Introduction of Short Circuit Protection Design for DIPIPMTM

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Abstract

DIPIPMTM is a series of Dual-in-line Package Intelligent Power Module of Mitsubishi Electric, which is designed for motor inverter control applications such as home appliances and industrial application. At present, DIPIPMTM has three key series, including Super Mini DIPIPMTM, Mini DIPIPMTM and Large DIPIPMTM. Short circuit (hereinafter called SC) is one of the key factors causing failure of power device, therefore, short circuit protection plays an important part in avoiding power device from destroying. The short circuit protection design for DIPIPMTM will be introduced in this paper.

1 Introduction

DIPIPMTM is a series of Dual-in-line Package IPM of Mitsubishi Electric, which is designed for motor inverter control, such as home appliances and industrial application.

As shown in the blue area of Fig.1, DIPIPMTM is composed of 6 IGBTs, 6 FWDis (Free Wheel Diode) to form a three-phase inverter. Integrated control ICs (HVIC and LVIC) provides IGBT gate drive, high-side level shift, fault signal output, together with some protection functions, such as control supply under voltage protection(UV Prot.), short circuit protection(SC Prot.), over temperature protection(OT Prot., and some products provide temperature analog output function\(V_{OT}\)) and etc. For the latest products, three BSDs (Bootstrap Diode) are inserted near the HVIC for P-side driving supply.

Fig.1 The concept of DIPIPMTM

At present, DIPIPMTM products have three key series from view of package, including Super
Mini DIPIP™ (5~35A/600V), Mini DIPIP™ (5~50A/600V and 5~10A/1200V) and Large DIPIP™ (50~75A/600V and 5~50A/1200V).

Short circuit is one of the key factors causing failure of power device, which occurs frequently because of the noise on control signal and lack of dead time. The power dissipation is very high under short circuit condition, which might destroy the power device. Therefore, it is very important to figure out how to detect the short circuit conditions and turn off the power device before it is destroyed, for which as the key point is to ensure the device operates in SCSOA area.[1] As an example, the typical SCSOA performance curve of 15A /600V Super Mini DIPIP™ Ver.6 (PSS15S92*6-AG) is shown in Fig.2 (Conditions: Vcc=400V, Tj=125°C at initial state, Vcc (surge) ≤500V (surge included), non-repetitive, length of load line is 2m.), it can shutdown safely at SC current that is about 5.8 times of its rated current under the conditions only if the IGBT conducting period is less than 2.7μs.

![Fig.2 Typical SCSOA performance curve of PSS15S92*6-AG](image)

There are mainly two methods of short circuit protection for DIPIP™. One is using external shunt resistors as current detector for short circuit protection, and the other is using inserted current sense IGBT as current sense (only for Large DIPIPM Ver.4/6). [2] Taking Super Mini DIPIP™ as an example, the short circuit protection design, which is based on DIPIPM’s integrated protection function together with external shunt resistors, will be introduced in next.

2 SC protection sequence and key SC protection circuits of DIPIP™

Short circuit protection function can be achieved by using external shunt resistor as current detector, together with the control IC which is inserted in DIPIP™. The internal protection circuit of control IC can capture the excessive high current by comparing with the CIN voltage which is generated at the shunt resistors with the referenced SC trip voltage \( V_{SC(ref)} \), then short circuit protection performs automatically. CIN is detecting terminal of short circuit current as shown in Fig.1. Normally, the short circuit protection trip level \( V_{SC(ref)} \) is typically 0.48V.

2.1 SC protection sequence

The short circuit protection sequence of DIPIP™ is shown in Fig.3, which is tested under the condition as N-side only with the external shunt resistors and RC filter.

- a1. Normal operation: IGBT ON and carrying current;
- a2. Short circuit current detection (SC trigger);
- a3. All N-side IGBTs gates are hard interrupted;
- a4. All N-side IGBTs turn off;
- a5. Fo outputs for \( t_{fo} \) minimum = 20μs (Super Mini DIPIP™ only);
- a6. Input = “L”. IGBTs off;
a7. Fo finishes output, but IGBTs don't turn on until next ON signal inputting (L\(\rightarrow\)H);
a8. Normal operation: IGBT ON and outputs current.

![Fig.3 Short circuit protection timing chart](image1)

2.2 **Key SC protection circuits based on shunt resistor**

Based on the shunt resistor, there are mainly two kinds of SC protection circuit for DIPIPMTM. One is based on one shunt resistor as shown in Fig.4, and the other is based on three shunt resistors as shown in Fig.5.

![Fig.4 SC protection based on one shunt resistor](image2)

![Fig.5 SC protection based on three shunt resistors](image3)

One shunt resistor circuit is quite cost-effective and simple and is able to provide good current sensing performance, but the control software is more complicated. Three shunt resistors circuit are more complicated and have more considerations, and it permits the detection of individual phase currents and control software is more simplified.

3 **Design guidance of SC protection based on shunt resistor**

3.1 **Shunt resistor selection**

The value of current sensing resistor is calculated by the following equation:

\[
R_{\text{shunt}} = \frac{V_{\text{SC(ref)}}}{I_{\text{SC}}}
\]

Where \(V_{\text{SC(ref)}}\) is the referenced short circuit trip voltage, and \(I_{\text{SC}}\) is the short circuit trip current. Higher gate voltage leads to higher short circuit current. For design of short circuit protection, the maximum short circuit trip level \(I_{\text{SC(max)}}\) of key series DIPIPMTM must be lower than that shown in Table.1.
### Product series

<table>
<thead>
<tr>
<th></th>
<th>( I_{SC(max)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super Mini DIPIP( \text{TM} )</td>
<td>1.7 times of rated current</td>
</tr>
<tr>
<td>Mini DIPIP( \text{TM} )</td>
<td>2 times of rated current</td>
</tr>
<tr>
<td>Large DIPIP( \text{TM} )</td>
<td>2 times of rated current</td>
</tr>
</tbody>
</table>

Table 1: The maximum short circuit trip level of key series DIPIP\( \text{TM} \)

Taking PSS15S92*6-AG as an example again, the maximum SC trip level \( I_{SC(max)} \) requires less than 25.5A. The parameters \( (V_{SC(ref)}, R_{shunt}) \) tolerance should be considered when designing the SC trip level. For PSS15S92*6-AG, there is +/-0.025V tolerance of \( V_{SC(ref)} \), as shown in Table 2.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>at ( T_j=25^\circ C ), ( V_0=15V )</td>
<td>0.455V</td>
<td>0.480V</td>
<td>0.505V</td>
</tr>
</tbody>
</table>

Table 2: Specification for \( V_{SC(ref)} \)

The range of SC trip level can be calculated by the following equations, which are in the case that shunt resistor tolerance is within +/-5%.

\[
R_{shunt(min)} = \frac{V_{SC(ref)\max}}{I_{SC(max)}}
\]

\[
R_{shunt(typ)} = R_{shunt(min)} / 0.95^{\circ} \quad \text{then} \quad I_{SC(typ)} = \frac{V_{SC(ref)\typ}}{R_{shunt(typ)}}
\]

\[
R_{shunt(max)} = R_{shunt(typ)} \times 1.05^{\circ} \quad \text{then} \quad I_{SC(min)} = \frac{V_{SC(ref)\min}}{R_{shunt(max)}}
\]

So the SC trip level range is described as Table 3.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>at ( T_j=25^\circ C )</td>
<td>20.9A</td>
<td>23.1A</td>
<td>25.5A</td>
</tr>
</tbody>
</table>

Table 3: Operative SC Range \( (R_{shunt} =19.8m\Omega \text{ (min), 20.8m\Omega \text{ (typ), 21.8m\Omega \text{ (max})})} \)

When SC occurs, the voltage on shunt resistor \( V_{SC} \) lower than 0.5V is recommended. \( V_{SC} \) will pull low \( V_{GE} \) of N-side IGBT, and when \( V_{SC} \) increases, power loss of IGBT also will also increases. Therefore, the value of shunt resistor should be not too big.

### 3.2 RC filter setting

It is necessary to set a RC filter to CIN terminal in order to prevent malfunction of SC protection from noise interference (Fig.6). The RC time constant depends on the applying time of noise interference and the SC SOA of the DIPIP\( \text{TM} \) (Fig.7).
When the voltage drop on the external shunt resistor exceeds the SC trip level \( V_{SC\text{ref}} \), the time \( t_1 \) that the CIN terminal voltage rises to \( V_{SC\text{ref}} \) can be calculated by the equation as below:

\[
V_{SC} = R_{\text{shunt}} \cdot I_c \cdot (1 - e^{-\frac{t_1}{\tau}})
\]

\[
t_1 = \tau \cdot \ln(1 - \frac{V_{SC}}{R_{\text{shunt}} \cdot I_c})
\]

Where \( V_{SC} \) is the CIN terminal input voltage, \( I_c \) is the peak current and \( \tau \) is the RC time constant. The typical time delay \( t_2 \) of inserted IC, which is from \( V_{SC} \) voltage reaches \( V_{SC\text{ref}} \) to IGBT gate shutdown, please find the detailed value in each product’s application note. The total delayed time from SC level current happened to the IGBT gate shutdown is \( t_{\text{Total}} = t_1 + t_2 \). [3]

The filter time constant should be set so that SC current is shutdown within 2μs depending on SC SOA of DIPIPMTM, and 1.5μs ~2μs is general value. SC interrupting time might vary with the wiring pattern, so the adequate evaluation should be done in the real system.

As shown in Fig.8 (a), R1 and C4 form the RC filter for the SC sensing circuit, which are recommended to select tight tolerance, temp-compensated type. The filtering result of the position of C4 has been tested, as shown in Fig.8 (b) and (c). When C4 is closer to CIN terminal, the filter effect will be better. Same as C4, the closer R1 is to CIN terminal, the better the filtering result is.

On the other hand, when the RC time constant is definite, the bigger the value of C4 is, the better the filtering result is.
3.3 Recommended wiring methods around shunt resistor and precautions for layout of PCB

In this part, two topics will be introduced, including the recommended PCB layout of SC protection circuit around shunt resistor and the influence of the stray inductance to short circuit.

Fig.9 Precautions for wiring on PCB around shunt resistor

Key precautions for wiring on PCB layout around shunt resistor of DIPIPM™ are shown in Fig.9, and the following three points should be avoided in the design process.

3.3.1 Control GND pattern overlaps power GND pattern

The surge voltage ($V_s$) which is generated by the parasitic inductance of wiring pattern and $\frac{di}{dt}$ of noncontiguous big current flows to power GND, transfers to control GND pattern. It causes not only the control GND level but also the input signal based on the control GND to fluctuate, then the arm short might occurs. To avoid this kind of issue, it is recommended to connect control GND and power GND at only a point N1, in which N1 is the welding spot of shunt resistor and GND.

3.3.2 Ground loop pattern exists

Stray current flows to GND loop pattern, so that the control GND level and input signal level (based on the GND) fluctuates. Then the arm short might occur. To avoid this kind of issue happen, is better to have some countermeasures to avoid loop design, such as use isolated power supply as power supply.

3.3.3 Parasitic inductance between N and N1 terminal

Long wiring pattern has large parasitic inductance and generates high surge voltage when IGBT is switching. This surge voltage will cause HVIC malfunction due to VS voltage (output terminal potential) dropping excessively, LVIC surge destruction and etc. It is recommended to make the parasitic inductance of this part (including the shunt resistor) under 10nH. For shunt resistor, low inductance SMD type is recommended. And the wiring between NU, NV, NW and shunt resistor should be as short as possible.
4 Discussion on a special case of three shunt resistors circuit

Some customers design SC protection circuit based on three shunt resistors together with OP amplifier as shown in Fig.10. This solution directly check the sum of currents on three shunt resistors and that is equivalent to checking DC bus current just like one shunt resistor solution. It is believed that the circuit cannot receive timely protection in some cases such as freewheeling mode. For the freewheeling mode, some shunt resistor’s voltage must be negative level. The OP amplifier input voltage Va is the average voltage of three shunt resistors, but OP amplifier output voltage Vo might become lower than the voltage of some phase’s shunt resistor when maximum actual current happens.

The circuit as Fig.10 shown has been tested by using 15A Super Mini DIPIPM™ Ver.4: PS21964, and shunt resistor selected 20mΩ.

![Fig.10 SC protection circuit based on OP amplifier](image)

As shown in Fig.11, we can see that at X point, V1=0.3V (@max. current: 15A), V2= 0.1V (@current=5A) and V3 = -0.4V (@current=-20A), so Va=(V1+V2+V3)/3=0V. At this point, the maximum current is 15A, but the value of Va is 0V.

![Fig.11 Waveform of three shunt resistors voltage and OP amplifier input Va](image)

As shown in Fig.12, at point X, V1 is over SC trip level, but Fo doesn't output because of the negative value of V2. And at point Y, V1 is almost same with the value at point X, but Fo outputs, because V2’s value at this point is larger than that at point X. SC trip level is affected by current condition of another phase.
Fig. 12 Waveform of SC trip condition

In this case, if short circuit occurs and one shunt resistor's voltage comes up to the SC trip level during the freewheeling mode, OP amplifier output Vo might be not able to come up to the SC trip level, that means SC protection function might not work. So the circuit with three comparators as Fig. 5 is recommended, where three shunt resistors’ voltages are mutually independent before input to comparator.

5 Conclusion

Based on the integrated SC protection function and shunt resistor, this paper focuses on the design of SC protection for DIPIPMTM. The two key SC protection circuits, which include one shunt resistor detection circuit and three shunt resistors detection circuit, are introduced. The key points of circuit design are introduced, such as how to select shunt resistor and setting RC filter time constant and etc. At last, a special case of three shunt resistors circuit is also discussed. The notes introduced in this paper have already achieved good effects in actual application.

6 References

2. Mitsubishi Electric Corporation. “1200V Large DIPIPMTM Ver. 4 Series Application Note”.