Linear Observer Based Linearizing Control of DC-DC Buck Converter

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Abstract: In this article; we process DC-DC buck converter by linearizing control (non linear control INPUT-OUTPUT). As one observes at the same time the inductor current not measurable by a linear state observer proposed. This method can control the system by varying the output voltages, input voltage and load resistance. The proposed method has a stable response capable of reaching the model reference smoothly.

Key–Words: DC-DC Buck Converter, Linearizing Control, Linear Observer, LYAPUNOV function.
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1 Introduction

In recent years, several other techniques that have previously been reported for average modeling of DC-DC Convertors are input/output linearization control for voltage regulation of Buck converter [1]. The majority of them rely on a cascade control structure involving the inductor's current in the control function due to its faster dynamics. In [2], a simple formulation for the design of a current observer is presented, but the control is linear. A sliding mode observer is based on an enlarged state model in [3], in [4] a current observer based on a model has been proposed, which is controlled by sliding mode [5], eliminating the sensor noise, reducing the circuitry complexity and overcoming the problem of large ripple current sensors but this for real buck. Work [6] presents a linear observer as it is a high gain observer. The determination of the gain by the pole placement method. [7] introduced the concept of functional observer design. Other work [8, 9, 10, 11]; it imposes the induction current is measurable although it is insufficien to achieve, and requires the use of an ampere-meter.

In this paper linear observer based linearizing control is designed. The order of the observer is equivalent to that of the state Buck. Under special cases the since estimation of only selected state variables are done the order of the designed observer is reduced, thus reducing the overall complexity and cost of the system.

This paper is organized as follows. Section 2 gives the converter models. Synthesis of linearizing control made in section 3. In section 4, presents linear current observer. In section 5, the simulation results of non-linear control INPUT-OUTPUT and proposed observer are shown. Finally, a conclusion is made in section 6.

2 Mathematical Model of DC-DC Buck Converter

Buck converter can be divided into two cases including Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM), according to the inductor current is continuous or not. If the inductance value is relatively large, the circuit works in CCM case. If the inductance value is relatively small, the circuit works in DCM case. The electrical circuit of the buck converter is presented in the figure1

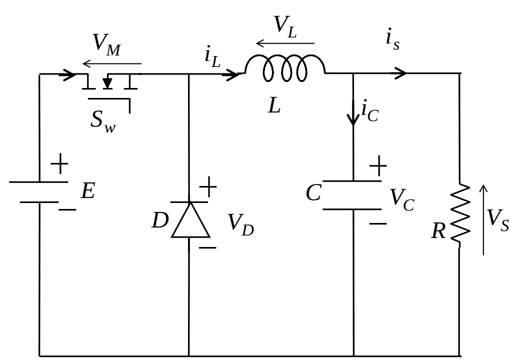

Figure 1: Buck converter diagram.

Therefore, the Buck converter in a cycle of work is in two different situations. The equivalent circuit of the buck converter shown in figur 1 is :

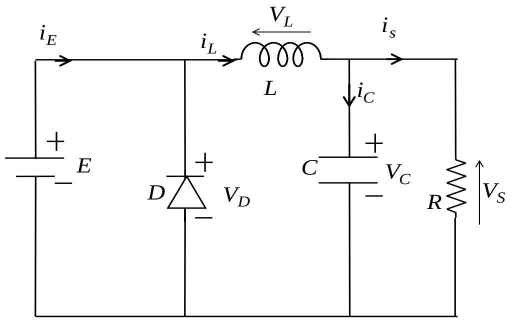

Figure 2: Schematic of the buck converter with S_w closed

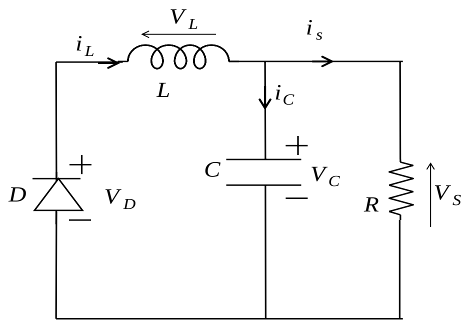

Figure 3: Schematic of the buck converter with S_w opened

In turn on switch S_w and the diode D is blocked. According to Kirchhoff Voltage Law (KVL) and current law. Inductor current and capacitor voltage are selected as state variables; the linear model which represents the circuit describes in figur 2 is given by :

$$\begin{bmatrix} \frac{dV_C}{dt} \\ \frac{di_L}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} V_C \\ i_L \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} E \quad (1)$$

where i_L is the inductor current. V_C is the capacitor voltage. L is the inductance parameter. C is the capacitance parameter. R is the load parameter. E is the DC voltage source. V_s is the output voltage.

Over turn off switch S_w and the diode D is conducting. According to kirchhoff voltage law (KVL) and current law, Buck converter model which represents the configuratio of the circuit described in the figur 3 is given by :

$$\begin{bmatrix} \frac{dV_C}{dt} \\ \frac{di_L}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} V_C \\ i_L \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} E \quad (2)$$

In the process of the opening and closing of the switch, most of the variables in Buck converters are mutated. Therefore, according to equation(1) and (2), we have the state space mean model for the buck converter is shown in equation (3).

$$\begin{bmatrix} \frac{dV_C}{dt} \\ \frac{di_L}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} V_C \\ i_L \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{\alpha}{L} \end{bmatrix} E \quad (3)$$

3 Synthesis of Linearizing Control

By taking as states $\begin{bmatrix} x_1 & x_2 \end{bmatrix}^T = \begin{bmatrix} V_C & i_L \end{bmatrix}^T$ and α the signal control, the Buck model (3) will be in the form :

$$\begin{bmatrix} \frac{dx_1}{dt} \\ \frac{dx_2}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{E}{L} \end{bmatrix} \alpha \quad (4)$$

And the $y = \begin{bmatrix} y_1 & y_2 \end{bmatrix}^T = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T$ To generate a direct relationship between the outputs y_1, y_2 and the input α, we derive the output y_1 and y_2 (see.[13]):

$$\dot{y}_1 = -\frac{1}{RC}x_1 + \frac{1}{C}x_2 \quad (5)$$

$$\dot{y}_2 = -\frac{1}{L}x_1 + \frac{E}{L}\alpha \quad (6)$$

Since $\dot{y}_1$ is not directly connected to the input α, we must differentiate again and we get :

$$\begin{aligned} \ddot{y}_1 &= -\frac{1}{RC}\dot{x}_1 + \frac{1}{C}\dot{x}_2 \\ &= \left(\frac{1}{R^2C^2} - \frac{1}{LC}\right)x_1 - \frac{1}{RC^2}x_2 + \frac{E}{LC}\alpha \end{aligned}$$

Clearly, this last equation is an explicit relationship between y_1 and α; if we choose the control entry in the form :

$$\alpha\frac{E}{L}\begin{bmatrix} \frac{1}{C} \\ 1 \end{bmatrix} = \begin{bmatrix} \ddot{y}_1 + \left(\frac{1}{LC} - \frac{1}{R^2C^2}\right)x_1 + \frac{1}{RC^2}x_2 \\ \dot{y}_2 + \frac{1}{L}x_1 \end{bmatrix}$$

$$\alpha = \frac{L}{E}.\frac{C}{1+C^2}\left(\ddot{y}_1 + \left(\frac{1}{LC} - \frac{1}{R^2C^2}\right)x_1 + \frac{1}{RC^2}x_2 + C\left(\dot{y}_2 + \frac{1}{L}x_1\right)\right) \quad (7)$$

That is to say the new inputs to be determined ν_1 and ν_2 which cancel the non-linearity..

$$\begin{cases} \ddot{y}_1 = \nu_1 \\ \dot{y}_2 = \nu_2 \end{cases}$$

Either e_1 and e_2 the errors $e_1 = y_1 - y_{1d}$ and $e_2 = y_2 - y_{2d}$. The tracking error dynamic is given by :

$$\begin{cases} \ddot{e}_1 + k_{v1}\dot{e}_1 + k_{v0}e_1 = 0 \\ \dot{e}_2 + k_{i0}e_2 = 0 \end{cases} \quad (8)$$

Where k_{v1}, k_{v0} and k_{i0} are positive constants.

Which represents an exponentially error dynamic; in other words, e converges exponentially towards zero. So,

$$\begin{cases} \nu_1 = \ddot{y}_{1d} - k_{v0}e_1 - k_{v1}\dot{e}_1 \\ \nu_2 = \dot{y}_{2d} - k_{i0}e_2 \end{cases} \Rightarrow$$

$$\begin{cases} \nu_1 = \ddot{y}_{1d} - k_{v0}(y_1 - y_{1d}) - k_{v1}\left(\dot{y}_1 - \dot{y}_{1d}\right) \\ \nu_2 = \dot{y}_{2d} - k_{i0}\left(y_2 - y_{2d}\right) \end{cases} \quad (9)$$

The control law (7) becomes in the form :

$$\alpha = \frac{L}{E}.\frac{C}{1+C^2}\left(\ddot{y}_{1d} - k_{v0}(y_1 - y_{1d}) - k_{v1}\left(\dot{y}_1 - \dot{y}_{1d}\right) + \left(\frac{1}{LC} - \frac{1}{R^2C^2}\right)x_1 + \frac{1}{RC^2}x_2 + C\left(\dot{y}_{2d} - k_{i0}\left(y_1 - y_{1d}\right) + \frac{1}{L}x_1\right)\right) \quad (10)$$

4 Linear Observer Design of the Buck Converter

In our work, when convergence of estimation error dynamic shall be slightly modifie compared to the result given in [12], we preserve the same form of the observer corresponding to model (3). Hence,

$$\begin{bmatrix} \frac{d\hat{V}_s}{dt} \\ \frac{d\hat{i}_L}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix}\begin{bmatrix} \hat{V}_s \\ \hat{i}_L \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{E}{L} \end{bmatrix}\alpha + \begin{bmatrix} k_1 \\ k_2 \end{bmatrix}\left(V_s - \hat{V}_s\right) \quad (11)$$

To study the stability of the observer (11), one uses the expression $\tilde{x} = x - \hat{x}$ where $x = \begin{bmatrix} V_s & i_L \end{bmatrix}^T$, $\hat{x} = \begin{bmatrix} \hat{V}_s & \hat{i}_L \end{bmatrix}^T$ and $\tilde{x} = \begin{bmatrix} V_s - \hat{V}_s & i_L - \hat{i}_L \end{bmatrix}^T$; from where one will have:

$$\begin{bmatrix} \frac{d\tilde{V}_s}{dt} \\ \frac{d\tilde{i}_L}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC} - k_1 & \frac{1}{C} \\ -\frac{1}{L} - k_2 & 0 \end{bmatrix}\begin{bmatrix} \tilde{V}_s \\ \tilde{i}_L \end{bmatrix} \quad (12)$$

That is

$$\dot{\tilde{x}} = \mathcal{A}_0\tilde{x} \quad (13)$$

Considering the function of LYAPUNOV candidate :

$$V(\tilde{x}) = \tilde{x}^T P\tilde{x} \quad (14)$$

Where $P = P^T > 0$ solution of :

$$\mathcal{A}_0^T P + P\mathcal{A}_0 = -Q \quad (15)$$

Proof

$$\begin{aligned} \dot{V}(\tilde{x}) &= \dot{\tilde{x}}^T P\tilde{x} + \tilde{x}^T P\dot{\tilde{x}} \\ &= (\mathcal{A}_0\tilde{x})^T P\tilde{x} + \tilde{x}^T P(\mathcal{A}_0\tilde{x}) \\ &= \tilde{x}^T\mathcal{A}_0^T P\tilde{x} + \tilde{x}^T P\mathcal{A}_0\tilde{x} \\ &= \tilde{x}^T\left(\mathcal{A}_0^T P + P\mathcal{A}_0\right)\tilde{x} \\ &= -\tilde{x}^T Q\tilde{x} \\ &\leq -\lambda_{\min}(Q)\|\tilde{x}\|^2 \end{aligned} \quad (16)$$

Using the matrix relation

$$\lambda_{\min}(Q)\|\tilde{x}\|^2 \leq V(\tilde{x}) = \tilde{x}^T P\tilde{x} \leq \lambda_{\max}(Q)\|\tilde{x}\|^2$$

By replacing this relation in the equation (16):

$$\dot{V}(\tilde{x}) \leq -\frac{\lambda_{\min}(Q)}{\lambda_{\max}(P)}V(\tilde{x}) \quad (17)$$

Pour $\frac{\lambda_{\min}(Q)}{\lambda_{\max}(P)} > 0$; $\dot{V}(\tilde{x}) \leq 0$. This proves the expential convergence of observer error.

5 Simulation Results

This work is based on the output voltage and inductor current generated by buck converter. This problem occurs when there are changes in output voltage. This research that will be carried out in a buck converter using a non linear control INPUT/OUTPUT.

To examine practical usefulness, the proposed regulator has been simulated for a Buck (see [14]), whose parameters are depicted in Table 1.

Table 1: DC-DC buck converter parameters[14].

Parameters	Notation	Value	Unit
Input Voltage	E	24	V
Output Voltage	V_s	12	V
Inductor	L	69	μH
Resistor Load	R	13	Ω
Capacitor	C	220	μF
Normal switching frequency	f	100	KHz
Switch off	Sw	$\alpha = 0$	
Switch off	Sw	$\alpha = 1$	

By using these parameters, the model of DC-DC buck converter (3) is utilized as a plant of the system. We show a detailed general diagram of linearizing control with linear observer in the figur 4.

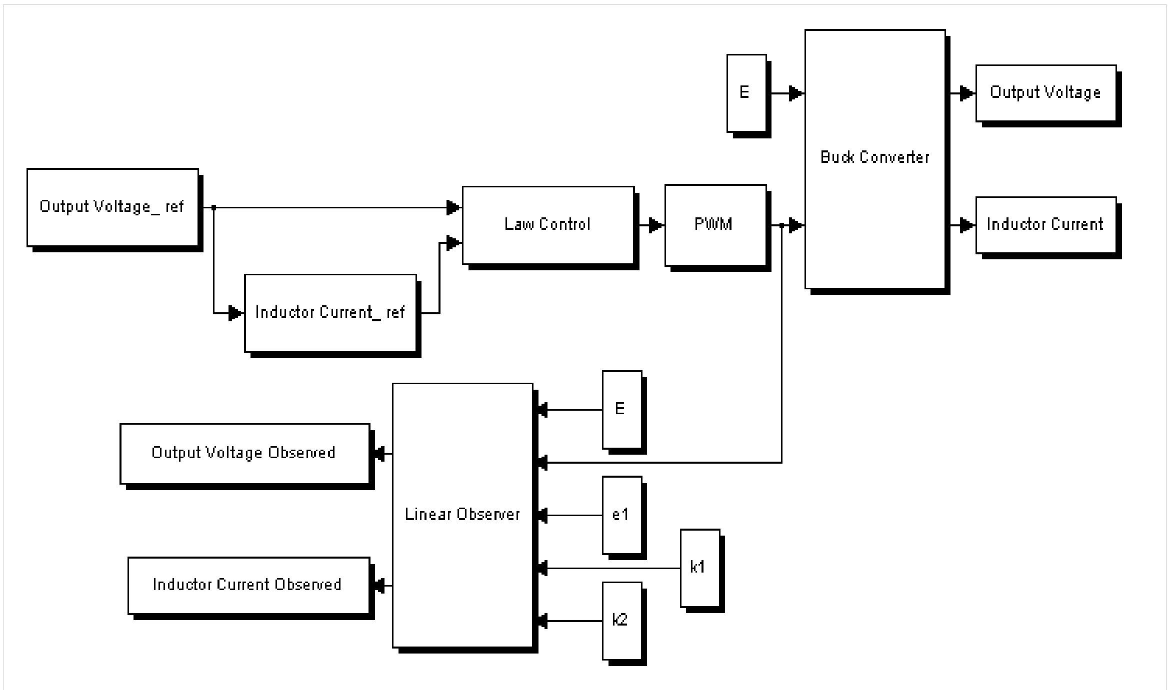

Figure 4: General diagram of non-linear control INPUT/OUTPUT for DC-DC buck converter with linear observer.

The performance of the non-linear control INPUT/OUTPUT with the proposed linear observer is proven by simulation.

5.1 Change in reference output voltage

The input voltage and resistor load of the buck converter are $24V$ and 13Ω, respectively.

Control performance

For the adjustment of the non-linear INPUT/OUTPUT control, the pole placement method is used. The regulation of the tension forces us to use the firs equation of the system (8). By choosing, the double pole $p_1 = p_2 = 2 \times 10^3$. Then $k_{v1} = 4 \times 10^6$ and $k_{v2} = 4 \times 10^{12}$. The adjustment gain k_{i0} is the adjustment pole of the inductor current. It is given by the second equation system (8). We impose $k_{i0} = 1 \times 10^3$.

The figur 5 represents the output voltage where at the moment $t = 0.1s$, it changes from $15V$ to $17V$. It follows the value desired. The output voltage error and the histogram with Gaussian distribution are shown by figur 6(a) and figur 6(b) respectively. The error means is equal $-7.9654 \times 10^{-5}V$ and the variance is 5.5263×10^{-6}.

The inductor current is given by the figur 7. We notice that there are oscillations along the desired trajectory but it follows it. The inductor current error and the histogram with Gaussian distribution are shown by figur 8(a) and figur 8(b) respectively. The error means is equal $-5.9877 \times 10^{-6}A$ and the variance is 5.2855×10^{-4}.

Observer performance

To determine the gains of observations k_1 and k_2, we choose the symmetric matrices and defin positive

$$P = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

and

$$Q = \begin{bmatrix} 6.576 \times 10^{12} & 6.576 \times 10^{12} \\ 6.576 \times 10^{12} & 6.576 \times 10^{12} \end{bmatrix}$$

.

Solving the equation (15), we get $k_1 + \frac{1}{RC} = 3.3515 \times 10^4 \Rightarrow k_1 = 331.6503 \times 10^2$ and $k_2 + \frac{1}{L} = 6.576 \times 10^{12} \Rightarrow k_2 = 6.576 \times 10^{12}$; our observer is initialized to $\begin{bmatrix} V_{s0} & i_{L0} \end{bmatrix}^T = \begin{bmatrix} 0.5 & 0.03 \end{bmatrix}^T$.

The inductor current observed and simulate are given by the figur 9. We notice that there are pick $165.483A$ at the start time then current observed follows current simulate. The inductor current observed error and the histogram with Gaussian distribution are shown by figur 10(a) and figur 10(b) respectively. The error means of inductor current observed is equal $4.3698 \times 10^{-4}A$ and the variance is $3,0235$.

5.2 Change in input voltage

The output voltage and resistor load of the buck converter are $15V$ and 13Ω, respectively. The input voltage is set to $24V$; at the instant $t = 0.08s$, it is changed to $29V$.

Control performance

The figur 11 represents the output voltage where it follows the value desired. The output voltage error and the histogram with Gaussian distribution are shown by figur 12(a) and figur 12(b) respectively. The error means is equal $-9.272 \times 10^{-5}V$ and the variance is 5.5244×10^{-6}.

The inductor current is given by the figur 13. We notice that there are oscillations along the desired trajectory but it follows it. The inductor current error and the histogram with Gaussian distribution are shown by figur 14(a) and figur 14(b) respectively. The error means is equal $-5.9877 \times 10^{-6}A$ and the variance is 5.2855×10^{-4}.

Observer performance

The inductor current observed and simulate are given by the figur 15. We notice that there are pick $0.2957A$ at the start time then current observed follows current simulate. The inductor current observed error and the histogram with Gaussian distribution are shown by figur 16(a) and figur 16(b) respectively. The error means of inductor current observed is equal $3.5488 \times 10^{-4}A$ and the variance is $3,0271$.

5.3 Change in the resistor load

The input voltage and output voltage of the buck converter are $24V$ and $15V$, respectively. The resistor load is set to 13Ω; at the instant $t = 0.1s$, it is changed to 26Ω.

Control performance

The figur 17 represents the output voltage where it follows the value desired. The output voltage error and the histogram with Gaussian distribution are shown by figur 18(a) and figur 18(b) respectively. The error means is equal $-7.3442 \times 10^{-5}V$ and the variance is 5.5272×10^{-6}.

The inductor current is given by the figur 19. We notice that there are oscillations along the desired trajectory but it follows it. The inductor current error and the histogram with Gaussian distribution are shown by figur 20(a) and figur 20(b) respectively. The error means is equal $-5.3177 \times 10^{-6}A$ and the variance is 5.2962×10^{-4}.

Observer performance

The inductor current observed and simulate are given by the figur 21. We notice that there are pick $168.03A$ at the start time then current observed follows current simulate. The inductor current observed error and the histogram with Gaussian distribution are shown by figur 22(a) and figur 22(b) respectively. The error means of inductor current observed is equal $3.9813 \times 10^{-4}A$ and the variance is 3.0228.

The table 2 and table 3 are collection of the preceding results.

Table 2: Means and variances of inductor current error for linearizing control.

Change in	output voltage	input voltage	resistor load
Mean $[A]$	$5.9877 * 10^{-6}$	$5.9877 * 10^{-6}$	$5.3177 * 10^{-6}$
Var	$5.2855 * 10^{-4}$	$5.2855 * 10^{-4}$	$5.2962 * 10^{-4}$

Table 3: Means and variances of inductor current error for linear observer.

Change in	output voltage	input voltage	resistor load
Mean $[A]$	$4.3698 * 10^{-4}$	$3.5488 * 10^{-4}$	$3.9813 * 10^{-4}$
Var	3.0235	3.0271	3.0228
Pick $[A]$	165.483	0.2957	168.03

We notice, in linearizing control, the means of errors and the variance of the inductor current are very small one says that they are null (look table 2). In observation the errors are zero with a variance equal to 3 (look table 3). Except that there are big spikes in the case of input voltage change and load resistance change. the peak is small $0.2957A$ in the case of input voltage change.

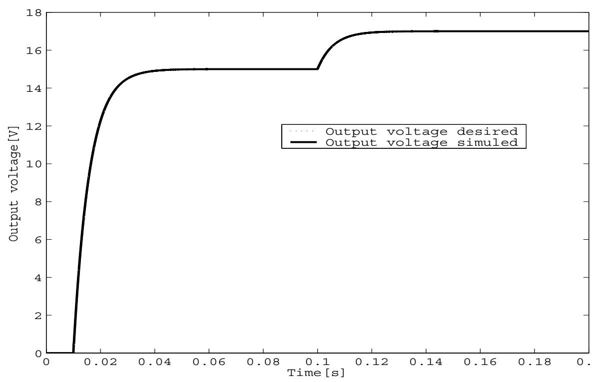

Figure 5: Output voltage simulate.

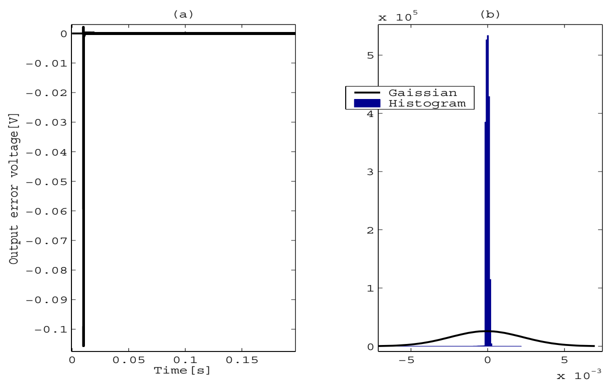

Figure 6: Output voltage simulate error with histogram and Gaussian distribution.

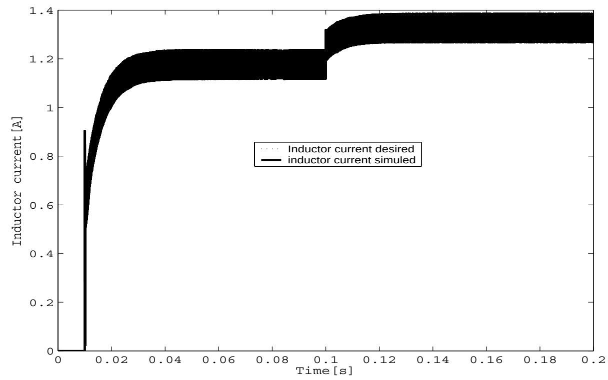

Figure 7: Inductor current simulate.

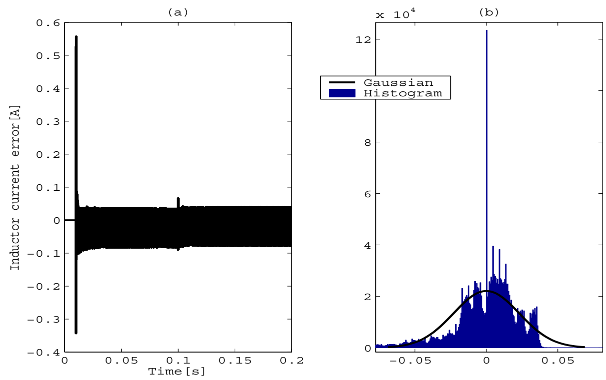

Figure 8: Inductor current simulate error with histogram and Gaussian distribution.

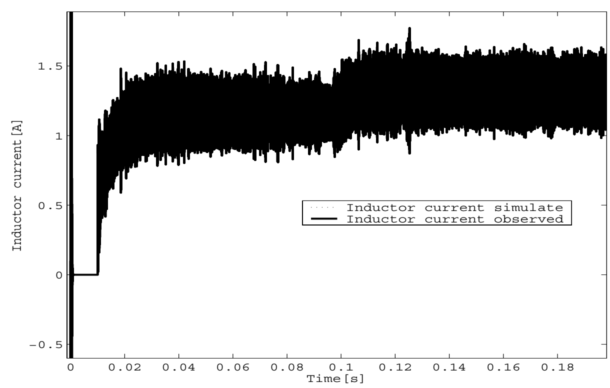

Figure 9: Inductor current simulate and observed .

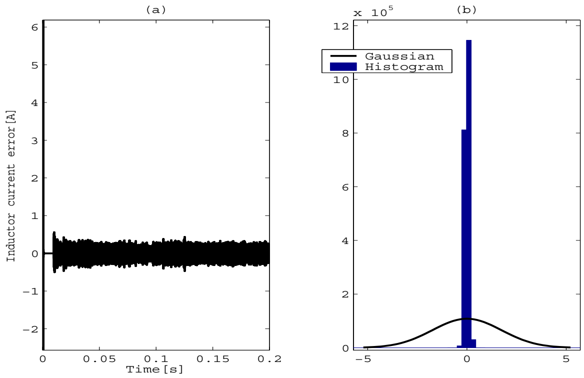

Figure 10: Inductor current observed error with histogram and Gaussian distribution.

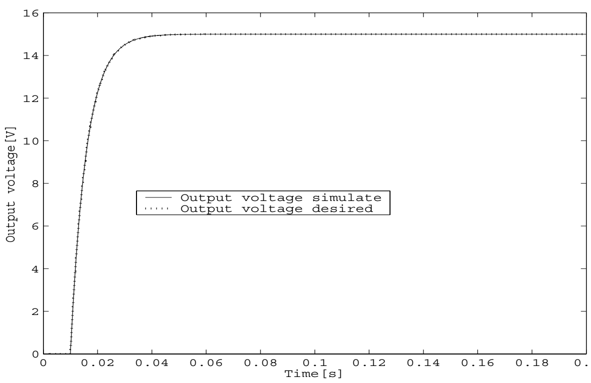

Figure 11: Output voltage simulate.

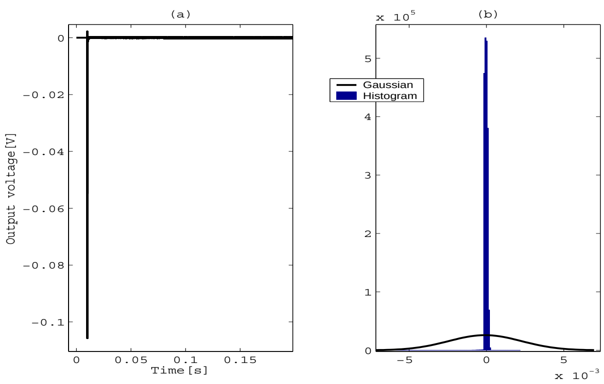

Figure 12: Output voltage simulate error with histogram and Gaussian distribution.

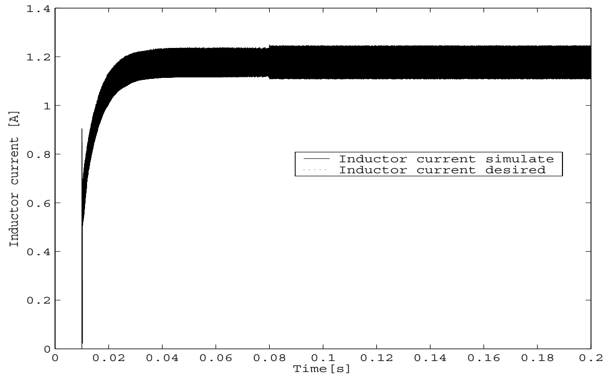

Figure 13: Inductor current simulate.

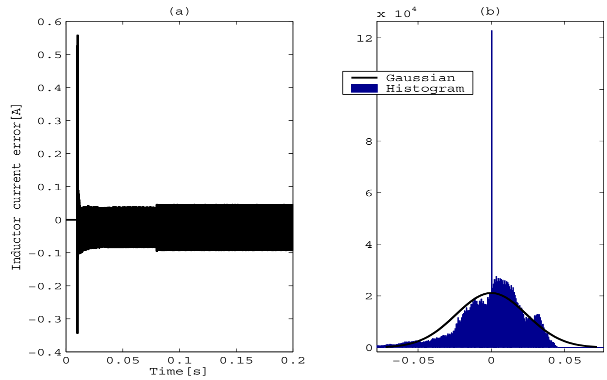

Figure 14: Inductor current simulate error with histogram and Gaussian distribution.

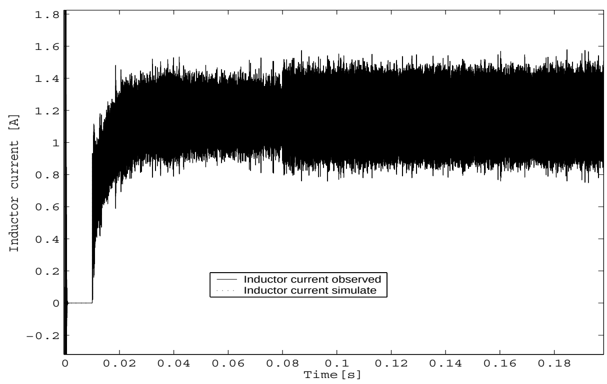

Figure 15: Inductor current simulate and observed .

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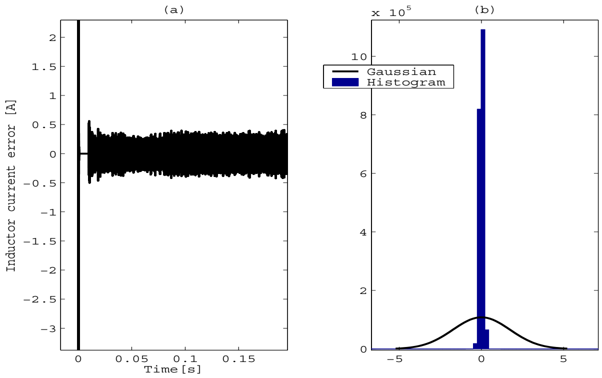

Figure 16: Inductor current observed error with histogram and Gaussian distribution.

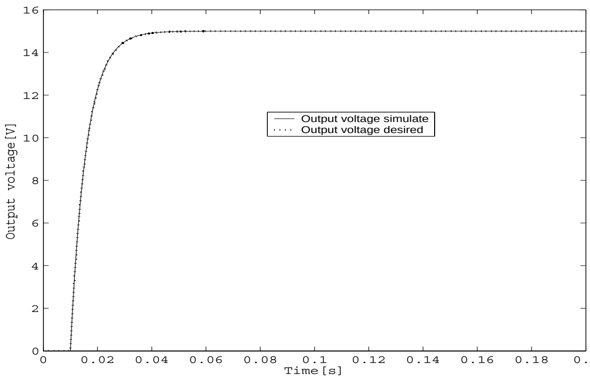

Figure 17: Output voltage simulate.

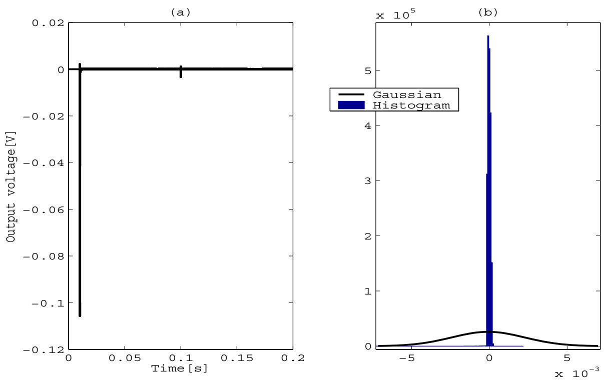

Figure 18: Output voltage simulate error with histogram and Gaussian distribution.

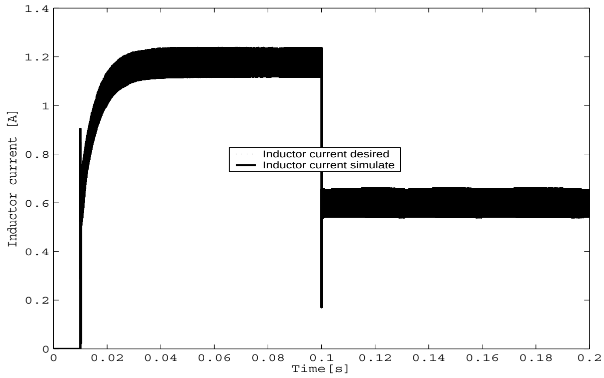

Figure 19: Inductor current simulate.

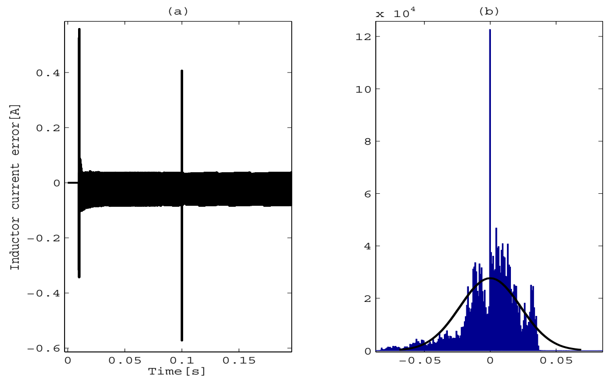

Figure 20: Inductor current simulate error with histogram and Gaussian distribution.

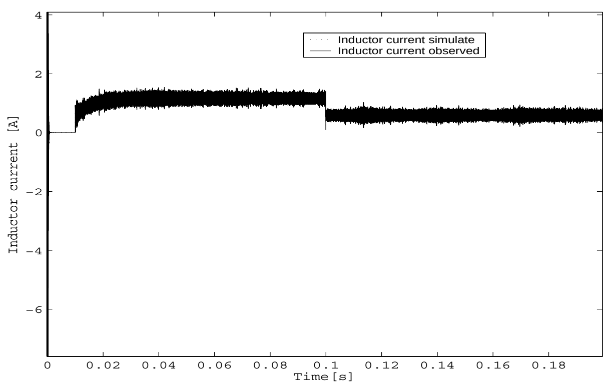

Figure 21: Inductor current simulate and observed .

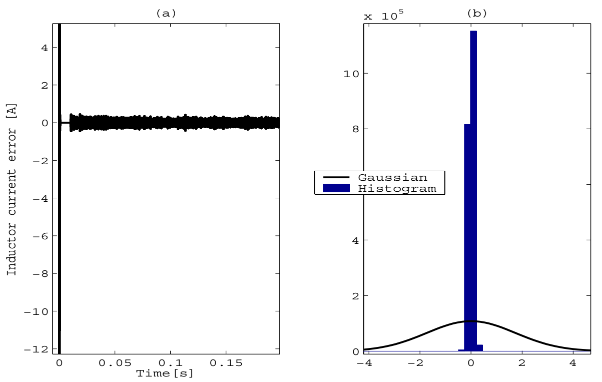

Figure 22: Inductor current observed error with histogram and Gaussian distribution.

6 Conclusion

In this paper, linearizing control is used for controlling DC-DC Buck converter without inductor current sensor where we change:

- Reference output voltage;
- Input voltage;
- Resistor load.

The software sensor used is linear observer. The simulation results show that the control of the output voltages gives very good results. Even for the linear observer except in the case of change in input voltage and change in resistor load there is a very large peak at start-up. Future work will consider more observers such as no-linear observer and more types of converters as boost converters and other inverters. I will applied this work in photovoltaic (PV) systems or DC motor.

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