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# A Novel Duty Cycle Sliding Control Methodology for Non-Isolated Cuk Converters Applied to Renewable Energy Systems

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*Abstract:* — **This paper discusses application of control of duty cycle for a non-isolated Cuk converter applied to provide continuous low ripple DC output from a hybrid renewable source consisting of a low power solar panel and windmill pair. The convention, in technology today is to utilise complex feedback loops to control output voltage with respect to sporadic swings in input. This paper provides simulational results for the efficacy of control methodology consisting of sliding the duty cycle and also a second order linear equation for the control characteristics with this method.**

***Index Terms*—DC to DC converter, Duty cycle sliding, Non isolated Cuk converter, State Space Averaging.**

## I. INTRODUCTION

DC-DC power converters have traditionally been used for power control applications in systems that require constant voltage levels, which include charging of batteries, automobile applications, in renewable sourcing and in LVDC.

Now, such controllers were initially of the Buck-boost type but were replaced by Cuk and SEPIC owing to their robust designs, high stability and infinitesimally small ripple. Cuk converters are of two configurations, namely the isolated type and the non-isolated type. Isolated Cuk converters employ a transformer and coupled inductors for further increase in performance, but such converters cause no difference in actual control or its validation, and hence, only non-isolated Cuk are discussed in this paper. The downside of such modern converters is that their control usually involves complex feedback loops or state feedback controllers and observers which are complex to implement and expensive. The proposed solution for this problem is that the duty cycle, which in traditional control stays fixed, is controlled. Control of the duty cycle is done within limits that are enforced, not by the controller, but by the non-ideality of the switching devices and power devices themselves. Also, duty cycle control has the added advantage of being simple enough to use traditional PID or very simple robust control techniques.

This particular implementation of the Cuk converter is simple to implement, both for simulation and for hardware and has, thus, been tested using simulation tools on general purpose solvers and their associated software packages. The necessary models have been provided in the respective chapters. Design equations have been followed as prescribed as only the control methodology has been introduced in this paper. Design is traditional. Control is classical and linear.

Section II describes the design of the Cuk converter. Section III deals with the state space averaged model and its derivation from the two states of the non isolated Cuk converter. Section IV describes the transfer function and its highly nonlinear relationship with duty cycle. Section V describes sliding of duty cycle to control output voltage with change in input voltage and its methodologies. Section VI are the results with a second order linear equation to describe control characteristics.

 

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## II. CUK CONVERTER DESIGN

Design specifications for the sake of simulation have been thus assumed and the Cuk Converter has been designed as per Fig 1.
Voltage ripple=5%
Current ripple=10%
Switching Frequency = 25kHz
Design of the Cuk for the above parameters has been carried out with respect to the design equations:

$$\Delta I_1 = \frac{Vdc*D}{L1*f}$$

$$\Delta I_2 = \frac{Vdc*D}{L2*f}$$

$$\Delta V_{c1} = \frac{Is*(1-D)}{C1*f}$$

$$\Delta V_{c2} = \frac{\Delta I2}{(S*C2*f)}$$

$$\text{Power}=V_o*I_o = \left(\frac{Edc*D}{1-D}\right)*\left(\frac{1-D}{D}\right)*Is$$

$$\Delta I_2 = \left(\frac{Edc*D}{(1-D)}\right)$$

***Equation set 1: General design equations for Non isolated Cuk.***

Here symbols have their usual meaning. For a given switching frequency of 25kHz, the individual components can be designed with:

$$C_2 = \frac{2}{8f}\Delta V_{c1}$$

$$C_1 = \frac{D*I_0}{\Delta V_g}$$

$$L_1 = \frac{Vdc*D}{\Delta I_1*f}$$

$$L_2 = \frac{12.2*(1-D)}{\Delta I_2*f}$$

$$\Delta I_1 = \frac{12.2*(1-D)}{L_1*f} = \Delta I_2$$

***Equation set 2: Design equations for component parameters.***

The values of various components obtained using the above equations are as shown in table 1.

***Table 1: Parameters of the Cuk converter***

| | |
|---|---|
| L1 | 6.5mH |
| L2 | 5.1mH |
| C1 | 6.8mF |
| C2 | 10uF |
| Rl(load) | 1.48Ω |

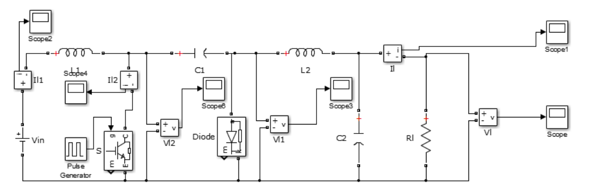


***Figure 1: Schematics and simulation model of non isolated Cuk Converter.***

## III. STATE SPACE AVERAGED MODEL

The two states of the Cuk can be described by state models each. The state model for the Cuk with the IGBT switch ON has been derived to be:

$$V_{in} - V_f = L_1 * \dot{X}_1$$

$$\dot{X}_1 = \frac{V_{in}-V_f}{L_1} = \frac{V_{in}}{L_1} - (V_{in} - V_f)\, R_{on} = \frac{V_{in}}{L_1} - \frac{(X_1 - X_2)\, R_{on}}{L_1}$$

$$V_f - V_{C_1} - V_{C_2} = L_2 * \dot{X}_2$$

$$L_2 * \dot{X}_2 = V_f - X_3 - X_4$$

$$\dot{X}_2 = \frac{V_f}{L_2} - \frac{X_3}{L_2} - \frac{X_4}{L_3}$$

$$C_2 \frac{dV_{C2}}{dt} = I_2 - \frac{V_{C_2}}{R_l}$$

$$C_2 * \dot{X}_4 = X_2 - \frac{X_4}{R_l}$$

***Equation set 3: Derivations for state model.***

The state equation may be obtained as

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\\ \dot{X}_3\\ \dot{X}_4\end{bmatrix} = \begin{bmatrix}\frac{-R_{on}}{L_1} & \frac{R_{on}}{L_1} & 0 & 0\\ \frac{R_{on}}{L_1} & \frac{-R_{on}}{L_1} & \frac{-1}{L_2} & \frac{-1}{L_2}\\ 0 & \frac{1}{C_2} & 0 & 0\\ 0 & \frac{1}{C_2} & 0 & \frac{1}{C_{2*R_l}}\end{bmatrix}\begin{bmatrix}X_1\\ X_2\\ X_3\\ X_4\end{bmatrix} + \begin{bmatrix}\frac{1}{L_1}\\ 0\\ 0\\ 0\end{bmatrix} U$$

$$Y = [0 \quad 0 \quad 0 \quad 1]\begin{bmatrix}X_1\\ X_2\\ X_3\\ X_4\end{bmatrix}$$

***Equation set 4: State equation for the Cuk when IGBT is ON.***

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\\ \dot{X}_3\\ \dot{X}_4\end{bmatrix} = \begin{bmatrix}\frac{-R_{fd}}{L_1} & \frac{R_{fd}}{L_1} & \frac{-1}{L_1} & 0\\ \frac{R_{fd}}{L_2} & \frac{-R_{fd}}{L_2} & 0 & \frac{-1}{L_2}\\ \frac{1}{C_1} & 0 & 0 & 0\\ 0 & \frac{1}{C_2} & 0 & \frac{1}{C_{1*R_l}}\end{bmatrix} * \begin{bmatrix}X_1\\ X_2\\ X_3\\ X_4\end{bmatrix} + \begin{bmatrix}\frac{1}{L_1}\\ 0\\ 0\\ 0\end{bmatrix} U$$

$$Y = [0 \quad 0 \quad 0 \quad 1]\begin{bmatrix}X_1\\ X_2\\ X_3\\ X_4\end{bmatrix}$$

***Equation set 5: State equation for the Cuk when IGBT is OFF.***

***The two state models are averaged to allow a single equation of state to describe system dynamics.***

$$A = DA_1 + (1 - D)\, A_2$$
$$B = DB_1 + (1 - D)\, B_2$$
$$C = DC_1 + (1 - D)\, C_2$$
$$D = DD_1 + (1 - D)\, D_2$$

$$\dot{X}_1 = \begin{bmatrix}(\frac{D(R_{fd}-R_{on})-R_{fd}}{L_1}) & (\frac{D(R_{on}-R_{fd})+R_{fd}}{L_1}) & \frac{D-1}{L_1} & 0\\ (\frac{D(R_{on}-R_{fd})+R_{fd}}{L_2}) & (\frac{D(R_{fd}-R_{on})-R_{fd}}{L_2}) & \frac{-D}{L_2} & \frac{-1}{L_2}\\ \frac{1-D}{C_1} & \frac{D}{C_1} & 0 & 0\\ 0 & \frac{1}{C_2} & 0 & \frac{1}{C_{2*R_l}}\end{bmatrix} X + \begin{bmatrix}\frac{1}{L_1}\\ 0\\ 0\\ 0\end{bmatrix} U$$

$$Y = [0 \quad 0 \quad 0 \quad 1]\; X$$

***Equation set 6: State space averaged model, showing dependence of system dynamics on D.***

## IV. TRANSFER FUNCTION DERIVATION

The transfer function of the Cuk can be derived from the above state space representation using the equation

***T(s) = C(sI-A)-1B+D from equation set 6.***

$$\frac{19607(s - 3962(D - D^2))}{(1.37e-4)s^4 - 9.15s^3 - (2510 - 7.92(D - D^2))s^2 + 10^5(5.18(D - D^2) + 2.57)s + 10^7(7.76D^2 - 15.5D + 7.51)}$$

***Is the transfer function of the Cuk***

## V. CONTROL BY SLIDING OF DUTY CYCLE

The state models defined above are for the sole purpose of system definition and mathematical representation. They have no significance, whatsoever, with respect to the control aspects. The transfer function derived is to prove the relation between possibilities of controlling the output voltage levels with just duty cycle. The dependence of this, on duty cycle, however is too complex to be taken into account using mathematical descriptions. Also, it is obvious that the dependence is strictly nonlinear. But implementing such nonlinear mechanisms for control defeats the whole purpose of this paper.

Thus, linear control architecture has been employed to study the performance of the converter.

In this regard, in order to avoid the complexities arising from heavy nonlinearity, the performance of the Cuk converter has been studied using simulations. The variation of output voltage with respect to the duty cycle for variations in input has been studied.

The practical aspects of this arise when a battery has to be charged at a constant voltage when the input from Solar PV and Wind vary sporadically. The input voltage is made to actuate the variance in duty cycle.

Simulation results have been used to get the duty cycle necessary for obtaining the stipulated output voltage for given input voltage. These readings may be incorporated into a look-up table for reference in the DSP TMS 28335 Simulink model. Hardware implementation of the same is to give comparable results.

Sliding of the duty cycle may be implemented for obtaining a smooth and rapid response to counter drifts in input voltage. Sliding may not be carried out over the entire spectrum of Duty cycles, namely [0,100%] but has to be restricted to [10% ,90%] due to the fact that the switch considered is not ideal, but a practical FET. The turn on and turn off criteria, coupled with electrical inertia of electromagnetic elements in the circuit are primary reasons for this. The circuit performs as expected in the zone [10% , 90%].

## VI. RESULTS

The The input voltage is subjected to drifts and the duty cycle is slid between [10% , 90%] to maintain a constant output voltage of 12V DC.

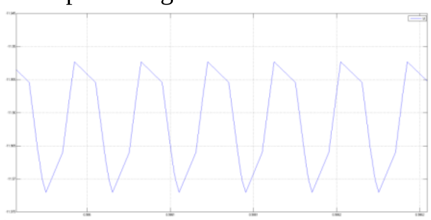

***Figure 2A: Output voltage with ripples between -11.97V to -11.95V for 14V input voltage and duty cycle 51%***

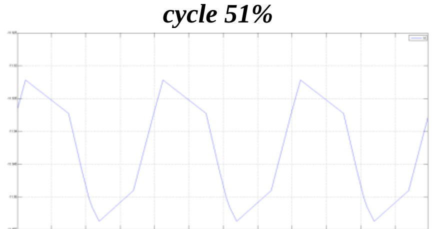

***Figure 2B: Output voltage with ripples between -11.935V to -11.955V for 16V input voltage and duty cycle 47.25%.***

***Table 2: Sliding of Duty cycle to maintain 12V DC when input voltage changes.***

| Input Voltage | Duty Cycle |
|---|---|
| 6 | 80 |
| 8 | 68 |
| 10 | 61 |
| 12 | 55.5 |
| 14 | 51 |
| 16 | 47.25 |
| 18 | 44 |

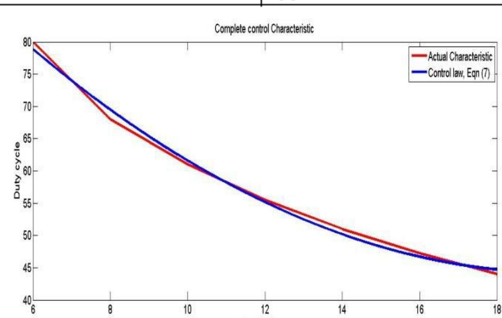


***Figure 3. Control Characteristics. Duty cycle(y) vs input voltage(x). Red line is the practical duty cycle sliding***

profile. Blue line indicates the theoretical control equation.

The control equation has been theoretically derived to be

$$D = 0.1845\, V_{in}^{\ 2} - 7.2768\, V_{in} + 115.9048 \quad \text{……….(7)}$$

The duty cycle to be set for maintaining a constant 12V output is obtained by substituting the value of Vin in (7).

## VII. CONCLUSION

The various aspects of control have been analysed for complexity and one can conclude that sliding of duty cycle to control output voltage with drifts in input voltage is the simplest and most cost effective method of control as it is strictly linear mechanism. Equation 7 gives a control law that is obtained experimentally and works to maintain a constant output voltage with respect to a drifting input and thus, is simpler to implement control with.

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