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Modeling and simulation of SEPIC controlled converter using PID controller

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ABSTRACT

The topology of SEPIC "Single-ended primary inductance converter" is considered as a suitable option for automotive power system where the value of the output voltage should be ranging between the low and high values of the input value of voltage. The main feature of the DC-DC converter is the stability of output voltage. This paper shows the SEPIC converter employing PID converter to be used in industrial applications. A SEPIC DC-DC converter can manage either step-down mode or step-up mode. The benefit of using this circuit is to supply a stable and controlled output voltage no matter how much the input voltage is. The simulated behaviors of the uncontrolled and controlled SEPIC converter are presented in this paper. The PID controller based on bat algorithm (BA) optimization method is used for searching of the best Proportional–Integral-Derivative (PID) gains. The solution has given very good performance and whatever the output reference voltage variation and load disturbance of the system.

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1. INTRODUCTION

The DC-DC converters that operate on a switched mode are an example of time-varying non-linear dynamic systems [1-6]. These converters contain specialized switches that can be applied to manipulate their topological structure over-time as well as the time variation in the energy storage ingredients as their diodes have non-linear current-voltage properties [7, 8]. Some of the common uses of DC-DC converters include controlling the traction motor in the engines of electric cars, forklift trucks, marine hoists, mine haulers, and trolley cars [1, 3, 9, 10]. This is primarily due to its increased efficiency in the rapid dynamic response and acceleration control [1, 3, 4, 11]. These converters can be applied to improve energy conservation in transportation systems that have frequent stops through the use of regenerative braking to return energy back to its supply in DC motors [12, 13]. The construction of DC-DC converters requires design analysis to determine the state variables and their modes of operation in developing a state space model. The direct current converters cannot be reliably used to determine a wide range of operation, especially with the need to attain up-and-down voltage conversion [14-17]. This creates the need to integrate a Single-Ended Primary Inductor Converter in the design in order to increase the range of operation and performance. Unlike other types of converters, SEPIC generates a positive and regulated output voltage based on the given input voltage. The converter utilizes different coupling capacitors in the current isolation in the event of short circuiting. Additionally, heat build-up and ripple in the SEPIC converter are prevented through the use of low-equivalent series resistance capacitors to improve the reliability of the diversified operation range. Techniques such as state space averaging or circuit averaging can be reliably used in the process of converter modeling to determine the signal transfer functions of the SEPIC converter. The converter analysis will be conducted using MATLAB computer software. Due to the impacts of the inductor resistance on the efficiency of SEPIC converters, low-resistance inductors will be used reduce the heat dissipation for increased efficiency of the converter. Direct Current converters are used in the generation of DC current from the voltage regulators that have a parallel alignment with the inductors [18]. It's important to note that the direct current power supplies contain SEPIC converters, which enhance their functional capability to operate in either step-up or step-down mode [19]. This is achieved through regular adjustment of the SEPIC converter circuit topology to boost its performance.

The research on the SEPIC converter is working in buck and boost mode. The functionality of a SEPIC converter is based on the variations in the voltage input and output that are used in the derivation of the ideal values for the optimal performance of the system. The PID controller values can be obtained through different approaches depending on factors such as the current voltage. This paper is focused on applying the PID controller tuning approach based on BA to generate the PID ganis that attain optimal performance. In conclusion, this paper presents the analysis and discussion of the predicted results that are obtained from the SEPIC converter.

2. RESEARCH METHOD

SEPIC Converter is a basic switching - mode converter circuit where the voltage of output could be higher, lower or equal than the voltage of input. The equivalent circuit of the SEPIC converter demonstrated in Figure 1. The SEPIC converter contains a power switch (MOSFET), a diode, an input filter capacitor, an output capacitor and coupled inductors. The mathematical model [14, 20] of the open loop transfer function is derived to apply an appropriate design technique for obtaining the ideal values for the controller parameters which will meet the specifications of the steady and transient state of the closed loops control system.

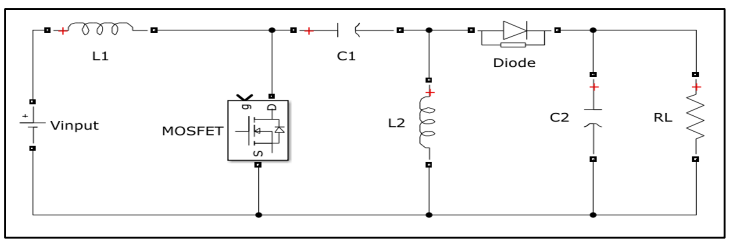

Figure 1. Circuit scheme of SEPIC converter

During the turn on the period of the circuit, In Figure 2, it could be noticed that the moment in which the power switch is turned on, the switch S is closed, and at the same time, L1 (the first inductor) will be charged from the input voltage source. Moreover, the second inductor L2 gets its energy from capacitor C2 while the function of C2 (the output capacitor) will be providing load current. Meanwhile, there is no energy provided to the load capacitor. The polarities of capacitor voltage and the inductor current are indicated in the next Figure [21].

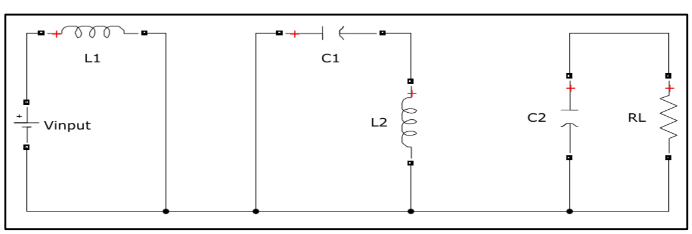

Figure 2. The diagram of an equivalent circuit for the SEPIC converter while the switch is turning ON

Figure 3, indicates the state of the circuit while the power switch is turned OFF, where the stored energy in L2 (the second inductor) is moving to C1 (the first capacitor). Moreover, the stored energy passed from L2 (the second inductor) to C2 (the output capacitor) out of the diode and providing the energy to the load [11]. L2 is also being connected to the load at this time. A pulse of current is seen by the output capacitor at the off time causing inherently noise more than a buck converter.

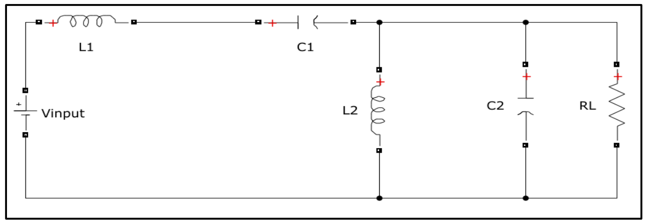

Figure 3. The diagram of an equivalent circuit for the SEPIC converter while the switch is turning OFF

Increase or decrease in the amount of voltages they convert (transformer) depends on the duty cycle (D) and the parasitic elements in the circuit. The inductor current iL2 rises with slope $+V_C/L2$ while switching on and reduces with slope $-V_O/L2$ while switching off, thus:

$$\frac{V_{C1}}{L2}DT = \frac{V_O}{L2}(1-D)T \tag{1}$$

$$V_{C1} = \frac{(1-D)}{D}V_O \tag{2}$$

The inductor current iL1 increases with slope $+V_I/L1$ during switching on and decreases with slope -($V_{C1}+V_O - V_I/L1$) during switching off. Thus:

$$\frac{V_I}{L1}DT = \frac{V_{C1}+V_O-V_I}{L1}(1-D)T \tag{3}$$

$$V_O = \frac{D}{(1-D)}V_I \tag{4}$$

The ratio voltage of the SEPIC converter is:

$$\frac{V_O}{V_I} = \frac{D}{(1-D)} \tag{5}$$

This converter either the voltage of output could be higher, lower or equal than the input voltage [21]. The output voltage of the suggested SEPIC converter functions in buck and boost mode. The system is modeled in MATLAB/simulink because model is more visual than script; therefore system is - easier to simulate nonlinear effects and different sample rates in Simulink.

3. THE PID CONTROLLER FOR THE SEPIC CONVERTER

The use of PID became worldwide in mainly complex industrial processes that need precise control in system performance. Proportional, integral and derivative of the error signal are combined in a PID controller, where each part gives some advantages for the overall system response [22]. A standard block diagram for the suggested control system arrangement is displayed in Figure 4.

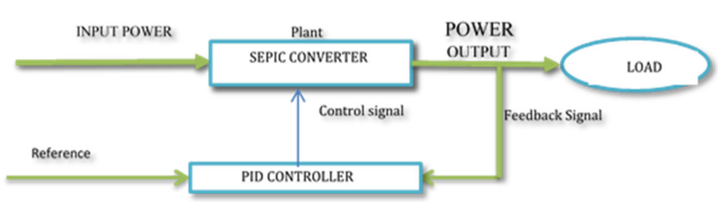

Figure 4. SEPIC converter with PID controller system block scheme

The PID control is proposed to safeguard the identifying required insignificant running point for SEPIC, then adjusting SEPIC, in order to remain very near to the insignificant running point if any unexpected disturbances happened, set point changes and noise. The PID controller will generate corresponding PWM pluses to control the switch of the SEPIC converter. The output voltage is sensed and compared to the reference set point required voltage the result of the error is passed to the PID controller to eliminate this difference through setting the Duty cycle value that used in PWM generation. Figure 5, shows the controller part configuration. In Figure 6, one can observe the output waveforms in one duty cycle, a recurring sequence block configured to the output in form of a saw-tooth wave of output values (0 1 0) with time values (0, 2/ Switching frequency, 1/ Switching frequency). This waveform is subtracted from the duty cycle to result in a PWM signal of the wanted duty cycle.

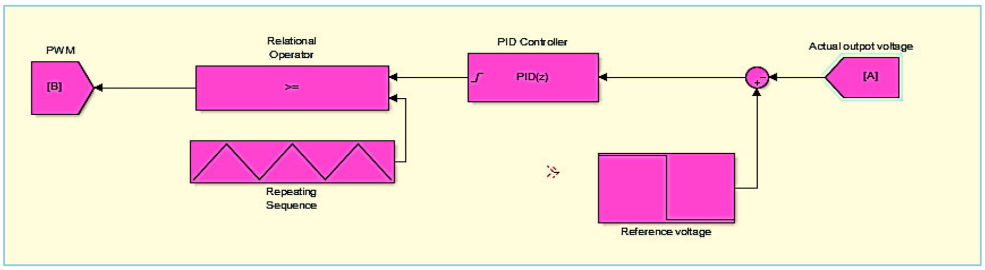

Figure 5. PID controller configuration in MATLAB program

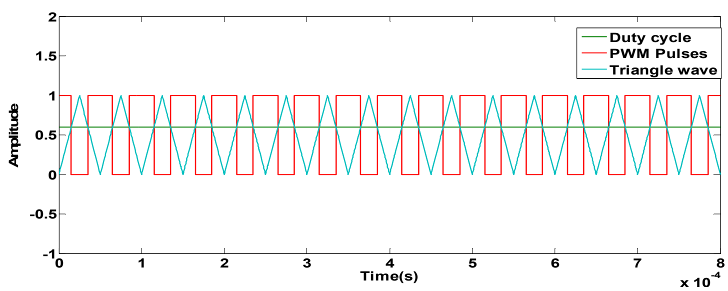

Figure 6. Duty cycle form.(D=0.6, Switching frequency=50KHz)

The transfer function regarding the PID controller could be stated as [1]:

$$C(z) = P + IT_s \frac{1}{z-1} + D \frac{N}{1+NT_s \frac{1}{z-1}} \quad (6)$$

where:
Ts: sampling time
P: Proportional gain
I: Integral gain
D: Derivative gain
N: filter coefficient

For design PID controller for SEPIC converter needs to locate correct values of proportional, integral, and derivative coefficients (P,I,D,N). However, carefully and analytically obtaining the group of coefficients which confirms the finest working for the control system is a difficult task [23, 24]. Using manual approaches could cause repetition and loss of time, and it may lead to damage if it's used on the hardware. It's impossible to linearize the designing a PID controller for the SEPIC converter because the converter model has nonlinear power electronic switch [25-28]. PID Tuning Achievement: There are many methods to tuning traditional PID, in this paper, two methods were selected for tuning:

3.1. MATALB PID tuner app.

It suggested using system identification for identifying a plant model by simulating input-output data. By MATLAB PID tuner (R2014a) .use simulation input-output data to create linear plant model and calculation the coefficients of PID controller. Table 1 shows the results of the parameters of the PID controller gains.

Table 1. Parameters of PID controller enhanced by MATLAB tuner

parameters	values
P	0.00883456973497108
I	0.232247263526474
D	-5.19677377986298e-05
N	106.542259609567

3.2. PID controller design using Bat Algorithm

A bat-inspired algorithm is a meta-heuristic search optimization established by Yang [29]. In this work, the BA is used to optimize the parameters of PID controller to enhance system performance and make the system able to operate in various system conditions such as set point variation, load disturbance, and line disturbance. The bat algorithm is constructed on the echolocation behavior of micro-bats with changing pulse emission and loudness [29]. Integral squared error (ISE), integral absolute error (IAE) and integral time absolute error criterion (ITAE) are chosen as the goal work in the controller strategy procedure. The error criteria IAE, ISE ITAE expressions are as develops [30].

$$IAE = \int_0^{Tss} abs\left(e(t)\right)dt \tag{7}$$

$$ISE = \int_0^{Tss} e(t)^2 dt \tag{8}$$

$$ITAE = \int_0^{Tss} t * abs\left(e(t)\right)dt \tag{9}$$

where (Tss) is the time at steady state. Figure.7 demonstrates the employment of the BA in the MATLAB computer software. This flowchart was then adapted into coding for simulation purposes. These bats will then work together towards the objective function (error minimization). In the proposed work it will work towards optimizing the controller parameters (Kp, Ki, Kd, N) based on (7)-(9) [31-32].

The suggested method is executed in MATLAB computer software/script(Sequence of MATLAB statements in file).Preliminary numerical tests is used to set the values of the BA control parameters.(Population size(n), Number of generation(ng), Frequency minimum(fmin), Frequency maximum(fmax), Loudness(A), Pulse rate(r)). All these algorithm parameters are selected according to the problems to be applied and characteristics needed by the designer. Table 2 reviews the gain estimates of the PID controller attained through using BA in MATLAB program.

Table 2. Gains of PID controller enhanced by BA

parameters	values
P	0.0116263478770415
I	2.50881375122572
D	-5.67699027887959e-06
N	2046.81903019188

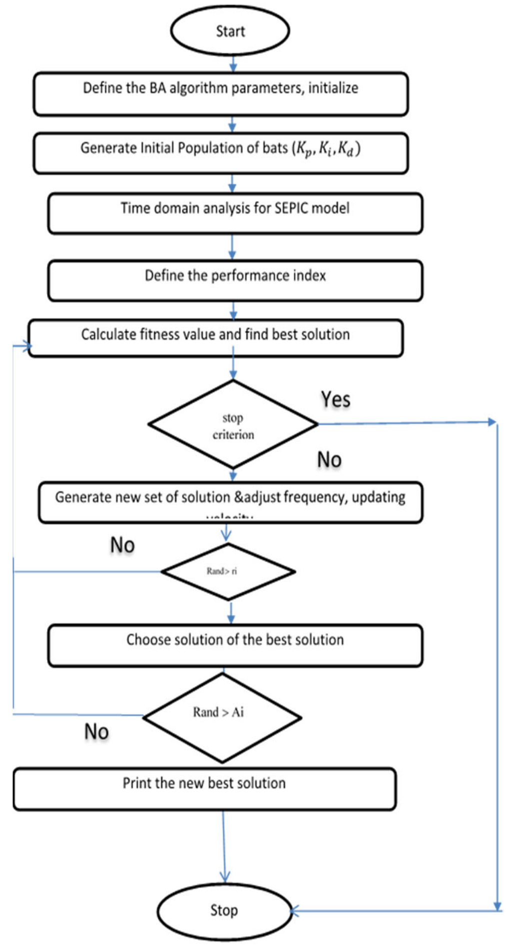

Figure 7. Flowchart of the BA

4. SIMULATION RESULTS AND DISCUSSION

To study the feasibility of the uncontrolled and controlled SEPIC converter proposed in this paper using MATLAB/simulink software and simulation has been performed by applying the values of converter circuit summarized in Table 3.

Table 3. Design parameters values of SEPIC converter.

Specification of SEPIC converter	
R	7.38 Ω
L1	460 µH
L2	460 µH
C1	8.4 µF
C2	0.0163 F
$\mathbf{V_I}$	29.3 V
$\mathbf{V_O}$	24 V
D	0.46
Switching frequency	20 KHz

The SEPIC converter circuit was first simulated as uncontrolled SEPIC converter then simulated as controlled SEPIC converter. Figure 8, showns the simulation model of uncontrolled SEPIC converter. The key waveforms for uncontrolled SEPIC converter are listed in Figure 9.

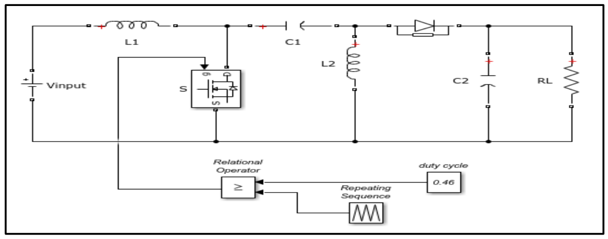

Figure 8. MATLAB/simulink simulation model of uncontrolled SEPIC converter.

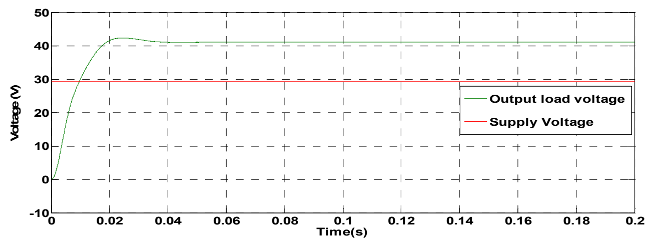

Figure 9. The waveforms of the input voltage, output voltage for the uncontrolled SEPICC (D=0.5)

Uncontrolled SEPIC converter can working with step up or step down without set point tracking, line regulation and any disturbance. Figure 10, shown the simulation model of controlled SEPIC converter with PID controller in closed loop system.

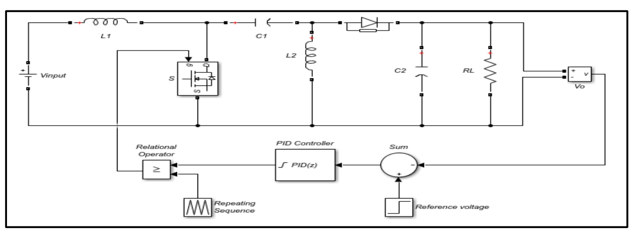

Figure 10. MATLAB/simulink simulation model of controlled SEPIC converter

The output voltage for controlled SEPIC converter using a PID controller at set point tracking for voltage mode control are shown in Figure 11.

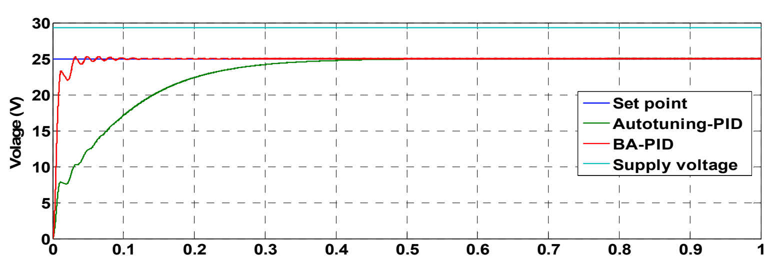

Figure 11. The load output voltage of SEPIC at 25 V Setpoint & supply voltage 29.3 V .

Figure 12 shows the SEPIC with PID controller (Auto tuning-PID & BA-PID) under line adjustment. When it subjected to step change of the line voltage, it decreased rapidly from 29.3 V to 27 V.

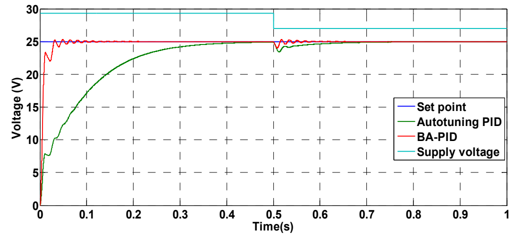

Figure 12. The output voltage of SEPIC supply change from 29.3 V to 27 V

Figure 13 shows the SEPIC with PID controller (Auto tuning-PID & BA-PID) under line regulation. When it subjected to step change of the line voltage, it increased rapidly from 29.3 V to 33 V.

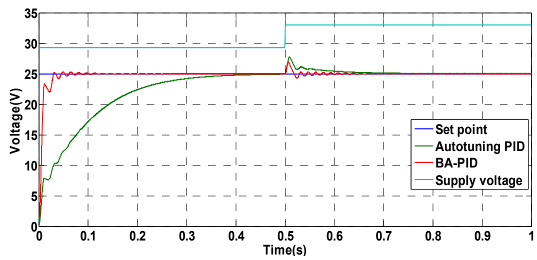

Figure.13. The output voltage of SEPICC - supply change from 29.3 V to 33 V

Figure 14 and 15 show the load regulation of SEPIC with Auto tuning-PID & BA-PID for step change in load current from 3.88 A to 2 A and vice versa.

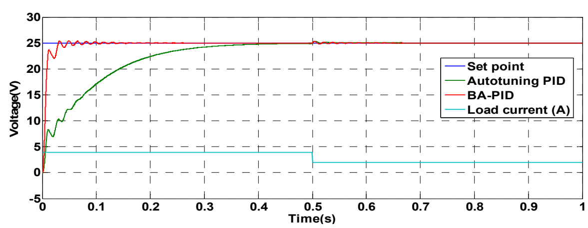

Figure 14. Load regulation of SEPICC Step change of load current from 3. 88A to 2A

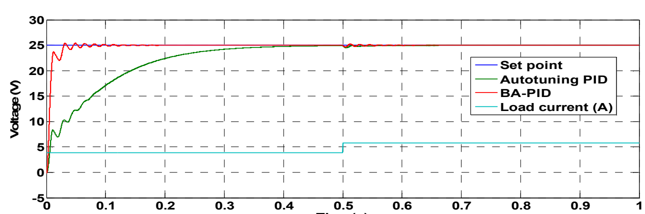

Figure 15. Load regulation of SEPICC Step change of load current from 3. 88A to 5.76A

For all the test cases under study the proposed controllers performed, the output voltage under the load regulation (3.88 A to 5.76 A) and line regulation when converter line voltage changed from 29.3V to 33V it is almost shown that when the reference voltage variation occurs whether the reference voltage goes down or up the output voltage remains constant according to the reference value. The function of the PID controller is modifying the duty cycle based on the step changing in the reference voltage wave. Moreover, it's not affected if the input voltage changes and load disturbance conditions. It's obvious from observing the output voltage waveform, that the performance is enhanced, which confirms that the controller is suitable. Figure 14 shows the comparison in dynamics performance of output response at different cases study.

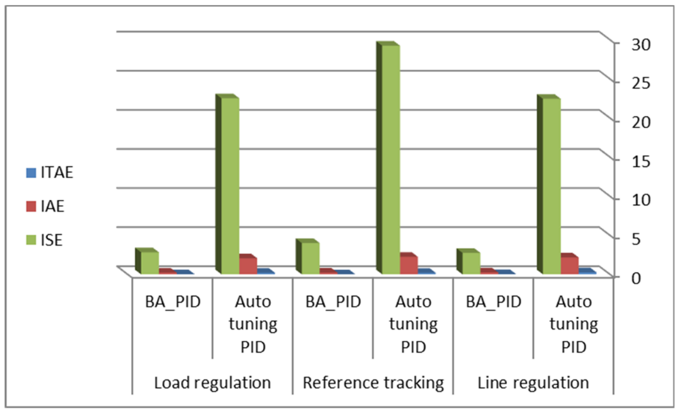

Figure 14. Controllers performance evaluation analysis

The simulation results provide important information about the dynamic behavior of the PID converter under different current values (Auto tuning PID & BA_PID). The DC-DC converter is designed to function within the specific load and condition parameters so that the presence of outlier values in the circuit output indicates the change of the dynamic behavior from the normal. This problem can be resolved by redesigning the PID controller to generate a constant voltage output of 24V and an input range of between 1-36V for improved stability and non-linearity of the SEPIC controlled converter. The computation of PID controller values is based on integral, derivative, and proportional value parameters that determine the process control action based on BA. Factors such as the capacitor and inductor resistance have a significant influence on the converter efficiency thus creating the need for using tuning the SEPIC converter to simulate continuous induction. The PID controller allows for the generation of PWM pulses required in the error minimization within the SEPIC converter through the application of duty cycle to eliminate the input-output variations. The system performance is also enhanced by tuning the PID controller to allow for multidimensional functionality based on the load disturbance parameters in the bat algorithm. However, high capacitor values are required in the SEPIC converter to promote a reduction in the response speed for the expansion of the input-output range. The PID controller functions to regulate the variation between the desired output values and the actual process value in order to generate a constant output voltage.

5. CONCLUSION

The voltage is being changed by SEPIC from positive source voltage to positive load voltage. By the reason of the time changing and switching nature of the power converters and the high non-linearity of the dynamic behavior of these converters. In this paper, a PID controller was developed to SEPIC converter, and the performance of the system was examined when the reference output voltage is changing. This study confirms that using a PID controller to the SEPIC converter is successful in design, analysis, and convenience, which operated as a step-down and step-up voltage regulator. Coefficient of PID calculated using BA algorithm on MATLAB computer software for load and line regulation. BA-PID has satisfactory results for regulation the output voltage. Consequently this proposed converter can be employed to different industrial applications.

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