**CUK Converter for Power Factor Correction Using Moth Flame Optimization-PI Controller**

Adinda Aisyah Pratiwi¹, Moh. Zaenal Efendi², Farid Dwi Murdianto³

¹,²,³Department of Electrical Engineering, Politeknik Elektronika Negeri Surabaya, Indonesia

¹adindaaisyah98@gmail.com, ²zen@pens.ac.id, ³farid@pens.ac.id

**Abstract.** Electronic equipment in household loads in the form of non-linear loads that require a circuit that requires a power supply in the form of a direct voltage (DC) that requires an AC to DC rectifier in the form of a full-wave rectifier. However, the installation of capacitor values in the circuit can cause the waveforms of the input current to become uneven or distorted so that the emergence of harmonics which results in a low power factor with the improvement of the power factor. It affects the output voltage to the load so we need control for the voltage regulator. The solutions to overcome the problem of input current defects can be overcome using a power converter used as a PFC. In this paper, CUK Converter used as PFC is expected to get close to 1 (one) results in increasing power factor and the need for a voltage regulator to regulate the voltage requirements for loads that are utilized by the Moth Flame Optimization algorithm method - PI method. This CUK Converter functions in DCM (Discontinuous Conduction Mode) which makes the system resistive. In conclusion from the results of simulations that have been done, the results obtained from the use of CUK Converter as PFC can improve the power factor from pf value 0.731 to 0.994 and with MFO-PI control it can maintain a constant output voltage of 12 volts with a current of 5 amperes.

1. Introduction

In electric power systems, there are two types of electrical loads called linear load and non-linear load. The load is called linear if the current is directly proportional to the load voltage and causes the current waveform to be the same as the waveform of the load. However, in non-linear loads, the current waveform is not the same as the voltage waveform or the distorted current waveform. The non-linear load that is commonly used in electrical equipment is one of them in the form of a diode rectifier circuit that will result in a non-pure sine input current. Non-sine currents indicate harmonics. Whereas at the household load it is often needed a series of diode rectifiers, namely electronic equipment such as television, computers, and others. With the use of a diode that causes the current wave to be distorted, this results in a low power factor value.

To overcome the high harmonic problem and increase the power factor of the rectifier circuit, one can be done by adding a converter that is used as Active Power Factor Correction (PFC) [1]. Adding a converter to the circuit can improve the input current so that it is sinusoidal in shape, a power factor closes to one, and low harmonics (according to international standards, IEC1000-3-2) [2][3]. The DC-DC converter circuit to improve the power factor that is often used is the Buck Converter, Boost Converter and Buck-Boost Converter [4-7]. The most popular converter among PFC converters is the boost converter, but the output voltage is higher than the peak supply voltage [8].

In this paper, a research was made on improving power factors using two converters in the form of CUK Converter and Buck Converter. CUK Converter is used as a PFC and Buck Converter is used as a voltage regulator. The CUK Converter can overcome the weakness of the Boost Converter in terms of noise that EMI usually does [9]. CUK Converter which is used as a PFC must have a resistive or near resistive impedance. For the use of CUK Converter as PFC, it is operated in a non-continuous condition or Discontinuous Conduction Mode (DCM) [10]. When the rectifier circuit is connected and supplies a
resistive load, the load current that flows back to the source has a sine waveform and resembles the input voltage waveform so that its power factor value approaches 1 (unity). Buck Converter is operated as a voltage regulator that serves to maintain the stability of the output voltage which is controlled using the Moth Flame Optimization-PI Controller method. The first Moth Flame Optimization method was developed by Mirjalili. This method is based on the moth navigation method in nature. Moths fly at night while maintaining a fixed angle to the moon, which is an effective mechanism for reaching straight lines at great distances [11]. Intended this method is used to find the fitness value used on the PI controller which later with the combination of the algorithm with the controller will be able to maintain the stability of the output voltage connected to the load.

2. Modelling and Design of DC-DC CUK Converter

2.1. CUK Converter as Power Factor Correction Converter

CUK Converter is a type of DC-DC converter which is a perfect complement of Buck-Boost Converter. The converter can increase and decrease the voltage and have negative polarity [12]. The CUK Converter circuit can be seen in Figure 1. The inductor on the input side works as a filter on the DC supply to prevent harmonics.

![Figure 1. CUK Converter Circuit](image)

The switching topology of the DC-DC CUK Converter circuit is shown in Figure 2 (a) and (b) [13].

![Figure 2. (a) CUK Converter is ON condition (b) CUK Converter is OFF condition](image)

In the on the condition, the switch is closed so that the current is passed, the diode does not work, and the Ci capacitor is discharged by the current from the Lo inductor. When the condition is off, the switch is open so that the diode flows currently from the Li and Lo inductors. In a state of shutdown, capacitors are also needed by the current from the Lo inductor.

To be operated as a PFC, a CUK Converter must have a resistive or near resistive impedance. CUK Converter is operated in DCM conditions, having an input current (I_{in}) expressed in Equation 1

\[
I_{in(t)} = \frac{D^2 T}{2L_1} \left( \frac{e}{e_{vci}} \right) \left( 1 - \frac{e}{vci} \right) \tag{1}
\]

The input impedance value is expressed in Equation 2:

\[
Z_{in(t)} = R_{in} + jX \tag{2}
\]

From a reactance value of less than one, the reactance value can be ignored in Equation 3 and Equation 4, thus:

\[
Z_{in(t)} = R_{in} \tag{3}
\]
Then the input resistance value can be stated in Equation 5:

\[ r_{it} = \frac{2L_o}{D^2T} \left(1 - \frac{e}{vc_1}\right) \]  \hspace{1cm} (5)

If value \( \frac{e}{vc_1} \ll 1 \) then the input resistance value becomes:

\[ r_{it} \approx \frac{2L_o}{D^2T} \]  \hspace{1cm} (6)

From Equation 6 it can be seen that the value of input resistance depends on the value of the inductor, duty cycle, and switching period. If the duty cycle value is constant then the input resistance value will also be constant. The input current will follow the shape of the input voltage. Then, there will be a reduction in harmonics on the input side. There will also be an improvement in the power factor.

2.2. Design PFC DC-DC CUK Converter

The following designs for PFC DC-DC CUK Converter are shown in Table 1.

| Variable                 | Value               |
|--------------------------|---------------------|
| Input Voltage (\( V_i \)) | 99.03 V             |
| Output Voltage (\( V_o \))| 50 V                |
| Output Current (\( I_o \))| 0.9615 A \( \rightarrow \) 1.5 A |
| Switching Frekuensi (\( f_s \))| 100 kHz            |
| Ripple Input Current     | 10%                 |
| Ripple Output Current    | 11%                 |
| Power                    | 66 W                |
| Inductor Input (\( L_1 \))| 760\( \mu \)H      |
| Capacitor Input (\( C_1 \))| \( \geq 0.59\mu\)F |
| Inductor Output (\( L_2 \))| 750\( \mu \)H      |
| Capacitor Output (\( C_2 \))| \( \geq 5.1\mu\)F |
| \( k \)                  | 0.9393              |
| \( L_m \)                | 1.5424 mH           |

The rating of inductors and capacitors can be found by following equation[14].

\[ L_2 = \frac{V_o.(1-D)}{f_s.(\lambda_1 i_1 + \lambda_2 i_2)} \]  \hspace{1cm} (7)

\[ L_m = L_2 \]  \hspace{1cm} (8)

\[ L_1 = \left(V_s - \frac{L_m \lambda_2 i_2 f}{D} \right) \times \left(\frac{D}{\lambda_1 i_1 f}\right) \]  \hspace{1cm} (9)

\[ k = \frac{\sqrt{L_2}}{L_1} \]  \hspace{1cm} (10)
\[
C_2 \geq \frac{1-D}{(\Delta V_o / V_o) 8L_2 f^2}
\] (11)

\[
C_1 \geq \frac{V_o D}{Rf \Delta V_{c_i}}
\] (12)

2.3. Operation and Design of Voltage Regulator Buck Converter

Buck Converter is a type of DC-DC converter that works to reduce voltage or step down by setting the duty cycle [15]. Shown in Figure 3.

*Figure 3. Buck Converter Circuit*

Buck Converter can produce a maximum voltage value equal to the input voltage. In this paper, the Buck Converter is used for voltage regulators connected to the load, following the design of the Buck Converter in Table 2.

**Table 2. Design Buck Converter for voltage regulator**

| Variable                      | Value            |
|-------------------------------|------------------|
| Input Voltage (V_s)           | 65 V             |
| Output Voltage (V_o)          | 12 V             |
| Output Current (I_o)          | 4.167 A → 5 A    |
| Switching Frekuensi (f_s)     | 100 kHz          |
| Ripple Current                | 12.5%            |
| Ripple Voltage                | 0.1%             |
| Daya                          | 66 W             |
| Inductor (L)                  | 139.669µH        |
| Capacitor (C)                 | 65.104µF         |

The rating of inductors and capacitors can be found by following equation [16].

\[
L = \left( \frac{1}{f_s} \right) \times (V_i - V_o) \times \left( \frac{V_o + V_f}{V_i + V_f} \right) \times \left( \frac{1}{\Delta I_L} \right)
\] (13)

\[
C_o = \frac{\Delta i_L \times T}{8\Delta V_o} = \frac{\Delta i_L}{8 \times f \times \Delta V_o}
\] (14)
3. Closed Loop Control Scheme and Design of Controller

3.1. Closed Loop Scheme of Proposed Method

This section explains about the closed control system of PFC CUK Converter by using the Moth Flame Optimization-PI. Shown in Figure 4.

![Figure 4. PFC CUK Converter circuit configuration with Moth Flame Optimization-PI Controller](image)

The input source from PLN is derived using a step-down transformer. Then, the AC source is converted to a DC source bypassing the bridge rectifier diode. The output of the rectifier circuit is a DC voltage which will be the input voltage of the CUK Converter which functions as a PFC. To make a converter as a PFC, the converter must be operated as if it is resistive. The converter must be operated in DCM (Discontinuous Conduction Mode), then connected to the Buck Converter voltage regulator. The voltage regulator will be kept constant at 12 volts. To maintain a constant voltage MFO-PI (Moth Flame Optimization-PI) is used. MFO here is used to determine the optimal value of the PI which will be used to control the output voltage.

3.2. Design Moth Flame Optimization-PI

The Moth Flame Optimization (MFO) algorithm is an algorithm adapted from the lateral movement of moths around bright objects such as candles, which are found in nature [20]. This MFO was first proposed in 2016 by Mirjalili [11]. In this MFO algorithm moth and flame are the main roles and both are considered as a result of this algorithm. However, there is a difference between the way they are updated through each iteration. Moths are search agents (e.g. they are parameter values of problems) and the flame is the best position of moths throughout the search space (it can be assumed that moths embed the best solution they obtained using flame) [17]. Because the MFO algorithm is a population-based algorithm, here is a matrix representing the population of Moth:

\[
M = \begin{bmatrix}
m_{1,1} & m_{1,2} & \cdots & m_{1,d} \\
m_{2,1} & m_{2,2} & \cdots & m_{2,d} \\
\vdots & \vdots & & \vdots \\
m_{n,1} & m_{n,2} & \cdots & m_{n,d}
\end{bmatrix}
\]  

\( n \) = Number of Moth
\( d \) = Number of variables (dimension)

For all Moth, it is assumed that an array to store the values match, as follows:

\[
OM = \begin{bmatrix}
OM_1 \\
OM_2 \\
\vdots \\
OM_n
\end{bmatrix}
\]
Another component in the proposed algorithm is Flame. This matrix is considered similar to the Moth matrix which is as follows:

\[
F = \begin{bmatrix}
FL_{1,1}, & FL_{1,2}, & \ldots, & FL_{1,d} \\
FL_{2,1}, & FL_{2,2}, & \ldots, & FL_{2,d} \\
\vdots & \vdots & & \vdots \\
FL_{n,1}, & FL_{n,2}, & \ldots, & FL_{n,d}
\end{bmatrix}
\]  

(17)

\[n = \text{Number of Moth} \]
\[d = \text{Number of variables (dimension)}\]

It is known that the dimensions of the arrays M and F are the same. For the Flame, it is assumed that it is in the form of arrays to store matching values, as follows:

\[
OF = \begin{bmatrix}
OFL_1 \\
OFL_2 \\
\vdots \\
OFL_n
\end{bmatrix}
\]  

(18)

The flowchart of the MFO algorithm is shown in Figure 5.

**Figure 5.** Flowchart Moth Flame Optimization [17]
To get the optimal value of PI control using *Moth Flame Optimization*, needed a limit of \( K_p \) and \( K_i \) values [18].

\[
\begin{align*}
K_p^{\text{MIN}} &\leq K_p \leq K_p^{\text{MAX}} \\
K_i^{\text{MIN}} &\leq K_i \leq K_i^{\text{MAX}}
\end{align*}
\] (19)

MIN = for the minimum value of the gains
MAX = for the maximum value of the gains.

In this process, the MFO algorithm is used to enhance the PI controller to control the working of the *Buck Converter* voltage regulator. This simulation is done with many Moth populations of 50 and many iterations of 500.

In Figure 6, is a toolbox from *Moth Flame Optimization* to find fitness values from \( K_p \) and \( K_i \) with predetermined parameters.

4. Simulation Result and Discussion

The proposed PFC *CUK Converter* is designed with DC-DC *CUK Converter* operated in DCM (*Discontinuous Current Mode*) mode which is directly connected to the rectifier output with a *CUK Converter* input of 99V and by connecting directly to the voltage regulator in the form of *Buck Converter* which is used to stabilize output voltage using the MFO-PI Controller (*Moth Flame Optimization - PI Controller*) control. By using a 100kHz switching frequency. The proposed method is expected to get the optimal value of the \( K_p \) and \( K_i \) parameters that will be used to control the voltage regulator system. And for series images can be seen in Figure 7.
Figure 7. Describes the simulation image of the whole system consisting of a CUK Converter as a Power Factor Correction (PFC) and a Buck Converter as a voltage regulator controlled using Moth Flame Optimization - PI Controller which in the MFO optimization algorithm uses a toolbox and is used to adjust the output voltage to be stable at 12 Volts with Kp and Ki settings on the PI controller toolbox.

Figure 8. (a) shows a 110V AC source voltage waveform and (b) shows an input current waveform distorted due to being connected to a 1 phase full-wave rectifier. Non-sine input waveforms due to the harmonic current content of the input current [19]. The distortion in the input current in Figure 8.(b) below is caused by the installation of a filter capacitor on the rectifier output side which causes the input current to flow when the capacitor is charging. So that the waveform becomes pulsating as a result the distortion factor does not approach 1(unity) but approaches 0. Which causes the pf to below.

Figure 8. (a) Source Voltage Waveform (b) Input Current Waveform without PFC CUK Converter at source voltage 110V

Figure 9. (a) Source Voltage Waveform (b) Input Current Waveform with PFC CUK Converter at source voltage 110V

Figure 9. shows the source voltage and input current wave connected to the PFC CUK Converter. Based on data obtained with 110V input voltage that the THD value of 1.58% is shown in Figure 10. In Figure 9 it can be observed the difference in the input current wave current before PFC installation and after PFC installation. When after the existence of the PFC circuit, the input current wave approaches sinusoidal so that the distortion factor approaches 1 and the displacement factor approaches 1 so that the pf value approaches 1. So that by installing the PFC circuit, the harmonic spectrum contained in the input current waveform becomes low or close to 0, the harmonic content is small.
Figure 10. Input Current Waveform and Harmonic Spectrum at a Source Voltage of 110V

Figure 11. shows the output voltage and output voltage waves with Vo values of 12 Volts and Io of 5 Ampere according to load requirements. The results of the simulation on the Buck Converter voltage regulator using the Moth Flame Optimization-PI Controller method can successfully control the output voltage by the set point. With the Moth Flame Optimization-PI Controller with various load changes, the output voltage and bias current remain constant according to the set point of 12Volt and 5 Ampere.

Figure 11. Output Voltage and Output Current Waveform at a source voltage of 110V

Figure 12. (a) Source Voltage Waveform (b) Input Current Waveform with PFC CUK Converter at Source Voltage 220V

Figure 12. represent the waveform when the source voltage changes with a value of 220Vrms. Figure 14. displays the current harmonics spectrum and obtained THD of 1.61%. Figure 13 is the output voltage waveform and input current when the source is 220V.
Figure 13. Output Voltage and Output Current Waveform at a Source Voltage of 220V

Figure 14. Input Current Waveform and Harmonic Spectrum at a Source Voltage of 220V

Figure 15 is a comparison of class D harmonics with the comparison when using the CUK Converter. It can be seen that this converter repairs or reduces harmonics components so as to increase the value of the power factor.

Figure 15. Comparison of class D harmonics with converter current harmonic testing
Table 3. shows the comparison after and before the installation of the CUK Converter with the total harmonic current distortion (THDi) value and the power factor (pf) value. It can be observed that the value of pf generated by the installation of a CUK Converter is equal to 0.98 and 0.99 which is affected by the current wave approaching or already the same as the voltage waveform in the form of sinusoidal. And THD values are 1.58% and 1.61% which are relatively small harmonic components.

| Performance  | Without PFC CUK Converter | With PFC CUK Converter |
|--------------|---------------------------|------------------------|
|              | 110V                      | 220V                   |
| THDi         | 5.7 %                     | 1.58%                  | 1.61%                  |
| Power Factor | 0.731                     | 0.994                  | 0.982                  |

5. Conclusion

The simulation results that have been submitted in this paper that discuss CUK Converter as PFC and with Moth Flame Optimization-PI for voltage regulators. This simulation experiment was conducted with MATLAB / Simulink and PSIM software by existing simulation results. From this design, the value of the power factor obtained using the CUK Converter can increase to 0.99 with a THD value of 1.58% and meet class D, IEC 61000-3-2 standards and for the utilization of the Moth Flame Optimization method that can determine the Kp and Ki is optimal, can maintain the output voltage according to the design.

References

[1] N A Bachok, M R Sahid and J A Aziz 2015 Bridgeless SEPIC Power Factor Correction with Coupled Inductors (Johor Bahru: IEEE Conference on Energy Conversion (CENCON)) pp 160-164
[2] Electromagnetic Compatibility (EMC) 2005 Part 3-2: Limits—Limits for Harmonic Current Emissions, Int. Std. IEC 61000-3-2
[3] M Z Efendi, F D Murdianto, F A Fitri, L Badriyah 2020 Power factor improvement on LED lamp driver using BIFRED converter (Yogyakarta : TELKOMNIKA) pp.571-578.
[4] U Kamnarn and V Chunkag 2009 Analysis and Design of a Modular ThreePhase AC-to-DC Converter Using CUK Rectifier Module With Nearly Unity Power Factor and Fast Dynamic Response (IEEE Transactions On Power Electronics)vol. 24 No. 8 pp. 2000 – 2012
[5] M Gotfryd January 2000 Output Voltage and Power Limits in Boost Power Factor Corrector Operating in Discontinuous Inductor Current Mode (IEEE Transaction on Power Electronics) Vol.15 No.1
[6] H Endo, T Yamashita and T Sugiura 1992 A High Power Factor Buck Converter (Toledo : IEEE Applied Power Electronics Conference) pp.1071-1076
[7] Y M Jiang and F C Lee 1993 A new control scheme for Buck+Boost power factor correction circuit (Blacksburg : Proceedings of the Virginia Power Electronics Seminar) pp. 189-193.
[8] D Wijeratne and G Moschopoulos 2011 A Novel Three-Phase Buck-Boost AC-DC Converter (Fort Worth : Applied Power Electronics Conference and Exposition (APEC), Twenty-Sixth Annual IEEE) pp 513-520
[9] F S Dos Reis, J Sebastian, J Uceda, 1993 Characterization of Conducted Noise Generation for Sepic, Cuk and Boost Converters Working as Power Factor Preregulators (Maui : IECON) pp. 965-970.
[10] N Jayaram and D Maksimovic 1998 Power Factor Correction based on Coupled-Inductor Sepic and Cuk Converter with Nonlinear-Carrier Control (Anaheim : Applied Power Electronics Conference and Exposition (APEC), Thirteenth Annual IEEE) pp 468-474
[11] S Mirjalili 2015 Know. Syst. Moth-flame optimization algorithm: a novel nature-inspired heuristic paradigm (Elsevier BV) vol. 89 pp. 228-249
[12] D W Hart 2015 McGRAW-HILL International Power Electronics
[13] M A Z A Rashid, A Ponniran, M K R Noor, J N Jumadril, M H Yatim and A N Kasiran 2019 Optimization of PFC Cuk Converter parameters design for minimization of THD and voltage ripple (International Journal of Power Electronics and Drive System (IJPEDS)) vol. 10 No. 1 pp. 514-521
[14] A Shrivastava and B Singh 2010 5th PFC Cuk converter based electronic ballast for an 18 W compact fluorescent lamp (Mangalore : International Conference on Industrial and Information Systems) pp. 393-397
[15] I Jamil, Z Jinquan and R Jamil 2013 Analysis,Design and Implementation of Zero-Current-Switching Resonant Converter DC-DC Buck Converter (International Journal of Electrical and Electronics Engineering (IJEEN)) ISSN 2278-9944 Vol.2 Issue 2 pp.1-12, 2013.
[16] Y Gu and D Zhang 2014 Voltage Regulator Buck Converter with a Tapped Inductor for Fast Transient Response Application (IEEE Transactions on Power Electronics) Vol 29 Issue 12 pp 6249 - 6254
[17] M Sharma, R K Bansal, S Prakash, S Dhundhara 2018 Frequency Regulation in PV integrated Power System using MFO tuned PIDF controller (Kurukshetra : IEEE 8th Power India International Conference (PIICON))
[18] S Chatterjee and M A Dalel, 2019 MFO Based Traditional PID Controller for Automatic Voltage Regulator (Journal of The Gujarat Research Society) ISSN 0374-8588 Vol. 21 Issue 8s pp. 736-745
[19] A ELSebaay, M Ramadan, M A A Adma 2017 Studying the Effect of Non-Linear Loads Harmonics on Electric Generator Power Rating Selection (European Scientific Journal) ISSN 1857-7881 vol.13 No.18
[20] K Kamalapathi, N Priyadarshi, S Padmanahan, J B Holm-Nielsen, F Azam, C Umayal, V K Ramachandaramurthy 2018 A Hybrid Moth-Flame Fuzzy Logic Controller Based Integrated Cuk Converter Fed Brushless DC Motor for Power Factor Correction (Article Electronics MDPI) pp 1-19