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Optimizing PI Controller for SEPIC Converter with Optimization Algorithm

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Abstract: This paper refers to work evaluating the performance of PI controllers integrated with optimization techniques designed for Single Ended Primary Inductance Converters (SEPIC). With the SEPIC converter, a constant voltage output can be retained while switching a range of dc voltages. Performance of PI controller has been combined with Artificial Bee Colony (ABC) Algorithm, Particle swarm optimization (PSO) Algorithm, Whale optimization algorithm (WOA). In this research, a performance analysis of the SEPIC dc-dc converter controller constructed with the aforementioned optimization strategies is carried out. Statistics proves WOA provides best stability exhibited with fast response when compared to other optimization techniques.

Index Terms: PI Controllers, Optimization, SEPIC, Artificial Bee Colony, Particle Swarm Optimization, Whale Optimization Algorithm.

1. Introduction

It is in need of a system that can step up and down the variable/fixed input DC voltage to the appropriate value depending on demand since renewable energy sources (RESs) like solar energy, wind energy, etc. are intermittent. The implementation of conventional converters with a Buck, Boost, or Buck-Boost configuration in conjunction with RESs has been widespread, although these have significant drawbacks. Pulsating input and output power, high switching losses, fabrication costs, and rating restrictions are a few of these [1]. As a result, sophisticated power converters have been developed to minimizing the ripple. The Cuk Converter, devised by Slobodan Cuk, stands out among other converters since it not only has continuous input and output currents and it also has the ability to perform in buck and boost modes by only changing the duty cycle for the circuit's single switch. Its distinct feature from other converters is its inverted output characteristic. On the other hand, high electrical stress is imposed on the electrical components during the functioning of both Cuk and buck-boost converters, which could culminate in component malfunction or overheating. SEPIC converters are able to address both of these problems. In fact, SEPIC converter helps to get non-inverted output that benefits circuits from uninterrupted and precise input.

2. Literature Review

In order to adhere to design specifications, it is important to control the input to specific sub-circuits [2]. While a converter can easily convert AC to AC, it is more challenging to convert DC to DC. Voltage bridges and diodes can reduce voltage to a certain extent; however, they are inefficient. A reference voltage can be provided via voltage regulators. Furthermore, as batteries deplete, their voltage drops, which can cause a slew of issues if there is no voltage management. There are five different kinds of dc-dc converters: First, there are Buck converters, which can only lower voltage; next, boost converters that can only raise it; finally, Cuk and SEPIC converters can perform both functions [3].

As per the application, suitable converter can be used for need bucking and boosting of voltage. It is possible, though, for the targeted output voltage to frequently fall within the input voltage range. In this circumstance, use of a converter that can regulate the voltage is the best alternative. Buck-boost converters can be less efficient since they only need one inductance and one capacitor [4]. On the other side, these converters have a lot of input current ripple. This ripple can create harmonics, necessitating the use of a large capacitor or an LC filter in many circumstances. As a result, the buck-boost is frequently costly or ineffective. Another difficulty with buck-boost converters is that they reverse the voltage. This can make them difficult to operate. Cuk converters use an additional capacitor and inductor to alleviate both of these issues. Since power converters are non-linear time-varying systems, designing controllers for systems always provides both intriguing and challenging problems [5]. The presence of duty ratio in the converter dynamics poses a considerable issue even though the most of converters can be controlled by a single switch. The development of power MOSFETs has made switching speeds of tens of megahertz attainable. On the other hand, two of the main problems with semiconductor devices associated with high switching frequency are high switching stress and switching loss.

Some of the references have been presented in Table 1as given below:

Table 1. Summary of review in the relevant area.

Reference	Year	Authors	Objective	Contribution	Methodology Used
[6]	2021	Meng Zhang, Ningfan Zhong and Mingyuan Ma	Sliding mode control of a photovoltaic system with a SEPIC converter	The suggested method varies from previous methods in that it uses the circuit output voltage in a closed-loop system to increase the control impact of the controller.	Photovoltaic system; SEPIC converter; maximum power point tracking; sliding mode controller
[7]	2021	Tewodros Gera Workineh, Elias Mandefro Getie, Abraham Hizikiel Nebey and Biniyam Zemene Taye	PV-fed small scale irrigation DC pump control using a PI-like fuzzy based synchronous SEPIC converter	The purpose of this research is to build a single-ended primary inductive converter with a fuzzy controller that works similarly to a PI.	PV feed small scale irrigation; PI-like fuzzy; Synchronous SEPIC
[8]	2016	M. Quamruzzaman, Nur Mohammad, M.A. Matin and M.R. Alam	For solar power systems, a DC–DC coupled inductor single-ended primary inductance converter provides very efficient maximum power point tracking.	This research looks at the performance of a single-ended primary inductance converter with connected inductors for maximum power point tracking (MPPT) in a PV system. Stability, current ripple reduction, and efficiency under varied operating conditions were used to evaluate the performance.	MPPT, DC–DC converter, current ripple, and linked inductor are all terms that can be used to describe photovoltaic power.
[9]	2020	Salam Ibrahim Khather, Muhammed A. Ibhrahim	Using a PID controller, model and simulate a SEPIC controlled converter.	The uncontrolled and regulated SEPIC converters' simulated behavior is presented in this work. A PID controller based on the bat algorithm (BA) optimization approach is used to find the optimal Proportional–Integral–Derivative (PID) gains.	SEPIC, Bat algorithm, DC-DC converter, Performance index PID controller, Performance index PID controller
[10]	2020	Ali Mohsin Kaittan, Aws Mahmood Abdullah , Mustafa Sabah Taha	The whale optimization approach was used to test the stability of a traditional sliding mode controller	The proposed research uses a single inverted pendulum as the research model to investigate the stability of a nonlinear system using a whale optimization method as one of the meta-heuristic optimization approaches	Conventional sliding-mode controller (CSMCR), Reaching stage, Sliding stage, whale optimization algorithm

3. Design of Single-ended Primary-inductor (SEPIC) Converter

SEPIC converters are single-ended primary-inductor devices that increase or decrease the input voltage using a boost control approach. A SEPIC is equivalent to a conventional buck-boost converter release of charge since converter can be considered as just a boost accompanied by an inverted buck-boost [1, 2]. When it comes to SEPIC converter operation, all dc-dc converters use a high frequency pulse to turn on and off a MOSFET. Resistances in inductors and capacitors can have a significant impact on converter efficiency and output ripple. Lower series resistance inductors allow less energy to be dissipated as heat, resulting in higher efficiency. When the input voltage is high and the MOSFET is turned on, the inductor L2 is charged along with the capacitor C1 and inductor L1. While the diode is off, capacitor C2 aids in preserving the output. The inductors are output to the load via the diode when the MOSFET is turned off as the pulse is low, charging the capacitors in the process. The output will be bigger if the pulse is low for a larger proportion of the duty cycle. The SEPIC converter's design is carried out in MATLAB. The entire design has been separated into two parts: a SEPIC converter and a PI controller.

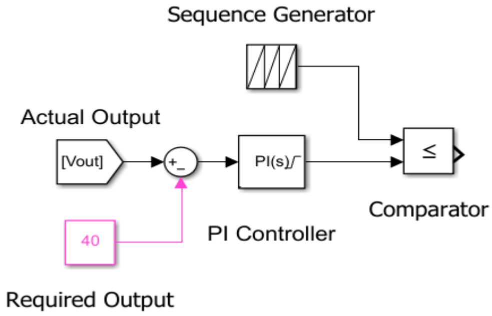

Fig.1. PI Controller MATLAB Model.

The Second part is that of PI controller has been shown in Fig. 1. The input to PI controller is the deviation from required output; this is calculated by subtracting the Actual value from required value. The output of the PI controller is given to a comparator, where the output of PI controller and Sequence generator's value is compared, if the PI converter's value is less than the sequence generator then the output is high (MOSFET On) and if not it goes to low (MOSFET Off). The complete Design of SEPIC and PI controller can be seen in Fig. 2.

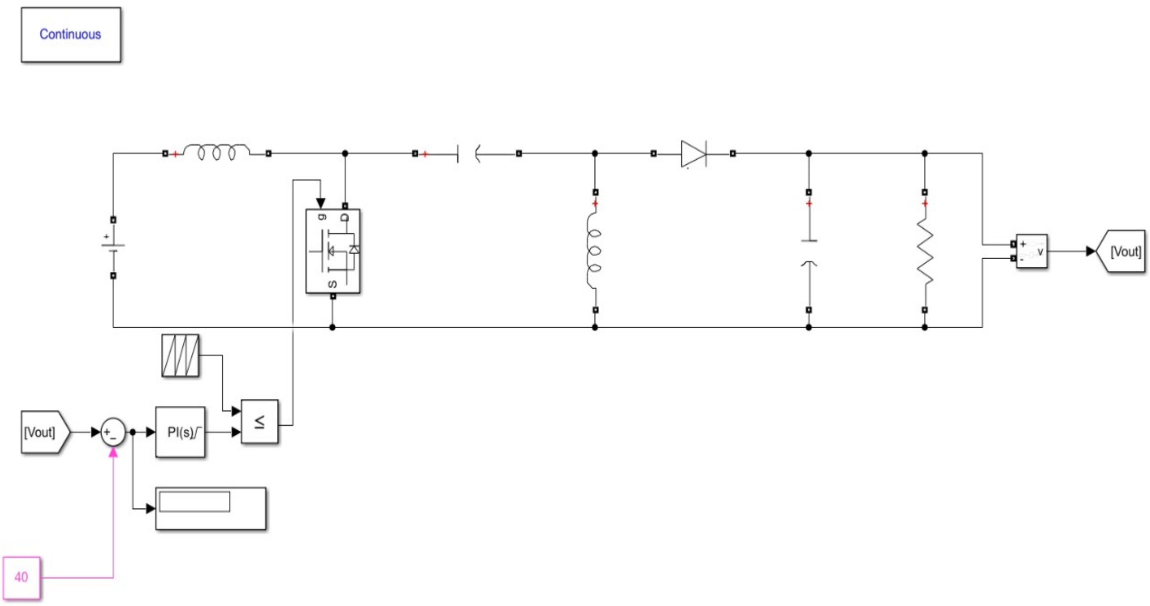

Fig.2. The complete design of SEPIC and PI controller.

4. Methodology Used

The optimization technique has received prominence in the last two decades due to its diverse optimal proficiency for both continuous and discrete evolutionary algorithms, including its ability to adapt to environmental changes and high eminence solutions. Many algorithms are derivative free stochastic optimization based on natural selection notions [11, 12], inspired by "nature's wisdom". Its application is not confined to a particular course of study. In this work, optimization algorithms have been combined with SEPIC converter and a PI controller to achieve preferred output.

4.1. Artificial Bee Colon (ABC) Algorithm

In the ABC algorithm, the fitness function as a function of the objective function value is defined as:

$$
\begin{aligned}
fit &= \frac{1}{(1+f)}, if \quad f \geq 0 \\
&= 1+|f|, if \quad f \geq 0
\end{aligned}
\tag{1}
$$

where fit is fitness function value and f is objective function value.

It can observe that the value of the fitness function is inversely proportional to the value of the objective function. Controller designed has been addressed to minimization problem since function is an error function, and main objective is to minimize the errors. To get the solution with the highest fitness is selected it is required to get greedy selection, as is standard practice with many mathematical optimizations. Greedy selection basically means discarding the solution with lower fitness and replacing it with a solution with higher fitness. That can be presented as:

$$Y = Y_{new}; f = f_{new}; if \ fit_{new} > fit \tag{2}$$

where,

Y = current solution,

Y_{new} = newly generated solution from the optimization

f = objective function value of the solution

f_{new} = objective function value of the new solution

fit = fitness of the solution

fit_{new} = fitness of the newly generated solution

To get Employed Bee Phase a random partner is chosen to generate new solution. New solution is generated by modifying a randomly selected variable, according to the equation:

$$Y_{new}^{j} = Y^{j} + \phi(Y^{j} - Y_{p}^{j}) \tag{3}$$

where, Y^{j} is the jth variable of the current solution, Y_{new}^{j} is the jth variable of the new solution, Y_{p}^{j} is the jth variable of the pth solution and ϕ is a random number between -1 and 1.

If the new solution is superior to the existing one, it should be used instead. Create a trial vector that contains just zeroes and grows by one each time an iteration fails to produce a better answer if the current one isn't any better. The trial counter is reset to zero on a failure if a better solution would then be generated.

Onlooker Bee Phase is the probability attached to a certain food source given by:

$$0.9 * (fit / \max(fit)) + 0.1 \tag{4}$$

fit = fitness of the solution (food source) and max (fit) is the maximum fitness of all the food sources taken into account.

Scout Bee Phase is solutions with trial value greater than the limit will be sent and discarded, and the entire solution will be replaced by a new random solution.

Using artificial life theory, five key ideas can be used to build swarm artificial life systems with cooperative behavior [13]:

Proximity: Simple chronological and geographical calculations should be possible for the swarm.
Quality: The swarm should be capable of recognizing changes in the surroundings' quality and responding to them.
Diverse response: The swarm shouldn't confine its resource-finding to a certain location.
Stability: In reaction to changes in the environment, the swarm's behavior mode shouldn't change.
Adaptability: When it is suitable, the swarm should modify its behavior when it is appropriate to do so.

4.2. Particle Swarm Optimization (PSO) Algorithm

Since they contain the essential characteristics of artificial life systems, these five concepts have served as the swarm artificial life system's guiding principles. PSO can be adjusted to satisfy the proximity and quality requirements by allowing particles to shift their locations and velocities in response to environmental changes. In PSO, the swarm does not impose any mobility restrictions and instead searches for the ideal resolution in the available solution space. While maintaining constant mobility, PSO particles can modify their mode of travel in response to environmental changes. PSO, which imitates how a flock of birds chooses where to settle, is one such technique. This location will be chosen so that the risk to food availability ratio is kept to a minimum [13].

For ith particle, the velocity and position can be updated using below equation:

$$\begin{aligned} v_{t+1}^{i} &= wv_{t}^{i} + c_1 r_1^{i}(pb^{i} - y_{t}^{i}) + c_2 r_2^{i}(Gb - y_{t}^{i}) \\ y_{t+1}^{i} &= y_{t}^{i} + v_{t+1}^{i} \end{aligned} \tag{5}$$

where,

$v_t^i \; y_t^i$: Velocity of ith iteration

y_t^i : Position of ith iteration

c_1 : Cognitive Parameter

c_2 : Social parameter

pb^i : ith particle best solution

Gb: Global Best solution of swarm

4.3. Whale Optimization Algorithm

The algorithm is based on the three distinct humpback whale behaviors [14, 15]. Prey detection and encirclement are skills possessed by humpback whales. The WOA algorithm indicates that the target prey or a very close neighbor is the best candidate solution at this time. Based on the criteria for the best search agents will try to attempt to adapt their locations in order to align with that agent. The following is a representation of this behavior:

$$\hat{D} = \left| \hat{C}\hat{Y}^*(t) - \hat{Y}(t) \right| \tag{6}$$

$$\hat{Y}(t+1) = \hat{Y}^*(t) - \hat{A}\hat{D}$$

where,

t= current iteration

$\hat{A}, \hat{C}$ = coefficient vectors and $\hat{Y}$ = position vector

$\hat{Y}^*$ = best solution of position vector

The vectors $\hat{A}, \hat{C}$ are calculated as: $\hat{A} = 2\hat{a}\hat{r} - \hat{a}$ and $\hat{C} = 2\hat{r}$, $\hat{r} \in (0,1)$

Exploitation Phase that mimics the bubble-net behavior of humpback whales as: shrinking encircling process and Spiral updating location. Additionally, $\hat{A}$ fluctuation range is reduced by $\hat{a}$. In between initial location and current best location search agent locate the new location. While Spiral updating location, the distance between the whale and the prey, which are respectively located at (Y, Z) and (Y^*, Z^*), is computed. The following spiral equation is then generated between the locations of the whale and the prey as:

$$\hat{Y}_{(t+1)} = \hat{D}' e^{bl} \hat{\cos}(2\pi l) + \hat{Y}^*_{(t)} \tag{7}$$

where $\hat{D}' = \hat{Y}^*_{(t)} - \hat{Y}_{(t)}$ indicates the distance of the ith whale to the prey

$\hat{A}$ is utilized with random numbers higher than or less than 1 in this example to drive the search agent to move away from the reference whale. In this technique, as $|\hat{A}| > 1$, encourage exploration and enable the WOA algorithm to do a worldwide search. The following is the mathematical model:

$$\hat{D} = \left| \hat{C}.Y_{rand} - \hat{Y} \right| \tag{8}$$

$$\hat{Y}_{(t+1)} = Y_{rand} - \hat{A}\hat{D} \tag{9}$$

where,

Y_{rand} are a random location vector (a random whale) chosen from the current population [14, 16].

5. Simulation Results

To achieve the desired output, the optimization algorithm-based work has been integrated into the SEPIC converter. The objective function has been depicted as follows:

The objective function shown in Fig. 3, which is a real-valued function in a mathematical optimization problem, is a value that needs to be minimized or maximized over a set of possible. It is the absolute sum of errors in the design. It is determined by subtracting the actual output from the desired output. By minimizing the objective function, the goal is to get the output closer to the desired values. Optimized values of controller have been shown in Table 2. Fig.4 represents the desired output of SCIPIC converter has been kept 40 Volts and with different algorithms output responses have been collected. Performance of these algorithms can be evaluated based on the transient response characteristics. The ripples and larger values in the ABC and PSO algorithms are indications of the design error, respectively. When Kp and Ki values are compared, it is clear that ABC and PSO have far higher Ki values than WOA does. As a greater value of Ki results in design instability, which may induce ripples in the output, this may be the main cause of the ripples. The ripple error could be dealt by modifying the algorithm and making it better in finding the solution as can see that WOA has overcome this problem. Performance of optimization techniques implemented to SCIPIC converter has been carried out based on time domain responses presented in Table 3.

```
function [J] = pid_optim(x)
s = tf('s');
plant = tf((15*s^2)/(((2.25e-8)*s^4 + (1500e-6)*s^3 + (18)*s^2 + (1e5)*s + (1e8))))

Kp = x(1);
Ki = x(2);

cont = tf(Kp + Ki*(1/s));

dt = 0.001;
t = 0:dt:100;

opt = stepDataOptions;
opt.StepAmplitude = 20;

% Optimization Function
e = 40 - step(feedback(plant*cont,1),opt,t);
J = (sum(t'.*abs(e)*dt));
```

Fig.3. MATLAB Code of Objective function.

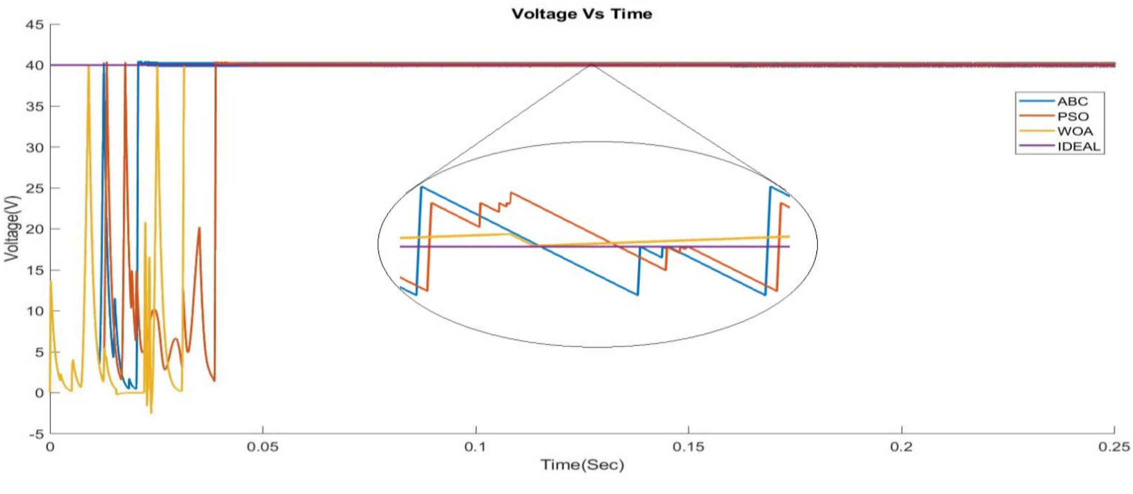

Fig.4. Voltage Vs Time.

Table 2. Optimized parameters.

Optimization Techniques	Kp	Ki	Error
ABC	1.99	498.15	0.1711
PSO	2.4579	478.1917	0.1625
WOA	17.1824	3.715	0.449

Table 3. Time Domain Response.

Optimization Technique	Overshoot (%)	Rise Time(μs)	Settling Time (ms)
ABC Algorithm	1.296	746.084	116.678
PSO Algorithm	1.320	621.885	82.831
WOA	0.532	832.117	157.708

6. Conclusions

The SEPIC converter topology offers advantages over other topologies owing to its simple construction and minimal component requirements. It enables the electrical potential (voltage) at the device's output to be greater than, lower than, or equal to the voltage at the input. Performance can be improved with specific output can be handled optimization techniques like ABC, PSO and WOA without any change in the components of the SEPIC converter. All three optimization algorithm is giving a satisfying output which is closer to ideal output. ABC and PSO algorithms output has a large ripple value as compared to WOA. On comparing the results based on rise time and settling time PSO is giving a better result. WOA has the least overshoot and ripple value but its settling time is slightly more than PSO. WOA exhibited the fastest reaction and the best stability when compared to other optimization techniques and least standard error.

Conflict of Interest

The authors declare no conflict of interest.

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