Performance Analysis of Single Ended Primary Inductor Converter (SEPIC) with Adaptive and Static Proportional Integral (PI) Control Variants

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***Abstract*- The Single-Ended Primary-Inductor Converter (SEPIC) is one type of DC-DC converter that has been widely utilized. In certain conditions, this DC-DC converter may exhibit inappropriate behavior regarding stability and reliability, thus requiring a controller to ensure that the voltage, current, or power values they produce align with the desired one. In this research, we examine and simulate the performance of the SEPIC converter using a Proportional Integral (PI) controller and compare the use of tuning methods: Ziegler-Nichols (ZN), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Fuzzy Logic in regulating the PI control parameters. Simulations will be performed through MATLAB. From the simulation results, it is observed that the PI tuning methods using GA, PSO, and Fuzzy Logic are superior to the ZN method, and with the advantage of adaptive process for PI tuning, the fuzzy logic method outperforms in terms of convenience to the other three methods.**

Keywords: ***SEPIC (Single-Ended Primary-Inductor Converter), PI (Proportional Integral), GA (Genetic Algorithm), PSO (Particle Swarm Optimization), Fuzzy Logic***

I. Introduction

In the modern electronics world, DC-DC converters have become a vital component in various applications spanning consumer electronics, automotive, industrial, and renewable energy power generation. DC-DC converters are easily found in portable electronic devices like cell phones and laptops, where their power is supplied by batteries. They are also used in electric vehicles to convert voltage from the car battery to the voltage level needed by the vehicle's electronic systems. In industrial applications, DC-DC converters serve as power supply components for various types of machinery and equipment. Meanwhile, in renewable energy power generation, such as solar or wind power plants, DC-DC converters maximize and stabilize electrical energy production, making them suitable for direct use or storage [1].

In the utilization of DC-DC converters, unpredictable and complex conditions can occur. Under such circumstances, DC-DC converters may exhibit behavior that is not consistent with stability and reliability, necessitating control to ensure that the voltage, current, or power values they produce align with the desired specifications [2]. With this rationale, we will test and simulate the performance of a specific type of DC-DC converter, namely the Single-Ended Primary-Inductor Converter (SEPIC), using a Proportional Integral (PI) controller. Additionally, we will compare the use of four tuning methods Ziegler-Nichols (ZN), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Fuzzy Logic as parameterization for the PI controller.

II. Methodology

There are several stages in this research, namely literature review, system modeling, simulation testing, and analysis. Some of them are as follows.

A. Related Research

In this research, the literature review is the initial stage, involving the examination of previous studies related to this research. The following is an elaboration of the results of several literature studies.

M. M. Nishat conducted a study on the output voltage stability of the SEPIC converter with a PI controller optimized using the GA method. The research revealed that using an Integral of Absolute Error (IAE) objective function resulted in PID controller parameters that could provide sufficiently stable output voltage from the SEPIC converter [3].

F. D. Wihartiko conducted research aimed at comparing the performance of GA and PSO in finding the most optimal travel path. It was found that the PSO algorithm yielded significantly better results in terms of accuracy and complexity [4].

J. John conducted a study to compare PSO and GA in optimizing PID controller parameters. The controlled systems were a DC motor and a hard disk drive controller. The results showed that both methods outperformed the Ziegler-Nichols tuning method [5].

B. *Single-Ended Primary-Inductor Converter (SEPIC)*

SEPIC converter is one of the most widely used types of choppers as it can both step up and step down the voltage. The advantage of SEPIC over conventional boost/buck converters is its ability to handle reversed output voltage polarity from the boost/buck converter [6]. The topology of SEPIC is shown in Figure 1.

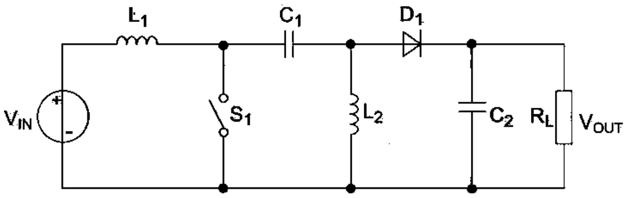


Figure 1. Topology of SEPIC [7]

The SEPIC works by utilizing the Continuous Conduction Mode (CCM), in which the current flowing through the conductor never reaches zero [8]. The SEPIC works in two states: when the switch is closed and when it is open. By deriving the formulas from the two states SEPIC in CCM and assuming the diode functions as an ideal switch, the relationship between input and output voltages is expressed by equation (1) where D represents the *duty cycle.* The equation used to determine the inductor and capacitor parameters can be seen in equations (2), (3), and (4).

$$V_{OUT} = \frac{D}{1-D} \times V_{IN} \quad (1)$$

$$L_1 = L_2 \geq \frac{V_{IN}\, D}{\Delta i_{L1,L2}\, f} \quad (2)$$

$$C_1 = \frac{D}{R\left(\frac{\Delta V_{C1}}{V_{OUT}}\right) f} \quad (3)$$

$$C_2 = \frac{D_{max}}{R\left(\frac{\Delta V_{OUT}}{V_{OUT}}\right) f} \quad (4)$$

In the equation above, the *f* value represents the frequency magnitude that will be used in the *Pulse Width Modulation* (PWM) signal generator. Dmax is the maximum *duty cycle* of PWM. For the value of $\Delta i_{L1,L2}$, ΔV_{C1} , and ΔV_{OUT} calculated based on $\Delta V_{IL1,IL2} = ripple \times I_{in}$, $\Delta V_{C1} = ripple \times V_{in}$, $\Delta V_{C2} = ripple \times V_{out}$.

C. *Proportional Integral (PI) Controller*

The PI controller consists of two actions, namely proportional (Kp) and integral (Ki) [9]. The working principle of PI control involves using the error value of the difference between the target or *setpoint* value and the output value of *the plant* and then calculated using the formula shown in equation [10].

$$u(t) = K_p\, e(t) + K_i \int_o^t e(t) \quad (5)$$

Which $u(t)$ is the output value of the PI controller and $e(t)$ is the error value that serves as input to the PI controller. K_p dan K_i is the constant or gains of proportional and integral action, respectively.

D. *System Modeling*

1. *Block Diagram Design*

The block diagram of the simulation process in general is shown in Figure 2. For the four tuning methods process is shown in Figure 2 (b).

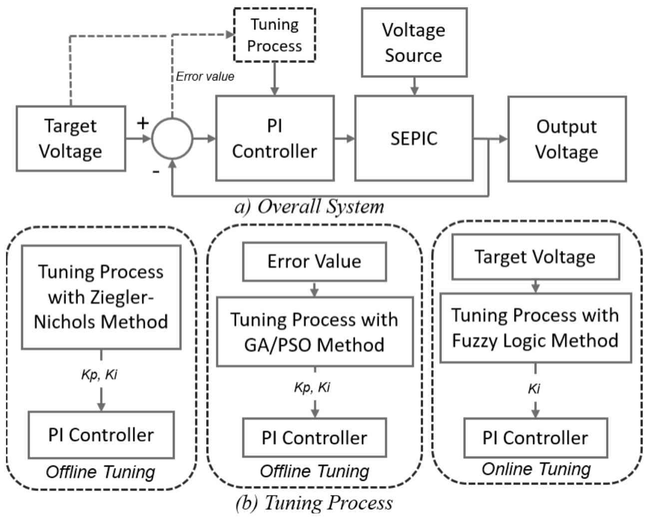


Figure 2. Simulation Block Diagram

2. *SEPIC with PI Controller Model Design*

The design of the SEPIC model with the PI controller is done through MATLAB. The results of determining the parameters are shown in Table 1.

Table 1. SEPIC Simulation Parameters

Component Parameters	Value
Input Voltage (V_{in})	8V – 48V
Output Voltage (V_{out})	14.2V
Frequency	50k Hz
Voltage Ripple	0.01V
Inductor (L_1)	3.8 mH
Inductor (L_2)	3.8 mH
Capasitor (C_1)	231.5 μF
Capasitor (C_2)	4.6 mF
Resistor (R_L)	1.44 Ω
Max Duty Cycle	65%

In order to work, SEPIC that uses MOSFETs as its switch requires a PWM generator. The SEPIC schematic of the design is shown in Figure 3.

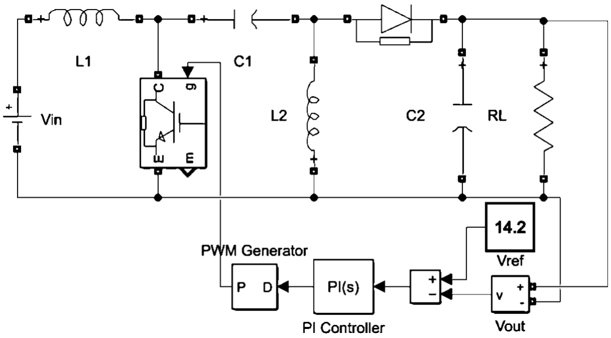


Figure 3. SEPIC with PI Controller Schematic

3. *ZN Tuning Method Design*

In the design of PID and PI controller using the Ziegler-Nichols (ZN) tuning method, the process begins with finding the ultimate gain value, Ku. The value of Kp is gradually increased until obtaining the best oscillation with Ki and Kd is inactive. Meanwhile, the ultimate period, Tu, is determined by observing at the period of oscillation with Kp chosen as Ku before. The design outcomes are presented in Table 2.

Table 2. ZN Tuning Method Parameters

Parameters	Value	Description
Ku	0.02	The selected Kp value that has stable oscillation
Tu	0.007	The period of the stable oscillation
PID - Kp	0.012	Using formula: $Kp = 0.6\ Ku$
PID - Ki	3.428571	Using formula: $Ti = 0.5\ Tu$, then $Ki = Kp/Ti$
PID - Kd	0.0000105	Using formula: $Ti = 0.125\ Tu$, then $Kd = Kp\ Td$
PI - Kp	0.012	Using formula: $Kp = 0.45\ Ku$
PI - Ki	2.065404	Using formula $Ti = 0.83\ Tu$, then $Ki = Kp/Ti$

4. *GA Tuning Method Design*

In this section, the results of the tuning process design using the GA method will be shown which can generally be seen in Figure 4. The parameters used in this method can be seen in Table 3.

Table 3. GA Tuning Method Parameters

Parameters	Value	Desc
Number of Population	100	Number of random Kp and Ki that will be simulated
Number of Generation	8	Number of iteration
Individual	[Kp Ki]	The output (parameters) of this method
Range	[3 3]	Maximum limit of the parameters
Mutation Rate	10%	Cutoff value for the gene that will be mutated
Objective Function	ISE	Integral of the squared error value as a reference for the fitness value
Selection Method	Tournament Selection	Comparing the fitness value of two individuals taken at random
Crossover Type	Single Cut Point	Number of gene exchange intersection points in a single crossover process

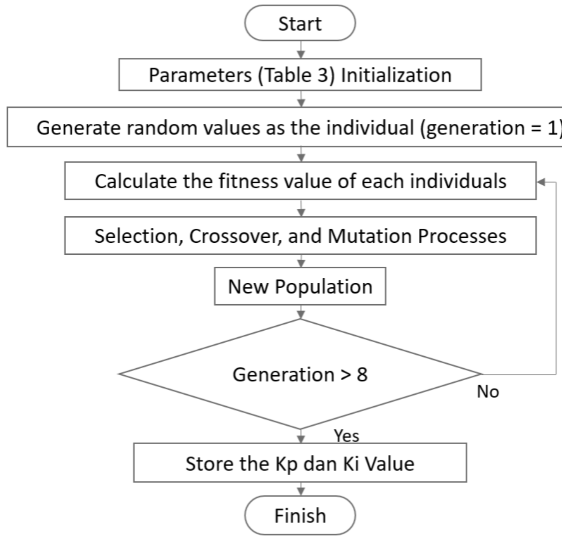


Figure 4. GA Tuning Method Flowchart

5. *PSO Tuning Method Design*

The process of modeling the PSO algorithm is carried out in several steps. The *tuning* process using the PSO method can generally be seen in Figure 5. The parameters used in this method can be seen in Table 4.

Table 4. PSO Tuning Method Parameters

Parameters	Value	Desc
Number of Particle	100	Number of random Kp and Ki that will be simulated
Number of Iteration	8	Number of search iteration
Particle	[Kp Ki]	The output (parameters) of this method
Range	[3 3]	Maximum limit of the parameters
Objective Function	ISE	Integral of the squared error value as a reference for the fitness value
w	$\frac{2}{\varphi - 2 + \sqrt{\varphi^2 - 4\varphi}}$	When $\varphi = \varphi_1 + \varphi_2 > 4$ (Clerc, 2006)
c_1	$c_1 = \chi\,\varphi_1$	Cognitive learning factors as a coefficient that affect pbest
c_2	$c_2 = \chi\,\varphi_2$	Social learning factors as a coefficient that affect gbest

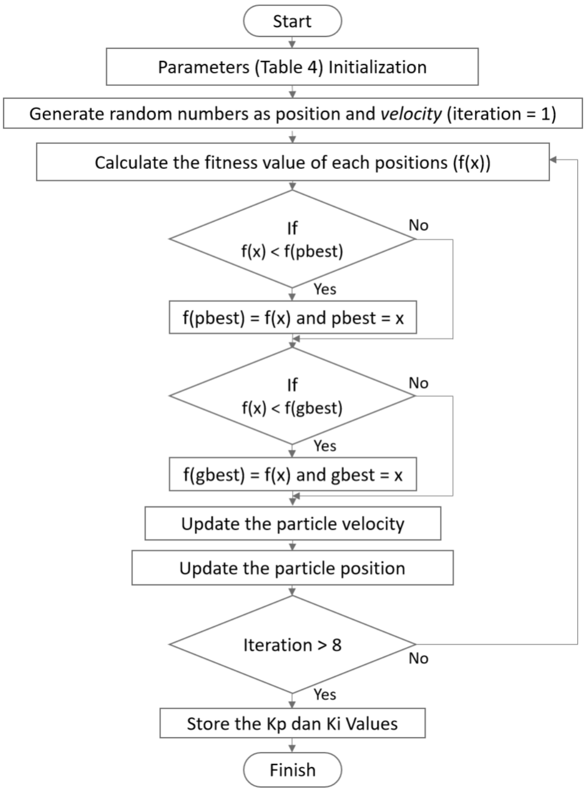


Figure 5. PSO Tuning Method Flowchart

6. *Fuzzy Logic Method Design*

The *Fuzzy Logic Controller* (FLC) modeling process is carried out in several steps using the MATLAB *Toolbox* with output in the form of Ki values. The value of Kp will be calculated by a simple equation without FLC. The *tuning* process using this method can generally be seen in Figure 6. The *rule base inference* in this method can be seen in Table 5.

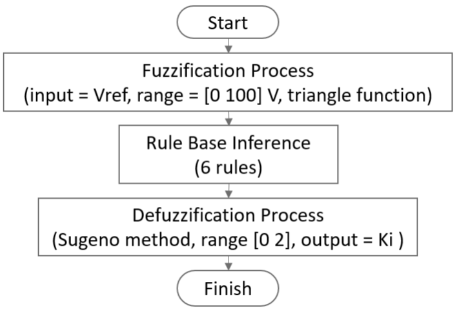


Figure 6. Fuzzy Tuning Method Flowchart

Tabel 5. Rule Base Inference of Fuzzy Tuning Method

No	*Rules Base Inference*
1	If Vref is 10V then output is Ki1
2	If Vref is 20V then output is Ki2
3	If Vref is 40V then output is Ki3
4	If Vref is 60V then output is Ki4
5	If Vref is 80V then output is Ki5
6	If Vref is 100V then output is Ki6

III. RESULT AND DISCUSSION

A. *Simulation Result of SEPIC without a Controller*

The first simulation is SEPIC without a controller in MATLAB. The input voltage value is 48 V and the *duty cycle* is 22.83%, and the parameters of each component according to Table 1. The output voltage signal results are shown in Figure 7.

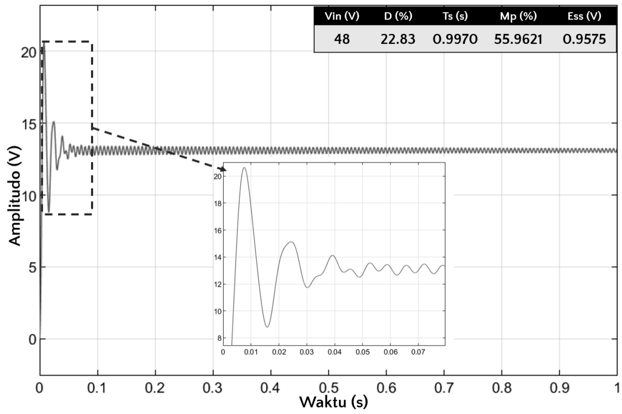


Figure 7. Output Signal of SEPIC without a Controller

From the table in the figure above, there is Ts which represents settling time (the time taken by the system to reach and maintain a steady-state level). There is also Mp which represents maximum overshoot (a value that expresses the ratio between the maximum value of response (overshoot) compared to the steady state value). The Ess represents a steady-state error (the absolute value of the difference between the output voltage and the reference voltage in a steady state).

Figure 7 shows the output signal of SEPIC without a controller that the time needed to reach a steady state (Ts) is almost 1 second with a fairly large overshoot that has a value of 55.96%. Based on equation (1), the expected output voltage value of SEPIC should be 14.2 V, but in the figure the output voltage is only 13.2425 V. This sufficiently demonstrates the need for a controller.

B. *Simulation Result of SEPIC with PID and PI Controller*

This simulation aims to compare PID and PI controllers with the ZN tuning method performed through MATLAB. The simulation results are shown in Figure 8.

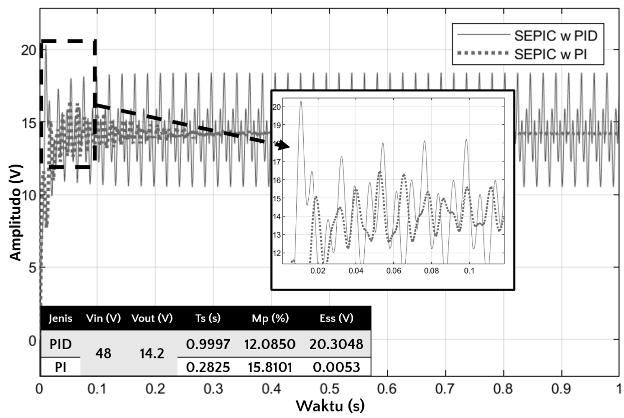
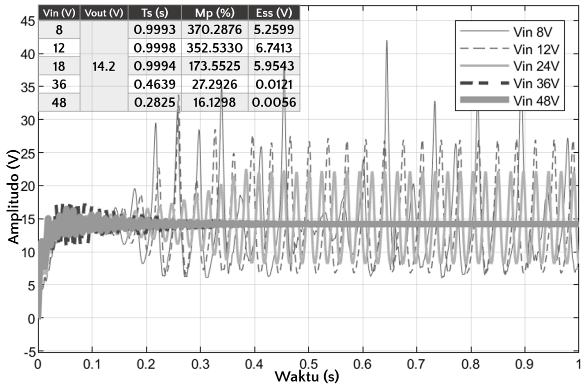


Figure 8. Output Signal of SEPIC with PID and PI Controller

The figure above shows that the output signal with the PID and PI controllers using the ZN tuning method in steady-state signal graph both show much different ripple and stability. This shows that the PID controller is not suitable for controlling SEPIC, while the PI controller is good enough to control the SEPIC output signal.

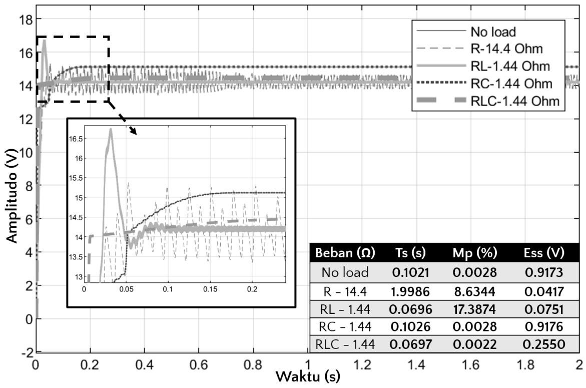
C. Simulation Result of SEPIC with PI-ZN Controller

Simulations using this method are conducted twice, both with varying Vin values and different load values. The simulation results are shown in Figure 9.



Vin (V)	Vout (V)	Ts (s)	Mp (%)	Ess (V)
8	14.2	0.9993	370.2876	5.2599
12		0.9998	352.5330	6.7413
18		0.9994	173.5525	5.9543
36		0.4639	27.2926	0.0121
48		0.2825	16.1298	0.0056

(a) Voltage Target is 14.2V with Different Vin



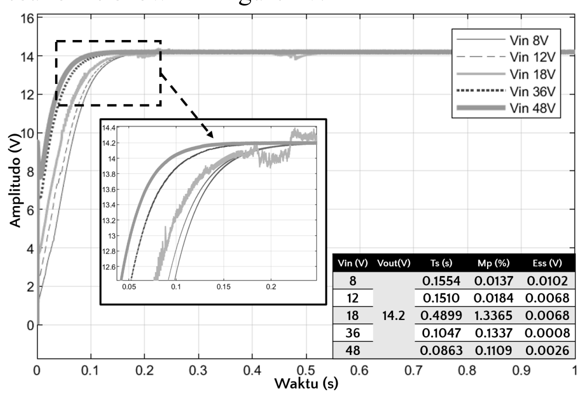
Beban (Ω)	Ts (s)	Mp (%)	Ess (V)
No load	0.1021	0.0028	0.9173
R - 14.4	1.9986	8.6344	0.0417
RL - 1.44	0.0696	17.3874	0.0751
RC - 1.44	0.1026	0.0028	0.9176
RLC - 1.44	0.0697	0.0022	0.2550

(b) Voltage Target is 14.2V with Different Load Values
Figure 9. Output Signal of SEPIC with PI-ZN Controller

From the table in the figure above, the average of Ts, Mp, and Ess at different input voltages respectively are 0.7490 s, 187.96 %, and 3.5947 V. Meanwhile, the average of Ts, Mp, and Ess at the change in load values respectively are 0.1147 s, 3.5426 %, and 0.2719 V.

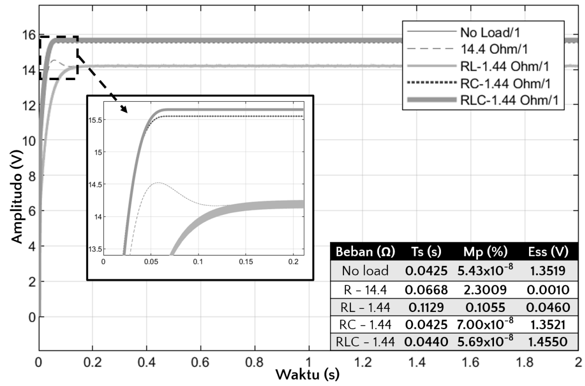
D. Simulation Result of SEPIC with PI-GA Controller

The parameters of the SEPIC and the GA algorithm in the simulation are based on the designThe simulation results are shown in Figure 10.



Vin (V)	Vout(V)	Ts (s)	Mp (%)	Ess (V)
8	14.2	0.1554	0.0137	0.0102
12		0.1510	0.0184	0.0068
18		0.4899	1.3365	0.0068
36		0.1047	0.1337	0.0008
48		0.0863	0.1109	0.0026

(a) Voltage Target is 14.2V with Different Vin



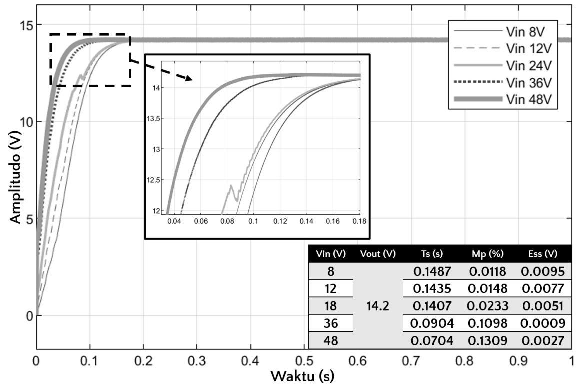
Beban (Ω)	Ts (s)	Mp (%)	Ess (V)
No load	0.0425	5.43×10^{-8}	1.3519
R - 14.4	0.0668	2.3009	0.0010
RL - 1.44	0.1129	0.1055	0.0460
RC - 1.44	0.0425	7.00×10^{-8}	1.3521
RLC - 1.44	0.0440	5.69×10^{-8}	1.4550

(b) Voltage Target is 14.2V with Different Load Values
Figure 10. Output Signal of SEPIC with PI-GA Controller

From the table in the Figure 10, the average of Ts, Mp, and Ess at different input voltages respectively are 0.1975s, 0.32 %, dan 0.0054 V. Meanwhile, the average of Ts, Mp, and Ess at the change in load values respectively are 0.0617 s, 0.48%, dan 0.8412 V.

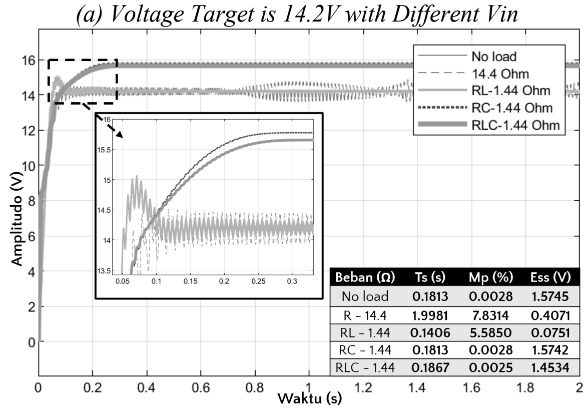
E. Simulation Result of SEPIC with PI-PSO Controller

The parameters of the SEPIC and the PSO algorithm in the simulation are based on the design. The simulation results are shown in Figure 10.



Vin (V)	Vout (V)	Ts (s)	Mp (%)	Ess (V)
8	14.2	0.1487	0.0118	0.0095
12		0.1435	0.0148	0.0077
18		0.1407	0.0233	0.0051
36		0.0904	0.1098	0.0009
48		0.0704	0.1309	0.0027

(a) Voltage Target is 14.2V with Different Vin



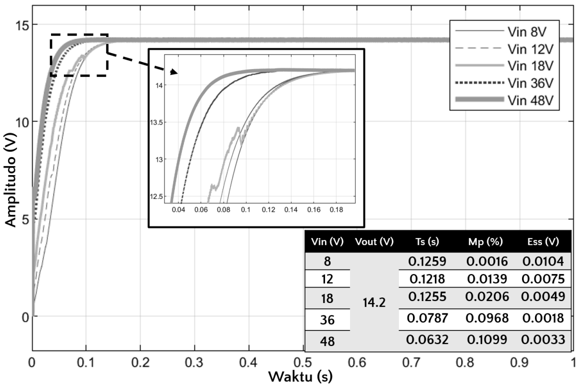
Beban (Ω)	Ts (s)	Mp (%)	Ess (V)
No load	0.1813	0.0028	1.5745
R - 14.4	1.9981	7.8314	0.4071
RL - 1.44	0.1406	5.5850	0.0751
RC - 1.44	0.1813	0.0028	1.5742
RLC - 1.44	0.1867	0.0025	1.4534

(b) Voltage Target is 14.2V with Different Load Values
Figure 11. Output Signal of SEPIC with PI-PSO Controller

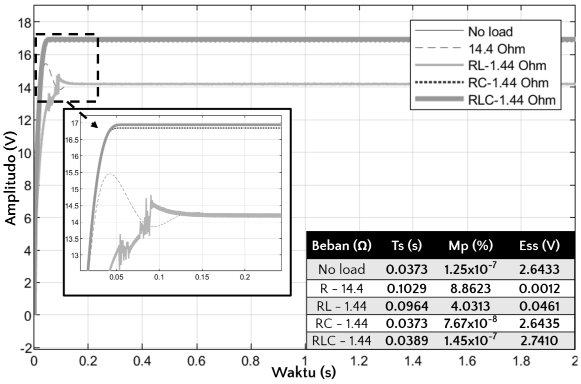
From the table in the Figure 11, the average of Ts, Mp, and Ess at different input voltages respectively are 0.1187 s, 0.06 %, dan 0.0052 V. Meanwhile, the average of Ts, Mp, and Ess at the change in load values respectively are 0.5376 s, 2.68 %, dan 1.0168 V.

F. Simultion Result of SEPIC with PI-Fuzzy Controller

The parameters of the SEPIC and the Fuzzy Logic method in the simulation are based on the design. The simulation results are shown in Figure 12.



(a) Voltage Target is 14.2V with Different Vin



(b) Voltage Target is 14.2V with Different Load Values

Figure 12. Output Signal of SEPIC with PI-Fuzzy Controller

From the table in the Figure 12, the average of Ts, Mp, and Ess at different input voltages respectively are 0.103 s, 0.05 %, dan 0.0056 V. Meanwhile, the average of Ts, Mp, and Ess at the change in load values respectively are 0.626 s, 2.58 %, dan 1.6150 V.

G. Comparison Analysis of SEPIC Performance with PI-ZN, PI-GA, PI-PSO, and PI-Fuzzy Controller

To more clearly observe the difference in output signals from the four methods, a direct comparison of graph between the four methods needs to be presented. The graph can be seen in Figure 13 and Figure 14.

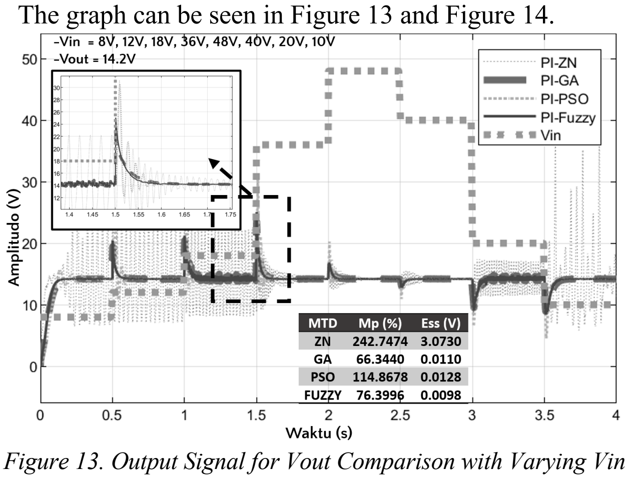


Figure 13. Output Signal for Vout Comparison with Varying Vin Over Time

Figure 13 above depicts the varying input signal within the range of 8 V to 48 V as a green line with an output target of 14.2 V. From the graph, it can be observed that the varying Vin values and based on the maximum overshoot measurement criterion, the best performance of SEPIC is shown by the PI-GA controller of 66.34%. Subsequently, in the steady-state error measurement criterion, the best performance is shown by PI-Fuzzy with the smallest value of 0.0098 V. The average of the three simulation processes, involving different Vin values, different load values, and varying Vin values over time, is shown in Figure 14.

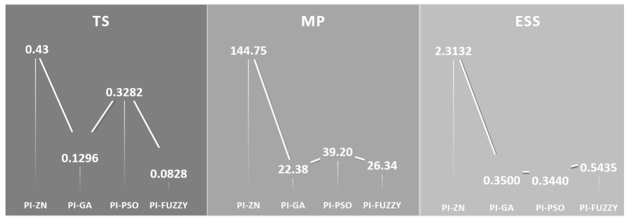


Figure 14. Comparison of the Four Methods on the Average Measurement Criteria

Of the three measurement criteria in the simulation results, SEPIC performance will be considered better if the numbers shown in the Ts, Mp, and Ess columns become smaller. By comparing the values of the measurement criteria shown in the table of each simulation which is then summarized into the graph of Figure 14, it is found that in the settling time measurement criterion, performance is best shown by the PI-Fuzzy controller with an average time of only 0.0828 s. Meanwhile, in the *maximum overshoot* measurement criterion, the best performance is shown by PI-GA with the smallest average value of only 22.38%. Lastly, in the *steady-state error* measurement criteria, performance is best shown by PI-PSO with an average of only 0.3440 so that its average Vout is 14.5440 V or 13.856 V where the target is 14.2 V.

VI. Conclusion

From various stages of the process and based on the simulation results in this study, it is known that the PI-GA, PI-PSO, and PI-Fuzzy controllers provide better SEPIC performance than PI-ZN controller. In terms of the settling time, the best performance is shown by the PI-Fuzzy controller with an average length of time of only 0.0828 s. Meanwhile, in the maximum overshoot measurement criterion, the best performance is shown by PI-GA with the smallest average value of only 22.38%. And in the steady-state error measurement criterion, the best performance is shown by PI-PSO with an average of only 0.3440 V. In short, the PI tuning method using GA, PSO, or Fuzzy Logic is better than the ZN method and with the advantages of PI-Fuzzy tuning which is adaptive or not due to manual Kp and Ki settings, the fuzzy logic method has advantages in terms of convenience over the other three methods.

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