International Journal of Scientific & Engineering Research, Volume 4, Issue 8, August 2013
ISSN 2229-5518

Buck & Boost(Mix-Voltage) Operation Of Single Inductor Dual Output Buck Converters

Dalphy Rani John, C.Benin Pratap

Abstract— A single-inductor dual-output (SIDO) buck converter has recently found applications in hand-held battery-powered devices. . The circuit operation and its functional interdependences among basic converter parameters such as voltage gains, duty cycles, and current values are much more complicated than those of the single-output buck converters. In this paper, certain analysis was conducted to develop dc equations in steady state operation for SIDO buck converters. In addition to this , from the analysis results, a new operating mode "mix-voltage" operation is mentioned and in "mix-voltage" operating mode, the converter can work even when the input voltage is lower than maximum of the two output voltages. Earlier, a SIDO buck converter is used for providing "pure-buck" outputs which means that both output voltages are lower than the input voltage. So that,this possibility opens up new applications in existing applications.

Index Terms—Continuous Conduction Mode(CCM), Dc-Dc Converters, Discontinuous Conduction Mode(DCM), Mix-Voltage Conversion, Single Inductor Dual Output(SIDO),

1 INTRODUCTION

IN recent years, the dual output DC-DC converters [14]have been used in many portable and handheld consumer applications, such as MP3 players and digital cameras for the requirement of small-size and lightweight .Conventionally, the transformer-based multi-output DC-DC converters are widely employed to provide dual output voltages[8]. However, the drawbacks of these transformer-type converters include the amount and cost of electronic components and circuit volume. The single-inductor dual-output DC-DC converters were developed to effectively reduce the amount of electronic components for providing dual output voltages (see Figure 1) shows the power circuit diagram of a SIDO buck converter[1]. In this paper, analysis in steady-state operation is used to develop useful equations for design purposes. More importantly, from the analysis results, a new mode of operation, "mix-voltage" operation, would be pointed out. In the "mix-voltage" operation, the input voltage can be lower than maximum of the two output voltages, as opposed to conventional "pure-buck" operation in which input voltage must be higher than both single-inductor dual-output (SIDO). In the paper, a basic review of SIDO buck converter is given. Analytical equations relevant to continuous and discontinuous conduction mode, dc voltage gains, and duty cycles will be developed for both the "pure-buck" and the "mix-voltage" operations. An equation will also be derived to estimate whether a mix-voltage conversion is possible for given specifications

2 O OF SIDO BUCK CONVERTER

SIDO buck converter [9]can be operated in both the continuous conduction mode (CCM) [2], [3]–[5] and discontinuous conduction mode (DCM) just like a conventional type single-output buck

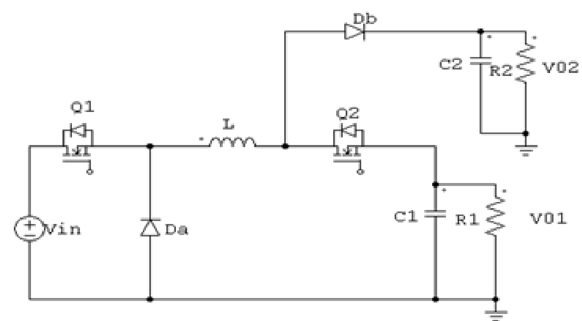

Figure 1: SIDO buck converter circuit diagram

converter(see Figure.2) shows the waveforms of the inductor current and transistor duty cycles with a time multiplexing control scheme [12] for both the CCM and DCM operations. According to the relative magnitude of transistor Q_1 duty cycle D_1 and transistor Q_2 duty cycle D_2, the waveforms are given for three cases: Case A ($D_1 < D_2$), Case B ($D_1 = D_2$), and Case C ($D_1 > D_2$). In the CCM operation, there are three periods: T_1 is the duration when both transistors Q_1 and Q_2 are ON. During this period, diodes *Da* and *Db* are OFF and the power is provided to V_{01} only. The period T_2 is the period when only one of the transistors is in conduction. If *Q*1,instead of *Q*2,is in conduction, then the inductor current flows through *Db* and the power is provided to V_{02} only. Otherwise, it flows through *Da* and the power is provided to V_{01} only. The period *T*3 is the period when both transistors are OFF. The inductor current is then flowing through *Da* and D_b and

- *Dalphy Rani John completed masters degree in power electronics and drives from Karunya University,Coimbatore,. E-mai:dalphyranijohn@yahoo.in*
- *C.Benin Pratap is currently working as Assistant Professor in Karunya University,Coimbatore,E-mail: benin@karunya.edu*

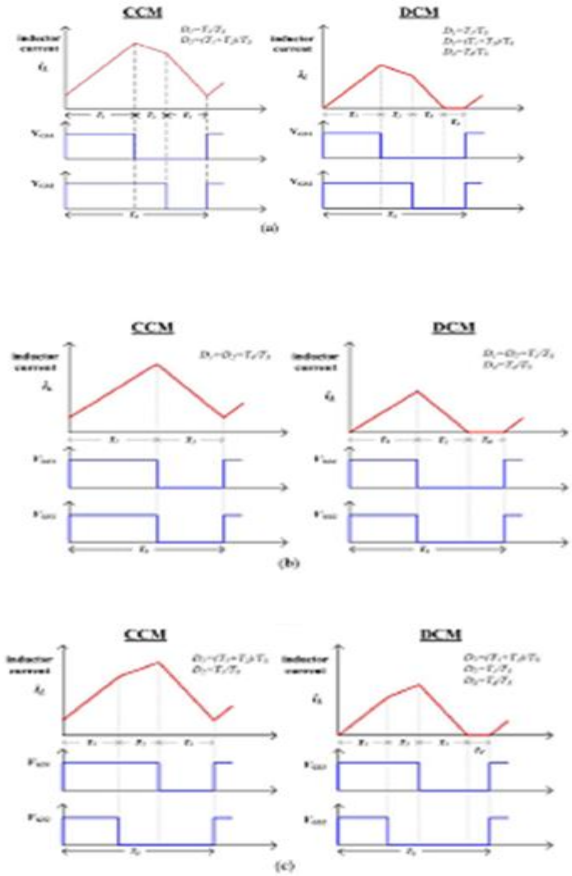

Figure 2:Operating waveforms of a SIDO buck converter for both the CCM and DCM operations: (a) Case A ($D1 < D2$); (b) Case B ($D1 = D2$); and (c) Case C ($D1 > D2$).

the power is provided only to V_{o2}. Notice that D_1 is, therefore, equal to T_1/T_S or (T_1 + T_2)/T_S, where T_S is the conversion switching period, depending upon whether it is Case A, B, or C. The same situation applies to D_2 . It is also clear that there is no T_2 period for Case B. All of these are shown along with the waveforms in (see Figure 2) For the DCM operation, there is an additional period *Td*[10] when the inductor current stays at zero and none of the switches is on. The duty cycle *Dd* is defined as Td/T_S . Just like a single output counterpart.

3. SIDO BUCK CONVERTER DC EQUATIONS

In this part, dc equations of the SIDO [13] buck converters in steady state operation is derived[1]. The derivation starts with inductor current waveform that varies according to the different cases of converter operation described in Section 2. Only Case A is used as an example for detailed derivation. Semiconductor switch conduction voltage drops will be included in the derivation.

3.1 Derivation for the DC Equations in CCM

(see Figure.3.1) shows the inductor current waveform of Case A of CCM. From the waveform, the input average current I_{in} is the average of the Q_1 current,i.e., the area below the inductor current waveform during the T_1 period divided by the total period T_s .This leads current I_{02} to the average of the inductor current of the Q_2 current. And (3) can be obtained by equating the output current I_{02} o the average of the Db current. In the equations,Vin is the input voltage, V_D and V_{DS} are, respectively, the conduction voltage drops of diodes and transistors, and V_{01} and V_{02} are the output voltages. I_X is the valley of the inductor current as shown in (see Figure 3) and T_S is the conversion switching period.

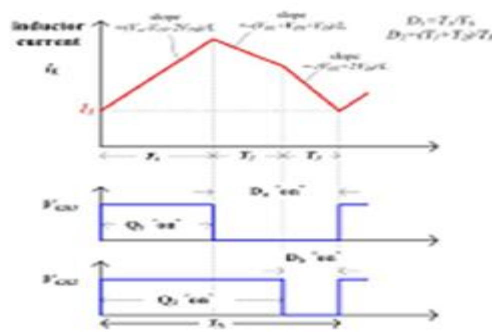

Figure 3.1: Illustration of current flow for Case A of CCM.

$$I_{in} = \frac{T_S}{2L}(V_{in} - 2V_{DS} - V_{01})D_1^2 + I_X D_1 \qquad (1)$$

$$I_{01} = \frac{T_S}{2L}[V_{in} D_1(2D_2 - D_1) - V_{01} D_2^2 + V_{DS}(D_1^2 - 2D_1D_2 - D_2^2) - V_D(D_2 - D_1)] \qquad (2)$$

$$I_{02} = \frac{T_S}{2L}(V_{02} + 2V_D)(1 - D_2) + I_X(1 - D_2) \qquad (3)$$

DC equations for Case A of CCM can then be obtained as (4) and (5). The values D_1 and D_2 can then be found by solving the two simultaneous (4) and (5), if the values of V_{01} and V_{02} are specified. On the other hand, the values V_{01} and V_{02} can be found by solving the same set of equations, if the values D_1 and D_2 are specified. The DC equations for the other two Cases of CCM operation can be obtained in a similar fashion. The results are listed in (see Table I). It should be pointed out that besides the equation complexity, the voltage gains in a SIDO converter[6] depend not only on duty cycles but also on inductor value, load currents, and switching period. That is very different from a conventional single-output buck converter.

3.2 Derivation for the DC Equations in DCM

The DC equations of a SIDO converter in DCM operation will be derived as follows. Case A will be used for the illustration of detailed derivation. (see Figure 3.2) shows the waveforms of such a case. Compared to a CCM operation, there are two differences in writing the equations for DCM operation. First, I_X is zero and an additional variable, duty cycle Dd, is involved. Setting I_X equal to zero and including the variable Dd in (2) and (3) leads, respectively, to (8) and (9) as shown in (see Table II). From the consideration of the inductor volt second balance in the steady-state DCM operation, (10) can be obtained. Again, a grouping of symbols is helpful. Compared to the CCM operation, the grouping in DCM is identical except that, there is an additional variable Dd involved. Therefore, there are five variables in DCM, namely V_{01}, V_{02} , D_1 , D_2 , and Dd. If two of the five variables are specified, the other three can be found out by solving the three simultaneous equations (8)–10). For example, if V_{01} and V_{02} in CCM and all the parameters are specified, then all the duty cycle information can be found. Table II lists the DC equations for the three Cases of DCM operation.

TABLE 1
DC EQUATIONS OF A SIDO BUCK CONVERTER IN CCM MODE

Case	DC equations in CCM	
Case A ($D_1 < D_2$) Or Case B ($D_1 = D_2$)	$I_{O1} = $ [illegible] $D_2 + $ [illegible] $(V_{O1} + 2V_D)(1-D_2)(D_1-D_2)$	(4)
	$I_{O2} = $ [illegible] $(1-D_2) - $ [illegible] $(V_{O1} + V_{O2} + V_D)(1-D_2)(D_1-D_2)$	(5)
Case C ($D_1 > D_2$)	$I_{O1} = $ [illegible] $D_2 + $ [illegible] $(V_{O1} + 2V_D)(1-D_2)(D_1-D_2)$ [illegible]	(6)
	$I_{O2} = $ [illegible] $(1-D_2) - $ [illegible] $(V_{O1} + V_{O2} + V_D)(1-D_2)(D_1-D_2)$ [illegible]	(7)

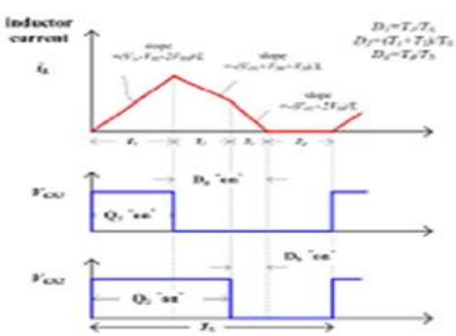

Figure 3.2: Illustration of current flow for Case A of DCM

3.3 Steps For Finding Duty Cycle Values

Normally, converter component values and operating conditions are given. From the equations in Tables I and II, one can see that if duty cycles D_1,D_2 ,and Dd are known, then proper Case and, therefore ,

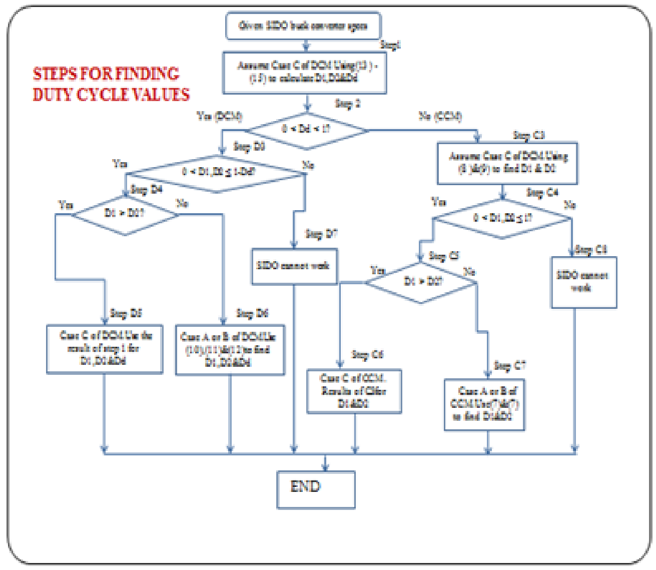

Figure 3.3 Steps to find operating modes and duty cycles

proper equations can be selected to solve for the output voltages V_{01} and V_{02} . However, it is more difficult to do that the other way around, that is, to determine the duty cycle values from the specified output voltage values. This is because, to use the proper equations, one needs to know in advance in which mode (CCM or DCM) and in which Case (A, B, or C) the converter[7] is being operated. This information can only be found out with an elaborate procedure. (see Figure 3.3) shows a proposed algorithm to do that Refer to the flowchart in . In the top block, a set of values including output voltages, component values, switching period, and input voltage are given. In Step 1, one assumes that the converter operates in Case C of DCM, and therefore, uses the corresponding equations to find out the values D_1,D_2,and Dd. In Step 2, Dd is used to determine the converter operation mode. If Dd is within the range of [0, 1], then it is a DCM operation. If not, then it is a CCM operation. In Step D_3, the duty cycle D_1 and D_2 values are checked to see if they stay in proper boundary. Obviously, they cannot be a complex number and have to be within the range of [0, 1-Dd]. If not, then there is no answer to the given set of starting parameters. In other words, it is not possible for a SIDO converter to provide the specified V_{01} and V_{02} under the specified conditions and parameters as indicated by Step D7. If otherwise, go to Step D4. In Step D4, it must be checked if $D_1 > D_2$ (Case C) because it was initially assumed to be Case C in Step 1. If the answer is "yes", then the values D_1, D_2 and Dd obtained in Step 1 are the final answers. Otherwise, go to Step D6 and use Case A or B equations to find out the duty cycle values. The discussion that took place earlier applies to the situation if the decision in Step 2 is "yes". If the decision in Step 2 is "no", then go through the CCM path to Step C3 and first assume it is in Case C and solve for the duty cycles. The rest of the path follows the same logic as used in the DCM path. At the end, either an answer can be found or it is not possible to meet the beginning specifications of the SIDO converter. This flowchart will be used in the next section to illustrate the Mix-Voltage concept.

TABLE 2
DC EQUATIONS OF A SIDO BUCK CONVERTER IN DCM MODE

Case	DC equations in CCM
CaseA ($D_1 < D_2$) Or CaseB ($D_1 = D_2$)	$I_{01} = \frac{T_S}{2L}[(V_{in}+V_D-V_{DS})(2D_2-D_1)D_1-(V_{01}+V_{DS}-V_D)D_2^2]$ (10) $I_{02} = \frac{T_S}{2L}(V_{02}+2V_D)(1-D_2-D_d)^2$ (11) $(V_{in}-V_{01}-2V_{DS})D_1 = (V_{01}+V_{DS}+V_D)(D_2-D_1)+(V_{02}+2V_D)(1-D_2-D_d)$ (12)
CaseC ($D_1 > D_2$)	$I_{01} = \frac{T_S}{2L}(V_{in}-V_{01}-2V_{DS})D_1^2$ (13) $I_{02} = \frac{T_S}{2L}[(V_{02}+2V_D)(1-D_2-D_d)^2-(V_{in}+V_D-V_{DS})(D_1-D_2)^2]$ (14) $1-D_d = \frac{(V_{in}+V_D-V_{DS})D_1+(V_{DS}+V_D-V_{01}-V_{DS})D_2}{V_{02}+2V_D}$ (15)

4. Mix-VOLTAGE CONVERSION FOR SIDO BUCK CONVERTER

Two examples will be given to illustrate the use of the flowchart in (see Figure 3.3). From the results, one can also see if "mix-voltage" conversion is possible for the specifications.

Example 1*:* Converter specifications are given in the following. V_{01} = 1.8V, V_{02} = 3.3V, I_{01} = 500mA, I_{02} = 200mA, L = 10 μH, V_{DS} = 0.01 V, V_D = 0.4 V, and T_S = 5 μs. The maximum input voltage Vin max = 5 V. Find the duty cycle information and the minimum operable input voltage Vin min.

Step 1: Vin is first set at 5 V and proceeded as follows: Two sets of solutions are obtained using (11)–(13). $(D1, D2, Dd)$ = {(−0.6763,−0.7931, 2.255) and (0.6763, 0.7931, −0.2546)}.

Step 2: Since Dd is outside the range of [0, 1] for both solutions, the converter works in CCM; therefore, go to Step C3.

Step C3: One set of solution is obtained $(D1, D2)$ = (0.5335, 0.6478) using (6) and (7).

Step C4: $D1$ and $D2$ stay within boundary.

Step C5: Need to check if $D_1 > D_2$. It turns out D_1 is less than D_2 . This means the assumption in Step C3 and the equation used to obtain D_1 and D_2 were incorrect. Therefore, go to Step C7. The duty cycles need to be recalculated.

Step C7: Solving for D_1 and D_2 using (4) and (5). (D_1, D_2) = (0.5268, 0.6670).

The data given earlier were obtained for Vin = 5V. For each selected Vin value, the operating duty cycle values can be found as described earlier. It turns out that the converter operates in the CCM for the entire input range. (see Figure 4(a)) shows the plot of the resultant duty cycle values versus Vin. As Vin is decreased, the $D1$ curve intersects with the $D1$ = 1 line at Vin min.

This crossover point is the minimum input voltage that the converter specifications can still be

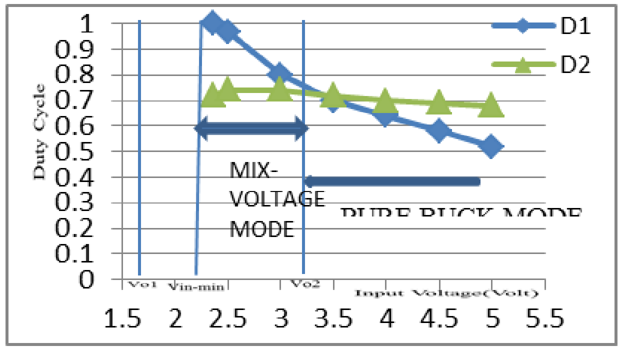

Figure 4(a): Plots of duty cycle values Vs *Vin* for Eg: 1

The data given earlier were obtained for Vin = 5V. For each selected Vin value, the operating duty cycle values can be found as described earlier. It turns out that the converter operates in the CCM for the entire input range. (see Figure 4(a)) shows the plot of the resultant duty cycle values versus Vin. As Vin is decreased, the $D1$ curve intersects with the $D1$ = 1 line at Vin min. This crossover point is the minimum input voltage that the converter specifications can still be met by the converter because D_1 must be no more than unity. From the figure, Vin min is about 2.36 V, which lies between V_{01} and V_{02} . So, mix-voltage conversion exists in this example. This example shows that the converter is capable of operating even when the input battery voltage is well below V_{02} value of 3.3 V.

Example 2*:* The converter specifications are the same as those of Example 1 with the exception of the load current values: I_{01} = 100 mA and I_{02} = 500 mA.

One can go through the flowchart of (see Figure 5) and the result is shown in (see Figure 4(b)). In this case, the converter operates in the CCM also for the entire input voltage range. However, Vin min is greater than both output voltages, which

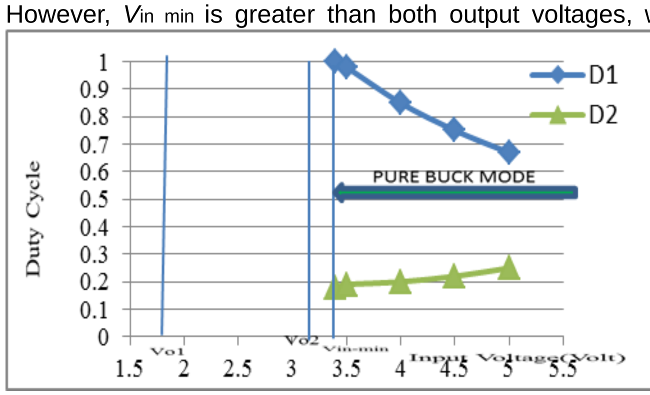

Figure.4(b): Plots of duty cycle values versus *Vin* for Eg: 2

International Journal of Scientific & Engineering Research Volume 4, Issue 8, August-2013
ISSN 2229-5518

5. SIMULATION RESULTS

Simulation of both open loop and closed operations are done in Matlab-Simulink. During open loop input is given as 5v and outputs are 1.8v and 3.3v.In closed loop simulation ,input is lowered to 3v and the outputs remain same at 1.8v and 3.3v.

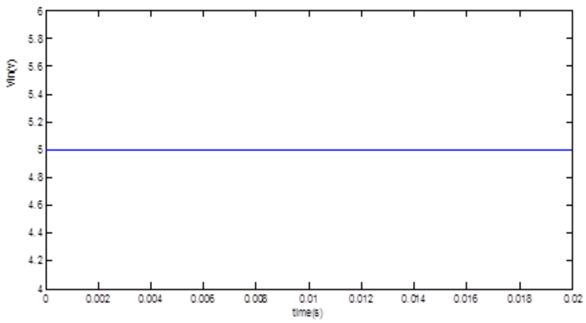

Figure 5.1(a):input voltage(5v)

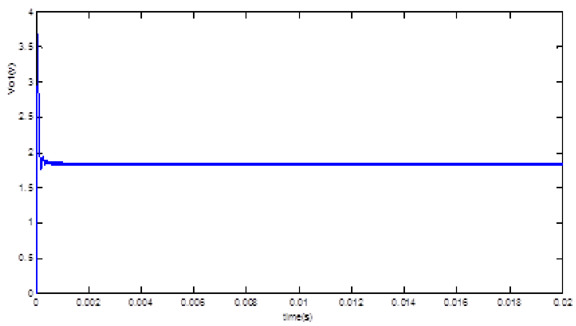

Figure 5.1(b):output voltage(1.8v

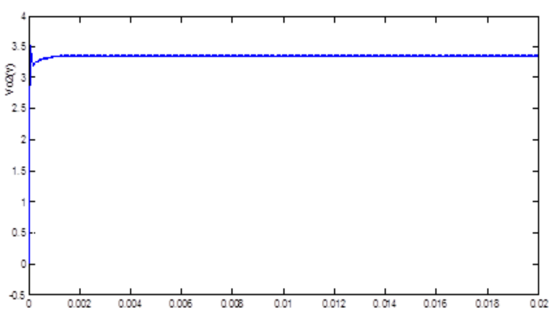

Figure 5.1(c):output voltage(3.3v)

5.2 SIDO BUCK CONVERTER (feedback loop)

Here in feedback loop configuration we are reducing the voltage to 3volts,even in that case the output voltages remain as 1.8v & 3.3v.

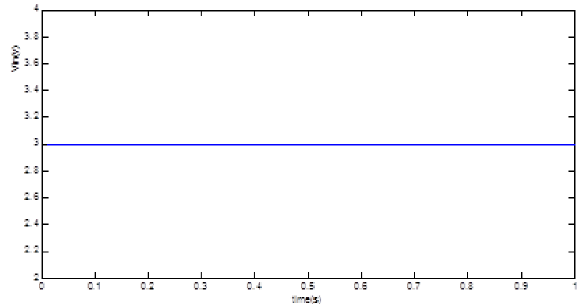

Figure 5.2(a):input voltage(3v)

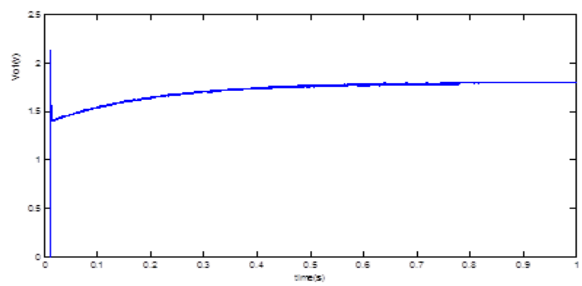

Figure 5.2(b):output voltage(1.8v)

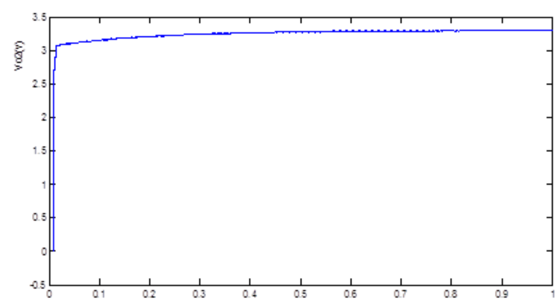

Figure 5.2(c):output voltage(3.3v)

6. CONCLUSION

A single inductor dual output buck converter is analyzed for steady-state operation[15]. The various operating modes were explained and certain equations for the design purpose is developed. These equations allow the designer to find out relationships among output voltages, duty cycles, and load currents. From the results, a mix-voltage operation is demonstrated. This new mode of operation opens up new applications for existing applications

REFERENCES

[1] D. Goder and H. Santo, "Multiple output regulator with time sequencing," U.S. Patent 5,617,015, Apr. 1997

[2] K.-Y. Lin, C.-S. Huang, D. Chen, and K. H. Liu, "Modeling and design of feedback loops for a voltage-mode single-inductor dual-output buck converter," in *Proc. IEEE Power Electron. Spec. Conf.*, 2008, pp. 3389– 3395.

[3] D. Trevisan, P. Mattavelli, and P. Tenti, "Digital control of single-inductor multiple-output step-down DC–DC converters in CCM," *IEEE Trans. Ind. Electron.*, vol. 55, no. 9, pp. 3476–3483, Sep. 2008.

[4] M. Belloni, E. Bonizzoni, and F. Maloberti, "On the design of single inductor multiple-output DC–DC buck converters," in *Proc. IEEE Int. Symp. Circuits Syst.*, 2008, pp. 3049–3052.

[5] W. Xu, X. Zhu, Z. Hong, and D. Killat, "Design of single-inductor dual output switching converters with average current mode control," in *Proc IEEE Asia Pac. Circuits Syst. Conf.*, 2008, pp. 902–905.

[6] E. Bayer and G. Thiele, "A single-inductor multiple-output converter with peak current state-machine control", Applied Power Electronics Conference and Exposition, 2006. APEC '06. Twenty-First Annual IEEE19-23 March 2006.

[7] P. Patra, S. Samanta, A. Patra and S. Chattopadhyay, "A novel control technique for single-snductor multiple-output DC-DC Buck Converters", Industrial Technology, 2006. ICIT 2006. IEEE nternational Conference, pp. 807–811, Dec. 2006.

[8] U.S. Patent 6,900,620, Eiji Nishimori et al., "Switching regulator having two or more outputs", May 31 2005.

[9] W.-H. Ki and D. Ma "Single-inductor multiple-output switching converters", Power Electronics Specialists Conference, PESC, IEEE 32nd Annual Vol.1 pp. 226 - 231, June 2001.

[10] Mohan, Undeland, Robbins, "Power Electronics" third edition,John Wiely & Soncs, Inc., 2003

[11] D.Ma,W.-H. Ki, and C.-Y. Tsui, "A pseudo-CCM/DCM SIMO switching converter with freewheel switching," *IEEE J. Solid-State Circuits*, vol. 38, no. 6, pp. 1007–1014, Jun. 2003.

[12] Dongsheng Ma, Wing-Hung Ki, Chi-Ying Tsui, Philip K.T. Mok "Single Inductor Multiple Output Switching Converters With Time-Multiplexing Control in Discontinuous Conduction Mode", *IEEE Journal of solid state circuits, Vol 38, No. 1, January 2003*

[13] N. Mohan, T.M. Undeland, and W.P. Robbins, "Power Electronics - Converters, Applications, and Design – Second Edition", John Wiley & Sons, INC., Ch. 7.

[14] B. Arbetter, R. Erickson, and D. Maksimovic, "DC-DC converter design for battery-operated systems", *IEEE Power Electronics Specialist Conference 1995*, vol. 1, pp. 103 – 109, June 1995.

[15] E. van Dijk, et al., PWM-Switch Modeling of DC-DC Converters, IEEE Transactions on Power Electronics, Vol. 10, No. 6, pp. 659–665, November 1995.