter with the PID controller as shown in Figure 1.0 is given in Equation (1.15). Further simplification of Equation (1.15) gives Equation (1.16).

$$V_{opid} = \frac{\left(4.83 + \frac{1.34e+04}{s} + 0.000436\right) \times \left(\frac{216}{6e-07s^2 + 0.001s + 6}\right) \times 1/3}{1 + \left(4.83 + \frac{1.34e+04}{s} + 0.000436\right) \times \left(\frac{216}{6e-07s^2 + 0.001s + 6}\right) \times 1/3} \qquad (1.15)$$

$$V_{opid} = \frac{0.09413 s^2 + 1043 s + 2.888e06}{1.8e-06 s^3 + 0.09713 s^2 + 1061 s + 2.888e06} \qquad (1.16)$$

XIV. Fuzzy-PID Design

In the Fuzzy-PID control system, the new proportional control is called GE (i.e. product of the new proportional gain K'_p and error), the new derivative control is called GCE (i.e. product of the new derivative gain K'_d and change in error), and the new integral control is called GIE (i.e. product of new integral gain K'_i and integration of error). GU is the product of K_p and the control variable. The numerical values of the modified PID gains for the Fuzzy-PID controller are defined as follows:

$$\left.\begin{aligned} K_p' &= 3.58 \\ K_d' &= \frac{K_d}{K_p} = 3.47e03 \\ K_i' &= \frac{K_i}{K_p} = 0.000922 \end{aligned}\right\} \qquad (1.17)$$

Therefore, with the modified PID parameters integrated with the designed FLC model, a Fuzzy-PID based control system was developed as shown in Figure 2.0.

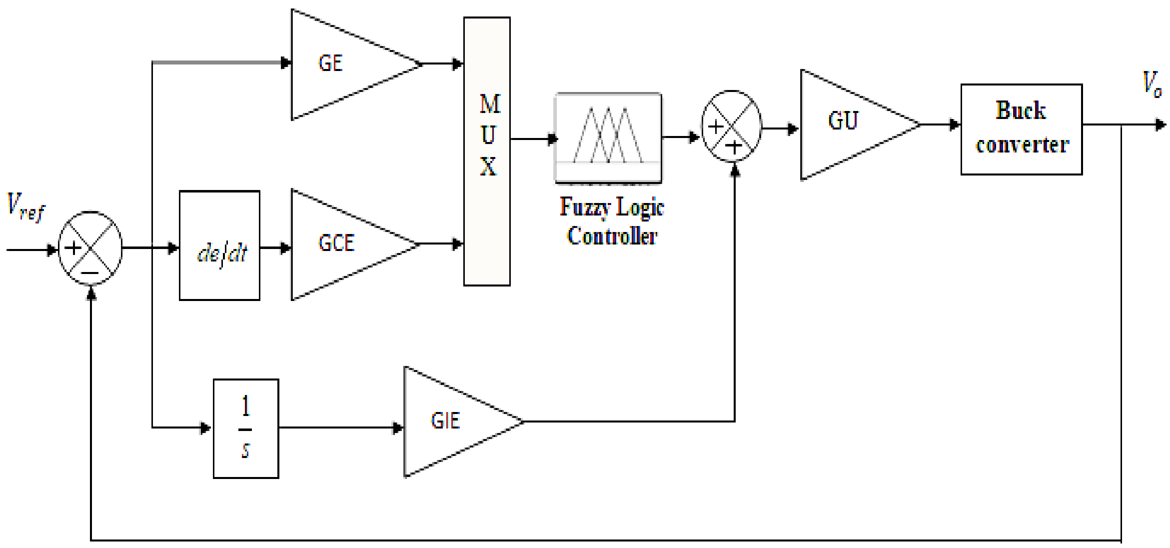

Figure 1.6: Fuzzy-PID control system.

XV. Simulation Parameter and Design Flowchart

The parameters of the buck converter are listed in Table 2.0. These parameters were entered in embedded blocks of the MATLAB/Simulink model developed for computer simulation test conducted to examine the dynamic responses of the cascaded control system for buck converter The design flow chart is shown in Figure 3.0.

Table 2.0 Buck converter parameters (Jabari *et al*., 2024).

Definition	Symbol	Value
Input voltage	V_g	36 V
Set-point voltage	V_{ref}	12 V
Resistance	R	6 Ω
Inductor	L	1 Mh
Capacitor	C	100 µF
Duty cycle	D	1/3
Switching frequency	F_s	40 kHz

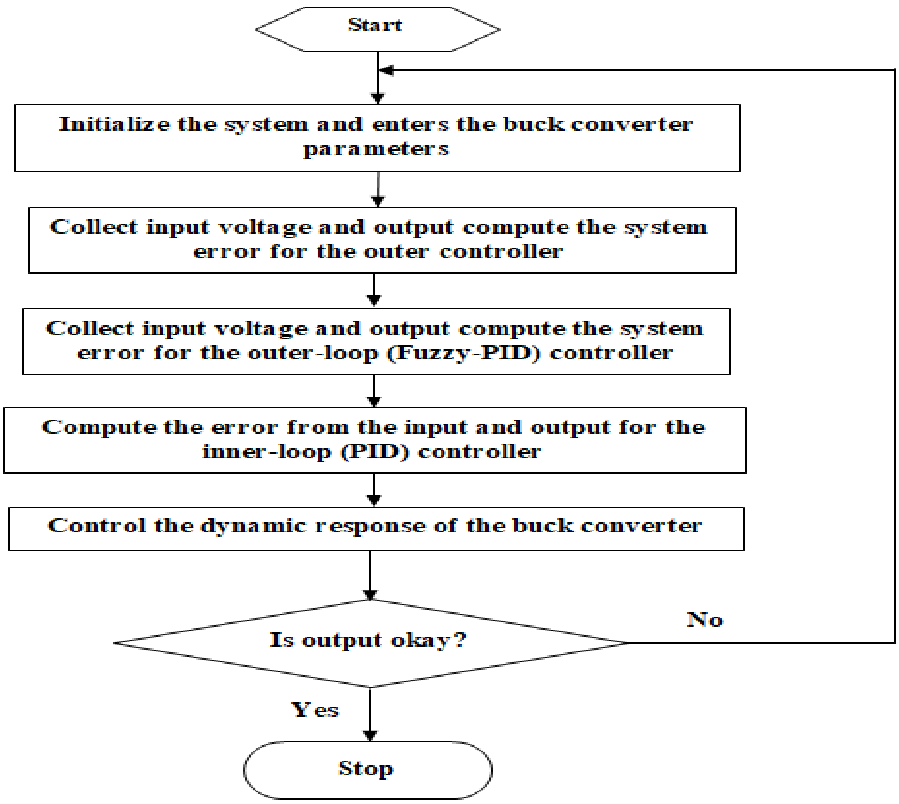

Figure 1.7 System Implementation Flowchart.

XVI. RESULTS AND DISCUSSION

Designed Cascade Control Robustness Test

This section presents the robustness test of the designed cascade control system incorporating fuzzy intelligent algorithm with PID. That is the analysis covers robust evaluation of the DC-DC buck converter when the cascade controller was operationalized and integrated into the control system.

The section offers valuable insights on the adaptability and performance viability of the DC-DC buck converter in different operational scenarios via MATLAB simulations. Two basic scenarios were conducted in terms of different input voltages and load conditions. An analysis of this kind allows for a better understanding of the converter's performance characteristics. In carrying out the analysis of the response performance of the cascade-controlled converter to different operational parameters, far-reaching insight of its capabilities and limitations can be achieved.

Analysing System for Different Input Voltage

In this subsection, further simulation was conducted to evaluate the robustness of the system for different input voltages in order to validate the ability of the proposed controller to adapt to changes in input while achieving the same transient response characteristics. Figure 1.8 shows the simulated output voltage waveforms for different input voltages: 12 V and 6 V. The time domain parameters are listed in Table 3.0.

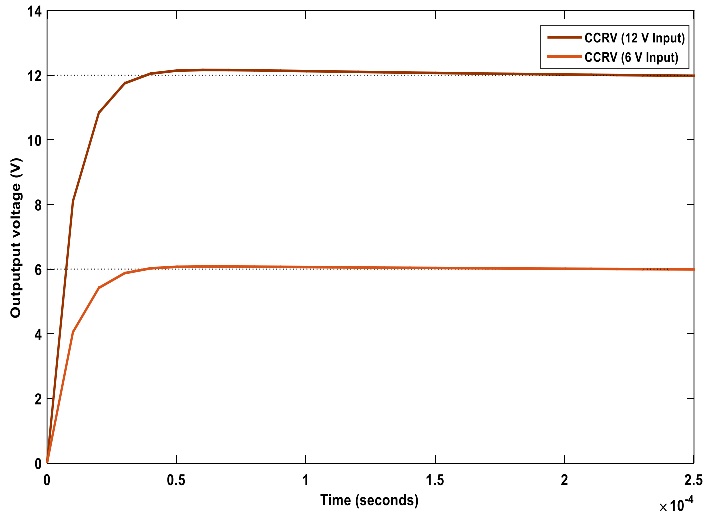

Figure 1.8: Step response for different input voltage.

Table 3.0: Cascade controlled buck converter transient response for different inputs.

System state	Rise time (s)	Settling time (s)	Peak time (s)	Overshoot (%)	Final value (V)
CCRV (12 V input)	1.88e-05	3.02e-05	6.29e-05	1.36	12
CCRV (6V input)	1.84e-05	3.03e-05	6.0e-05	1.35	6

Looking at Figure 1.8 and the numerical evaluation of the transient response of the output voltage waveform, it can deduce that the designed cascade control system was able to maintain nearly similar rise time (approximately 1.8e-05s), settling time (approximately 3.0e-05s), peak time (approximately 6.0e-05s), and overshoot of (approximately 1.4%), respectively. This analysis proves the ability of the designed cascade controller to provide the same transient response characteristics for different input voltages.

Analysing System Performance for Varied Load Conditions

It should be noted that the DC-DC buck converter has been so far simulated in terms of standard stated parameters in Table 3.1 in which the load is of 6 Ω resistance. In this case, the load was increased by +20% (i.e., from 6 to 7.2 Ω) and decreased by -20% (i.e., from 6 to 4.8 Ω). The resulting step responses are shown in Figure 4.8. The numerical analysis of each simulated transient response of the output voltage waveform is listed Table 4.0.

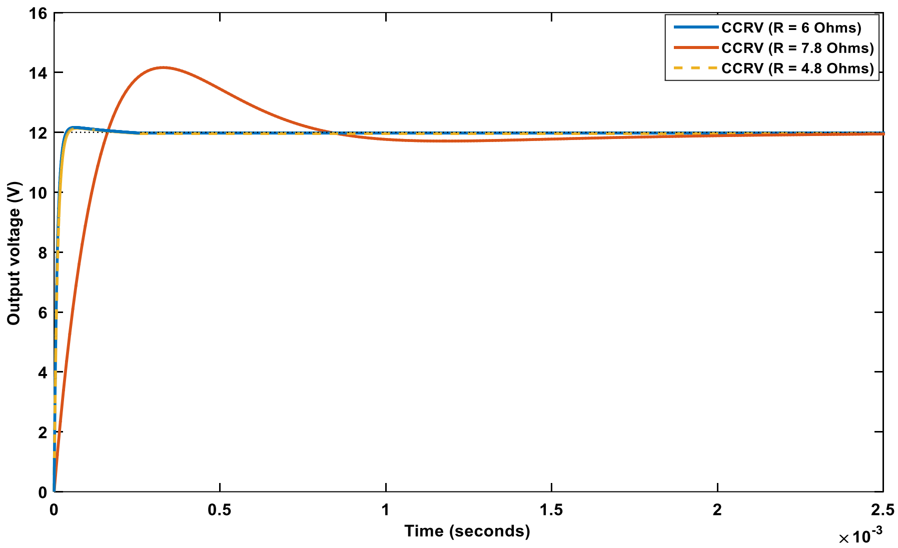

Figure 1.9: Step responses for different load conditions.

Table 4.0: Cascade controlled buck converter transient response for different inputs.

System state Under loading	Rise time (s)	Settling time (s)	Peak time (s)	Overshoot (%)	Final value (V)
CCRV (6 Ω)	1.88e-05	3.02e-05	6.29e-05	1.36	12
CCRV (7.2Ω)	1.21e-04	1.45e-03	3.28e-04	18	12
CCRV (4.8 Ω)	2.13e-05	3.46e-05	6.99e-05	1.11	12

The transient response analysis of the cascade-controlled converter reveals very vital information on the performance of power electronic systems (which is also common among electrical and electronic devices). It can be seen, looking at Table 4.0, that an increase in load caused the transient response of the converter's output voltage to overshoot the setpoint value by a very high percentage (18%). This indicates the effect of increasing load in the performance of power electronic systems, which over time becomes unstable due to overloading. However, the cascade controller ensured that the desired voltage is maintained at the output.

The Bode plots for 7.2 Ω and 4.8 Ω loads are shown in Figures 2.0 and 4.10. The essence of these bode plots is to compare the stability performance of the designed cascade control buck converter in different loads scenarios. Table 4.0 shows the frequency response performance of the cascade control converter under different loading.

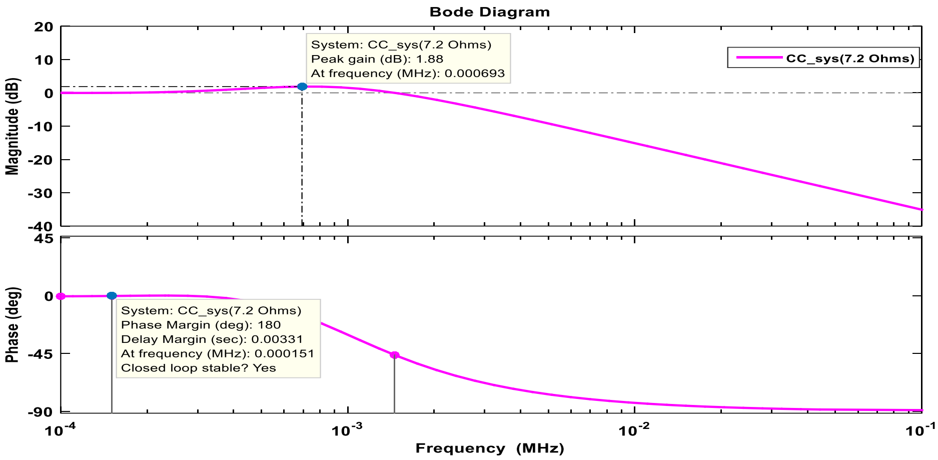

Figure 2.0: Simulated Bode plot of cascade control buck converter with load 7.2 Ω.

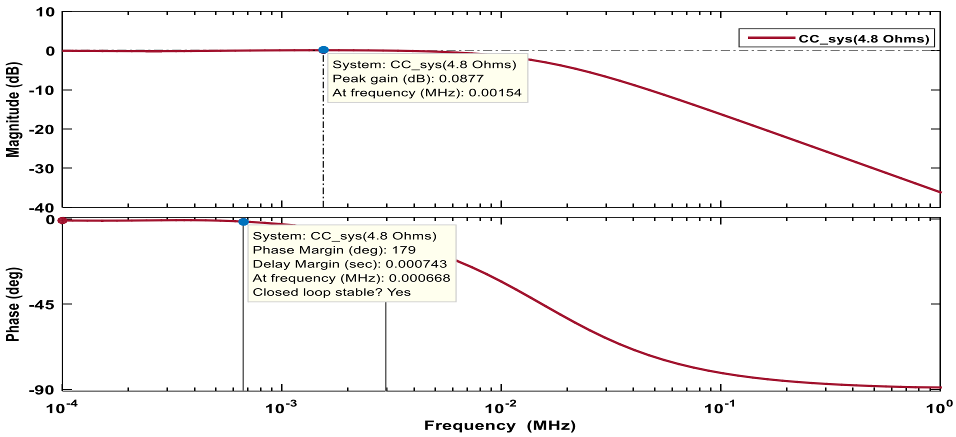

Figure 2.1: Simulated Bode plot of cascade control buck converter with load 4.8 Ω

Table 5.0: Bode analysis of the cascade control buck converter under different loads.

System state Under loading	Peak gain (dB)	Gain margin (dB)	Phase margin (deg.)	Bandwidth (Hz)
CC_sys (6 Ω)	0.111	Infinite	179	1.79×10^4
CC_sys (7.2 Ω)	1.88	Infinite	180	2.31×10^3
CC_sys (4.8 Ω)	0.0877	Infinite	179	1.59×10^4

In evaluating the performance of controllers in frequency domain, fundamental parameters like peak gain, gain margin, phase margin, and bandwidth are very much essential. From Table 5.0 presents the frequency response domain performance indices for the various loading conditions of the cascade control converter. It can be seen looking at the table, which reflects the Bode plots of the various loading condition that the cascade controller exhibited the best stable frequency response when the load is 6 Ω. It suffices to say that the system exhibited certain level of robustness considering the values of the phase margins.

XVII Performance Comparison with PID Control System

In this section, the intelligent aid cascade control system is compared with classical PID control system that has largely implemented in previous literatures. Figure 2.2 shows the transient response comparison of the open-loop, PID, and the designed cascade control system using the standard parameters of the DC-DC buck converter listed in Table 2.0.

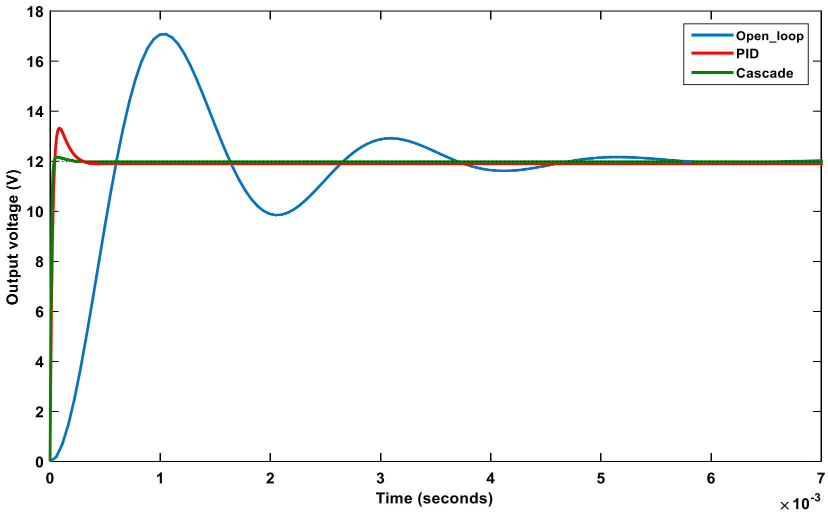

Figure 2.2: Step response comparison of different control system.

The numerical evaluation of the step response waveforms in Figure 2.2 is presented in Table 6.0.

Table 6.0: Performance comparison of buck converter transient response.

System state	Rise time (s)	Settling time (s)	Peak time (s)	Overshoot (%)	Final value (V)
Open loop	4.05e-04	0.00443	0.00105	42.3	12
PID control	3.01e-05	0.000223	8.45e-05	10.9	12
Cascade	1.88e-05	3.02e-05	6.29e-05	1.36	12

The transient response performance of the buck converter under different control conditions as listed in Table 6.0 according to the comparison plots in Figure 2.2 revealed that the cascade control buck converter offered the best results. In fact, it offers the fastest response (in terms of rise time), the most rapid convergence to steady-state (based on settling time), time to reach the peak value (according to peak time), and most stable and smoothest response (with respect to overshoot).

XVIII. CONCLUSION AND RECOMMENDATIONS

Summary of Discussion

This work has presented a DC-DC buck converter circuit that combines cascade control techniques based on Fuzzy-PID and PID algorithms for improved transient response performance. With most DC-DC converters of practical interest requiring the improvement in system stability while maintaining satisfactory transient response and efficient voltage/power transfer to improve electrical demand of external load, accomplishing this involves the introduction of an automatic control system with an integration element that will ensure that the forward path error is reduced. A DC-DC buck converter was designed, and Fuzzy-PID and PID controllers were incorporated to the system to improve transient response performance in terms of rise time, settling time, and overshoot with high voltage/power transfer efficiency. Simulations were conducted in MATLAB/Simulink to ascertain the effectiveness of the system, and the results of the simulations were evaluated against certain key parameters in the transient response time domain and frequency domain and thereafter, a comparison test with a classical cascade control system was performed.

XIX. Summary of Findings

The cascade control system proved its superiority over the classical PID control system. This was basically evident in the fast-tracking of setpoint voltage and smooth response. Thus, an enhanced system stability and overshoot were achieved compared to the PID controller.

The fuzzy logic algorithm offered improved control capability to solve the nonlinear dynamic effects and enhanced tracking for more efficient regulation of the voltage.

XX. CONCLUSION

Conclusively, the use of cascade controllers in power electronics converters embedded with fuzzy logic system offers significant improvements in dynamic response and stability of the overshoot, settling time and frequency. The results of this study demonstrate the effectiveness of the fuzzy logic control system embedded in the PID cascade controllers strategy renewable energy and consumer electronics.

Contribution to Knowledge

The cascade combination of Fuzzy-PID and PID controller to enhance the transient response time and frequency domain performances of a DC-DC buck converter has been realised.

In this work, the dynamic challenges common with power electronic systems, especially during loading, were demonstrated via computer-based simulations.

Recommendations for Future researchers

Hardware implementation is urgently needed to validate the effectiveness of the cascade control technique in practical applications. This will help to bridge the gap between theoretical investigation and real-world application.

Other control strategies, such as adaptive controllers and multi-objective optimization methods, should be investigated together with the designed cascade control scheme in this work.

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