Application Note

Estimate, Measure, and Reduce the Voltage Drop of Buck Converter in Battery Power Applications

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ABSTRACT

In battery power applications such as doorbells and E-locks, a buck converter is often required to obtain power rails with different voltage levels. To fully utilize the battery, the output voltage must be as close as possible to the input voltage in the dropout zone. This application note first introduces system power rails in battery power applications. We then discuss how to calculate, estimate and measure the voltage drop considering both the situation with or without temperature influence. The test data of TPS629210 and LMR51610 were used to verify the theory. A summary of this application note and how to choose a low voltage drop buck converter is proposed.

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1 Introduction

In building automation applications, such as E-Lock, doorbell, temperature and humidity sensors, all the applications that require battery power need at least one buck to create corresponding power rails to provide energy for post-stage circuits such as LDO or directly connect to the chips. Figure 1-1 shows typical power rails in battery power applications.

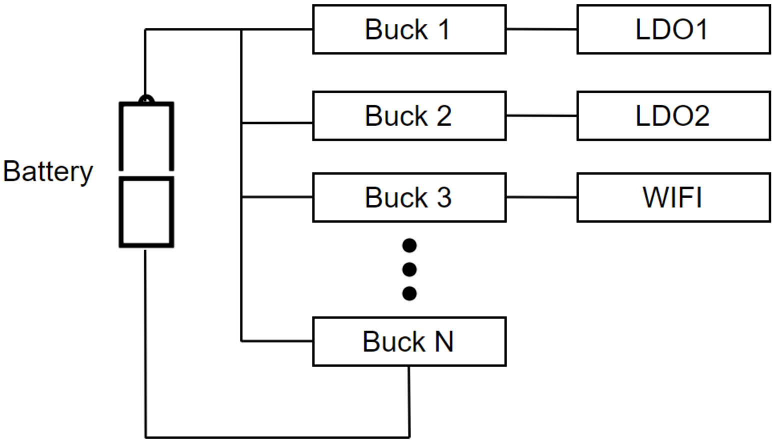


Figure 1-1. Power Rails of Battery Power Application

Assuming that one buck's load is an LDO, the LDO has a lower input voltage limit to output the system required voltage. Therefore, to maintain LDO operation, the output voltage of the buck converter needs to be larger than the lower input voltage limit of the LDO. Moreover, to fully use the batter power, we need to keep the input voltage and output voltage of the buck converter sufficiently close. This means that the buck needs to have a low voltage drop. If the voltage drop of Buck converter is very large, we cannot keep LDO working even if the battery has enough power. Figure 1-2 shows this relationship.

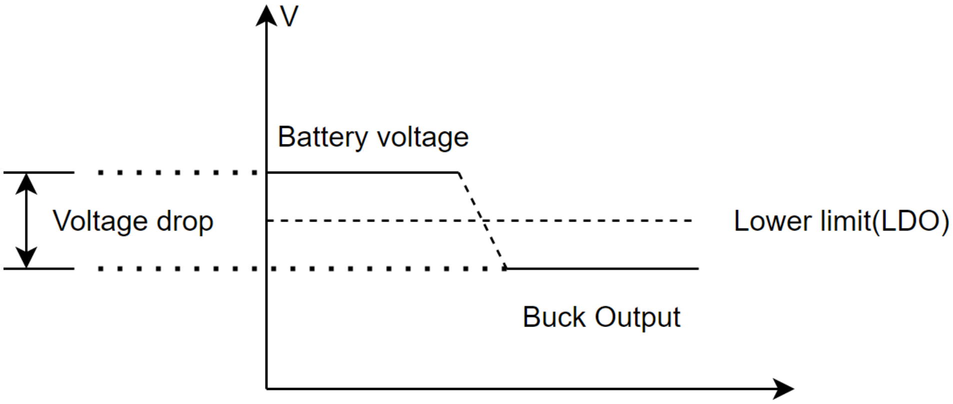


Figure 1-2. Voltage Relationship

Based on the analysis, an effective way to fully use the battery is to reduce voltage drop in buck converter.

2 Estimate and Measure the Voltage Drop in Buck Converter

To reduce the voltage drop in the buck converter, the first step is to analyze the components of the voltage drop. In this section, the estimation and measurement of the voltage drop of the buck converter are included.

2.1 Estimation of Voltage Drop in Buck Converter Working in CCM

In the buck converter, there are two main reasons causing the voltage drop: duty cycle and resistance. Equation 1 shows this relationship.

$$V_{drop}=(V_{duty}+V_R) \tag{1}$$

Where:

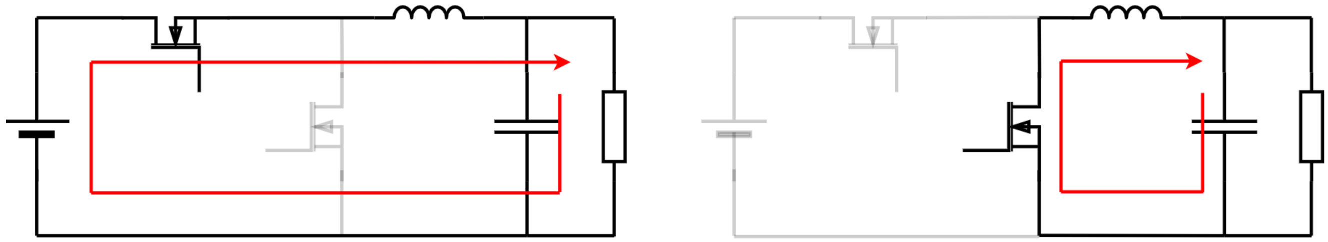
- V_{duty} is the voltage drop caused by the duty cycle
- V_R is the voltage drop caused by the resistance

The voltage drop caused by the duty cycle is easy to obtain, as shown in Equation 2.

$$V_{duty}=[V_{in}(1\text{-}D)] \tag{2}$$

- V_{in} is the input voltage
- D is the duty cycle

To further analyze the voltage drop caused by the MOSFET, Figure 2-1 shows the basic operating mode of buck converter.



Mode 1

Mode 2

Figure 2-1. Operating Mode

In mode 1, the high-side MOSFET is on, so the high-side MOSFET and inductor can be modeled as two resistors, R_{mos1} and R_L. In mode 2, the high-side MOSFET is off but the low-side MOSFET is on, so there are still two resistors, R_{mos2} and R_L.

Based on the operating mode, the battery only powers the system when the high-side MOSFET is on. Therefore, the basic concept involves the conservation of energy and power balancing. A few assumptions were made to simplify the calculations:

1. The capacitor is ideal which means no ripple in the output
2. The inductor average current is equal to the RMS value
3. Battery is a stable DC source

In one cycle, the power provided by the battery or the input power is only consumed by the resistor and then provided to the output. Although there is some switching loss, the loss is negligible compared with the conduction loss caused by the resistor. In addition, the SW voltage in the dropout zone is relatively low, which reduces the switching loss.

According to the previous analysis, we can obtain the power balanced equation.

$$V_{in}I_LDT=I_L{}^2[R_LT+R_{mos1}DT+VR_{mos2}(1\text{-}D)T+V_{out}I_{out}T] \tag{3}$$

Where:

- V_{in}, V_{out} are the input and output voltage
- I_{out}, I_L are the output current and inductor average current
- R_{mos1} and R_{mos2} are the on-state resistance of the high-side and low-side FETs.
- T is the period
- R_L is the DC resistance of the inductor used

Based on Equation 3, I_L is equal to I_{out}, which is similar to assumption 2, and we can obtain simplified Equation 4.

$$V_{in}D - I_{out}[R_L T + R_{mos1}DT + R_{mos2}(1 - D)T] = V_{out} \tag{4}$$

As we can see from the Equation 4, $V_{in}D$ is the voltage drop caused by the duty cycle, the latter one is caused by the equivalent resistors.

Now, slightly transform the Equation 4 and we can obtain Equation 5.

$$V_{drop} = V_{in}\left(1 - D/P\right) \tag{5}$$

$$P = [1 + (R_L + R_{mos1}D + R_{mos2}(1 - D))/R_{out}] \tag{6}$$

Where:

- P is a coefficient to simplify the equation

Equation 5 provides a convenient method to estimate the voltage drop in a buck converter. Some of TI buck converter have the 100% duty cycle function for the battery applications. In these products, the voltage drop can be easily obtained using Equation 7 because the drop is conducted directly.

$$V_{drop} = I_{out}\left(R_L + R_{mos1}\right) \tag{7}$$

In later chapter, we further discuss how to reduce the voltage drop to further use the battery.

2.2 Measurement of Voltage Drop of Buck Converter

In this section, to verify the theory, we measure the voltage drop with different output current. We choose TPS629210 and LMR51610 to perform these tests. TPS629210 is the newest TI 3-17V, 1A synchronous buck converter with 100% duty cycle function. LMR51610 is TI newest wide range V_{in}, 1A synchronous buck converter with 98% maximum duty cycle.

An important factor influencing the measurement of the voltage drop in a buck converter is the deviation of the feedback resistor from the standard value. Deviation of the feedback resistor causes the output voltage to deviate from the calculated value. Therefore, we cannot consider the calculated output voltage to be the designed for value. To make sure that the buck converter operates in the dropout zone, making sure that the device has reached the maximum duty cycle.

The TPS629210 has 100% duty cycle function. First we choose a fixed output voltage and then the voltage drop can be measured by adjusting the input voltage when the duty cycle reaches 100%.

The LMR51610 designed for duty cycle is 98%. The cycle is limited by the minimum off time and maximum on time as shown in Equation 8 which is 200nS and 5uS respectively. However, in practice, the minimum off time can have some deviation. The practical duty cycle of LMR51610 is measured during in the following chapter.

$$D = T_{onmax}/\left(T_{onmax} + T_{offmin}\right) \tag{8}$$

Where:

- T_{onmax} is the maximum on time
- T_{offmin} is the minimum off time

Based on Equation 8 and the typical number in data sheet, the calculated duty cycle is 96%.

3 Voltage Drop Comparison Between Calculation, Simulation, and Measurement

Based on the typical number in the data sheet, this section compares the voltage drop between the calculation, simulation and actual measurement. Table 3-1 shows the specifications of the TPS629210.

Table 3-1. TPS629210 Specification

Parameter	Value	Unit
Input Voltage	5	V
Output Voltage	5(Ideally)	V
Output Current	0.1-0.9	A
Duty Cycle	100	%
High-side Resistance	250	mΩ
Low-side Resistance	85	mΩ
Inductor DC resistor	37	mΩ

Table 3-2 shows the actual measurement results of TPS629210.

Table 3-2. TPS629210 Test Results

Input voltage(V)	Input current(A)	Output Voltage(V)	Output Current(A)	Voltage drop(V)
4.9691	0.0956	4.9386	0.0980	0.0305
4.9667	0.1946	4.9046	0.1972	0.0621
4.9645	0.2932	4.8710	0.2968	0.0935
4.9621	0.3927	4.8365	0.3952	0.1256
4.9598	0.4932	4.8017	0.4929	0.1581
4.9574	0.5925	4.7660	0.5920	0.1914
4.9551	0.6925	4.7295	0.6915	0.2256
4.9528	0.7920	4.6918	0.7910	0.2610
4.9505	0.8900	4.6527	0.8890	0.2978

Then, using Equation 7, we can simply calculate the voltage drop, or we can use Equation 8 to calculate by setting D equal to 1. For a more detailed comparison, a simulation model is made in plecs. Relevant parameters, such as resistance, duty cycle, and output resistor, were embedded into the model.

Table 3-3 summarizes the voltage drops based on the calculations, simulations, and real tests. To compare the deviations of the calculation and simulation from the actual parameters, the parameters used in the calculation and simulation were consistent with the actual test values.

Table 3-3. Voltage Drop in Calculation, Simulation and Actual Test in TPS629210

Output current(A)	Calculation(V)	Simulation(V)	Test(V)
0.1	0.0283	0.0283	0.0305
0.2	0.0566	0.0563	0.0621
0.3	0.0853	0.0854	0.0935
0.4	0.1137	0.1137	0.1256
0.5	0.1419	0.1420	0.1581
0.6	0.1706	0.1731	0.1914
0.7	0.1996	0.2020	0.2256
0.8	0.2286	0.2286	0.2610
0.9	0.2573	0.2574	0.2978

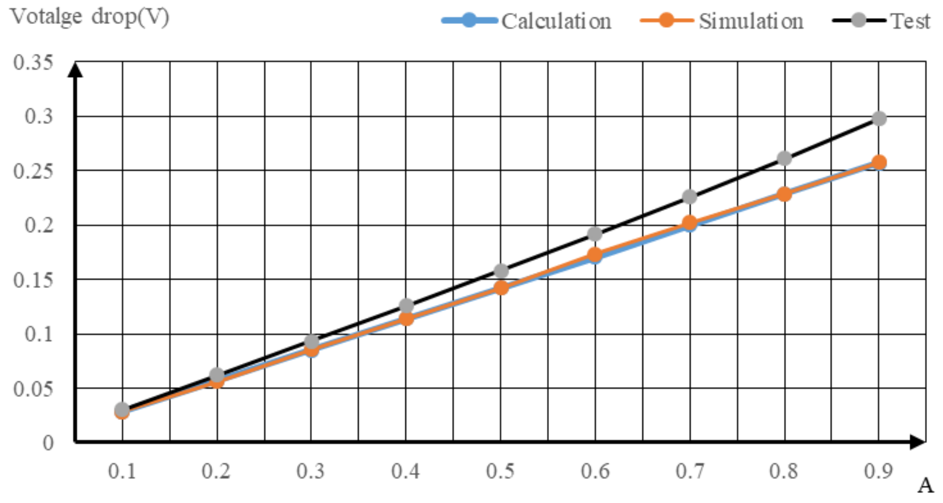


Figure 3-1. Voltage Drop Comparison of TPS629210

Table 3-4. Table 3-4 Specification of LMR51610

Parameter	Value	Unit
Input Voltage	5	V
Output Voltage	5(Ideally)	V
Output Current	0.1-0.9	A
Duty Cycle	98%(Ideal)	%
High-side Resistance	700	mΩ
Low-side Resistance	360	mΩ
Inductor DC resistor	137	mΩ

Table 3-5. LMR51610 Test Results

Input voltage(V)	Input current(A)	Output Voltage(V)	Output Current(A)	Voltage drop(V)
5.3889	0.0905	5.0799	0.1004	0.309
5.3865	0.1852	4.9827	0.1991	0.4038
5.3842	0.2812	4.8860	0.2988	0.4982
5.3820	0.3762	4.7851	0.3976	0.5969
5.3797	0.4698	4.6770	0.4949	0.7027
5.3774	0.5650	4.5594	0.5950	0.818
5.3752	0.6605	4.4293	0.6945	0.9459
5.3729	0.7540	4.2773	0.7945	1.0956
5.3708	0.8510	4.0572	0.8930	1.3136

Table 3-6. Voltage Drop in Calculation, Simulation and Actual Test in LMR51610

Output current(A)	Calculation(V)	Simulation(V)	Test(V)
0.1	0.3118	0.3089	0.3090
0.2	0.3961	0.3905	0.4038
0.4	0.5669	0.5560	0.5969
0.5	0.6522	0.6388	0.7027
0.6	0.7413	0.7254	0.818
0.7	0.8326	0.8142	0.9459
0.8	0.9290	0.9080	1.0956

Table 3-6. Voltage Drop in Calculation, Simulation and Actual Test in LMR51610 (continued)

Output current(A)	Calculation(V)	Simulation(V)	Test(V)
0.9	1.0381	1.0145	1.3136

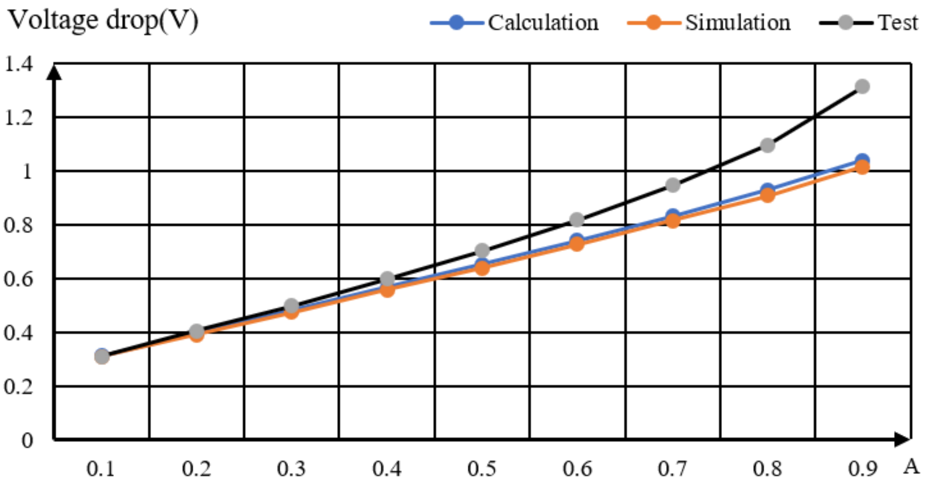


Figure 3-2. Voltage Drop Comparison of LMR51610

For the voltage drop in TPS629210, based on Table 3-2, Table 3-6, and Figure 3-1 we can see that the calculation based on Equation 5 is very close to the simulation results, but there is some deviation from the real test results.

With an increase in the output current, the deviation gradually increases. The maximum value was 0.0404V or 40.4mV. This is close to the calculation and simulation results. The reason for this deviation is the MOSFET temperature offset and practical resistance of the MOSFET and R_L.

- Practical resistance of MOSFET and R_L

In the calculation, we calculated the voltage drop using the typical conduction resistance in the data sheet. 250mOhm for TPS629210 and 37mΩ for the inductor used in EVM, but the practical resistance can not be very accurated 250mΩ and 37mΩ.

- Rdson Temperature offset of FETs

Based on the ATE characterization data, Rdson of the internal FET has a deviation range based on the typical value over temperature. When the voltage increased, Rdson of the FET also increased. This introduced an additional voltage drop and let the curve exhibit a certain degree of nonlinearity.

For LMR51610, as shown in Table 3-6 and Figure 3-1, the calculation and simulation results also maintain high consistency. Deviation and nonlinearity are also caused by the aforementioned issue. However, the test results of LMR51610 showed more nonlinearity because the resistances of the FETs and inductor were higher and caused a greater temperature increasement than that of TPS629210.

In addition, for LMR51610, the typical number of maximum duty cycle is 98%, but in real tests, the duty cycle has some differences, and the maximum duty cycle can be calculated using the equation in the data sheet. In this test, the duty cycle was 96% and decreased to 95.72% when the output current increase from 0.1A to 0.9A as we can see from the Period and Minimum Off Time in LMR51610, Period. But the good thing is that the practical duty cycle is close to the calculated duty cycle based on Equation 8.

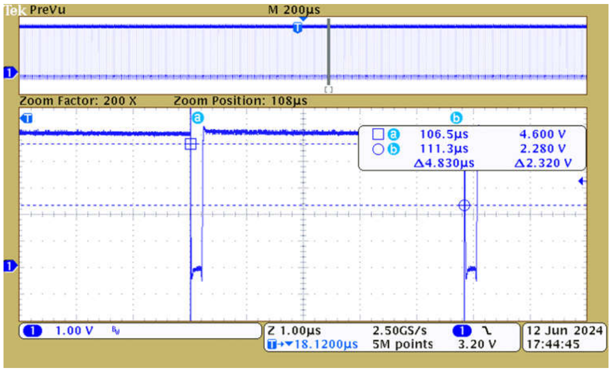


Figure 3-3. Period and Minimum Off Time in LMR51610, Period

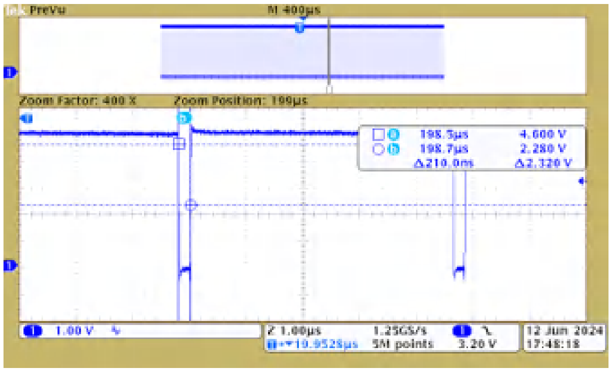


Figure 3-4. Period and Minimum Off Time in LMR51610, Off time

Therefore, by considering the effect of temperature on Rdson, the calculated results can be made more accurate. In the TPS629210EVM, there is difficulty to estimate the junction temperature increase caused by the inductor, which is related to the layout, PCB material, and copper thickness. Therefore, we mainly considered the temperature raising caused by the FETs. We can calculate the temperature raising by the power loss and effective junction to ambient resistor by reading the data sheet or the EVM guideline. Equation 9 shows the equation to calculate the temperature raising.

$$T_j = T_A + \left(R_{\theta JA} I_{out}{}^2 R_{dson}\right) \tag{9}$$

Where:

- T_j is the practical temperature
- T_A is the room temperature
- $R_{\theta JA}$ is the effective room to ambient resistor

After T_j is obtained, R_{dson} can also be obtained at a specific temperature. If the relationship between temperature and Rdson is not given in data sheet, we can use experience equation to estimate the R_{dson}. Normally, R_{dson} at 150 °C is twice as high as that at 25 °C.

Table 3-7 and Figure 3-5 is the comparison table between calculated voltage drop after considering the temperature raising and practical test results. The $R_{\theta JA}$ is 60℃/W for TPS629210EVM and the R_{dson} is 275mΩ

Table 3-7. Comparison Between Calculation and Test in TPS629210

Output current(A)	Tj(℃)	Rdson(mΩ)	Calculation(V)	Test(V)
0.1	25.151	275	0.0307	0.0305
0.2	25.642	276	0.0617	0.0621
0.3	26.453	277	0.0932	0.0935
0.4	27.577	278	0.1247	0.1256
0.5	29.009	280	0.1564	0.1581
0.6	30.783	282	0.1891	0.1914
0.7	32.890	284	0.2226	0.2256
0.8	35.320	287	0.2570	0.2610
0.9	43.150	291	0.2920	0.2978

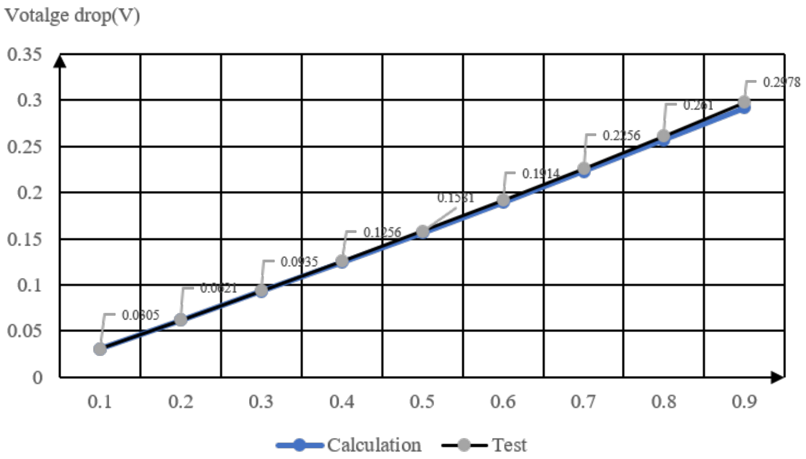


Figure 3-5. Comparison Between Calculation and Test in TPS629210 (Add Temperature Influence)

Table 3-8. Comparison Between Calculation and Test in LMR51610

Output current(A)	Tj(℃)	Rdson(mΩ)	Rdson_Low(mΩ)	Calculation(V)	Test(V)
0.1	25.656	704	362	0.3218	0.3090
0.2	27.580	714	367	0.4085	0.4038
0.3	30.811	733	377	0.5004	0.4982
0.4	35.280	758	390	0.5979	0.5969
0.5	40.944	789	406	0.7029	0.7027
0.6	48.042	829	426	0.8210	0.818
0.7	56.393	876	450	0.9516	0.9459
0.8	66.084	930	478	1.0991	1.0956
0.9	76.902	991	509	1.2726	1.3136

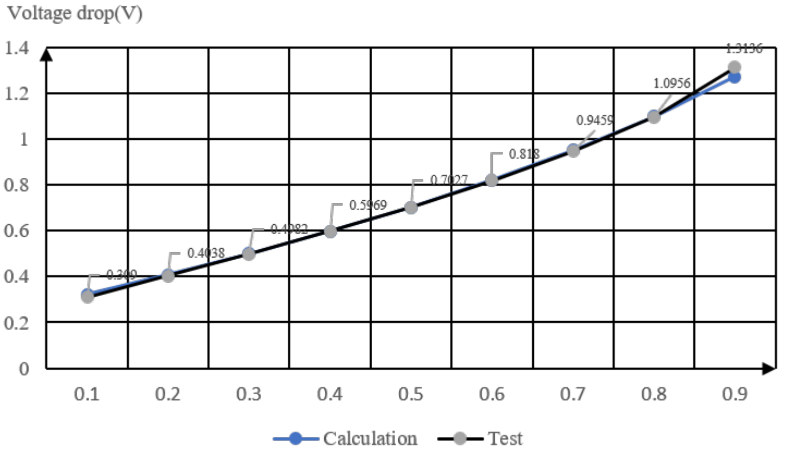


Figure 3-6. Comparison Between Calculation and Test in LMR51610(Add Temperature Influence)

As shown in the results, once adding the temperature influence on the resistance of the FET, the calculation results were more accurate.

4 Summary

This application note provides a mathematical method for calculating the theoretical voltage drop in the buck converter. The simulation model and practical tests in TPS629210 and LMR51610 were used to verify this theory. The calculation and simulation results showed a high degree of consistency. In practice, the temperature offset of the FETs introduces a certain level of nonlinearity. The calculation results are highly accurate once we add the influence of the temperature in the FETs.

Therefore, based on the above theoretical analysis, simulation and test results. This application note provides an easy way to calculate the voltage drop and how to select proper devices to fully utilize the battery.

- Devices with low R_{dson}

From Equation 4, the main contributor to the voltage drop is the $R_{dson}$of the FETs. In addition, when devices operate in the dropout zone, the duty cycle always increases to the upper limit of the duty cycle. Therefore, the R_{dson} of the low-side FETS is negligible, and we need to choose a device with a lower R_{dson} of the high-side FETs to decrease the voltage drop as much as possible.

- Devices with 100% duty cycle control mode

To further decrease the voltage drop in dropout zone, we can select a device with 100% duty cycle function. A 100% duty cycle indicates direct conduction from the input to the output. This eliminated the influence of the duty cycle.

5 References

- Texas Instruments, *Low Dropout Operation in Buck Converter*, application note.
- Texas Instruments, *TPS629210, 3-V to 17-V, 1-A, High-Efficiency, Low-IQ, Synchronous Buck Converter in SOT-583 Package*, data sheet.
- Texas Instruments, *LMR516xx SIMPLE SWITCHER® Power Converter, 4-V to 65-V, 0.6-A/1-A Buck Converter in a SOT-23 Package*, data sheet.

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