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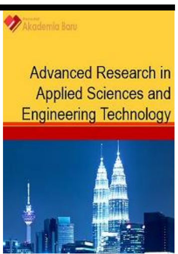

Analysis of SEPIC-Boost Converter Using Several PID Feedback Tuning Methods for Renewable Energy Applications

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ABSTRACT

Design of a SEPIC-Boost converter using PID feedback control is presented in this paper. The proposed design combines the key characteristics in SEPIC and Boost topology to increase the static gain in its operation and maintains its simple single switching technique. Several PID tuning methods are employed to investigate its effect on the converter design. Based on the analysis, modified Zeigler-Nichols tuning method has shown the best dynamic characteristic for the output. The generated outputs are 48V, 2A with ripple at 289.3mV indicating an extremely well-regulated output suitable for a lot of renewable energy applications. Fast settling time at 30.2ms without any overshoot and steady-state error is also achieved using this proposed design tuned with modified Ziegler-Nichols tuning method.

Keywords:
SEPIC-Boost converter; PID feedback;
Ziegler-Nichols; renewable energy

1. Introduction

With rapid advancement in photovoltaic (PV) technology, many new designs and applications have been developed which able to convert solar energy to electrical energy as its main source. The efficiency of the PV module has been greatly improved with efficiency as high as 29.52% has been reported in its production [1,2]. Nowadays, using renewable energy (RE) to power modern designs and applications is showing positive trend in its acceptance. This technology provides clean, cheap, safe and sustainable solution over non-renewable sources such as petroleum, natural gas and coal. Furthermore, this eco-friendly technology also is vital to combat the global warming issue and to mitigate the shortage supply of non-renewable sources in the future. Many renewable energy applications are categorized in low and medium voltage ranges which is between 12V to 150V. Selection of input supply for RE applications within this range is popular because it leads to low complexity, low maintenance and cost-efficient design.

Having to step up the input voltage level, many articles related with step up conversion have been studied to find the best approach in designing a reliable DC-DC converter for renewable energy applications [3-11]. Generally, the DC-DC converter can be classified into four major families which are isolated/non-isolated, unidirectional/bidirectional, voltage-fed/current-fed and hard switched/soft switched. Isolated topology usually used in medium to high wattage applications

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where output level can be easily stepped-up using the transformer. Besides, it also provides electrical isolation between input and output particularly when high current is introduced in the topology. Non-isolated topology is used in low wattage applications where all elements are tied with similar ground. This topology has low complexity and cheaper than isolated topology, but it did not provide isolation between input and output during fault. Unidirectional converter is used in many applications where only single direction power flow from the input supply to the absorbing elements is implemented. In this topology, single-quadrant switches are utilized along with the diodes to allow only one way flow of the current. To realise the bidirectional power flow, the single-quadrant switches can be replaced by two-quadrant types which enable current to flow in all directions. Typically, bidirectional topology is used in storage, regenerative and vehicular system when the fluctuation in output level is expected. Voltage-fed topology is used for applications with step down characteristic whereas current-fed is used for applications with step up characteristic. Voltage-fed topology is known by having capacitive input capacitor at its input stage, while current-fed topology can be easily recognized by the input inductor at its input stage. Soft-switching topology is mandatory for high efficiency design with low losses. However, this topology has higher complexity and production cost compared to the traditional hard switching. Typically, hard switching topology has simple complexity and widely used in low voltage applications. From these literatures, it is found out that two distinguish topologies that are economical for RE applications are SEPIC and Boost topology. Some advantages of SEPIC are, it able to step up or step down its output without polarity reversal, has good static gain and highly efficient topology. Traditional Boost topology able to step up using minimal components and very popular for low to medium range applications. Some literatures related with SEPIC, SEPIC-Boost and modified SEPIC were studied to fulfill the criteria mentioned earlier. In [12], a non-isolated, high static gain SEPIC-Boost converter is designed which employed voltage multiplier at its output stage. This multiplication technique has proven to increase the output voltage level and efficiency at 96.3%. Reported in [13], high static gain converter based on SEPIC is designed using magnetic and non-magnetic coupling topology. The design presented a high static gain with reduced switch voltage and efficiency up to 92.2%. A modified high step up non-isolated converter based on SEPIC is also presented in [14]. The design achieved reduction in input current ripple and low switching voltage stress with efficiency up to 92.5%. Active clamp circuitry is applied in [15], resulted in low voltage stresses at the switches and diodes. Because of its soft switching technique, the efficiency of the design has shown staggering 93.83% and very suitable for high voltage RE applications. In [16], double Boost-SEPIC converter is presented with capability to use single switching and without extreme duty cycle for high voltage application.

Regulating the output waveforms is crucial when designing a converter especially when it needs to handle variations in load or sudden change in input state. The output level needs to be always in stable state and the regulation control must be performed automatically. Closed-loop feedback control is one of the widely schemes used for automatic regulation in DC-DC converter design. Many control techniques have been investigated to compare the approach for closed-loop control [17-20]. Some of the popular techniques are current mode control, voltage mode control, PID (proportional, integral, and derivative) control, sliding mode control (SMC), model predictive control (MPC), state space modelling (SSM), fuzzy logic control (FLC) and neural network (NN). Generally, all these control techniques can be categorised into analogue, digital and intelligent control. Amongst these control techniques, PID control is widely employed in a lot of applications due to its rich features such as simple implementation and complexity, faster response time, easy integration with other control methods and suitable for linear control. Due to these advantages, introducing PID control in a DC-DC converter design is a good choice for design's simplicity and cost benefit.

Based on the consideration to build a design that has these characteristics i.e., non-isolated, step up, good static gain, automatic regulation and non-inverting output, design of SEPIC-Boost converter using several PID (proportional, integral, and derivative) feedback controls is proposed in this paper. This proposed design is based on combination of SEPIC and Boost topology where the key characteristics of both topologies is combined to produce a highly reliable design. Using solar energy as the main source, PV module is used as the input supply. The input voltage will be stepped up to a higher level of output using the proposed SEPIC-Boost converter. High switching frequency is utilized in the proposed design to increase the design's efficiency and to lower the inductance value of the choke. PID feedback control is used to stabilise the generated output at the desired level during its operation.

2. Design of the Proposed SEPIC-Boost Converter

2.1 DC-DC Converter Design

The block diagram of the proposed SEPIC-Boost converter using PID feedback control is depicted in Fig. 1. The diagram shows the complete system where the input supply is powered by the solar source. Next, it will be stepped-up using the proposed converter and finally, the output will be used by the needed RE applications. One of the most important criteria when designing DC-DC converter is the feedback control. Feedback control is essential to regulate the output voltage as close as to the desired system's requirement. In this design, the input supply is powered by the solar source using 12V PV module. Then, it will be stepped up to 48V by the proposed SEPIC-Boost converter. The generated output voltage will be compared to the 48V reference voltage for stability and regulation purpose. By using error amplifier, the error signal will be fed to the PID controller for regulation correction. The corrected signal will be fed to the PWM generator to produce reliable and steady pulse waveform to be fed to the gate driver for automatic control of SEPIC-Boost converter's operation.

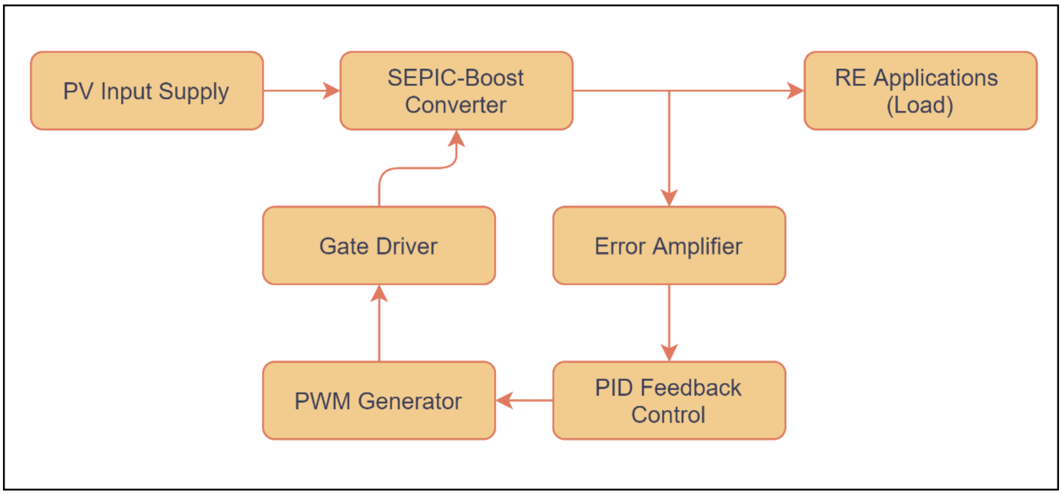

Fig.1. Block diagram of the proposed design

Figure 2 shows the complete schematic of the proposed design where combination of SEPIC and Boost topologies can be clearly seen. Two identical chokes, L_i and L_s are used to perform the step-up conversion. M_1 is the MOSFET switch which the PWM signal is being fed from the PID controller. D_s and D_o are the two ultra-fast Schottky diodes to perform the unidirectional rectification. C_s is the

SEPIC buffering capacitor while C_{o1} and C_{o2} are the output capacitors for the Boost and SEPIC converter, respectively. PID feedback control is used to perform the feedback control and will be explained in detail in section 2.2.

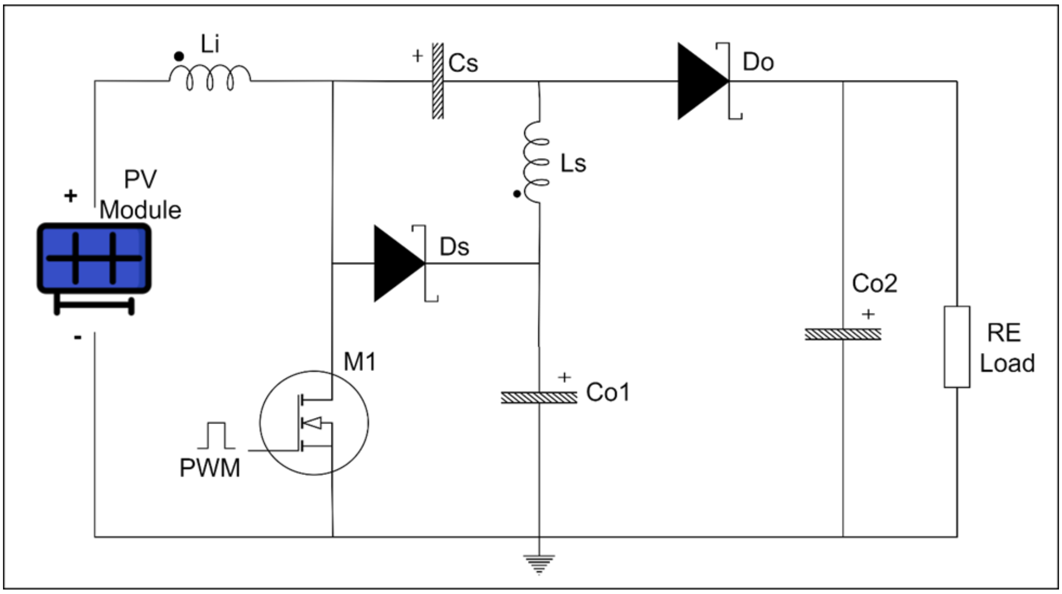

Fig. 2. Schematic diagram of the proposed SEPIC-Boost converter

Static gain, M is one of the important parameters in determining the versatility and effectiveness of a converter. Static gain is the ratio of the output and input voltage. It is also an indicator for the output behaviour when changes occurred in input during its steady-state operation. Along with static gain, other important considerations are low switches stress, high efficiency, low ripple and cost effective. These key considerations can be achieved using this proposed SEPIC-Boost converter using PID feedback control.

The proposed converter is based on the combination of SEPIC and Boost topologies. Hence, there are three static gains that can be extracted using Eqs. (1) - (3).

The static gain of the proposed SEPIC-Boost converter at RE Load is:

$$\text{Static gain SB, } M_{SB} = \frac{V_{o2}}{V_i} = \frac{1+D}{1-D} \quad (1)$$

The static gain of the Boost converter at capacitor C_{o1} is:

$$\text{Static gain Boost, } M_B = \frac{V_{o1}}{V_i} = \frac{1}{1-D} \quad (2)$$

The static gain of the SEPIC converter at capacitor C_s is:

$$\text{Static gain SEPIC, } M_S = \frac{V_{cs}}{V_i} = \frac{D}{1-D} \quad (3)$$

The duty cycle of SEPIC-Boost converter is:

$$\text{Duty cycle, } D = \frac{V_{o2} - V_i}{V_{o2} + V_i} \quad (4)$$

Where V_i is the input voltage, D is the duty cycle, V_{o2} is the voltage across RE Load, V_{o1} is the voltage across capacitor C_{o1} and V_{cs} is the voltage across capacitor C_s.

The two identical chokes L_i and L_s inductance value is:

$$L_i \text{ and } L_s \text{ inductance, } L_i = L_s = \frac{V_i D}{\Delta I_L f_{sw}} \tag{5}$$

where ΔI_L is the peak-to-peak ripple current and set at 40% of the maximum input current.

The two identical C_s and C_{o1} capacitance value is:

$$\text{Capacitor } C_s \text{ and } C_{o1}, C_s = C_{o1} = \frac{I_o}{\Delta V_c f_{sw}} \tag{6}$$

where ΔV_c is the peak-to-peak capacitor voltage ripple and is set between 5% to 10%. I_o is the total output current.

The capacitance value at C_{o2} is:

$$\text{Output capacitor, } C_{o2} = \frac{D}{R(\frac{\Delta V_{o2}}{V_{o2}}) f_{sw}} \tag{7}$$

where ΔV_{o2} is practically set between 1% to 5%.

2.2 PID Feedback Controls

One of the most widely used closed-loop controls is PID feedback due to its simplicity and reliability to regulate the output behaviour of a system. It consists of three modes namely proportional, integral and derivative control. Referring to Fig. 1., the PID controller manipulates the error signal from the error amplifier to produce a stable PWM signal which will be fed to MOSFETS's gate. However, with appearances of switching element and high circuit switching, it makes the determination of PID gains a challenging task. This is due to the switching element that makes the model linearizes to zero. Thus, it is impossible to determine the PID gains using straight forward method. Many popular techniques have been researched and developed to overcome this issue. These techniques can be classified under two categories namely the control scheme and the tuning method. Some of the popular control schemes are feedback, feedback plus feed-forward, cascade and cascade plus feed-forward [21]. For tuning method, it can be classified under open loop and closed-loop method. Some popular methods for PID closed-loop control are Ziegler-Nichols, Modified Ziegler-Nichols, Tyreus-Luyben and Damped Oscillation method. Whereas for open loop control are Open Loop Ziegler-Nichols, Cohen-Coon, Fertik, Ciancone-Marline, Internal Mode Control, and Minimum Error Integral Criteria method [22-24]. Figure 3 shows the chart of the PID tuning methods commonly used in DC-DC converter design.

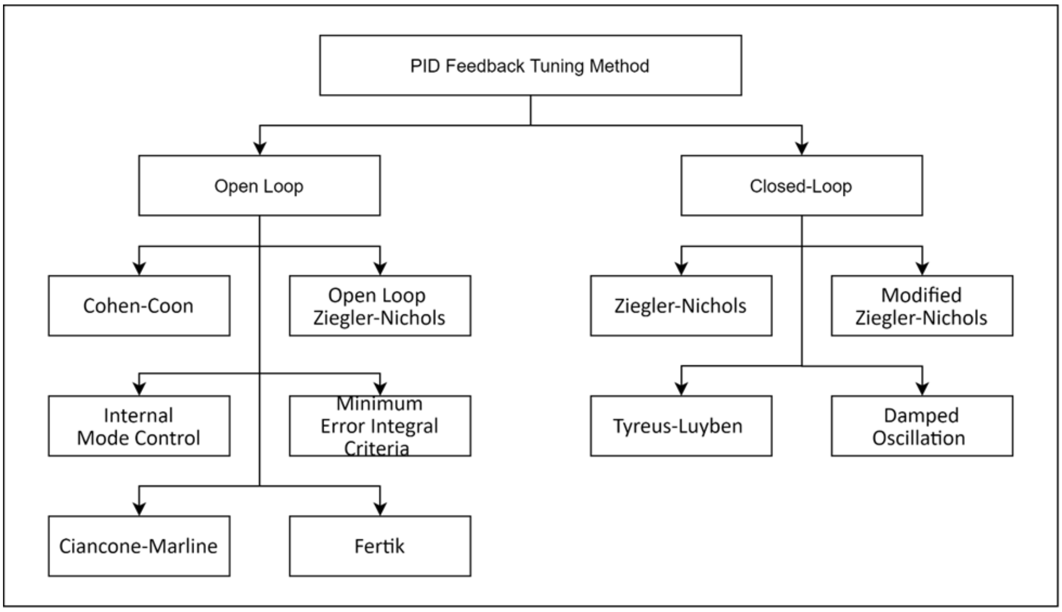

Fig. 3. PID Tuning Methods Chart

In this proposed design, analysis is initially applied using open loop control. Then, some parameters from the open loop control will be utilized to continue the analysis of the converter's performance using closed-loop PID feedback. The selected method for the PID tuning is based on second method Ziegler-Nichols (ZN) tuning rule. This method is very useful because the proposed design shows an unknown plant dynamic and some overshoot during its operation [25, 26]. This method is also known as ultimate gain or continuous cycling tuning method. Other popular methods derived from ZN are modified Ziegler-Nichols (MZN) and Tyreus-Luyben (TL) tuning method. All of these methods will be used in analysing the converter's dynamic performance. Table 1 summarizes the parameters involved in the tuning of the SEPIC-Boost converter where K_u is the ultimate gain and P_{cr} is the critical steady-state oscillation period.

Table 1
Gain Estimator Chart

Tuning method	K_P	T_I	T_D
Ziegler-Nichols (ZN)	$0.60\ K_u$	$0.5P_{cr}$	$0.125P_{cr}$
Modified Ziegler-Nichols (MZN)	$0.33K_u$	$0.5P_{cr}$	$0.33P_{cr}$
Tyreus-Luyben (TL)	$0.45K_u$	$2.2P_{cr}$	$0.16P_{cr}$

The relation between the PID gains is shown in Eq. (8):

$$\text{PID gain, } G_{PID}(s) = K_P + K_I\frac{1}{s} + K_D s = K_P\left(1 + \frac{1}{T_I s} + T_D s\right) \tag{8}$$

Where K_P is the proportional gain, K_I is the integral gain, K_D is the derivative gain, T_I is the integral time, and T_D is the derivative time. Based on the K_P value from Table 1, the integral and derivative gains can be determined using Eqs. (9) and (10).

$$\text{Integral gain, } K_I = \frac{K_P}{T_I} \tag{9}$$

$$\text{Derivative gain, } K_D = K_P * T_D \tag{10}$$

There are four important characteristics in dynamic response that can be affected by the PID tuning which are signal overshoot, settling time, rise time and steady-state error. Signal overshoot is the difference between the highest peak of the targeted signal and the desired level during its transient condition. Settling time is the time for the targeted signal to converge to its steady state condition. Rise time is the time for the targeted signal to rise at 90% of its desired level for the first time and steady-state error is the difference between the targeted signal and the desired level at its steady state condition. By using PID feedback control, the dynamic response can be altered by manipulating the inputted PID gains. Optimal value of PID gains can make a system to become fully regulated, without overshoot and having swift settling time to its steady-state level.

2.3 Design Specifications

The black box parameters for the design is calculated based on Eqs (1)-(7). In this design, the input supply is set at 12V, while the switching frequency of the system is set at 100kHz with duty cycle at 0.6. The desired output is 48V, 2A with static gain, M equals to 4 which categorises it as a standard static gain converter. Table 2 simplifies the parameter used in the proposed design.

Table 2
Electrical parameters of the proposed converter

Parameter	Value	Parameter	Value
Input voltage, V_i	12.0V	L_i and L_s inductances	20.2µH
Output voltage, V_{o2}	48.0V	C_s and C_{o1} capacitances	13.3µF
Output current, I_o	2.0A	C_{o2} capacitance	5µF
Operating frequency, f_{sw}	100kHz	Equivalent Load	24Ω

Figure 4 shows the Matlab/Simulink schematic to analyse the proposed converter performance and its dynamic response using several PID tuning methods.

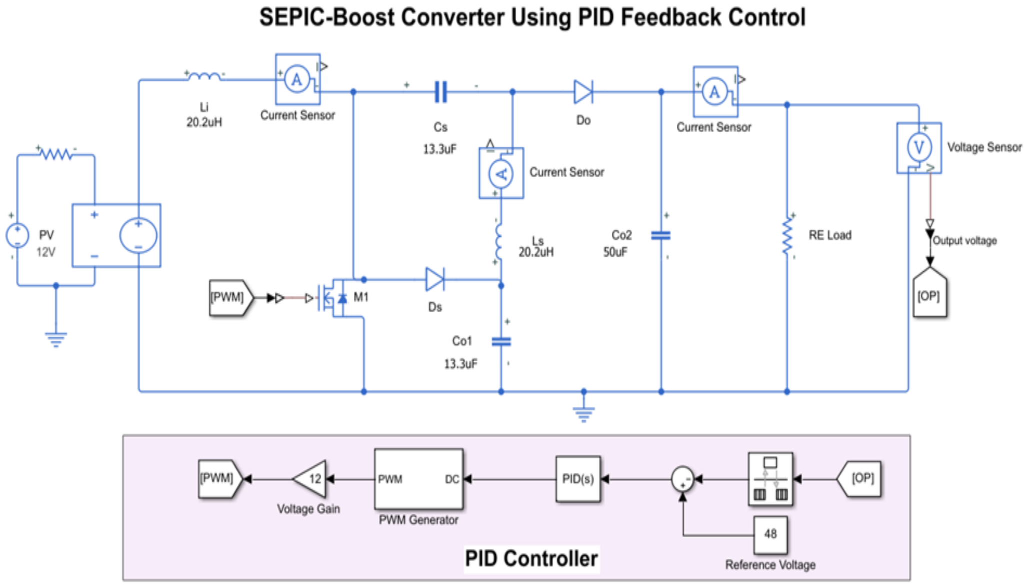

Fig. 4. Matlab/Simulink schematic diagram

3. Results and Discussion

The proposed SEPIC-Boost converter can generate higher level of output compared to the conventional SEPIC and Boost topology when operated under similar duty cycle. This is due to its architecture that combines both topologies in its entire operation. Table 3 shows the comparison of the three topologies when different duty cycle is applied to the system. Clearly, when the duty cycle is set at 0.6, the proposed converter able to produce the desired 48V output voltage whereas it takes 0.8 for SEPIC and more than 0.7 for Boost topology. This reflects lower losses in switching element and better cost benefit compared to the traditional topologies. Figure 5 shows the comparison graph of the three converters. Obviously, the proposed SEPIC-Boost converter can produce higher output level when the duty cycle is increased from 0.5 onwards which makes it a promising solution for higher wattage RE applications. Based on the graph also, it is proven that this proposed design has better static gain over SEPIC and Boost topology.

Table 3
Comparison of the converter's output voltage

	Output Voltage (V)		
Duty Cycle	Boost	SEPIC	Boost-SEPIC
0.1	13.3	1.3	14.7
0.2	15.0	3.0	18.0
0.3	17.1	5.1	22.3
0.4	20.0	8.0	28.0
0.5	24.0	12.0	36.0
0.6	30.0	18.0	48.0
0.7	40.0	28.0	68.0
0.8	60.0	48.0	108.0
0.9	120.0	108.0	228.0

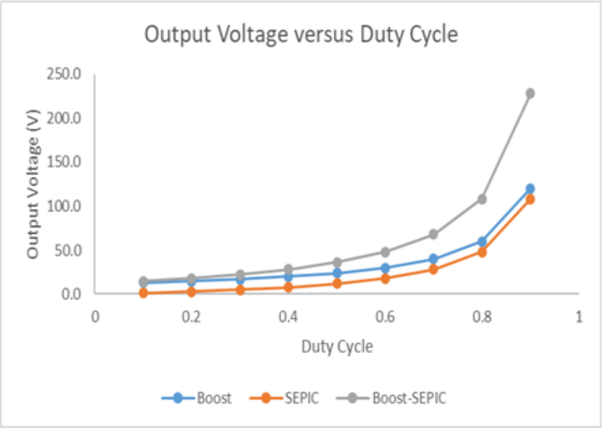

Fig.5. V-D characteristics for converters

The implemented PID tuning method based on Table 1 is applied for the feedback purpose. Initially, the K_P value is estimated using second method Ziegler-Nichols tuning rule and the final satisfactory value for the proportional gain is 0.0080 with P_{cr} period equals 1.143ms. Table 4 summarises the tuning parameters for ZN, MZN and TL tuning methods which is implemented in the analysis.

Table 4
Tuning parameters for PID feedback

Tuning Method	K_P	T_I (ms)	T_D (µs)	K_I	K_D
Ziegler-Nichols (ZN)	0.0080	0.572	142.9	14.0	5.60×10^{-6}
Modified Ziegler-Nichols (MZN)	0.0044	0.572	377.2	7.7	1.66×10^{-6}
Tyreus-Luyben (TL)	0.0060	2.515	182.9	2.4	1.10×10^{-6}

Figures 6 to 10 show the generated output waveforms under open loop and three closed-loop PID controls. These figures show the dynamic response of the voltage and current waveforms in its operation. Figure 6 shows the output waveforms under open loop control. The converter exhibits overshoot in its voltage and current waveforms capped at 78.3V and 3.3A, respectively. The time taken to reach 90% of its steady value is 0.24ms with settling time at 6ms. This control settled at the quickest pace compared to the closed-loop control, but the steady-state voltage only reaches 46.4V which contributes to 3.4% steady-state error using similar 0.6 duty cycle. The measured peak-to-peak output voltage ripple is 340.8mV.

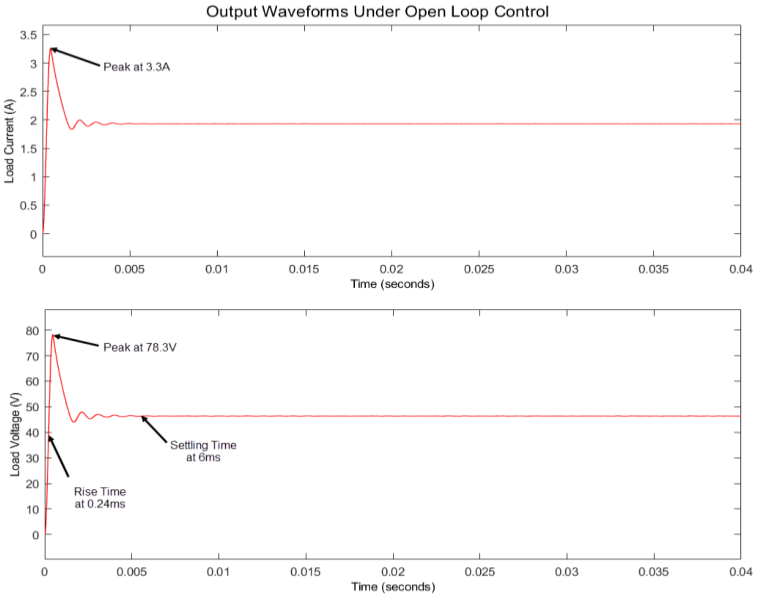

Fig.6. Output waveforms under open loop control

Figure 7 shows the output waveforms for current and voltage using second method ZN tuning. Tremendous improvement can be clearly seen without any overshoot in its operation with rise time at 4.56ms and settling time at 32ms. The measured peak-to-peak output voltage ripple is 361.4mV which less than 1% indicating a well-regulated output is achieved using this PID control.

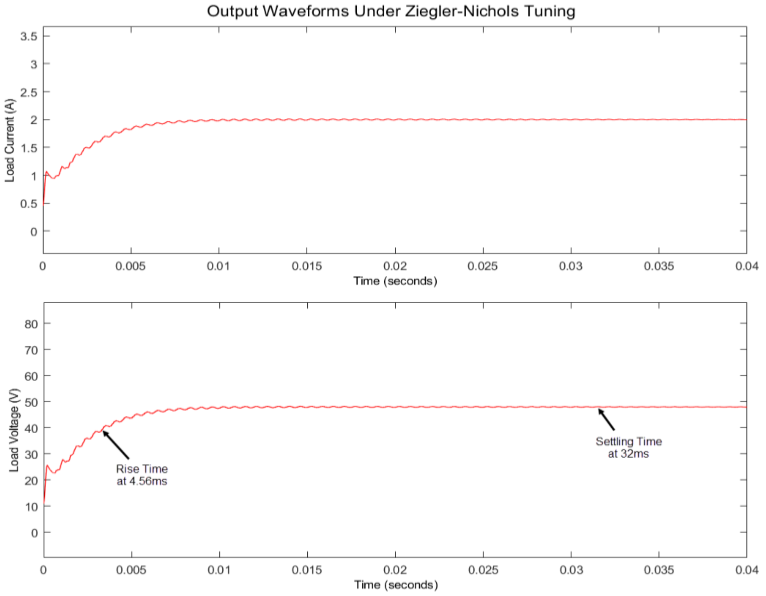

Fig. 7. Output waveforms under Ziegler-Nichols tuning

Derived from the initial ZN tuning, MZN method is applied, and the output waveforms is shown in Fig. 8. This tuning also exhibits an extremely well-regulated output as designed. The rise time and settling time also show shorter time than the ZN method which are 4.21ms and 30.2ms, respectively. A tiny 289.3mV peak-to-peak output voltage ripple is recorded using MZN tuning.

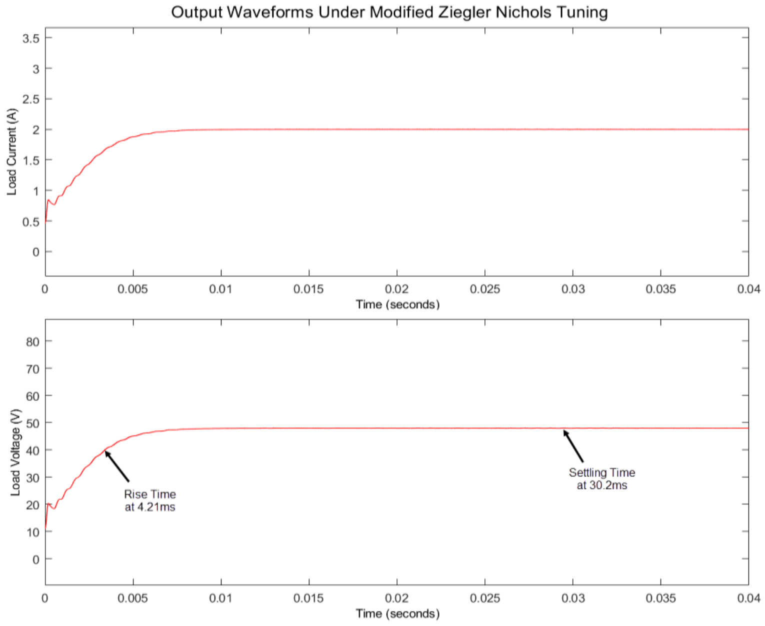

Fig. 8. Output waveforms under modified Ziegler-Nichols tuning

Tyreus-Luyben tuning method also shows well-regulated output waveforms are achieved in its steady-state condition as depicted in Fig.9. However, this method exhibits the slowest rise time and settling time at 14ms and 35.1ms, respectively. The measured peak-to-peak output voltage ripple is 291.5mV which is less than 1% as experienced by ZN and MZN tuning methods.

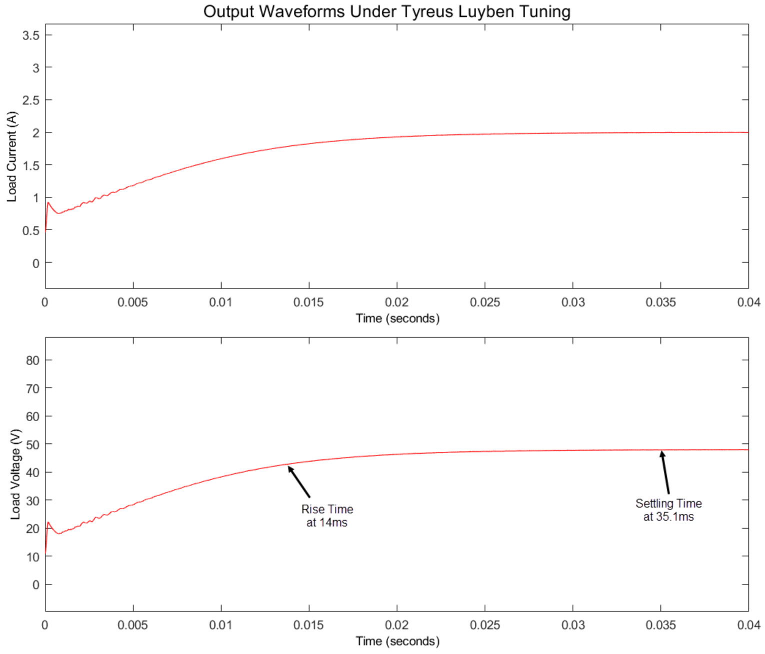

Fig. 9. Output waveforms under Tyreus-Luyben tuning

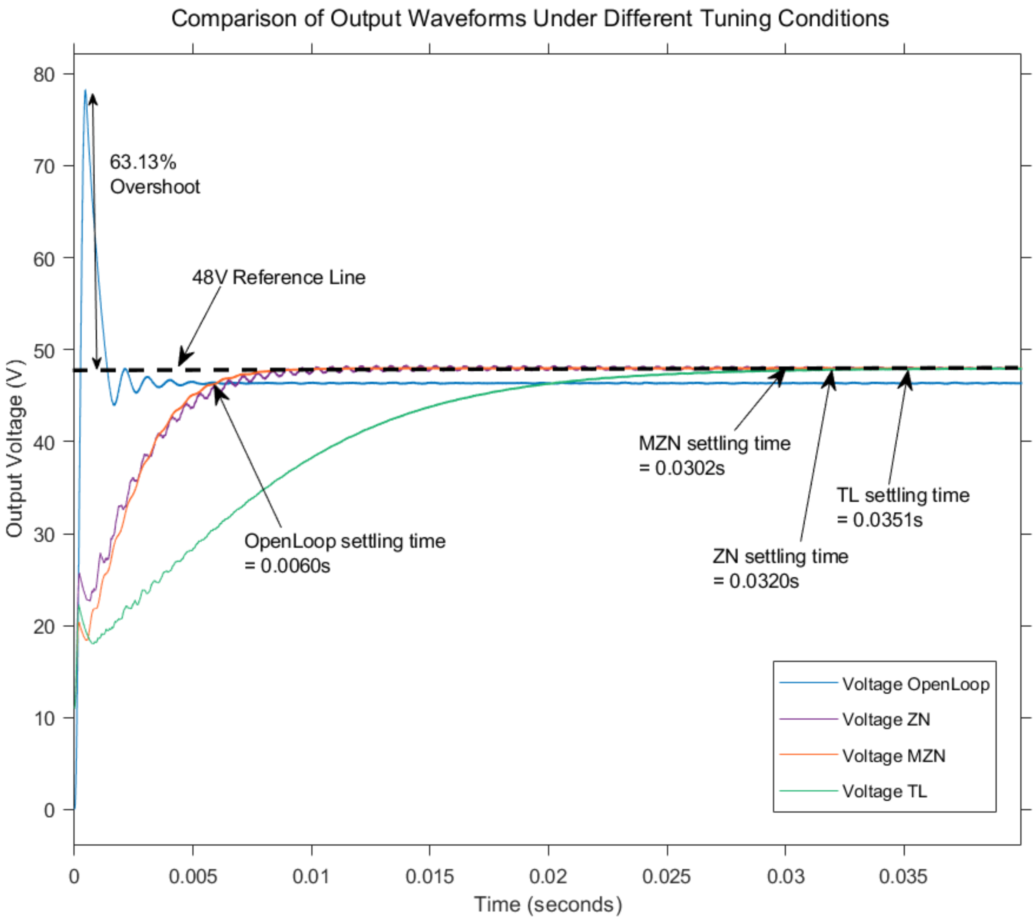

Fig. 10. Full comparison of output waveforms for all tuning methods

Figure 10 shows the complete comparison of the open loop and all PID controls used in this analysis. An overshoot of 63.13% is experienced by the design when it is operated using open loop control. Under PID controls, all tuning methods able to produce well-regulated outputs at the desired level which is 48V and 2A. Table 5 summarises all key parameters associated with the open loop and PID feedback controls. Based on the rise time and settling time criterions, it is found out that the MZN tuning is the most suitable method to be applied in this proposed SEPIC-Boost converter design.

Table 5
Dynamic performance comparison for all tuning methods

Tuning Method	Overshoot (V)	Settling time (ms)	Rise time (ms)	Steady-state error (%)	Peak-to-peak ripple (mV)
Open Loop	78.3	6.0	0.24	3.4	340.8
Ziegler-Nichols (ZN)	-	32.0	4.56	-	364.1
Modified Ziegler-Nichols (MZN)	-	30.2	4.21	-	289.3
Tyreus-Luyben (TL)	-	35.1	14.00	-	291.5

4. Conclusions

A SEPIC-Boost converter using PID feedback control based on combination of SEPIC and Boost converter for renewable energy applications has been successfully analysed in this paper. Compared to the conventional SEPIC and Boost topology, this modified design has shown the ability to significantly increase the static gain when operated with similar duty cycle. Complexity of the control circuit is maintained with only one switching MOSFET embedded in its topology. Using PID feedback control, it has shown well-regulated output waveforms over open loop control without any overshoot and steady-state error. Different PID tuning methods have been applied to find the best dynamic performance and simulation results have shown that the modified Ziegler-Nichols tuning is the best PID tuning to be applied. Validation of the proposed SEPIC-Boost converter has shown that it able to produce a reliable 48V, 2A outputs with ripple less than 1% in its operation.

References

[1] Green, Martin A., Yoshihiro Hishikawa, Ewan D. Dunlop, Dean H. Levi, Jochen Hohl-Ebinger, and Anita WY Ho-Baillie. "Solar cell efficiency tables (version 52)." *Progress in Photovoltaics: Research and Applications* 26, no. 7 (2018): 427-436.

[2] Hutchins, M. "Oxford PV retakes tandem cell efficiency record." (2021).

[3] Gorji, Saman A., Hosein G. Sahebi, Mehran Ektesabi, and Ahmad B. Rad. "Topologies and control schemes of bidirectional DC–DC power converters: An overview." *IEEE Access* 7 (2019): 117997-118019.

[4] Tofoli, Fernando Lessa, Dênis de Castro Pereira, Wesley Josias de Paula, and Demercil de Sousa Oliveira Júnior. "Survey on non-isolated high-voltage step-up dc–dc topologies based on the boost converter." *IET power Electronics* 8, no. 10 (2015): 2044-2057.

[5] Singh, S. N. "Selection of non-isolated DC-DC converters for solar photovoltaic system." *Renewable and Sustainable Energy Reviews* 76 (2017): 1230-1247.

[6] Gul, Mehreen, Yash Kotak, and Tariq Muneer. "Review on recent trend of solar photovoltaic technology." *Energy Exploration & Exploitation* 34, no. 4 (2016): 485-526.

[7] Yadav, Apoorva, and Arunima Verma. "Sepic DC–DC Converter: Review of Different Voltage Boosting Techniques and Applications." In *2020 2nd International Conference on Innovative Mechanisms for Industry Applications (ICIMIA)*, pp. 733-739. IEEE, 2020.

[8] Raghavendra, Kummara Venkat Guru, Kamran Zeb, Anand Muthusamy, T. N. V. Krishna, SVS V. Prabhudeva Kumar, Do-Hyun Kim, Min-Soo Kim, Hwan-Gyu Cho, and Hee-Je Kim. "A comprehensive review of DC–DC converter topologies and modulation strategies with recent advances in solar photovoltaic systems." *Electronics* 9, no. 1 (2019): 31.

[9] Revathi, B. Sri, and M. Prabhakar. "Non isolated high gain DC-DC converter topologies for PV applications–A comprehensive review." *Renewable and Sustainable Energy Reviews* 66 (2016): 920-933.

[10] Jagadeesh, Ingilala, and V. Indragandhi. "Review and comparative analysis on dc-dc converters used in electric vehicle applications." In *IOP Conference Series: Materials Science and Engineering*, vol. 623, no. 1, p. 012005. IOP Publishing, 2019.

[11] Forouzesh, Mojtaba, Yam P. Siwakoti, Saman A. Gorji, Frede Blaabjerg, and Brad Lehman. "Step-up DC–DC converters: a comprehensive review of voltage-boosting techniques, topologies, and applications." *IEEE transactions on power electronics* 32, no. 12 (2017): 9143-9178.

[12] de Assis, Bruno G., Eduardo PC Braga, Claudinor B. Nascimento, and Eloi Agostini Júnior. "High-Voltage-Gain Integrated Boost-SEPIC DC-DC Converter for Renewable Energy Applications." *Eletrônica de Potência* 24, no. 3 (2019): 336-344.

[13] Gules, Roger, Walter Meneghette Dos Santos, Flavio Aparecido Dos Reis, Eduardo Felix Ribeiro Romaneli, and Alceu Andre Badin. "A modified SEPIC converter with high static gain for renewable applications." *IEEE transactions on power electronics* 29, no. 11 (2013): 5860-5871.

[14] Saravanan, Subramani, and Neelakandan Ramesh Babu. "A modified high step-up non-isolated DC-DC converter for PV application." *Journal of applied research and technology* 15, no. 3 (2017): 242-249.

[15] Premkumar, Manoharan, Umashankar Subramaniam, Hassan Haes Alhelou, and Pierluigi Siano. "Design and development of non-isolated modified SEPIC DC-DC converter topology for high-step-up applications: investigation and hardware implementation." *Energies* 13, no. 15 (2020): 3960.

[16] Sabzali, Ahmad J., Esam H. Ismail, and Hussain M. Behbehani. "High voltage step-up integrated double Boost–Sepic DC–DC converter for fuel-cell and photovoltaic applications." *Renewable energy* 82 (2015): 44-53.

[17] Mumtaz, Farhan, Nor Zaihar Yahaya, Sheikh Tanzim Meraj, Balbir Singh, Ramani Kannan, and Oladimeji Ibrahim. "Review on non-isolated DC-DC converters and their control techniques for renewable energy applications." *Ain Shams Engineering Journal* 12, no. 4 (2021): 3747-3763.

[18] Bajoria, Nishtha, Pragya Sahu, R. K. Nema, and Savita Nema. "Overview of different control schemes used for controlling of DC-DC converters." In *2016 International Conference on Electrical Power and Energy Systems (ICEPES)*, pp. 75-82. IEEE, 2016.

[19] Lynser, Ferrarison B., Morningstar Sun, Maiarta Sungoh, Nuki Taggu, and Pushpanjalee Konwar. "Comparative Analysis of Different Control Schemes for DC-DC Converter: A Review." *ADBU Journal of Electrical and Electronics Engineering (AJEEE)* 2, no. 1 (2018): 8-13.

[20] Hariharan, K., and Santanu Kapat. "Need for variable frequency control in DC-DC switching converters-Challenges and opportunities using digital implementation." *Proceedings of the Indian National Science Academy* 84, no. 3 (2018): 657-668.

[21] Kumar, R., S. K. Singla, and V. Chopra. "Comparison among some well known control schemes with different tuning methods." *Journal of applied research and technology* 13, no. 3 (2015): 409-415.

[22] Ibrahim, Oladimeji, Nor Zaihar B. Yahaya, and Nordin Saad. "PID controller response to set-point change in DC-DC converter control." *International journal of power electronics and drive systems* 7, no. 2 (2016): 294.

[23] Korsane, Diwakar T., Vivek Yadav, and Kiran H. Raut. "PID tuning rules for first order plus time delay system." *Int. Journal of Innovative Research in Electrical, Instrumentation and Control Engineering* 2, no. 1 (2014): 582-586.

[24] Shahrokhi, Mohammad, and Alireza Zomorrodi. "Comparison of PID controller tuning methods." Department of Chemical & Petroleum Engineering Sharif University of Technology (2013): 1-2. https://doi.org/10.1002/cjce.5450830412

[25] Ziegler, J. G., and N. B. Nichols. "Optimum settings for automatic controllers." (1993): 220-222.

[26] Ogata, Katsuhiko. *Modern control engineering*. Vol. 5. Upper Saddle River, NJ: Prentice hall, 2010