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Neuro-Fuzzy Controller for a Non-Linear Power Electronic DC-DC Boost Converters

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***Abstract*—The current paper aims to explore the possibility of improving the performance of one of the important systems (boost DC-DC converter) in the field of electrical energy by contributing to the use of electronic power converters to provide the scheduled voltage to the loads with changing operating conditions using traditional (PID control) and expert (Neuro-fuzzy logic control) methods. Test cases are proposed to verify the possibility of improvement and the effectiveness of the system through approved measurement criteria such as improving stability, response time, efficiency, or a performance measure for overshoot and undershoot rates and rise time in addition to steady-state error through which comparison can be made to know the best between the methodology used to evaluate the performance of PID controllers and ANFIS (Adaptive Neuro-fuzzy Inference System). The current paper deals with a study of the operation of non-linear DC-DC Converters with a Neuro-Fuzzy Controller. To verify the system's effectiveness, proposed tests are conducted to simulate operation in real-time. The assumptions adopted are that the input voltage value is available from a direct current source with a voltage of (12) volts, and what is required to supply a load with a voltage ranging between (22-120) depending on the load change. The necessary calculations were made to calculate the converter parameters. The required inductance value was (160µH) and the capacitance value was (276µF). The simulation test was conducted using a model consisting of a resistive load and a step-up converter in addition to the supply source in both the open-loop and closed-loop system states. System tests were also conducted in the presence of the proposed controllers to verify the system's effectiveness.**

Keywords*—Boost DC-DC Converter; PID Control; ANFIS; Open Loop System; Closed Loop System: Pulse Width Modulation (PWM).

I. INTRODUCTION

Converters in general and DC-DC Converters in particular are widely used in many applications, including industrial ones, to provide the specified voltage to loads with changing operating conditions. The importance of using DC-DC converters is due to the need to address changing operating conditions, which require an appropriate methodology to resolve changes such as transients and noise that result in an error leading to an unstable system, which requires returning the system to a stable state [1]-[3].

When designing a boost transformer, especially non-isolated converters, which are usually used when the voltage change is relatively small. When the switch is ON condition, the changes in the inductance and the current entering it are very important as they affect the efficiency of the converter operation [4]-[6].

With the application of DC-to-DC converters, it has become possible to reduce the noise condition that occurs and also protect the circuit from high voltages that lead to damage to the operating switches, as the electronic circuits are modified by changing the efficiency of the circuit and changing the ripples in addition to responding to the transient load, so the basic and ideal parameters of the circuit depend on the operating conditions, so the specifications and requirements of the input and output must be taken into account [7]-[9].

One of the approved methods is to build and design a system that works with an algorithm that suits the required processors, including the closed-loop system as an alternative to the open-loop. To provide the required output, the reference value is set and compared with the actual value and is input to the controller, from which the error in the system is detected. After that, it is the controller's role to address the error and return the system to a stable state. Another method is to test expert systems that can be trained to identify and detect the error and how to return the system to a stable state, including using a hybrid controller that combines fuzzy logic and a neural network. Systems that include Converters are built through the transformer function that is required to be implemented, whether it is to raise or lower the value of the transformer's input voltage from the transformer's output value. It is worth noting that the components of the transformer are electronic power devices represented by electronic switches, which are transistors, as well as the inductor and capacitor. Electronic switches operate with a system of opening and closing with a controlled amount of time to determine the duration of charging and discharging the inductor and capacitor to obtain the appropriate output. One of the techniques used to provide the appropriate pulses to open and close these switches is the pulse width modulation technique. The problem of operating under different conditions is considered to be hypotheses and predictions through an extensive study and review of numerous studies and mathematical calculations, it is possible by conducting tests and through a prototype that is developed and reaching an advanced design that suits the proposed operating conditions. It is possible to adopt the results of the research, analyze it, and conclude it as a reference for subsequent studies that fall within the scope of the research and the limits of the current hypotheses for similar or close operating conditions.

Fuzzy logic (FL) is considered an extension of multivalued logic. It has become important to adopt a Fuzzy Logic Controller (FLC) and one of the intelligent controllers for the appliances. The power feedback control unit for the DC converter is important to regulate the input without any error occurring in the next state, in addition to slightly exceeding the required value of the output and with a quick response, which gives the circuit high performance and efficiency, ideally and according to requirements. The control medium of FC can be illustrated, which has a closed loop that feeds the external voltage to maintain the stability of the output voltage. In contrast, the internal loop acts as an input current sensor. This gives power and ease to the fuzzy logic operation in controllers. FLC can be used to know the nature of the changing shape of FC. It can also provide a way to quickly respond to the input voltage and output current changes to get the appropriate value. It will also offer a dynamic response. FLCs have shown clear progress over PID in terms of efficiency, performance, and speed of response. It is possible to develop the work of the fuzzy controller in a way that makes it superior to its predecessor, by adding intelligent information to the fuzzy rules. This is done by resetting them through the use of artificial neural networks (ANN) resulting from the integration of ANN. And FL, with the use of each of the features of the two control circuits in a sequential manner, the technology for these systems has emerged in artificial intelligence and is considered important and practical solutions when some complex non-linear problems and issues are difficult to solve and analyze using regular or traditional techniques. Thus, these units have demonstrated Their superiority over other control units.

In [10]-[11] applies an artificial intelligence or fuzzy logic strategy to improve the performance of photovoltaic systems to variations of I-V and P-V characteristics resulting from irradiance and temperature that create maximum power point (MPPT) variation, resulting in fluctuation of the DC voltage at the input of the boost step converter.

In [12] the work proposed and evaluated 5 MPPT algorithms. These types are respectively a proportional-integral controller (PI), a non-linear control based on sliding modes (SMC), a backstepping approach (BSC), a control using artificial intelligence based on neural network (ANNC), and a fuzzy logic control (FLC). Two different wind parts, a step wind, and a real wind, were considered for the comparative study.

Parametric adaptive PID control [2] includes Adaptive PID pole placement control, Adaptive PID control based on cancellation principles, and Adaptive PID control based on quadratic performance indices: It achieved extensive development in non-parametric adaptive PID control, from artificial intelligence, and it can optimize parameters [13].

The work presented a double boost converter (DBC) integrated with a three-level diode-clamped multilevel inverter (TLDCI)and the converter achieved twice the output voltage in comparison with the conventional boost converter. The DBC was designed and simulated under open-loop and closed-loop operating conditions by using Proportional integral (PI) and fuzzy logic controllers (FLCs) in closed-loop operations, the DBC was integrated with a three-level diode-clamped inverter [14]-[17].

In this manuscript comparison of the PID controller with MPC is made and the responses are presented. MPC is an advanced control strategy that uses the internal dynamic model of the process a history of past control moves and a combination of many different technologies to predict the future plant output [18][19].

PID controllers are considered one of the most important and simplest controllers used in various applications, including controlling the transformer output voltage for industrial applications. Many technologies have emerged to represent control units, including expert and intelligent, which are algorithms inspired by nature for human, animal, and plant organisms, including the fuzzy logic technology (FL), the neural network (ANN), the neural fuzzy inference system (ANFIS), in addition to the genetic algorithm (GA) and others.

The development is taking place in all sciences, including engineering science, where many algorithms have emerged that mimic living organisms such as plants, including roses, and other animals such as the wolf, and others that specialize in genes, which is the genetic algorithm, in addition, another type.

In this study, two non-linear control circuits were presented, one of which is the open circuit and the closed circuit, and the design and analysis of the DC boost converter circuit was carried out, as the control unit is represented by the use of FLC and PID controllers to improve the circuit's work performance and develop it in a way that ensures its highest levels. A comparison of the two enhancement circuits without FLC is an open loop. And enhanced with closed-loop FLC. To develop a proposed control unit that is capable of dealing with all operating conditions, the block diagrams were simulated by conducting testing using MATLAB/Simulink, which consists of the FLC process, validation of the result obtained, and adjusting the parameters: membership function, FIS, conclusion. Based on the obtained result, the simulation results are presented and the normalization and peak overshoot time are used to measure the performance. It aims to determine the high performance of Neuro-Fuzzy controllers compared to conventional PI controllers and Fuzzy controllers at different operating points of high voltage and boost converters.

II. METHOD

The method adopted in the current study can be described by describing the parts and components of the system. Fig. 1 shows the parts of the proposed system to conduct appropriate tests through which the research objectives can be achieved by verifying the knowledge of the system behavior in different operating conditions, which will be detailed later. The converter part can also be described, and its other part can be described, which is the traditional controller, the expert controller, the converter output connected to the load, and the converter input connected to the source, as follows: [20].

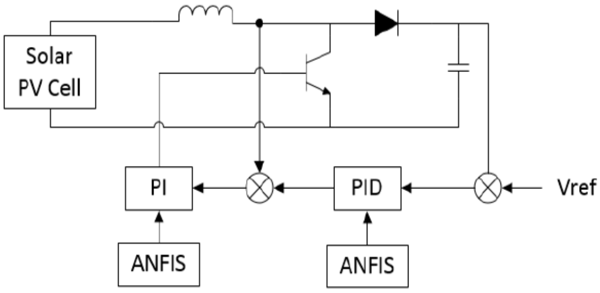


Fig. 1. Diagram of the system [20]

A. Boost DC/DC Converters Converters

When looking at the system components, we find that the focus of the system is DC/DC converters, one of which is DC boost converters, or step-up converters, as they give an output voltage greater than the input voltage [21]-[22]. The concept and importance of boost converters, there are problems with low-current and boost-converters when transmitting the output signal in the continuous conduction mode (CCM) using specific values of bandwidth in the closed-loop condition so the bandwidth is less than the corner frequency because at some negative near-zero points the system will have a small and slow signal response so new methods have been developed and invented to solve these problems and get a fast response using a new system and there are two ways either to develop a high-precision nonlinear model of the converter or to use an artificial intelligent control system. The most widely used technology in control systems is fuzzy logic to obtain a circuit. The modules work better. The intelligent controller is designed with an approximate system and model. Many researchers have contributed to the development of artificial intelligence (AI) controllers for buck converters and boost converters [1][2].

Basics of Boost DC/DC Converters, the power source in these converters is numerous and must be constant current, such as batteries, solar panels, rectifiers, and DC generators, to stabilize and maintain the energy obtained from inside the converter, the output current must be less than the input current or the source current. Therefore, the selection of the parameters of the electronic circuit must be designed to suit the requirements. Non-isolated step-up converters are among the most important converters with an output voltage higher than the input voltage. They consist of a set of two switched-mode semiconductor switches (SMPS), in addition to one of the energy storage components, which is the use of capacitors, which are connected to the output resistance to improve the performance of the converter, as well as the use of inductance, or both. It is possible to increase the efficiency of the circuit by raising the output voltage and the efficiency of some converters may reach 96% [24]-[26].

The techniques were used for analog integrated circuits, and the design technology for control in the linear system. With the development of high-speed digital circuit technology, digital control has gradually been replaced by the analog control unit currently used in converters. High-frequency switching is a very important role in smart power supply in the aviation, communications, and automotive industries [27]-[29].

They are also easy to use, cheap, and lightweight. Importance in power electronics of boost converters, the importance of electronic converters as one of the electronic power systems is highlighted in connecting the sources of electrical power generation from the power sources such as generating electrical energy from a solar source and connecting it to the converter, and the conversion is linked to a load or storage unit such as batteries or the national grid or to a micro-grid. The analysis of the inductor current in the boost converter circuit is very important in the dynamic response of the boost converter. Also, it can provide the storage energy information in the converter. That means, any changes that will happen in the inductor current may affect the output voltage that will provide steady-state conditions, the three parameters needed when designing boost converters are the power switch, inductor, and capacitor. to obtain the desired output voltage and stability designing the power switch [30]. To design a boost converter by using the equivalent circuit in Fig. 2 and the mathematics in equations (1)-(7) below:

Calculate duty ratio:

$$\frac{V_{out}}{V_{in}} = \frac{T_S}{T_{off}} = \frac{1}{1-D} \tag{1}$$

$$D = 1 - \frac{V_{in}}{V_{out}} \tag{2}$$

Calculate minimum inductance:

$$V_L(t) = L\frac{di}{dt} \tag{3}$$

$$\Delta I_L = \frac{V_{o,min}}{f_s} D \tag{4}$$

$$L_{min} \geq \frac{D(1-D)^2 Ro}{2f_s} \tag{5}$$

Calculate 25% larger than the minimum inductance

$$L = 1.25L_{min} \tag{6}$$

Calculate minimum capacitance:

$$C_{min} \geq \frac{I_o D}{\Delta V_{out} f_s} \tag{7}$$

ΔV_{out} is taken as 1%× V_{out}

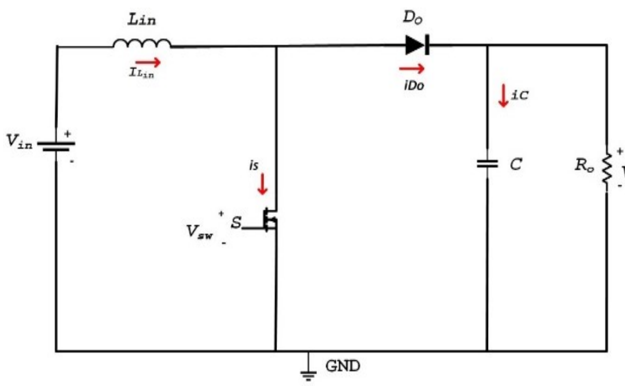


Fig. 2. Circuit Diagram of the boost converter

B. PID Controller

Types of controllers, Proportional Integral Derivative (PID), the traditional PI, PD, and PID control units are considered among the most commonly used control units in most cases of electronic closed circuits, and the most widely used of them is the proportional integral derivative (PID) control, which is considered the most popular control algorithm in the industry. This is attributed to the advantages of this system to the PID control units as a result of the integration of Its performance and operating conditions, as well as its ease of operation simply and directly [31]-[33].

It is demonstrated that different controllers provide performance measures such as stability with response speed, voltage regulation at the specified value, and overcoming disturbances and transient states of the system. The study included using a traditional controller type (PID controllers).

The control unit, known as the PID, is widely used because of its importance and its major role in electronic circuits. It is composed of three basic axes:

The first includes the proportional, the second the integral, and the third axis is called the derivative. This controller represents a diagram of the operation of the system of the control unit, which works using derivation, for the variables that enter the system, which includes the plan signal, the first part to which the signal enters is called the proportional, which in turn immediately acts on the error, and then the integral is added to it to make compensation for all errors, and then to the derivative, which performs future predictions of errors, and through these three axes, the procedure of improving controller performance by reducing steady-state errors and rise/fall times respectively [20][34][35].

The basic idea of this system's work is to read the sensor, and through calculations of the responses to the three axes, the required parameters are extracted for the output part of the electronic circuit. This system is used in a closed loop, as the process of reading the sensor is carried out by taking the appropriate values and repeating them as an output of the circuit in a fixed loop rate, as was explained in Fig. 3 [36].

The proportional response includes the point of difference or error, where proportionality depends on the state of the difference between the point that was determined and the point of change and the result of the process or what is called the output, where the relative gain represents the KC ratio of the output response to that error, and increasing the response speed will lead to an increase in the relative gain of the control system for that. It can be noticed in the output voltage the increase and fluctuation in value as a result of the increase in KC, and to a greater extent, also notice that the system is unstable as a result of the increase in the variable of the line process, and the fluctuation remains continuous and may be outside the system.

Integrated response, the work of the integrated axis is to collect the resulting error, and this will lead to an increase in the value over time, but slowly, and thus an increase in the integrated axis, and thus the response will increase, but provided that the error for this case does not have a zero value and continues until it reaches a certain point called the saturation state of the control unit, which The integrator is in the finished state, as in this case the control unit does not direct the error signal towards zero.

Derived response, the work of this derivative axis represents the final results if the variable increases rapidly. Therefore, there is a proportionality between the response to that derivative with the rate of change of that process. Therefore, the derivative time parameter Td, as shown in Fig. 4 [36] works to make the control system more effective and powerful, and its effectiveness is greater with that. Changes in error, which result from an increase in the speed of the overall response of the system, and usually a small value for Td is chosen because the response to the derivative axis is highly sensitive and is affected by any noise signal, and if such cases and high noise occur, this may lead to the system becoming unstable.

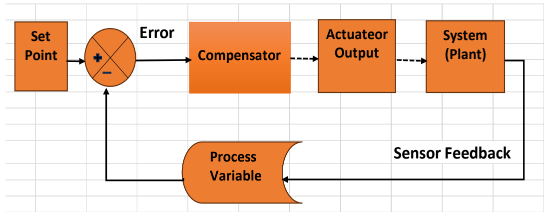


Fig. 3. Block diagram of a typical closed loop system [36]

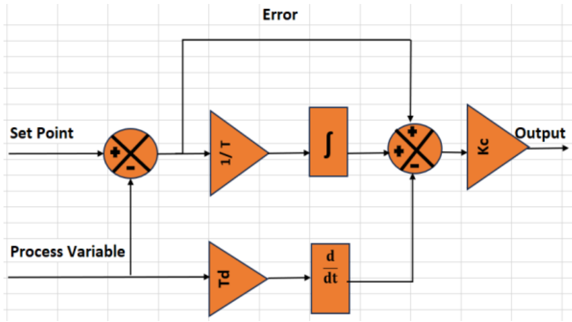


Fig. 4. Block diagram of a basic PID control algorithm [37]

The PI controller is used to regulate to obtain the required value of the transformer's output voltage regardless of the disturbances that occur in the load. The performance of the control unit was evaluated and worked in a situation where the settlement time is a measure of the performance and efficiency of the system and the PI makes the overshoot less [38]. In [39], this research, a design of a new structure PID controller of the boost converter is offered to optimize the system and stability compared to the conventional PID. In this research, a hybrid smart PID controller with a fuzzy logic controller (FLC) was proposed in a DC-DC converter, as it represents a non-linear closed loop and is designed effectively. Its continuously adjusting the PID parameters according to the load condition, it is possible to improve the performance of the DC-DC converter.[40], It uses a single-switch cascade DC-DC boost converter, which has higher voltage gain and greater efficiency than traditional cascade converters and other boost-type converters. Because the proposed single-switch DC-DC boost converter includes one ontrol switch, it is more efficient, has a smaller size, and has a lower cost when compared to other types, the transformer is tested using traditional PID control methods and fuzzy logic to monitor the dynamic performance [41].

Conventional proportional-integral (PI), proportional integral derivative (PID), and nonlinear sliding mode control (SMC) control techniques are presented and implemented in double-loop control for DC-DC enhancement and the dynamic behavior of the converter is observed through comparative analysis and the response of the controller is compared. The SMC + SMC controller displays superior control action for various disturbances compared to the PI + PI and PID + PID controllers [42].

C. Fuzzy Logic Controller (FLC)

FLC represents knowledge-based controllers, and the figure shows the structure of the fuzzy logic controller in the closed-loop system [43][44]. It consists of four parts: the beginning of the distorted signal input, which is called the interference interface (FI), and the noise-free output signal, which is called the interference removal interface (DI). These two processes include some processes including the rule base (RB), and the inference mechanism (IM) [45][46].

The way the system works is to input the signals and classify them through FI into appropriate language values/sets. To the rule base, RB consists of fuzzy sets (database) and fuzzy control rules, and then to the inference mechanism, which is the core and focus of the fuzzy neural control system, where it can simulate the human decision-making process, according to the concepts, knowledge, and inferences of control delays, by establishing relationships and inference rules. Then it goes to the IM process, which gives the outputs and inputs to the factory. The fuzzy logic controller acts as an intelligent controller, and the fuzzy logic design of the controller can provide the dynamic performance of small signal and large signals at the same time, which cannot be achieved by linear control technology, and can improve the robustness of DC-DC converters. The fuzzy control action is inferred from the knowledge of control rules and definitions of linguistic variables, and the defuzzification interface produces a non-fuzzy control action from the inferred fuzzy control action [47]. Fuzzy control systems are based on specialized knowledge that transforms human linguistic concepts into automatic control strategies without any complex mathematical model [48]. The simulation is performed in a boost converter to verify the proposal.

Fig. 5 structure of the fuzzy logic controller on a closed-loop system, is considered an extension of multivalued logic, and one of the intelligent controllers for the appliances [49].

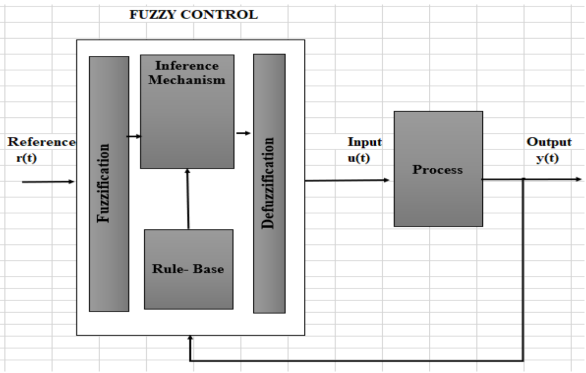


Fig. 5. Structure of the fuzzy logic controller on a closed-loop system [49]

The power feedback control unit for the DC converter is important to regulate the input without any error occurring in the next state, in addition to slightly exceeding the required value of the output and with a quick response, which gives the circuit high performance and efficiency, ideally and according to requirements [50][51]. In [52] The control medium shows the current state of the FC, which contains a closed loop feeding the external voltage to keep the output voltage stable, while the inner loop works as a device to sense the input current. This gives strength and ease to perform the fuzzy logic process in the control units. In [53] represents a way to quickly respond to changes in the input voltage and output current to obtain the appropriate value and a dynamic response.

FLCs have shown clear progress over PID in terms of efficiency, performance, and speed of response. And by developing the work of the fuzzy controller to make it superior to its predecessor, by adding intelligent information to the fuzzy rules. This is done by resetting them through the use of artificial neural networks (ANN) resulting from the integration of ANN. And FL, with the use of each of the features of the two control circuits in a sequential manner, technology for these systems has emerged in artificial intelligence and is considered important, and practical solutions to some complex non-linear problems are difficult to solve and analyze using regular or traditional techniques. Thus, these units have demonstrated superiority over other control units [53][54]. In Fig. 6, the block diagram of the complete system, along with the circuit diagram, is presented [55].

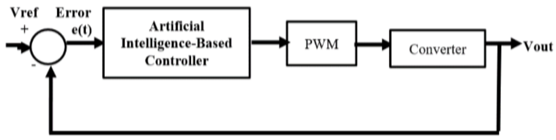


Fig. 6. Block diagram of the complete system [40]

III. Simulation and Verification

When we want to simulate a circuit, it is necessary to take into account the main points and specifications for controlling the circuit, as they are challenged by the operation of the circuit, which includes the following:

The occurrence and determination of the fault condition, the stabilization time of the value, the state of the voltage or current value that can be exceeded, or the transient value that achieves the desired result, as well as the amount of frequency. The obtained stable error state has a major role in the amount of gain for the DC loop. The relationship is inverse. In the case of increased gain in the DC loop for the open loop, we notice a decrease in the error state for the stable.

Using pulse width modulation (PWM), Pulse width adjustment represents an important technique for regulating the average output voltage, as it is used to convert alternating current power in electronic circuit systems, especially converters, by varying the duty cycle of the converter at a higher conversion frequency, which leads to obtaining a low-frequency voltage or current value at the output.

The simulation is performed on the circuit by using pulse width modulation (PWM), and a proportional-integral-derivative (PID) controller for the load regulation of the boost converter. The values of the parameters of the boost converter are shown in Table I.

TABLE I. THE PARAMETERS AND VALUES FOR THE BOOST DC-DC CONVERTER

parameters	Rated value
Input Voltage (Vin)	12 V
Inductor(L)	160µH
Capacitance (C)	276µF
output Resistance (Rout)	9Ω
Output Voltage (Vout)	22V
Switching frequency(fs)	10kHz
Duty cycle	0.454
Power	53.78W
Output current (Iout)	2.44A

In this section, the first state simulation of the open loop uses the simulation model in Fig. 7 for the boost converter's circuit diagram and the response result at this state. That is shown in Fig. 8 below:

- Using pulse width modulation (PWM) Generator DC-DC with constant 0.485

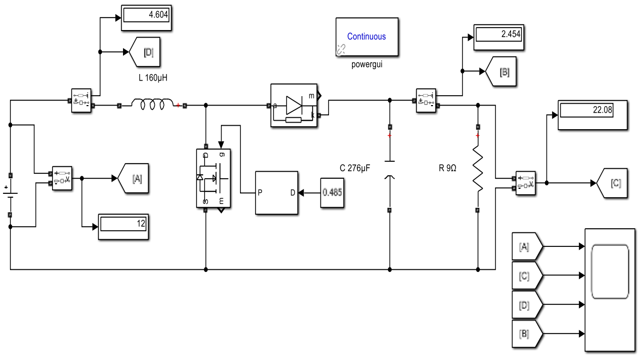


Fig. 7. Design of boost converter open loop using (PWM), Vin=1v, Vout=22.08v, Iout=2.454A, Iin=4.604A

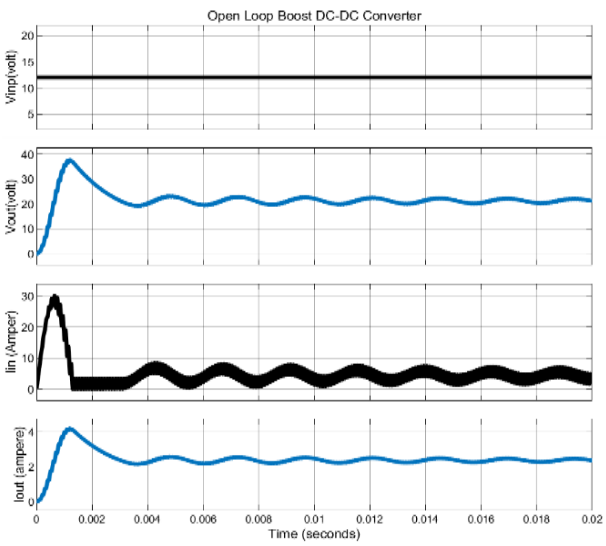


Fig. 8. Iout, Rise time=412.530µs, Slew Rate=4.710(/ms) Iin, Rise time=374.116µs, Slew Rate=58.826(/ms)

- Using pulse width modulation (PWM)

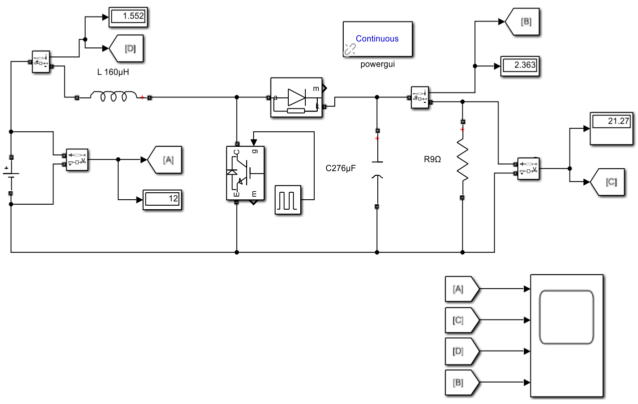


Fig. 9. Design of boost converter open loop using (PWM), Vin=12V, Vout =21.27V, Iout=2.363A, Iin=1.552A

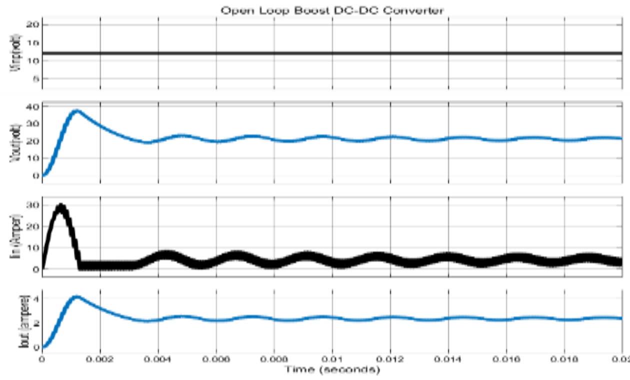


Fig. 10. Vout, Rise time=412.53µs, Slew Rate=42.394(/ms) Iout, Rise time=412.530µs, Slew Rate=4.710(/ms), Iin, Rise time=374.116µs, Slew Rate=58.826(/ms)

In this section, the second state simulation of a closed loop uses the simulation model (PI, PD, PID), in Fig. 11, Fig. 13, Fig. 15 for the circuit diagram of the boost converter and the result for response at this state. that shown in Fig. 12, Fig. 14, Fig. 16, below:

- Using proportional-derivative (PI)

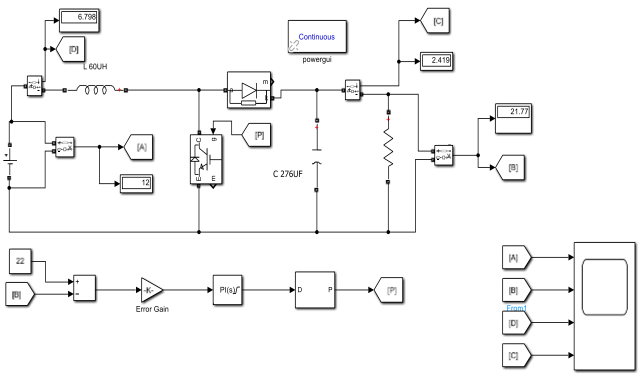


Fig. 11. Design using proportional-Integrated (PI), P=5, I=68, Vout =21.77, Iout=2.419A, Iin=6.798A

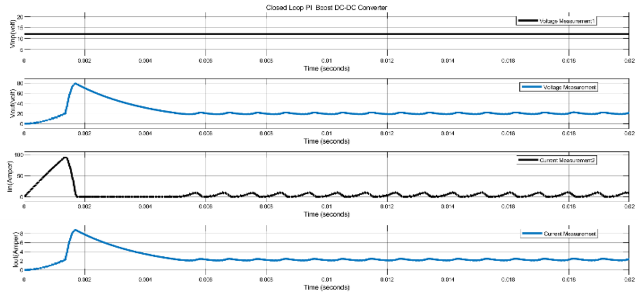


Fig. 12. Rise Time and Slew Time of the output and input (V, I)

- Using proportional-derivative (PD)

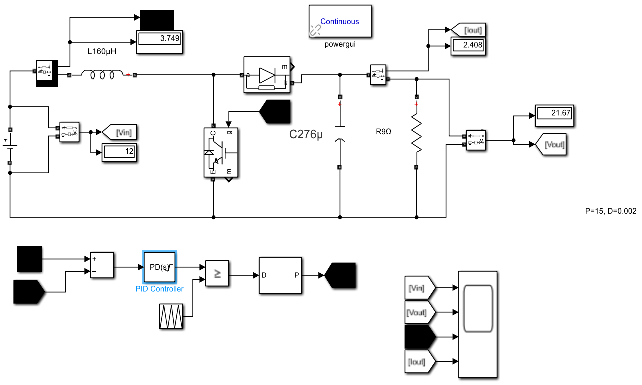


Fig. 13. Design using proportional-integrated (PI), P=15, D=0.002, Vout =21.67, Iout=2.408A, Iin=3.749A.

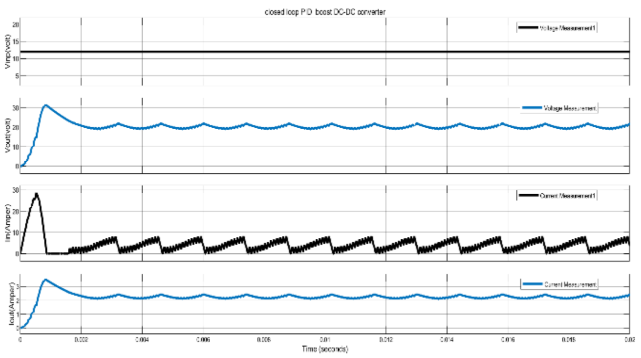


Fig. 14. DVout, Rise time =130.176µs, slew Rate=57.600(/ms) Iout, Rise time =130.176µs.slew Rate=6.400(/ms), Iin, Rise time =275.173µs, slew Rate=64.298(/ms), Fall time=168.740µs, Slew rate=-104.854(/ms).

- Using proportional-derivative (PID)

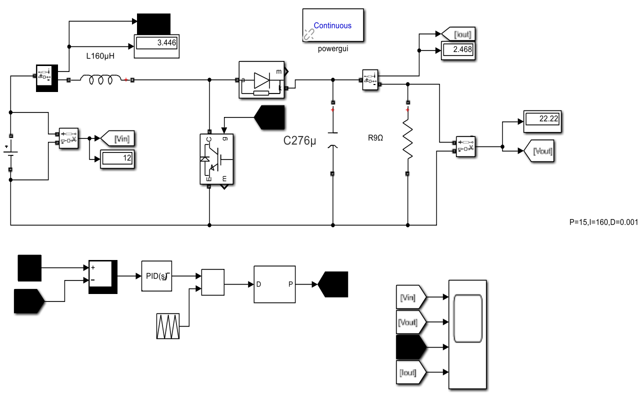


Fig. 15. Design of boost converter using close loop (PID)controllers, P=15, I=160, D =0.001, Vout= 22.22V, Iout =2.468A, Iin=3.446A

Fig. 16. Vout, Rise time=130.018µs, Slew Rate=57.660(/ms) Iout, (Rise time=130.018µs, Slew Rate=6.408(/ms), Iin, Rise time=275.173µs, Slew Rate=64.298(/ms)

The third state simulation of a closed loop, in this section, uses the simulation model NFLC:

It is possible to work on developing and using a hybrid system of fuzzy logic and a neural network with the training process to obtain learning and prediction for nonlinear systems. The process of adjusting the system parameters can carried out according to basic data that depends on an appropriate output, with changing operating conditions such as changing the load, the Performance can be known through the behavior and results of the system to determine the effectiveness and efficiency of the system according to the scale of the required rate determined for the output voltage, the parameters of the under and overpass, the stabilization time, and the rise time. From this, the level of performance can be revealed through the simulation results of the proposed test cases,

- Analytical Terminology

For the requirements of conducting the design of the converter circuit, the appropriate switches must be chosen for this purpose, as there are a few switches that are used to perform the development and analysis process in the fuzzy logic system unit. These switches include the following: BJT, power MOSFET, IGBT, and others.

- Membership Functions in Fuzzy Logic

Fuzzy controllers are designed based on general knowledge, as they do not require mathematical calculations, but rather a model for conducting the design process in the boost converter. The controllers are designed to adapt to different operating points using a fuzzy inference system on the model Mamdani. By using two input variables, error (e) and change error (de) where the single output variable in this fuzzy logic system is the duty cycle(D) of the PWM [38]. That is shown in Fig. 17 to Fig. 20.

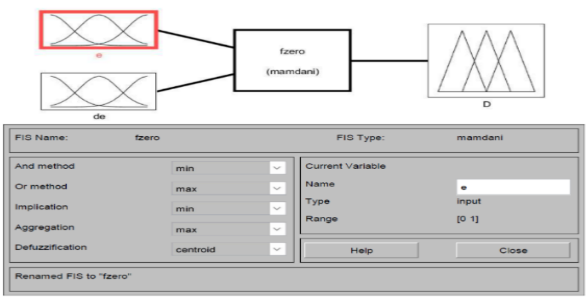


Fig. 17. The membership function plots

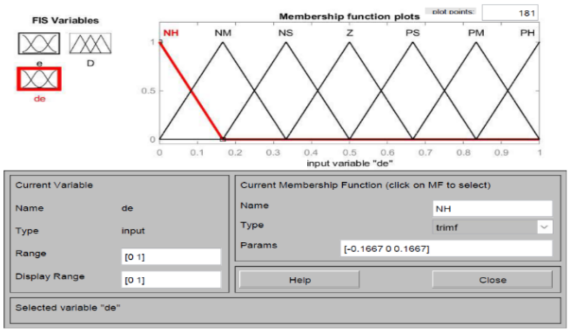


Fig. 18. The membership function plots of (de)

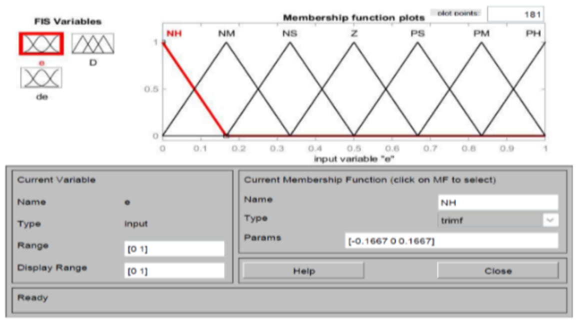


Fig. 19. The membership function of (e) error

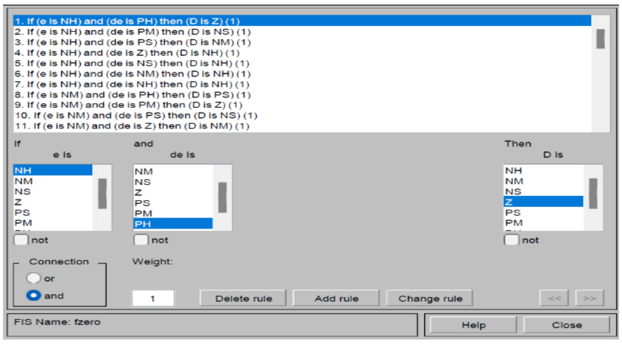
Fig. 20. The membership function of (D) error

- Table Rules in Fuzzy Logic

To create a table that includes the states used to control the output of the boost converter. The error and error change it considered as inputs to the fuzzy logic controller and the rules of the fuzzy logical table [56]-[58]. According to the details in Table II, seven sets of inputs it used, NS- negative small, NH- negative high, ZO-zero area, PS- positive small, and PH-positive high, as well as the rules for the control process. In Fig. 21(a) and (b), an adaptive neuro-fuzzy inference system (ANFIS) with two inputs with seven membership functions for each input, one output, and 49 rules. Fig. 22 shows the 3D representation of the rule surface relating to the value of the output for any combination of the two inputs.

TABLE II. THE ERROR RULES, DE ERROR, D

D		error						
		PH	PM	PS	Z	NS	NM	NH
de	NH	Z	DNS	DNM	DNH	DNH	DNH	DNH
	NM	DPS	Z	DNS	DNM	DNH	DNH	DNH
	NS	DPM	DPS	Z	DNS	DNM	DNH	DNH
	Z	DPH	DPM	DPS	Z	DNS	DNM	DNH
	PS	DPH	DPH	DPM	DPS	Z	DNS	DNM
	PM	DPH	DPH	DPH	DPM	DPS	Z	DNS
	PH	DPH	DPH	DPH	DPH	DPM	DPS	Z



(a)

(b)

e=1, de=1, D=0.948

Fig. 21. Adaptive neuro-fuzzy inference system (ANFIS) general architecture with two inputs (with seven membership functions for each input, one output, and 49 rules (a), (b).

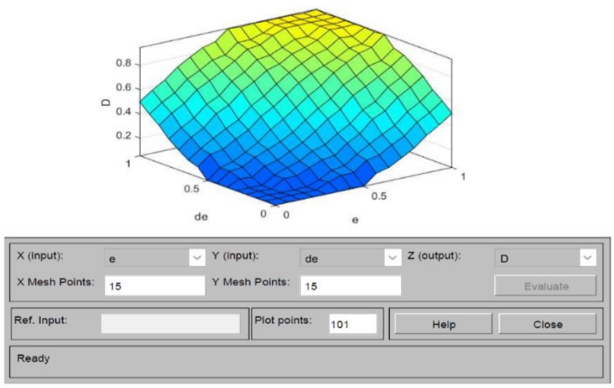


Fig. 22. Rules representation by the 3D surface view

- Simulation results of ANFIS-Based Controller for a Non-Linear Power are shown In Fig. 23 and Fig. 24.

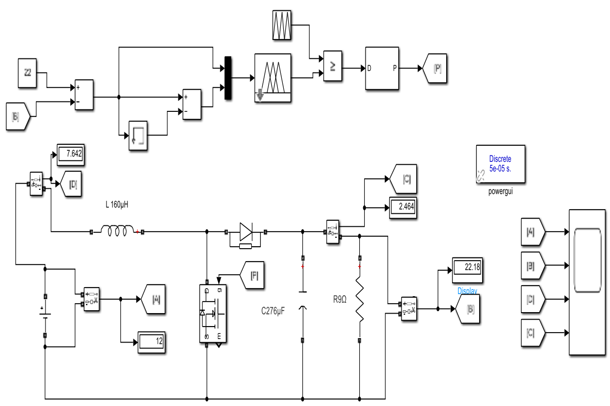


Fig. 23. Design of boost converter using close loop NFLC controllers, Vout=22.18V, Iout=2.464A, Iin=7.642A.

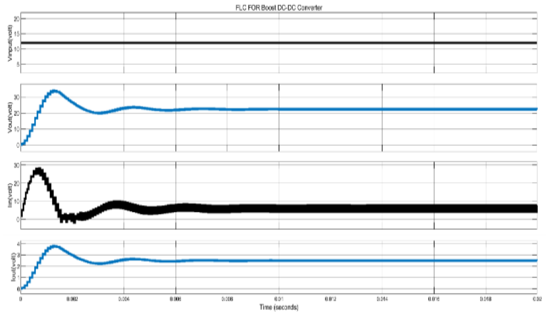


Fig. 24. Vout, Rise time =275.173µs, slew Rate=64.298(/ms), Iin, Rise time =280.763µs, slew Rate=50.508(/ms), reshoot =32.919% overshoot =16.102%, undershoot=17.058%, Fall time=168.740µs, Slew rate=-104.854(/ms)

IV. Discussion the Results

Through the results obtained for the boost converter circuit and the parameters that were chosen to design the circuit, it is noticed that:

In the case of an open circuit loop, the results showed that the output voltage reaches a value in the overshoot (30 volts) and gradually decreases with its fluctuation and stabilizes at a value of (22.08 volts), (21.27 volts) and the output current value is (2.454 A), (2.363A) depends of the duty cycle that is showed in Fig.7 to Fig. 10.

In the case of a closed loop, using the PID controller in three types(PI, PD, PID)the output voltage rises to the value of (80volts) it begins to fluctuate slightly until it stabilizes at a value of (22.77 volts), (21.67 volts), (22.22) and output current value of up to (2.363), (2.419), (2.408) and that depends on the types of the PID controller also depends to the tuning of the values of the elements that is shown in Fig.10, Fig. 11 to Fig. 16, (PI, PD, PID).

Fig. 23 and Fig. 24 show the simulation using the NFL controller, the output values overshoot (30 volts) and then fluctuate slightly until it stabilize at a value of (22.18 volts), and the output current reaches (2.464A). This transitional phase and the rapid response to reach a stable value for the Vout state of (22 volts) shows the difference between the open and closed-loop systems. The wave diagram also shows the state of the current and its transition to stability very quickly, which resulted from simulating the induction current.

Table III Shows the changes in both cases (open-loop circuit and closed-loop circuit), showing the readings of the output voltage deviation, the overshoot percentage, the rise time, the slew time, and the fall time. A closed-loop circuit with a fuzzy controller has a faster rise time, a faster settling time, and a lower voltage deviation which is the difference between the reference voltage setting and the output voltage, and an open-loop circuit has a slightly higher voltage deviation.

Table IV shows the simulation results of the FLC circuit with the variables Rout. At D (45.4 %), Vin (12v), and Vout (22v), the change in the output voltage appears very slight, approaching the required value, which shows the superiority of fuzzy logic control circuits is evident. Fig. 25 to Fig. 32 when using variable duty cycle D values in the circuit of fuzzy control with the variable Rout.

TABLE III. The Difference is between the Two Cases of an Open and Closed Circuit

parameters	When D=45.4 %, Vin= 12v, V out =22v				
Rout(Ω)	9	10	40	70	100
I out(A)	2.464	2.226	0.573	0.327	0.229
I in(A)	7.641	7.167	3.897	3.418	3.29
Pout(watt)	54.65	49.55	13.01	7.49	5.258
V out(volt)	22.18	22.26	22.81	22.88	22.9

TABLE IV. The Change in Output Resistance

Details	Open Loop Circuit		Closed Loop Circuit			
	PWM with constant	PWM	PI	PD	PID	NFL
Vin (Volts)	12	12	12	12	12	12
Vref. (Volts)	22	22	22	22	22	22
Vout (Volts) Act.	22.08	21.27	22.77	21.67	22.22	22.18
Overshoot Voltage%	-	-	-	-	-	16.102
Undershoot Voltage%	-	-	-	-	-	17.298
Iout (A)	2.454	2.363	2.42	2.408	2.468	2.46
Iin(A)	4.604	1.552	6.79	3.749	3.446	7.64
Iout, Rise Time(µs)	453.92	412.53	-	130.176	130.018	275.17
Iin, Rise Time(µs)	361.142	374.11	-	275.173	275.17	280.76
Vout, Rise Time(µs)	453.917	412.530	-	130.176	130.018	275.17
Iout, Slew Rate(/ms)	4.307	4.710	-	6.400	6.408	-
Iin, Slew Rate (/ms)	50.113	58.826	-	64.298	64.29	50.51
Vout, Slew Rate (/ms)	38.77	42.394	-	57.600	57.66	64.298
Fall time µs	-	-	-	168.74	-	168.74

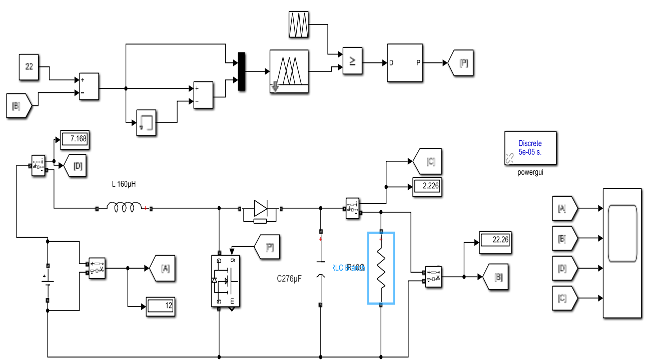


Fig. 25. The circuit when Rout= 10Ω

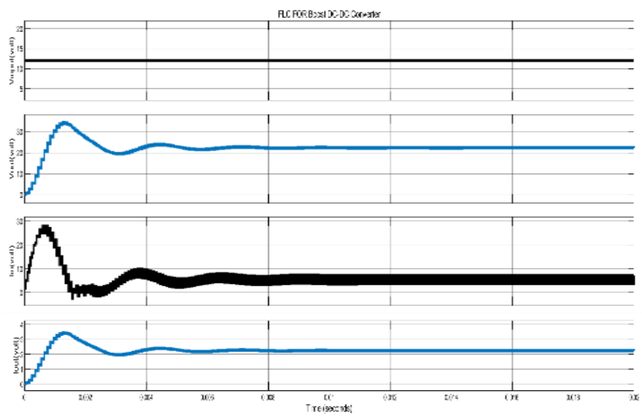


Fig. 26. Vout=22.26v, Iout=2.226A, Iin=7.167A

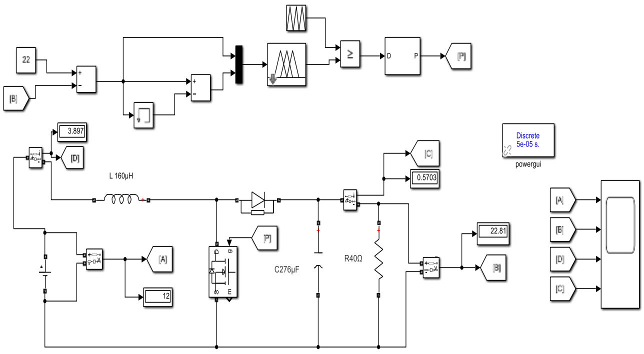


Fig. 27. The circuit when Rout=40Ω

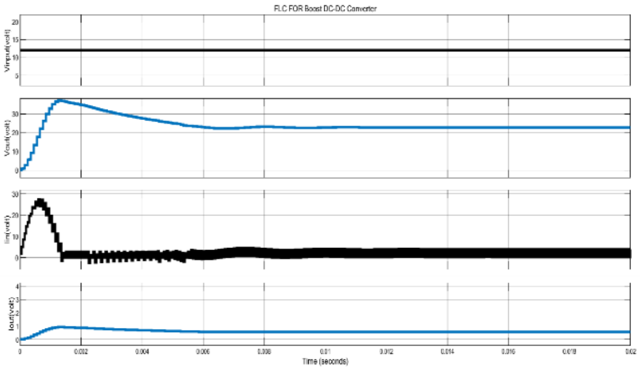


Fig. 28. Vout=22.81v, Iout=0.573A, Iin=3.897A

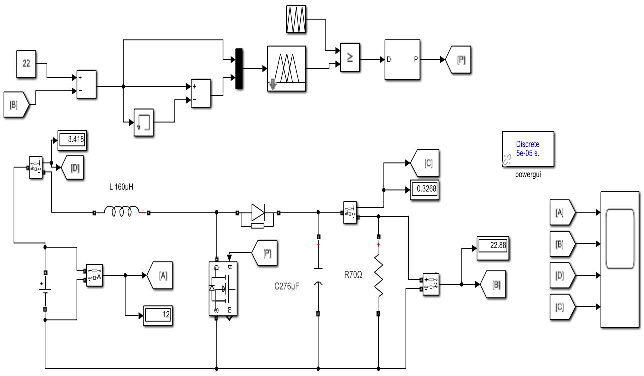


Fig. 29. The circuit when Rout=70Ω

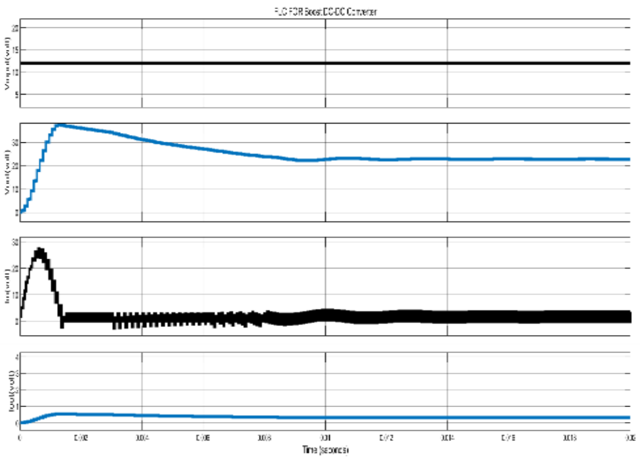


Fig. 30. Vout=22.88v, Iout=0.327A, Iin=3.418A

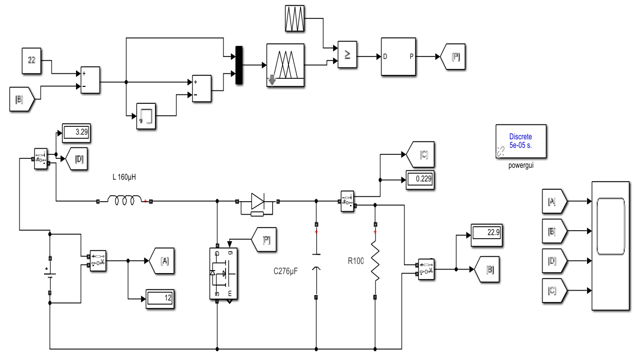


Fig. 31. The circuit when Rout=100Ω

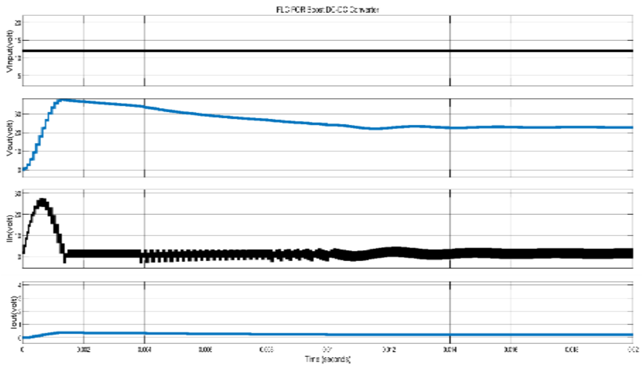


Fig. 32. Vout=22.9v, Iout=0.229A, Iin= 3.29A

Also, when using variable duty cycle D values in the circuit of fuzzy control with the variable Rout. It gives the same value as the Table IV.

Case1. When D=70%, Vin= 12v, Vout=40v
Case2. When D=80%, Vin= 12v, Vout=60v
Case3. When D=90%, Vin= 12v, Vout=120v

Fig. 33 to Fig. 35, shows the work of NFL control when Rout = 9 Ω, Vin=12v, D and Vout change:

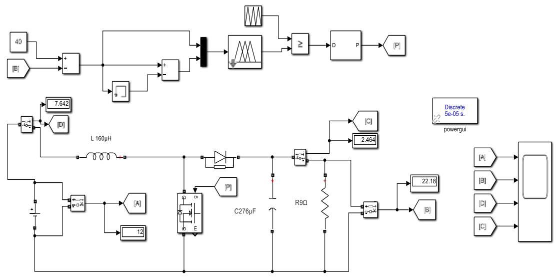


Fig. 33. The circuit when D = 70%, Vout = 40v, Rout=9Ω.

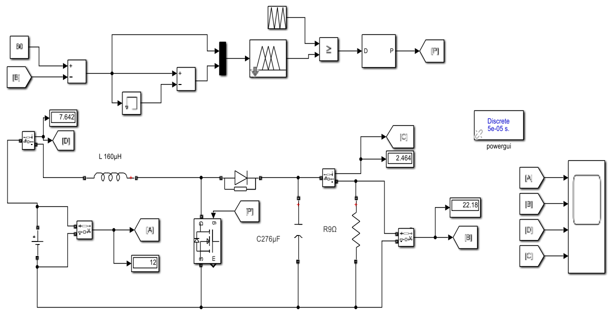


Fig. 34. The circuit when D = 80%, Vout = 60v, Rout=9Ω

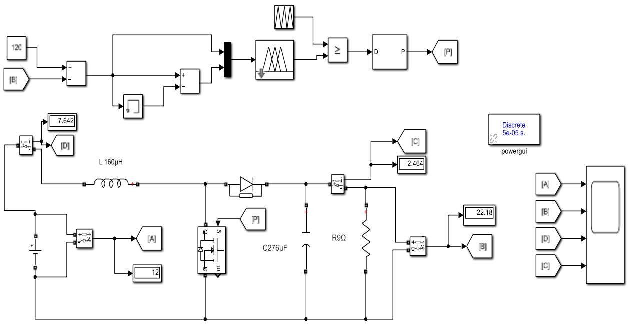


Fig. 35. The circuit when D = 90%, Vout = 120v, Rout=9Ω.

In Fig. 36 to Fig. 38, Shows when Rout =100 Ω, Vin=12v, D and Vout change:

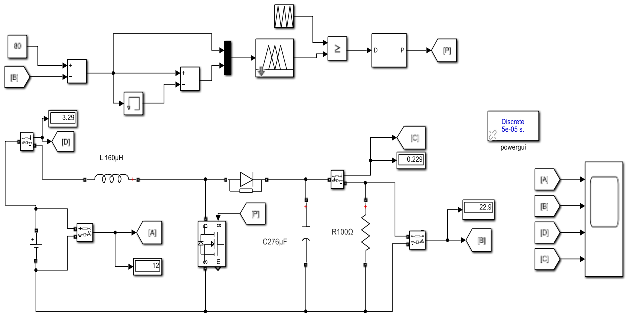


Fig. 36. The circuit when D = 70%, Vout = 40v, Rout=100Ω

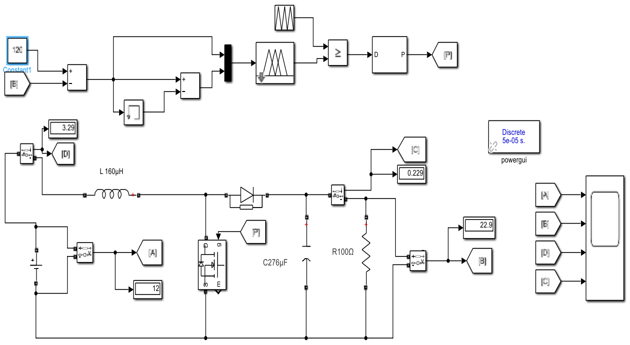


Fig. 37. The circuit when D = 80%, Vout = 60v, Rout=100Ω.

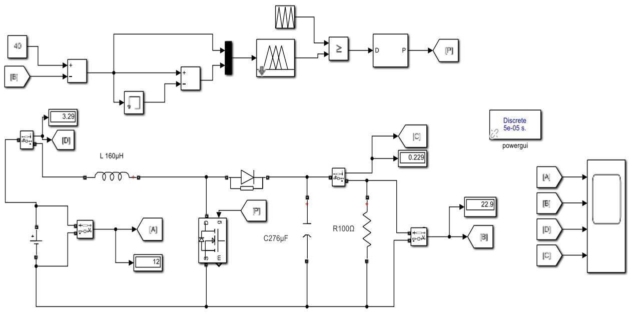


Fig. 38. The circuit when D = 90%, Vout = 120v, Rout=100Ω.

V. CONCLUSION

The research provides a comprehensive analysis of the performance and behavior of the system according to the proposed test cases, in addition, evaluates the effectiveness of the methods used to regulate the converter output voltage using the proposed control units suitable for industrial applications through experimental evidence of various test cases as a result of changing operating conditions and identifying the behavior of the system along with the performance of those algorithms in adjusting and regulating the converter output appropriate. The simulation aims to build and design a high-quality system, through the latest and best technologies in various fields, including regulating the output voltage of the boost converter with Adaptive Neural Fuzzy Inference (ANFIS) technology.

Through the results, appropriate control methods can be determined, which makes the work and direction of the researchers and its status a reference for similar future work.

REFERENCES

[1] M. S. M. Sarif, T. X. Pei, and A. Z. Annuar, "Modeling, design and control of bidirectional DC-DC converter using state-space average model," *2018 IEEE Symposium on Computer Applications & Industrial Electronics (ISCAIE)*, pp. 416-421, 2018.

[2] W. Jiang, S. H. Chincholkar, and C. -Y. Chan, "Investigation of a Voltage-Mode Controller for a dc-dc Multilevel Boost Converter," in *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 65, no. 7, pp. 908-912, July 2018.

[3] M. A. Shahid, A. R. Yasin, and S. Ahmad, "Practical sliding mode controller in Dc-Dc converters for use in hybrid vehicles," *2016 19th International Multi-Topic Conference (INMIC)*, pp. 1-7, 2016.

[4] Maksimovic, Zane, and Erickson, "Impact of digital control in power electronics," *2004 Proceedings of the 16th International Symposium on Power Semiconductor Devices and ICs*, pp. 13-22, 2004.

[5] S. W. Shneen, A. L. Shuraiji, and K. R. Hameed, "Simulation model of proportional integral controller-PWM DC-DC power converter for DC motor using matlab," *Indones. J. Electr. Eng. Comput. Sci*, vol. 29, pp. 725-734, 2023.

[6] M. Afkar, R. G-. Ghoachani, M. Phattanasak, S. Pierfederici, and W. Saksiri, "Local-Stability Analysis of Cascaded Control for a Switching Power Converter," *Journal of Robotics and Control (JRC)*, vol. 5, no. 1, pp. 160-172, 2024.

[7] O. Diouri, A. Gaga, S. Senhaji, and M. O. Jamil, "Design and PIL test of high-performance MPPT controller based on P&O-backstepping applied to DC-DC converter," *Journal of Robotics and Control (JRC)*, vol. 3, no. 4, pp. 431-438, 2022.

[8] A. Mansouri, R. G-. Ghoachani, M. Phattanasak, and S. Pierfederici, "Nonlinear cascaded control for a dc-dc boost converter," *Journal of Robotics and Control (JRC)*, vol. 4, no. 4, pp. 521-536, 2023.

[9] A. A. Mutlag, M. K. Abd, and S. W. Shneen, "Power Management and Voltage Regulation in DC Microgrid with Solar Panels and Battery Storage System," *Journal of Robotics and Control (JRC)*, vol. 5, no. 2, pp. 397-407, 2024.

[10] M. D. H. Almawlawe, M. Al-badri, and I. H. Alsakini, "A Step-Up Controller Based on Fuzzy Logic Strategy to be Implemented in Photovoltaic Systems," *IOP Conference Series: Materials Science and Engineering*, vol. 1067, no. 1, 2021.

[11] I. H. Alsakini, M. D. Almawlawe, and I. A. Dahham, "Controlling Switched Dc-Dc Converter Using ANFIS in Comparison with PID Controller," *IOP Conference Series: Materials Science and Engineering*, vol. 870, no. 1, 2020.

[12] M. Yessef *et al.*, "Overview of control strategies for wind turbines: ANNC, FLC, SMC, BSC, and PI controllers," *Wind Engineering*, vol. 46, no. 6, pp. 1820-1837, 2022.

[13] Y. Zhou, "[Retracted] A Summary of PID Control Algorithms Based on AI-Enabled Embedded Systems," *Security and Communication Networks*, vol. 2022, no. 1, p. 7156713, 2022.

[14] Y. L. Chuang, M. Herrera, and A. Balal, "Using PV fuzzy tracking algorithm to charge electric vehicles," *International Journal of Robotics and Control Systems*, vol. 2, no. 2, pp. 253-261, 2022.

[15] M. Boutouba, A. El Ougli, S. Miqoi, and B. Tidhaf, "Asymmetric Fuzzy Logic Controlled DC-DC Converter for Solar Energy system," *Renewable Energy and Sustainable Development*, vol. 2, no. 1, pp. 52-59, 2016.

[16] Y. Cheddadi, F. Errahimi, and N. Es-sbai, "Design and verification of photovoltaic MPPT algorithm as an automotive-based embedded software," *Solar Energy*, vol. 171, pp. 414-425, 2018.

[17] P. K. Varanasi, S. N. Rao, and P. Duraiswamy, "Intelligent Control of Double Boost Converter Interfaced with Multilevel Inverter for Electrical Vehicle Applications," *Journal of The Institution of Engineers (India): Series B*, pp. 1-9, 2022.

[18] T. Alamirew, V. Balaji, and N. Gabbeye, "Comparison of PID controller with model predictive controller for milk pasteurization process," *Bulletin of Electrical Engineering and Informatics*, vol. 6, no. 1, pp. 24-35, 2017.

[19] Y. B. Khare and Y. Singh, "PID control of heat exchanger system," *International Journal of Computer Applications*, vol. 8, no. 6, pp. 22-27, 2010.

[20] J. Darvill, A. Tisan, and M. Cirstea, "An ANFIS-PI based boost converter control scheme," *2015 IEEE 13th International Conference on Industrial Informatics (INDIN)*, pp. 632-639, 2015.

[21] D. Maksimovic, A. M. Stankovic, V. J. Thottuvelil, and G. C. Verghese, "Modeling and simulation of power electronic converters," in *Proceedings of the IEEE*, vol. 89, no. 6, pp. 898-912, 2001.

[22] D. H. Shaker, S. W. Shneen, F. N. Abdullah, and G. A. Aziz, "Simulation Model of Single-Phase AC-AC Converter by Using MATLAB," *Journal of Robotics and Control (JRC)*, vol. 3, no. 5, pp. 656-665, 2022.

[23] P. Warrier and P. Shah, "Design of an Optimal Fractional complex order PID controller for the buck converter," *Journal of Robotics and Control (JRC)*, vol. 4, no. 3, pp. 243-262, 2023.

[24] S. W. Shneen, D. H. Shaker, and F. N. Abdullah, "Simulation model of PID for DC-DC converter by using MATLAB," I*nternational Journal of Electrical and Computer Engineering*, vol. 11, no. 5, p. 3791, 2021.

[25] S. Eltief and M. Matin, "Performance Enhancement of Isolated DC-DC Converter based on Wide Band-Gap Technology Applied for Electrical Vehicle applications," *2024 IEEE Green Technologies Conference (GreenTech)*, pp. 126-131, 2024.

[26] A. P. Mohamed, K. R. M. Vijaya, Chandrakala, S. Balamurugan, U. Subramaniam, and D. Almakhles, "Adaptive maximum power extraction technique in fuel-cell integrated with novel DC-DC converter topology for low-power electric vehicle applications," *Engineering Science and Technology, an International Journal*, vol. 54, p. 101723, 2024.

[27] R. Gurunathan and A. K. S. Bhat, "A zero-voltage transition boost converter using a zero-voltage switching auxiliary circuit," in *IEEE Transactions on Power Electronics*, vol. 17, no. 5, pp. 658-668, Sept. 2002.

[28] S. Musumeci, "Special issue "advanced DC-DC power converters and switching converters"," *Energies*, vol. 15, no. 4, p. 1565, 2022.

[29] A. Mikhaylov, "An Overview of the Roles of Inverters and Converters in Microgrids," *International Conference on Collaborative Endeavors for Global Sustainability*, pp. 69-85, 2024.

[30] W-. C. So, C. K. Tse, and Y-. S. Lee, "Development of a fuzzy logic controller for DC/DC converters: design, computer simulation, and experimental evaluation," *IEEE Transactions on Power Electronics*, vol. 11, no. 1, pp. 24-32, Jan. 1996.

[31] G. C. Goodwin, S. F. Graebe, and M. E. Salgado. *Control system design*. vol. 240, Upper Saddle River: Prentice Hall, 2001.

[32] A. L. Shuraiji and S. W. Shneen, "Fuzzy Logic Control and PID Controller for Brushless Permanent Magnetic Direct Current Motor: A Comparative Study," *Journal of Robotics and Control (JRC)*, vol. 3, no. 6, pp. 762-768, 2022.

[33] Z. B. Abdullah, S. W. Shneen, and H. S. Dakheel, "Simulation Model of PID Controller for DC Servo Motor at Variable and Constant Speed by Using MATLAB," *Journal of Robotics and Control (JRC)*, vol. 4, no. 1, pp. 54-59, 2023.

[34] M. Zadehbagheri, A. Ma'arif, R. Ildarabadi, M. Ansarifard, and I. Suwarno, "Design of Multivariate PID Controller for Power Networks Using GEA and PSO," *Journal of Robotics and Control (JRC)*, vol. 4, no. 1, pp. 108-117, 2023.

[35] A. Ma'arif and N. R. Setiawan, "Control of DC motor using integral state feedback and comparison with PID: simulation and Arduino implementation," *Journal of Robotics and Control (JRC)*, vol. 2, no. 5, pp. 456-461, 2021.

[36] K. Deepa, R. Jeyanthi, S. Mohan, and M. Vijaya Kumar, "Fuzzy based flyback converter," *2014 International Conference on Advances in Electrical Engineering (ICAEE)*, pp. 1-4, 2014.

[37] J. W. Webb and R. A. Reis. *Programmable Logic Controllers: Principals And Applications*. Prentice-Hall, Inc, 1994.

[38] T. A. Odhafa, I. A. Abed, and A. A. Obed, "Controlling of Boost Converter by Proportional Integral Controller," *International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies*, vol. 12, no. 4, pp. 1-8, 2021.

[39] H. N. Shabrina, E. A. Setiawan, and C. R. Sabirin, "Designing of new structure PID controller of boost converter for solar photovoltaic stability," *AIP Conference Proceedings*, vol. 1826, no. 1, 2017.

[40] M. D. Pham and H. H. Lee, "Adaptive control of DC-DC converter based on hybrid fuzzy PID controller," in *Intelligent Computing Methodologies: 13th International Conference, ICIC 2017, Liverpool, UK, August 7-10, 2017, Proceedings, Part III 13*, pp. 253-263, 2017.

[41] S. Kart, F. Demir, İ. Kocaarslan, and N. Genc, "Increasing PEM fuel cell performance via fuzzy-logic controlled cascaded DC-DC boost converter." *International Journal of Hydrogen Energy*, vol. 54, pp. 84-95, 2024.

[42] R. Yoganathan, J. Venkatesan, T. V. Narmadha, and I. W. Christopher, "Performance Comparison of a DC-DC Boost Converter With Conventional and Non-linear SMC Controller in Dual Loop Structure," *Electric Power Components and Systems*, pp. 1-16, 2024.

[43] M. K. Al-Nussairi, R. Bayindir, and E. Hossain, "Fuzzy logic controller for Dc-Dc buck converter with constant power load," *2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA)*, pp. 1175-1179, 2017.

[44] G. Feng, "A Survey on Analysis and Design of Model-Based Fuzzy Control Systems," in *IEEE Transactions on Fuzzy Systems*, vol. 14, no. 5, pp. 676-697, 2006.

[45] K. Swathy, S. Jantre, Y. Jadhav, S. M. Labde, and P. Kadam, "Design and Hardware Implementation of Closed Loop Buck Converter Using Fuzzy Logic Controller," *2018 Second International Conference on Electronics, Communication and Aerospace Technology (ICECA)*, pp. 175-180, 2018.

[46] P. Mattavelli, L. Rossetto, G. Spiazzi, and P. Tenti, "General-purpose fuzzy controller for DC-DC converters," in *IEEE Transactions on Power Electronics*, vol. 12, no. 1, pp. 79-86, 1997.

[47] K. Bendaoud *et al*., "Fuzzy logic controller (FLC): Application to control DC-DC buck converter," *2017 International Conference on Engineering & MIS (ICEMIS)*, pp. 1-5, 2017.

[48] H. Y. Kanaan, K. Al-Haddad, and S. Rahmani, "Switch-mode power converters for harmonics mitigation in power systems — Technology progress," *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, pp. 6328-6337, 2012.

[49] J. I. Corcău and P. Constantinache, "An adaptive current mode fuzzy logic controller for dc-to-dc converters," in *6th International Conference Electromechanical and power systems, Octomber*, pp. 4-6, 2007.

[50] S. -C. Tan, Y. M. Lai, C. K. Tse, L. Martinez-Salamero, and C. -K. Wu, "A Fast-Response Sliding-Mode Controller for Boost-Type Converters With a Wide Range of Operating Conditions," in *IEEE Transactions on Industrial Electronics*, vol. 54, no. 6, pp. 3276-3286, 2007.

[51] M. Salimi, J. Soltani, A. Zakipour, and V. Hajbani, "Sliding mode control of the DC-DC flyback converter with zero steady-state error," *4th Annual International Power Electronics, Drive Systems and Technologies Conference*, pp. 158-163, 2013.

[52] V. R. Chandranadhan and G. Renjini, "Average current mode control of improved bridgeless flyback rectifier with bidirectional switch," *2015 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2015]*, pp. 1-6, 2015.

[53] H. K. Iqbal and G. Abbas, "Design and analysis of SMC for second order DC-DC flyback converter," *17th IEEE International Multi Topic Conference 2014*, pp. 533-538, 2014.

[54] Y. Oğuz, "Fuzzy PI Control with Parallel Fuzzy PD Control for Automatic Generation Control of a Two-Area Power System," *Gazi University Journal of Science*, vol. 24, no. 4, pp. 805-816, 2011.

[55] M. A. Shahid *et al*., "Artificial intelligence-based controller for DC-DC flyback converter," *Applied Sciences*, vol. 9, no. 23, p. 5108, 2019.

[56] V. S. C. Raviraj and P. C. Sen, "Comparative study of proportional-integral, sliding mode, and fuzzy logic controllers for power converters," in *IEEE Transactions on Industry Applications*, vol. 33, no. 2, pp. 518-524, 1997.

[57] K. Viswanathan, D. Srinivasan and R. Oruganti, "A universal fuzzy controller for a non-linear power electronic converter," *2002 IEEE World Congress on Computational Intelligence. 2002 IEEE International Conference on Fuzzy Systems. FUZZ-IEEE'02. Proceedings (Cat. No.02CH37291)*, vol. 1, pp. 46-51, 2002.

[58] L. Guo, J. Y. Hung, and R. M. Nelms, "PID controller modifications to improve steady-state performance of digital controllers for buck and boost converters," *APEC. Seventeenth Annual IEEE Applied Power Electronics Conference and Exposition (Cat. No.02CH37335)*, vol. 1, pp. 381-388, 2002.