Comparison of Fractional Order Proportional Integral and Proportional Integral Controllers for super-lift Luo converter

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Abstract. Today, as a result of the immense applications which are used the ac-dc then step down voltage by using dc-dc converter such as the charger of mobile as well as for using the power produced from wind and solar power plants. The present work recommends the hypothesis and utilization of the fractional order proportional integral (FOPI) controller to manage and control the suggested super-lift Luo converter. Super-lift Luo converter is considered as modern technology converter which has numerous points of interest over different converters which are introduced in the literature. Fractional order proportional integral is contrasted with traditional proportional integral (PI) to demonstrate the capability of this controller to improve the rendering of the super-lift Luo converter. Various determinations for the response have been likewise estimated in this paper. At last, the FOPI is examined with different estimations of λ and the better worth is chosen. Matlab/Simulink R2017a has been utilized as a simulation software for all the results.

Keywords: Super-lift Luo converter, fractional order PI controller, duty cycle, time specifications

1. Introduction
Beside its use in photovoltaic (PV) system, DC-DC converter is considered the most commonly used in computer hardware and modern applications, such as traction motor control in marine hoists, electric automobile, forklift trucks and mine haulers [1]. To get a converter for voltage lift technique with specified advantages such as possessing high-voltage transfer gain, high power density, high efficiency, reduced ripple in voltage and current, super-lift Luo converter has utilized [2]. On other side, and because the problems of other type of converters that suffering from such as parasitic elements, a super-lift Luo converter has given an opportunity to overcome this problem. A super-lift method has been effectively utilized in the outline of DC-DC converters. In addition to that its output voltage increases in arithmetic progression, stage by stage and it effectively enhances the voltage transfer gain in power series [3, 4]. In order to get the way of controlling the output voltage of Luo converter, many control methods are proposed in the literature; fractional order proportional integral (FOPI) controller is a proportional integral (PI) controller with fractional numbers rather than integers design stage. It has a lot of advantages as compared with conventional PI controller due to its ability to deal with complex system [5,6].
The applications of FOPI controller out of its use in PV system, for example, its use in a close loop drive systems like in speed control of brushless DC motor [7, 8]. It is also used for a basic control in motion control [9] and to improve the stability and dynamic response of automatic voltage regulator system [10].

This paper suggests the control of positive super lift Luo converter by FOPI controller. The DC input is coming from supply of 12 V. Therefore, it is necessary to show a better performance in converter output from fluctuation point of view in the voltage waveform rather than its performance using conventional PI controller. The reminder of this paper will be; section 2 explains the design and the equations that classify the positive super lift Luo converter and the use of FOPI strategy to control the switching of the controller; section 3 presents the Matlab/Simulink modeling and simulation results. The conclusion is given lastly.

2. Positive Output Super-Lift Luo Converter

A DC-DC Luo converter behaves like switching mode boost converter. It is a step-up power converter with output DC voltage greater than its input. It has high gain with generally lesser number of components. When connect in cascaded this gain expand stage by stage just in arithmetic [11,12]. This converter performs the voltage lift from positive source to positive load therefore, it is called positive output converter. Fig.1 shows the positive output super-lift Luo converter.

![Figure 1. Positive output super-lift Luo converter](image)

It consists of an inductor $L_1$, diode $D_1$, capacitor $C_1$, which represent one voltage lift circuit and a switch $S$ in the left side. The right side has a diode $D_2$ and a capacitor $C_2$ in parallel with the load $R$.

Where

Vin=input voltage (V)

$L_1$=inductance (μH)

$S$=switch

$D_1$ and $D_2$ =diode 1 and diode 2

$C_1$ and $C_2$=capacitance1 and capacitance2 (μF)

$VC_1$ and $VC_2$=voltage of $C_1$ and $C_2$ (V)

$R$=Resistive load (Ω)

$V_0$=output voltage (V)
2.1 Basic operation of positive output super-lift Luo converter

Mode 1

During switch on period DT (when switch S is closed) the voltage \( V_{c1} \) across \( C_1 \) increases to \( V_{in} \) and current \( i_{L1} \) of inductor \( L_1 \) that flowing through it increases with voltage \( V_{in} \) in a short time in addition to that and at this moment the diode \( D_2 \) will be blocked, so \( i_{D2} = 0 \) and \( i_0 = \frac{V_o}{R} \) as shown in fig.2[13]. So that during mode1 will be (inductor \( L_1 \) is charged, capacitor \( C_1 \) is charged to \( V_{in} \), capacitor \( C_2 \) is supplied the load, \( D_1 \) is ON and \( D_2 \) is OFF)[14,15].

![Figure 2. Equivalent circuit of mode 1.](image)

The circuit equations of mode1 can be derived as follows:

\[
V_{L1} = V_o 
\]

\[
L_1 \frac{\Delta i_{L1}(closed)}{DT} = V_o 
\]

\[
\Delta i_{L1}(closed) = \frac{V_o DT}{L_1} = \frac{V_{in} DT}{L_1} 
\]

Where

\( V_{L1} \) = Voltage of inductance (V)

\( D \) = duty ratio

\( \Delta i_{L1}(closed) \) = Change of inductance current when switch is closed (A)

\( T \) = Time (sec.)

Mode 2

On the other side during switch off period (1-D)T(when switch S is opened) as in fig.3 the inductor current \( i_{L1} \) flows through \( L_1 \), \( C_1 \)[13] and the behaviour of circuit will be (inductor current flows to \( C_1 \), capacitor \( C_1 \) is charged, diode \( D_1 \) is OFF and \( D_2 \) is ON).

![Figure 3. Equivalent circuit of mode 2.](image)
During mode2 the current of the inductor $i_{L1}$ decrease with voltage $(V_o-2V_in)$, also as mentioned before during mode1 the inductor $i_{L1}$ increase with voltage $V_{in}$ [13]. Fig.4 shows some current waveforms and the derivative of the circuit equations.

![Waveforms of currents](image)

| Figure 4. Waveforms of currents. |

Then,

$$V_o=V_{in}-V_{L1}+V_{in}$$  \hspace{1cm} (4)

$$-V_{L1} = V_o-2V_{in}$$  \hspace{1cm} (5)

$$-\frac{\Delta i_{L1} \text{ (opened)}}{\left(1-D\right)T} = V_o-2V_{in}$$  \hspace{1cm} (6)

$$\Delta i_{L1} \text{ (opened)} = -\frac{(V_o-2V_{in})(1-D)T}{L_1}$$  \hspace{1cm} (7)

At steady-state operation

$$\Delta i_{L1} \text{ (closed)} + \Delta i_{L1} \text{ (opened)} = 0$$  \hspace{1cm} (8)

$$\frac{V_{in}DT}{L_2} - \frac{(V_o-2V_{in})(1-D)T}{L_1} = 0$$  \hspace{1cm} (9)

$$\frac{V_{in}DT}{L_3} = \frac{(V_o-2V_{in})(1-D)T}{L_1}$$  \hspace{1cm} (10)

$$\frac{V_{in}D}{(1-D)} = V_o-2V_{in}$$  \hspace{1cm} (11)

$$V_o = \frac{2-D}{1-D} \cdot V_{in}$$  \hspace{1cm} (12)

From equation (12) the voltage transfer gain is

$$G = \frac{V_o}{V_{in}} = \frac{2-D}{1-D}$$  \hspace{1cm} (13)

And, thus by increasing the number of capacitors and inductors to the circuit of super lift Luo converter get the desired voltage and the voltage transfer gain equation increase to (k) as describe below [11,12].
The number of stages of super lift Luo converter can be constructed by cascading.

From figs. 2&3 when switch S is closed the input current equal to \( i_{L1} + i_{C1} \) and when switch S is opened the inductor current \( i_{L1} \) equal to capacitor current. In steady state the average charge across capacitor \( C_2 \) should not change \([3, 5, 13]\) and that yield the accompanying relations.

\[
G = \frac{V_o}{V_{in}} = \frac{(2-D)k}{(1-D)k} \tag{14}
\]

Where

\( k \) : is the number of stages of super lift Luo converter can be constructed by cascading.

If the value of \( L_1 \) is sufficiently substantial, \( i_{L1} \) is about equivalent to its average current \( \bar{i}_{L1} \).

\[
i_{in-off} = i_{C1-off} = i_{L1-off} \tag{15}
\]

\[
i_{in-on} = i_{L1-on} + i_{C1-on} \tag{16}
\]

\[
DTi_{C1-on} = (1-D)Ti_{C1-off} \tag{17}
\]

Where

\( i_{in-on} \) = input current at switch is closed

\( i_{in-off} \) = input current at switch is opened

\( i_{L1-on} \) = inductance current at switch is closed

\( i_{L1-off} \) = inductance current at switch is opened

\( i_{C1-on} \) = capacitance current at switch is opened

\( V_{in} \) = \( \frac{(1-D)^2}{2-D} \) \( V_o \) = \( \frac{(1-D)^2}{2-D} \) \( R_o \)

The ripple of output voltage \( V_o \) is.

\[
\Delta V_o = \frac{\Delta Q}{C_2} = \frac{L_o (1-D)T}{C_2} = (1-D) \frac{V_o}{C_2} \frac{R_o}{R} \tag{23}
\]

\[
r = \frac{\Delta V_o}{V_o} = \frac{(1-D)}{F C_2 R} \tag{24}
\]

Where

\( r \) = is the output voltage ripple and the variation ratio of the output voltage \( V_o \) is.
\[ \epsilon = \frac{\Delta V_o}{2V_o} = \frac{1-D}{2RF_c_2} \]  

(25)

Where

\( \epsilon \) = is the variation ratio of the output voltage.

2.2. Design of the positive output super-lift Luo converter

The design of the super-lift Luo converter primarily represents how the values of the inductance \((L_1, C_1, C_2)\), and \(R\) are chosen. These electrical components are picked with the goal that the continues current mode (CCM) activity is fulfilled. Ordinarily, the positive super-lift Luo converter works in continuous conduction mode (CCM), and inductor current is continuous for this situation [3,13]. In addition to that, in order to make sure more about selection these components values, usually \((R)\) is in K\(\Omega\), switching frequency \((F)\) at 10 kHz, and \((C_2)\) in \(\mu\)F, this ripple is smaller than 1\% [3]. Table (1) shows the electrical parameters which are used to design super-lift Luo converter and fig.5 represent the Simulink model of this converter[16,17].

**Table 1.** Parameters of the proposed positive output super-lift Luo converter

| Parameters name       | symbols | value       |
|-----------------------|---------|-------------|
| Input voltage         | \(V_{in}\) | 12V         |
| Inductor              | \(L_1\) | 10\(\mu\)H |
| Capacitors            | \(C_1, C_2\) | 100 \(\mu\)F, 1500 \(\mu\)F |
| Switching frequency   | \(F_s\) | 10KHz       |
| Load resistance       | \(R\) | 1000 \(\Omega\) |

**Figure 5.** Model simulation of super-lift Luo converter with FOPI controller.
2.3. Super-lift Luo converter based FOPI controller

In the recent decades and because of developing electronics devices an advance DC-DC converters are needed. However, the increase in the complexity of equipment and instrument will need improvement of control methods but should be able to overcome the accompanying problems of development such systems like tuning parameters of controller. The classical PI controllers are easy in design, have good performance including low percentage overshoot and reduce settling time of the controlled systems[11]. On the other hand, fractional order controller of equation (26), can accomplish input control targets for such systems. Hence, numerous applications and control projects use the concept of fractional order systems have been as of late drawing in more considerations because the ability in computation power permits simulation and execution of such systems with reasonable precision [18,19]. This way has greater adaptability and offers opportunity to better sufficient the progression of control system. Fig.6 shows Simulink of fractional order proportional and integral.

\[
\frac{U(s)}{E(s)} = K_p + K_i s^{-\lambda}
\]  

(26)

Where

U(s) : Output of controller system  
K_p : Constant gain of proportional  
K_i : Constant gain of integral  
E(s) : Error value  
\lambda: Order of integration

![Simulink model of fractional PI.](image)

**Figure 6.** Simulink model of fractional PI.

3-Simulink Model and Simulation Results

The simulations of fractional proportional integral and traditional proportional integral controllers are done using Matlab/Simulink also both Simulink are connected in fig.7.

![Luo converter with (FPI, PI, and 36V output voltage (desired)).](image)

**Figure 7.** Luo converter with (FPI, PI, and 36V output voltage (desired)).
The duty cycle can be created by comparing the output from FOPI with sawtooth carrier signal, and then to get the square wave pulses contrast these signs by comparator to know the different between two signals which make duty cycle 0.8 [20,21] as shown in Fig. 8.

![Model simulation of duty cycle generator.](image)

Figs. 9 and Fig. 10 illustrate the difference in the response of output voltage for super-lift converter for both controllers FOPI and PI. The change in FOPI parameters effect on Luo converter response by changing the value of $\lambda$ and make $K_p$ and $K_i$ constant. Let the value of to be $\lambda = 0.5$.

![Comparison between FOPI and PI controllers when $K_p = 0.1$, $K_i = 0.04$, and $\lambda = 0.5$.](image)

In order to show the impact of increasing the value of $\lambda$ on the response of Luo converter, take $\lambda = 1$, then, it can be note from fig.10 there is no different in the system response between values of FOPI and PI at this value of $\lambda$. If the value of $\lambda=1.5$ as shown in fig.11 after that when $\lambda = 2$ is presented in fig.12.

![Voltage-Time curve](image)
Figure 10. Comparison between FOPI and PI controllers when $K_p = 0.1$, $K_i = 0.04$ and $\lambda = 1$

![Voltage-Time curve](image1)

Figure 11. Comparison between FOPI and PI controllers when $K_p = 0.1$, $K_i = 0.04$, and $\lambda = 1.5$

![Voltage-Time curve](image2)

Figure 12. Comparison between FOPI and PI controllers when $K_p = 0.1$, $K_i = 0.04$ and $\lambda = 2$.

From figs.11&12 the response of FOPI at $\lambda = 1.5$ is better than that of $\lambda = 2$, the rise time of FOPI is very good, low percentage overshoot and small settling time as compare with PI. To prove the optimal and precise output voltage of Luo converter two different values of $\lambda$ were used in this paper ($\lambda = 2.05$, $\lambda = 2.09$) as shown in Figs. 13&14. The record of the responses with the points of the time for PI, FOPI at $\lambda = 1.5$, and FOPI $\lambda = 2$ are presented in table 2.

Figure 13. Output voltage of super-lift Luo converter with FOPI at $\lambda = 2.05$. 

![Voltage-Time curve](image3)
Table 2. Comparison results of FOPI and PI with the time.

| Time (sec) | FOPI $\lambda=2$ | PI | FOPI $\lambda=1.5$ |
|------------|------------------|----|-------------------|
| 0          | 24               | 24 | 24                |
| 1          | 28.33            | 32.91| 25.97            |
| 2          | 29.16            | 37.52| 28.95            |
| 3          | 30.15            | 34.82| 32.24            |
| 4          | 30.92            | 36.83| 34.68            |
| 5          | 31.59            | 35.37| 35.69            |
| 6          | 32.16            | 36.45| 35.94            |
| 7          | 32.66            | 35.66| 35.99            |
| 8          | 33.09            | 36.25| 36                |
| 9          | 33.46            | 35.82| 36                |
| 10         | 33.79            | 36.13| 36                |
| 11         | 34.08            | 35.9 | 36                |
| 12         | 34.33            | 36.07| 36                |
| 13         | 34.54            | 35.95| 36                |
| 14         | 34.73            | 36.04| 36                |
| 15         | 34.9             | 35.97| 36                |
| 16         | 35.04            | 36.02| 36                |
| 17         | 35.17            | 35.98| 36                |
| 18         | 35.28            | 36.01| 36                |
| 19         | 35.37            | 35.99| 36                |
| 20         | 35.45            | 36.01| 36                |

Figure 14 Output voltage of super-lift Luo converter with FOPI when $\lambda = 2.09$. 
4-Conclusion

Two different values of controller which are fractional order PI controller and PI controller have been compared. The response of the system has been noted by comparing both controllers with reference value and which one has priority to get that reference. Fractional order PI controller has been introduced for super-lift Luo converter. Simulations is utilizing in Matlab/Simulink for different parts of system as well as the results which are demonstrated with variety values of $\lambda$. From the results, it can be inferred that the suggested FOPI controller enhances the execution characteristics and provides flexibility and robust stability as compared to the classical PI controller applied to the Luo converter.

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