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Analysis of super lift Luo converter with discrete time controller

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Abstract. An observer based analysis is carried out to improve the dynamic responses of the super lift Luo converter with positive output voltage along with a digital controller. The dynamics of the closed-loop system is investigated using discrete time modeling technique which includes the dynamic compensation in the form of prediction observer controller for obtaining output voltage regulation. The implementation which includes the digital state feedback and a load estimator is very simple and well-suited for the digitally controlled PWM converters. A suitable feedback matrix and a load estimator are selected to eliminate the error and to estimate the unmeasurable state variables. Thus we can obtain zero output voltage error, stability, robustness and stiff voltage regulation at the output. The feasibility and functionality of the discrete system are verified using simulation and experimental prototype of digitally controlled PWM superlift Luo converter.

Keywords. Luo converter; super lift; discrete observer controller; PWM; observer.

1. Introduction

During the past few decades, digital control of PWM DC-DC power converters is widely carried out and investigated. Digital control has numerous salient features such as low sensitivity to disturbances and disparity in resonant components, simplicity to assimilate through other digital structures, the capability to realize sophisticated control methods and possibility of modernizing controllers by using software [1]. Power Electronics is a vast field which mainly places a challenge on controlling the non-linear dynamics of the wide varieties of dc-dc converter topologies. One amongst the recent advancement in converter family is LUO converters. LUO converters are the simplest converters obtained from Buck-Boost converters used for step-up as well as step-down operation with elevated power density and improved energy efficiency.

With the advent of new technique like voltage lift technique, several types of research are being carried out in implementing this method in the dc-dc converters which in turn paves the way to design high gain converters. Voltage lift technique efficiently improves the voltage gain transfer in power converters. The super lift Luo converters with voltage lift technology are extensively used in many appliances such as in computer peripheral equipments and industrial applications [2].

In this paper, an effort is made to investigate the performance of the sensorless digital current mode control of super lift Luo converter. Since the state space averaging technique is a simpler and the most widely used method for modeling, the positive output super lift Luo (POSLL) converter is modeled using this approach. The performance analysis of the POSLL converter is done by operating the converter in continuous conduction mode.

2. System description

One of the most well-known methods mainly used for electronic circuit design is the voltage lift technique and in recent years this method finds wider application in dc-dc power converters. One such type of a converter is the super lift Luo converter, and figure 1 illustrates the schematic diagram. Using voltage lift technique, this kind of converter converts positive voltages into positive voltages and the first quadrant operation is obtained with larger voltage amplification when compared with the Boost converters.

In figure 1 V_S denotes the positive input dc voltage, V_O denotes the corresponding output voltage, SW denotes an n-channel MOSFET, D_1 and D_2 are the freewheeling diodes, L is the inductor and C_1, C_2 are the capacitors. The converter operates in continuous conduction mode to obtain high power density. Moreover, all the parameters are assumed as ideal one.

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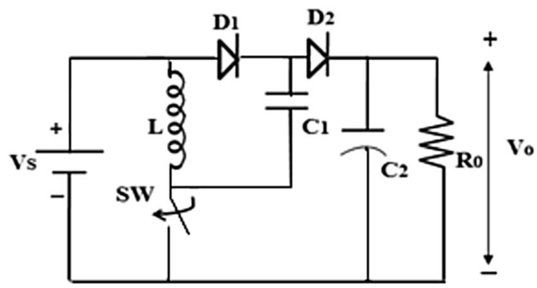


Figure 1. Schematic diagram of a POSLL Converter.

3. State model of the positive output Luo converter

The dynamic equations describing the system functions are state affine and time invariant which is depicted as follows,

$$\begin{aligned}\dot{x}(t') &= A_1 x(t') + B_1 V_S(t'), sw = 1\\ \dot{x}(t') &= A_2 x(t') + B_2 V_S(t'), sw = 0\end{aligned} \tag{1}$$

Here sw = 1 signifies the on state of the switch and sw = 0 signifies the off state of the switch. A_1, A_2, B_1 and B_2 are the coefficient matrices given by,

$$A_1 = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-\alpha}{R_o C_2} \end{bmatrix}; A_2 = \begin{bmatrix} 0 & \frac{\alpha - 1}{L} \\ \frac{1-\alpha}{C_2} & \frac{\alpha - 1}{R_o C_2} \end{bmatrix}; B_1 = \begin{bmatrix} \frac{\alpha}{L} \\ 0 \end{bmatrix} \text{ and } B_2 = \begin{bmatrix} \frac{2-2\alpha}{L} \\ 0 \end{bmatrix} \tag{2}$$

The output equation of the converter is represented as,

$$V_0(t') = [0 \quad 1] x(t') \tag{3}$$

By using the analog coefficient matrices, discrete equivalent is acquired by utilizing the corresponding associated equations,

$$\begin{aligned} G' &= e^{AT'_S} H' = \int_{\tau=0}^{T'_S} e^{A\tau} d\tau B \\ C'_d &= C D'_d = D \end{aligned} \tag{4}$$

Where G', H', C'_d and D'_d are the coefficient matrices for the discrete time system [4–6]. For discrete signals, the equations describing super lift Luo converter are obtained as follows with the help of the designed data,

$$\begin{aligned} G' &= \begin{bmatrix} 0.9998 & -0.0334 \\ 0.0111 & 0.9990 \end{bmatrix} \\ H' &= \begin{bmatrix} 0.0133 \\ 0.0001 \end{bmatrix} \end{aligned} \tag{5}$$

4. Discrete controller design and analysis

Discrete observer controller is designed for the Luo converter which comprises a discrete gain feedback matrix and a load estimator. The digital state feedback is designed using pole placement technique primarily to obtain the stability of the converter. The load estimation is made by deriving the full order observer gain matrix. It is obtained using the similar pole assignment procedure with the eventual objective of estimating the unmeasurable state parameters. The observer always aims to act upon the error resulting in faster response of the converter. The design of both the digital feedback matrix and load estimator are discussed below [7–9].

4.1 *Digital state feedback matrix*

The closed loop equations for a continuous time system along with digital state feedback control (m) are as follows:

$$\begin{aligned} \dot{x}(t'+1) &= Gx(t'+1) + H(r' - m'x) \\ &= (G' - H'm)x'(t'+1) + Br'(t'+1) \end{aligned} \tag{6}$$

In this case, t' is being replaced by $(t'+1)$ and assume $t'+1$ be k'. Thus equation (6) can be rearticulated as,

$$\dot{x}(k') = (G' - H'm')x(k') + Br(k') \tag{7}$$

The response of the system is defined as follows,

$$y(k') = \left(C'_d - D'_d m'\right)x(k') + C'_d r(k') \tag{8}$$

To satisfy the indispensable and adequate condition for the system to be entirely state controllable all the Eigen values of $(G'\text{-}H'm')$ are assigned in the left half of z plane for the discrete system. (G′, H′) pair is equivalent to $\check{G}', \check{H}'$in the canonical form and it is given by,

$$\begin{aligned} \check{G}' &= \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \dots \\ -\rho_0 & -\rho_1 & -\rho_2 & \dots & -\rho_{n-1} \end{bmatrix} \\ \check{H}' &= \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{bmatrix} \end{aligned} \tag{9}$$

It is indispensable to change the structure of the system to reachable canonical form, and the following equation describes the transformation matrix T'_r that converts the super lift Luo converter into canonical form,

$$T'_r = \left[H' \vdots G'H' \vdots \cdots \vdots G'^{n-1}H' \right] \begin{bmatrix} d_1 & d_2 & \ldots & d_{n-1} & 1 \\ d_2 & d_3 & \ldots & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ d_{n-1} & 1 & 0 & \ldots & 0 \\ 1 & 0 & 0 & \ldots & 0 \end{bmatrix} \quad (10)$$

Where d_1, d_2 … d_n are the coefficients for the converter characteristic equation and is described as,

$$z^n + d_1 z^{n-1} + \ldots + d_{n-1} z + d_n = 0 \quad (11)$$

The closed loop system is constructed by feeding back every state variable to u, thereby forming,

$$u = -m'x \quad (12)$$

Where

$$m' = [\, m'_1 \quad m'_2 \quad \ldots \quad m'_n \,] \quad (13)$$

By using equation (7) with equations (9) and (13), the converter matrix (G′-H′m′), for closed loop system is,

$$G' - H'm' = \begin{bmatrix} 0 & 1 & 0 & \ldots & 0 \\ 0 & 0 & 1 & \ldots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ -(d_0 + m'_1) & -(d_1 + m'_2) & -(d_2 + m'_3) & \ldots & -(d_{n-1} + m'_n) \end{bmatrix} \quad (14)$$

By examining equation (14), it is understood that the system is in canonical form and hence by inspection the solution can be obtained as follows,

$$|zI - (G' - H'm')| = z^n + \left(d_{n-1} + m'_n\right) z^{n-1} + \left(d_{n-2} + m'_{n-1}\right) z^{n-2} + \ldots + \left(d_n + m'_2\right) z + \left(d_0 + m'_1\right) = 0) \quad (15)$$

By examining equations (11) and (15), it splendidly implicates that the desired characteristic equation of the super lift Luo converter which is in controllable canonical form can be obtained from the open loop characteristic equation by appending the suitable m'_i to every coefficient. The desired characteristic equation of the super lift Luo converter for appropriate pole assignment is assumed as,

$$z^n + \omega_{n-1} z^{n-1} + \omega_{n-1} z^{n-1} + \ldots + \omega_2 z^2 + \omega_1 z + \omega_0 = 0 \quad (16)$$

Where ω_i's are the desired coefficients. On comparison of equations (15) and (16) it can be obtained as,

$$\omega_i = d_i + m'_{i+1}, i = 0, 1, 2, \ldots n - 1 \quad (17)$$

From which,

$$m'_{i+1} = \omega_i - d_i \quad (18)$$

Using the above discussed steps, the values for the digital state feedback matrices obtained for super lift Luo converters are, $m' = [\, 99.4 \quad 6763.1 \,]$.

4.2 *Design of the load estimator*

For the appropriate location of the observer poles, the following assumptions are made as defined by the thumb rule.

The natural frequency of oscillation (observer controller) is approximately equal to two to five times more than the natural frequency of oscillation of the converter. Now, the dynamic equation of the super lift Luo converter together with a full-order state observer is described as follows:

$$\dot{x}(k' + 1) = (G' - H'm')x(k') + H'm'_1 r(k') \quad (19)$$

Here, m_1 represents the coefficient of the digital state feedback matrix and r represents the unit step signal.

The system equation along with the full order observer is defined as follows,

$$\tilde{x}(k' + 1) = G\tilde{x}(k') + Hu(k') + g'(y(k') - C'\tilde{x}(k')) \quad (20)$$

Here, g' represents the full order observer gain matrix.

By employing an efficient separation principle, the transfer function for the discrete observer controller for super lift Luo converter is obtained. It is an effective combination of the digital state feedback matrix and full order state observer matrix, and it is given by,

$$\frac{\mathrm{U(s)}}{-\mathrm{Y(s)}} = \frac{795.4\mathrm{z} - 721.5}{\mathrm{z}^2 + 0.1027\mathrm{z} + 0.03477} \quad (21)$$

The above said matrices could be derived separately and combined efficiently to obtain the robust dynamic compensation for the super lift Luo converter.

5. Simulation results

An appealing imminent into the dynamic performance of the super lift Luo converter along with discrete observer controller is obtained by carrying out an extensive simulation using MATLAB/Simulink. The results thus obtained are illustrated in table 1. It is observed that the closed loop system exhibits an improved dynamic response with a settling time of the order of just 0.005 s. There are no overshoots and undershoots. The system also executes splendidly with zero steady state error and output ripple voltage. Table 1 also exemplifies the parameters in comparison with its analog counterpart. It is evident that the POSLL converter with prediction observer shows better results than the already existing closed loop PWM converters. Again the input voltage and load resistance are varied over a range of 10% to 20% and the results thus obtained are illustrated in figure 2.

Table 1. Performance evaluation of super lift Luo converter with discrete observer controller.

Sl. no.	Performance specifications	Discrete controller	Analog controller
1	Settling time (s)	0.009	0.0.02
2	Peak overshoot (%)	0	0
3	Steady state error (V)	0	0.02
4	Rise time (s)	0.0005	0.01
5	Output ripple voltage	0	0

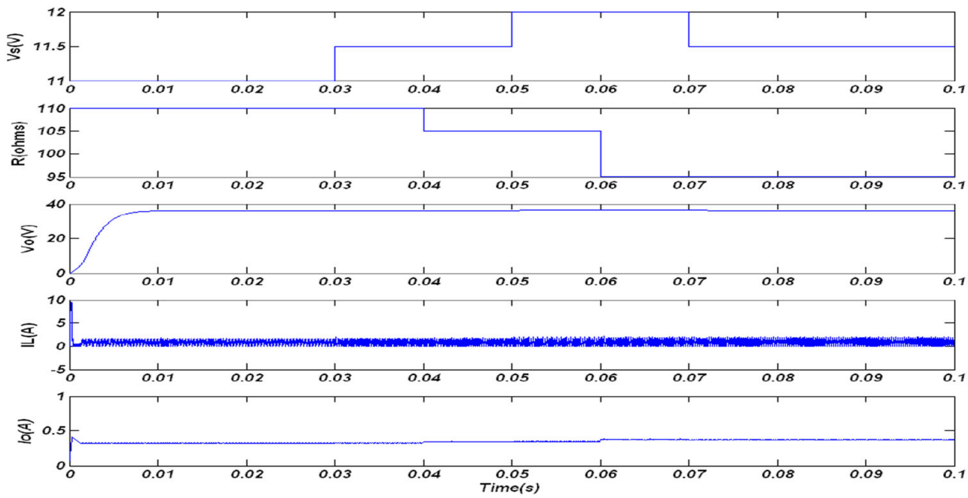


Figure 2. Simulated results for super lift Luo converter (Vs – Source voltage, R – Load Resistance, V_O – Voltage across the load, I_L – inductance current, I_O – current through the load).

The results prove that the system is dynamic and vibrant. By analyzing the performance, it is understood that the super lift Luo converter with discrete controller demonstrates enhanced performance than its analog counterpart. Figure 3 illustrates the comparative analysis of the proposed controller along with the conventional PID controller. It is well understood that the performance specifications of POSLL converter with discrete controller shows improved performance. It settles down faster with a settling time as 9 ms as against 0.02 s for PID controller. The values used for simulation are L = 100 μH; C1 = C2 = 30 μF; V_S = 12 V; P_o = 25.92 W; f_s = 100 kHz; R_o = 40-120 Ω.

6. Hardware results

The controller platform is evaluated using LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench). The prototype is established using the same values as specified in section 5. The corresponding outputs thus obtained are shown in the figure 4a and b, respectively. Figure 4b shows the output corresponding to the line variation of 10 V and figure 4c shows the output for 12 V input voltage. It proves that the POSLL converter along with discrete observer controller powerfully tracks the reference voltage of about 36 V for both the input voltage variations. No overshoots and undershoots are evident. Steady state error is absolutely zero.

7. Conclusion

Discrete observer controller is designed and analyzed for the super lift Luo converter in the continuous time domain employing pole assignment method and separation principle. To ensure the robustness of the controller, load estimator is derived using full order state observer. The investigation and analysis are carried out using root locus method which endows with a competent and effectual compensation for the dc-dc converter. LabVIEW realizes the discrete observer controller hence proposed for the super lift Luo converter as a control platform and demonstrates the outcomes. The digital examination, simulated results, and experimental readings show that the discrete observer controller designed for super lift Luo converter accomplishes rigid voltage regulation, excellent vibrant characteristics, and better effectiveness. The super lift Luo converter with discrete observer controller can be used for any of the applications like modern portable electronic

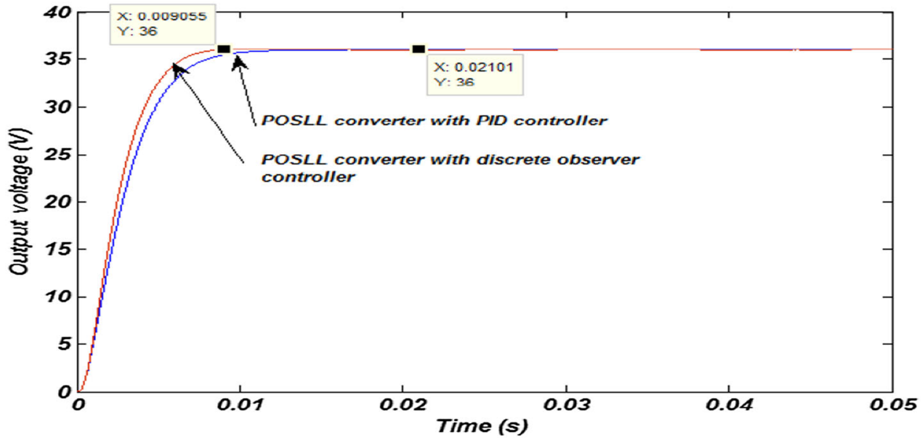
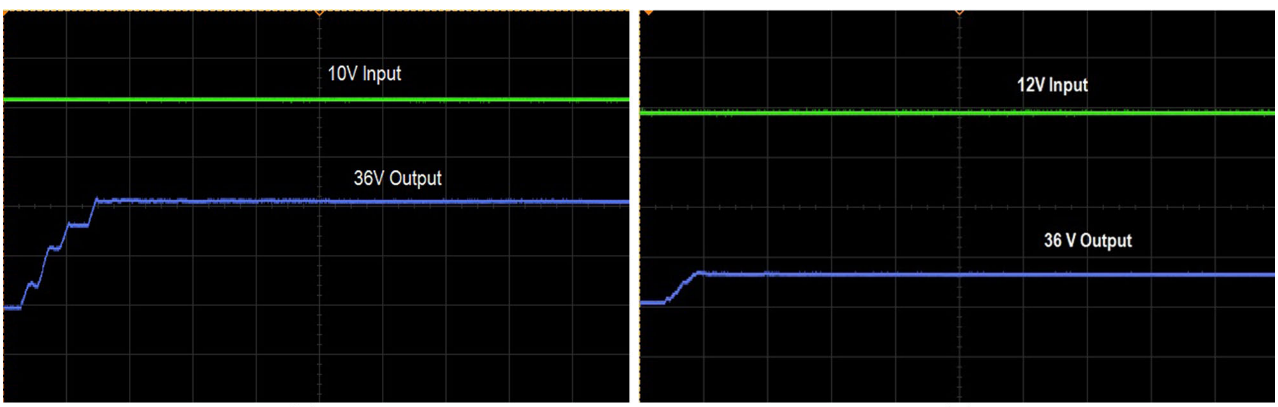


Figure 3. Comparison of output voltage for POSLL converter with PID controller and Discrete Observer controller.



(a) (b)

Figure 4. (**a**) Output response for 10 V input. (**b**) Output response for 12 V input.

devices, computer peripherals, medical equipments, power factor correction or fuel cell applications.

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