Introduction

MYC0409-NA is a DC-DC converter with 48V input. An architecture applies a charge pump to realize a low-profile and higher efficiency. The module converts from input voltage (V_{IN}) to output voltage (V_{OUT}) with a fixed conversion ratio divided by 4. It offers a complete power solution that achieves up to 6A of output current with a wide input voltage range(20-60V). In addition, it can be paralleled to deliver more than 6A.

In general, it needs to select DC-DC converter with an appropriate current rating according to the load. Therefore, it is necessary to adopt many types of converters depending on the load. On the other hand, DC-DC converters that support parallel operation can be adapted to systems with low power to relatively high power with one type of module by increasing the number of parallels. And it is possible to improve the thermal performance by distributing current to each module and can be realize a low-profile power supply without a large inductor.

DC-DC converter will not inherently share the load. One or more of the converters in parallel will try to assume a disproportionate or excessive fraction of the load unless the current-share control is designed into the system. When DC-DC converters are connected in parallel and load current is concentrated in one of the modules, excessive stress is applied to it, causing failure and shorten lifespan.
Therefore, stackable DC-DC converters are equipped with a function to share current with each converter. When parallel converters are used to increase power, current sharing is achieved by a number of approaches. This paper describes a method of current sharing using the droop characteristic of the charge pump, a method for calculating the power derating in order to optimize the current sharing for maximum output power, and the evaluation result of the current sharing on our evaluation board.

Droop Characteristics

MYC0409-NA is an open-loop controlled adapting a charge pump circuit and has a droop characteristic in which the output voltage decreases as the load current increases. Since the voltage conversion ratio is constant, it can be shown by a simple model of an ideal voltage conversion and an output equivalent resistance (ROUT) as shown in Figure 1. It shows the voltage conversion of a fixed magnification, and voltage drop with respect to the load current are expressed by ROUT. In Figure 1, the output voltage of the charge pump can be expressed by the following equation.

$$VOUT = \frac{VIN}{Voltage\ conversion(DIV\ N)} - ROUT * Iout$$

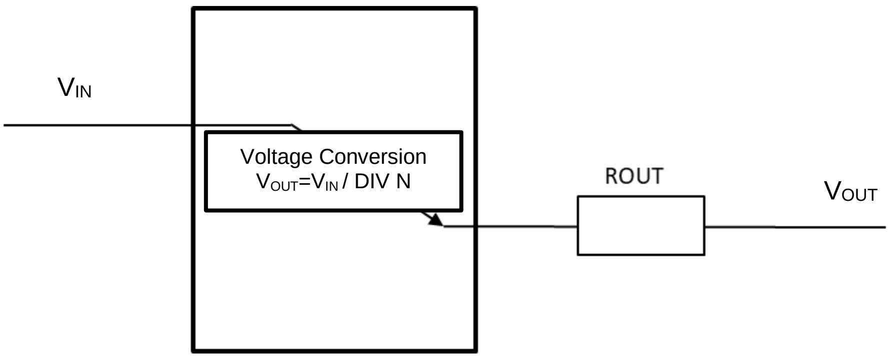


Figure 1. Simple model for charge pump

It is possible to perform current sharing between each module using this droop characteristic without complicated current sharing circuits or additional external components.

Figure 2 shows I–V characteristic of the droop control method, it shows the relationship between output voltage and output current (I_{OUT}) when two modules are operated in parallel. Depending on the ROUT shown as indicated previously and the parasitic resistance in PCB of each module, the slope of Module1 and Module2 in Figure 2 changes.

This slope determines the current flowing between each module. If the ROUT, parasitic impedance in PCB and temperature of both modules are the same, the half of output current (I_{OUT} / 2) flows through each module. On the other hand, if there is a difference in the slope of the droop, as shown in Figure 2, I_{OUT1} flows in Module1 and I_{OUT2} flows in Module2, and "$I_{OUT1} > I_{OUT}/2 > I_{OUT2}$"state.

However, a temperature rising of module occurs due to increasing loss since a high current flow through in Module1 compared to Module2. ROUT increases as the rising temperature of the module, therefore the current in Module1 decreases. The current balance between Module1 and Module2 is automatically performed so that the current difference is less.

In Figure 2, the output voltage of each module at no load is assumed to be the same. On the other hand, a current circulation occurs between modules if there is a difference of the output voltage at no load. The current flows to the positive direction in Module 1, and the current (reverse current) flows to the negative direction in Module 2 until the output voltage becomes stable. The unnecessary current flows due to the circulation of current in this time, so that the loss at no-load increases.

The MYC0409-NA applies a charge pump, and the output voltage at no load does not depend on ROUT as described above, therefore the output voltage would be almost the same without trimming or correction.

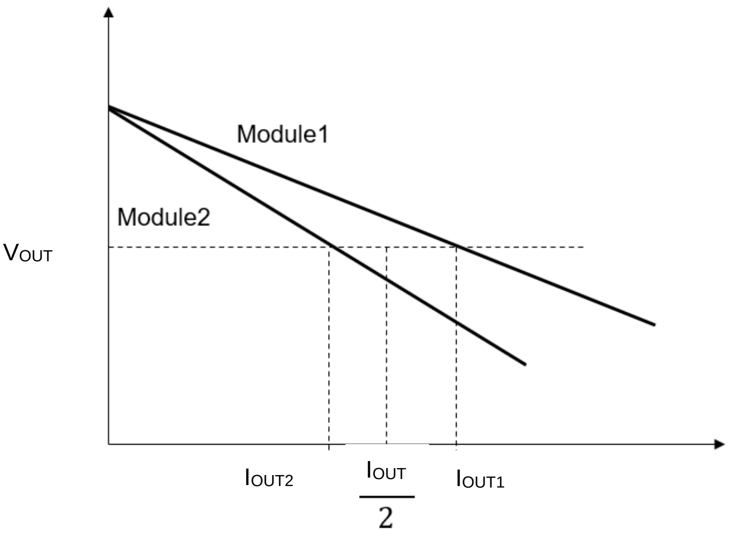


Figure 2. I–V characteristic of the droop control method

Maximum power derating in parallel

The maximum output current in parallel operation is not multiply the rated current for single by the number of parallels. The reason is that it is hard to share the output current completely equal. As described above, the output voltage at no load is $V_{OUT}=V_{IN}$ / 4, the values are generally the same. However, the droop characteristic of each module differs depending on the variation of the components inside the module and the variation of the parasitic resistance connecting the modules. In addition, since the slope of the droop changes depending on the module temperature, it is necessary to determine the power derating in consideration of the mounting environment, heat dissipation structure, and parasitic resistance in PCB.

Figure 3 shows an equivalent circuit diagram of a system equipped with the MYC0409-NA. Figure 3 shows four modules in parallel, and ROUT * is the ROUT of each module.

Figure 4 shows the measurement point of ROUT for MYC0409-NA. From Figure 4, the measurement of input and output voltage is detected in the red frame, and the output current is measured outside the module, and ROUT is calculated.

Rip * and Rop * are the resistance of the PCB trace from the power supply and load to the module measurement point shown in Figure 4. In the evaluation board used in this paper described later, Rip* and Rop * are sufficiently low impedance compared to the ROUT of the module, therefore this value can be ignored.

However, depending on the conditions under which the PCB trace is longer due to adaptation to the distributed power system, the copper thickness of the substrate, and the layer configuration, Rip* and Rop* affect the current sharing. In this case, it is necessary to calculate including these parameters.

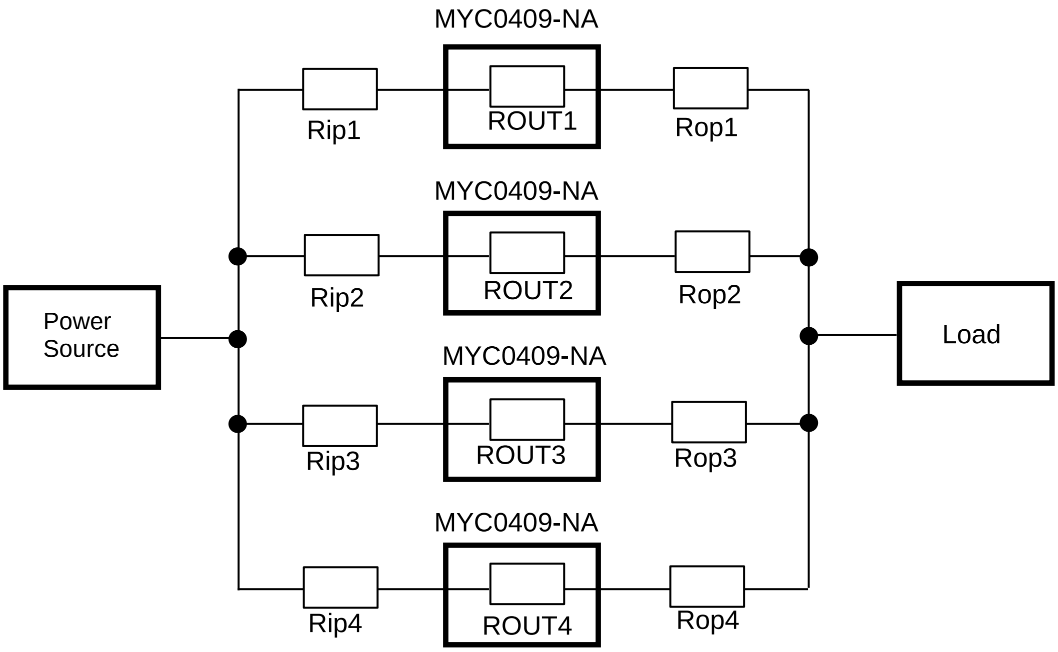


Figure 3. Equivalent circuit diagram of a system equipped with the MYC0409-NA

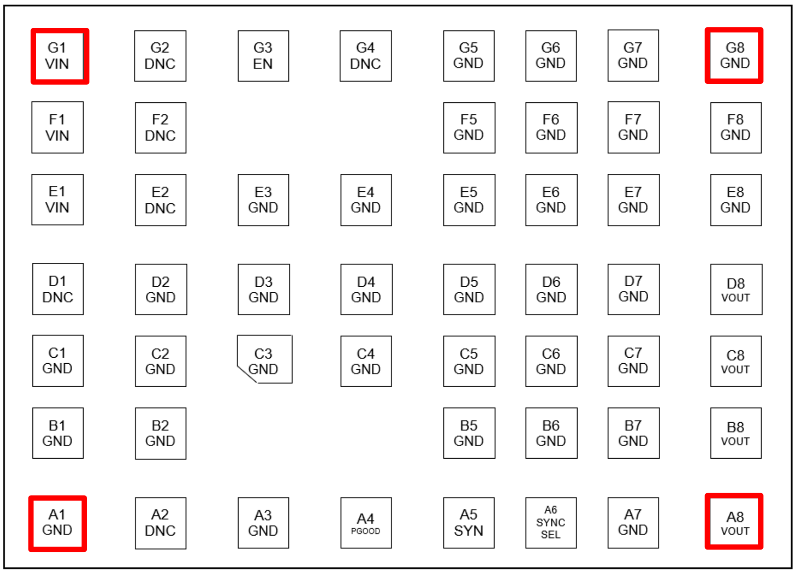


Figure 4. Measurement points of ROUT

Temperature coefficient

As mentioned above, ROUT is affected by the module temperature. The temperature characteristics of ROUT were measured to confirm the effect of temperature on ROUT. It has a temperature coefficient that is almost proportional to the module temperature, and that coefficient differs for each input voltage. There are multiple factors that compose of ROUT, such as Rds(on) and parasitic resistance of semiconductors and parasitic resistance in PCB, DC bias characteristics of multilayer ceramic capacitors, etc. Therefore, the temperature coefficient differs depending on the applied input voltage.

Table 1 shows the measurement results of temperature coefficient.

Table 1. Temperature coefficient for MYC0409-NA

V_{IN}(V)	Temperature coefficient
20	0.151
24	0.149
36	0.141
48	0.120
54	0.105
60	0.089

Formula

In parallel operation, the maximum current flows to the module with the lowest sum of PCB parasitic resistance and ROUT. The total output current (IOUT_4para) is calculated based on the condition that the module with the highest current is 6A.

The formula for the maximum output current assuming that the sum of ROUT1 and the parasitic resistance in PCB (R_{ip1}, R_{op1}) is the lowest condition as follows. This formula determines the derating of the output current in parallel. These are just formulas, and it is necessary to make sure that the module never exceed 6A in steady-state operation on your system.

$$Iout\_4para := \left(1 + \frac{TRout1}{TRout2} + \frac{TRout1}{TRout3} + \frac{TRout1}{TRout4}\right) \cdot 6$$

$$TRout1 := \frac{Rip1}{4} + Rout1 + K \cdot (T1 - 25) + Rop1$$

$$TRout2 := \frac{Rip2}{4} + Rout2 + K \cdot (T2 - 25) + Rop2$$

$$TRout3 := \frac{Rip3}{4} + Rout3 + K \cdot (T3 - 25) + Rop3$$

$$TRout4 := \frac{Rip4}{4} + Rout4 + K \cdot (T4 - 25) + Rop4$$

ROUT* :	ROUT each module (T_A=25degC)
R* :	Parasitic resistance in PCB
K :	Temperature coefficient
T* :	Module temperature

Similarly, the following formula applies under the condition that two modules are connected in parallel.

$$Iout\_2para = \left(1 + \frac{TRout1}{TRout2}\right) \times 6$$

Evaluation results

Figure 5 shows the evaluation board used to evaluate the current sharing. It was measured the current sharing when four MYC0409-NAs were mounted on the evaluation board. For the current detection, current sense shunt resistors were mounted on the output of each module, and the differential voltage were measured during current flowing. Figure 6 shows a schematic.

Figure 7 was resulted the current sharing for each input voltage, and Figure 8 was resulted the difference in current from ideal current sharing for each input voltage. From this result, the current sharing of ±3% or less can have been realized in the region where more than I_{OUT}=1A without trimmed. In general, current sharing tends to be different between modules because it is less affected by the temperature coefficient at light load. One of the variations is the measurement environment. Measurement methods that improve measurement accuracy at light loads, such as the offset voltage of the Op-Amp and the accuracy of the measuring equipment, are future tasks.

Figure 9 shows the temperature characteristics. The evaluation was performed under the condition of natural convection at T_A = 25degC. In this measurement, heat dissipation was not performed by the heat sink, therefore the temperature of the two central modules (CH2 and CH3) were risen. If forced air cooling is performed from the CH1 side or CH4 in Figure 5, the temperature of the module mounted on the fan side decreases and current flows further. Since forced air cooling can worsen the current sharing between modules, attention should be paid to the direction of the fan.

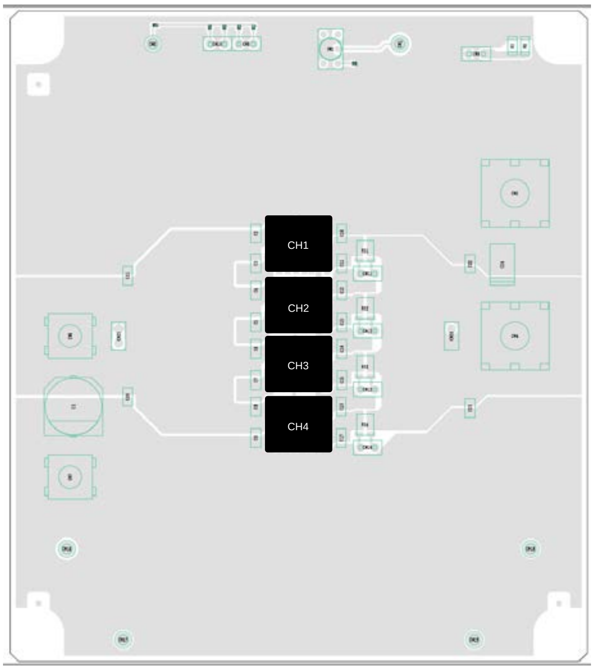


Figure 5. Evaluation board of MYC0409-NA

114.5 x 101.5 x 1.6mm (4 Layer FR-4)
Outer layer(1,4) =2oz, Inner layer(2,3) =1oz

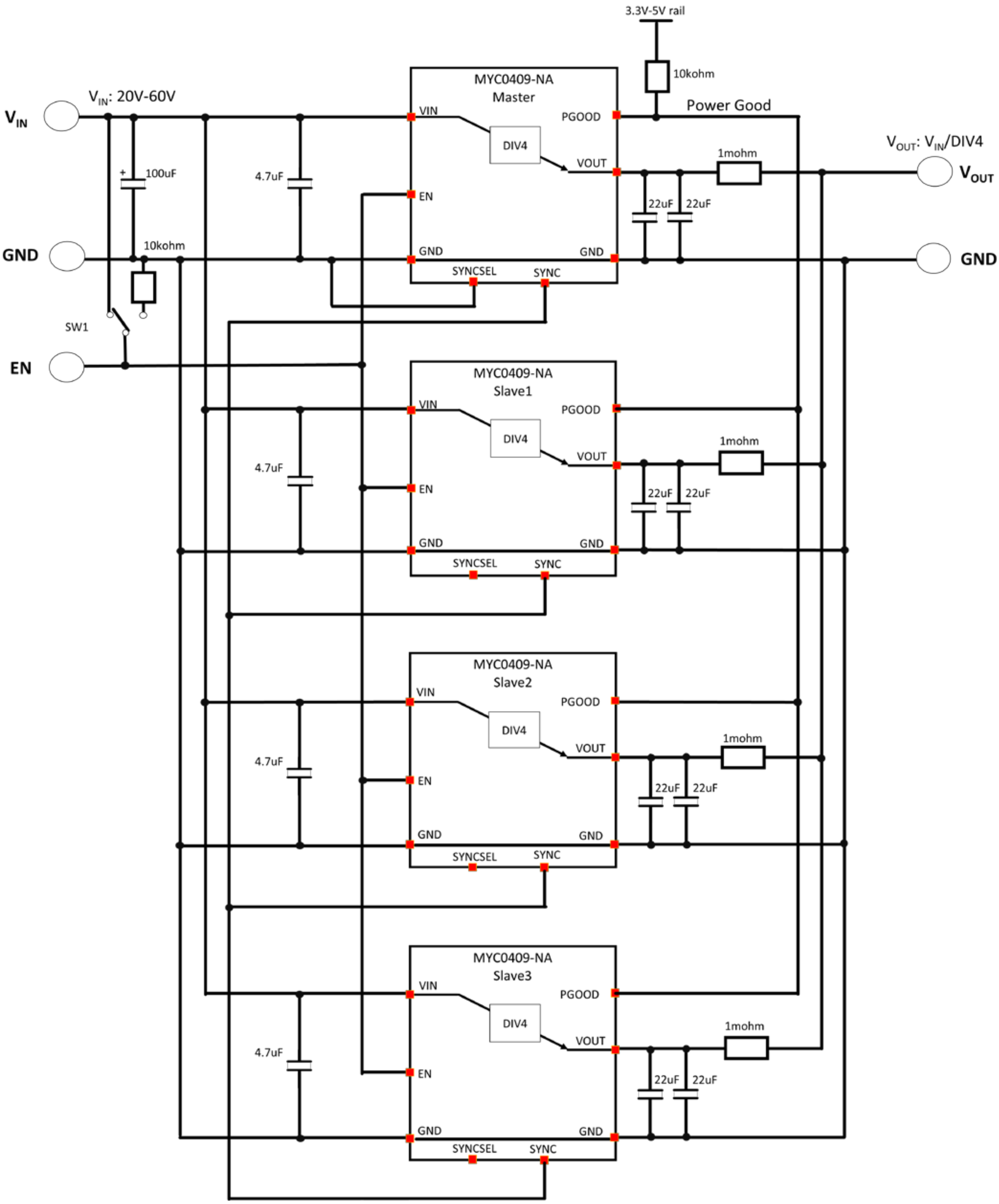


Figure 6. Schematic

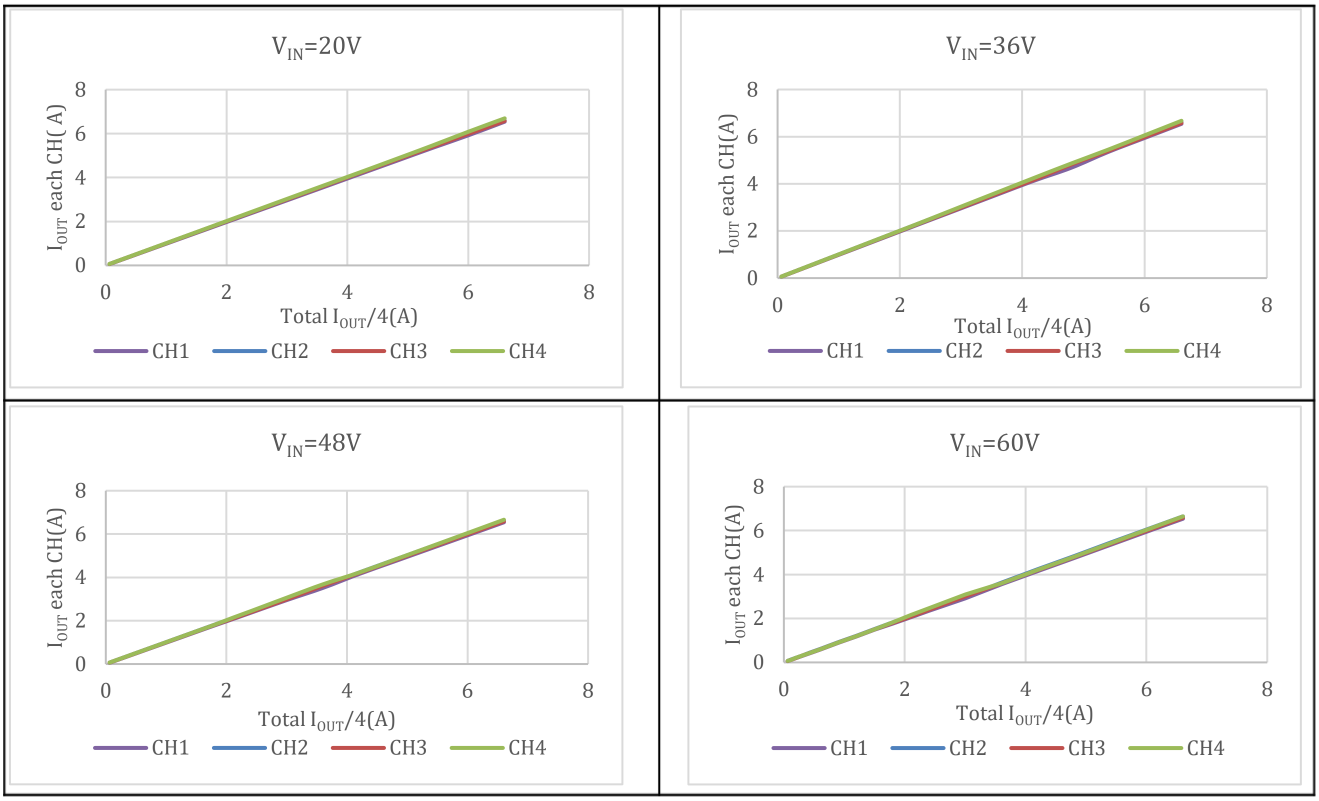


Figure 7. Current sharing for each input voltage

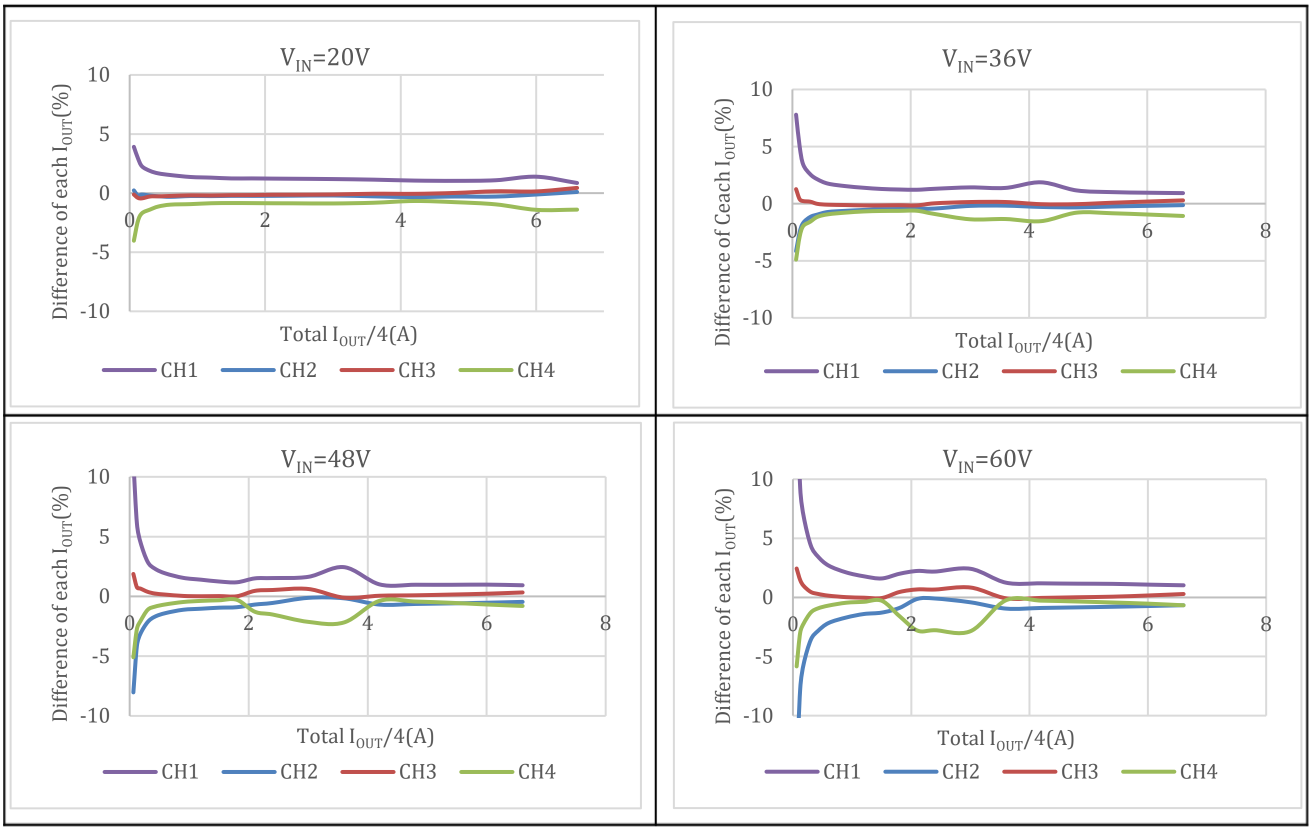
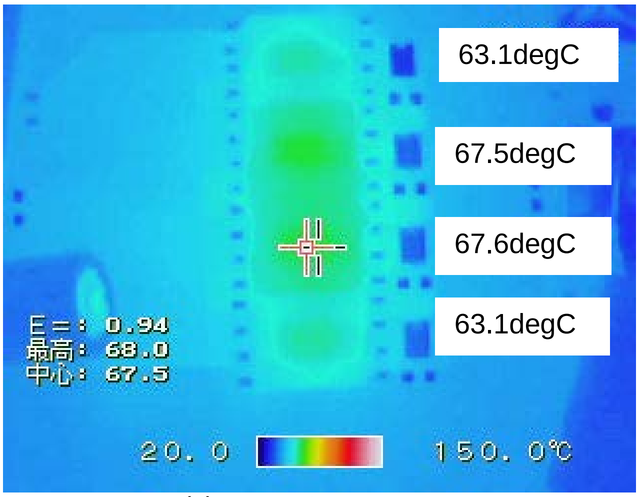
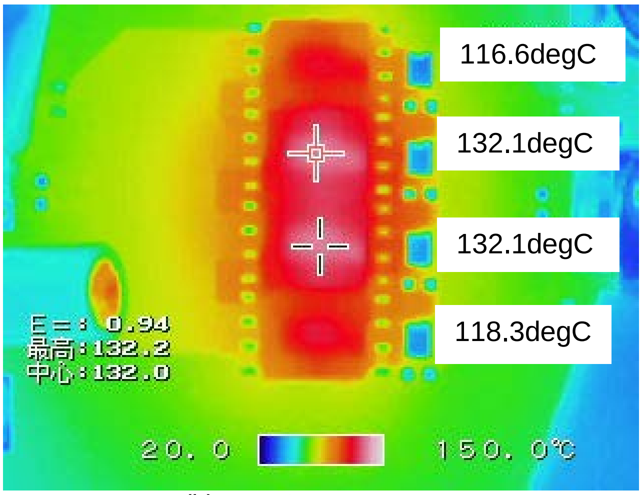


Figure 8. Difference of between each I_{OUT} and ideal current (I_{OUT}/4)



(a) I_{OUT}=12A



(b) I_{OUT}=24A

Figure 9. Temperature charactristics(V_{IN}=48V, V_{OUT}=12V)

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