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FNA21012A

1200 V Motion SPM® 2 系列

特性

- 通过 UL 第 E209204 号认证 (UL1557)
- 1200 V - 10 A 三相 IGBT 逆变器 (包含提供栅极驱动和保护的控制 IC)
- 低损耗、短路额定的 IGBT
- 采用 DBC (Al₂O₃) 基板实现非常低的热阻
- 内置自举二极管和专用的 Vs 引脚以简化印刷电路板布局
- 低端 IGBT 的独立发射极开路引脚用于三相电流感测
- 支持单接地电源供电
- 内置负温度系数热敏电阻可实现温度监测和管理
- 集成 sense-IGBT 实现可调节过流保护
- 绝缘等级: 2500 Vrms / 1 分钟

应用

- 运动控制 - 工业电机 (交流 400 V 类别)

相关资料

- [AN-9075 - Users Guide for 1200V SPM® 2 Series](#)
- [AN-9076 - Mounting Guide for New SPM® 2 Package](#)
- [AN-9079 - Thermal Performance of 1200V Motion SPM® 2 Series by Mounting Torque](#)

概述

FNA21012A 是一款先进的 Motion SPM® 2 模块, 为交流感应、无刷直流电机和 PMSM 电机提供非常全面的高性能逆变器输出平台。这些模块综合优化了内置 IGBT 的栅极驱动以最小化电磁干扰和能量损耗。同时也提供多重模组保护特性: 欠压闭锁、过流关断、热量监测和故障报告。内置的高速 HVIC 只需要一个单电源电压, 将逻辑电平栅极输入转化为适合驱动模块内部 IGBT 的高电压, 高电流驱动信号。独立的 IGBT 负端在每个相位均有效, 可支持大量不同种类的控制算法。

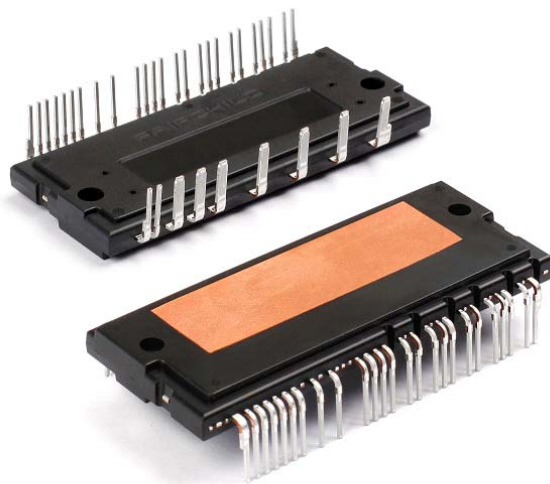


图 1. 封装概览

封装标识与订购信息

器件	器件标识	封装	包装类型	数量
FNA21012A	FNA21012A	SPMCA-A34	Rail	6

集成的功率功能

- 1200 V - 10 A IGBT 逆变器，适用于三相 DC / AC 功率转换（请参阅图 3）

集成的驱动、保护和系统控制功能

- 对于逆变器高端 IGBT：栅极驱动电路、高压隔离的高速电平转换控制电路欠压锁定保护 (UVLO) 可用自举电路示例如图 5 和图 15 所示。
- 对于逆变器低端 IGBT：栅极驱动电路、短路保护 (SCP) 控制电路、欠压锁定保护 (UVLO)
- 故障信号：对应 UV（低端电源）和短路故障
- 输入接口：高电平有效接口，可用于 3.3 / 5 V 逻辑电平，施密特触发脉冲输入

引脚布局

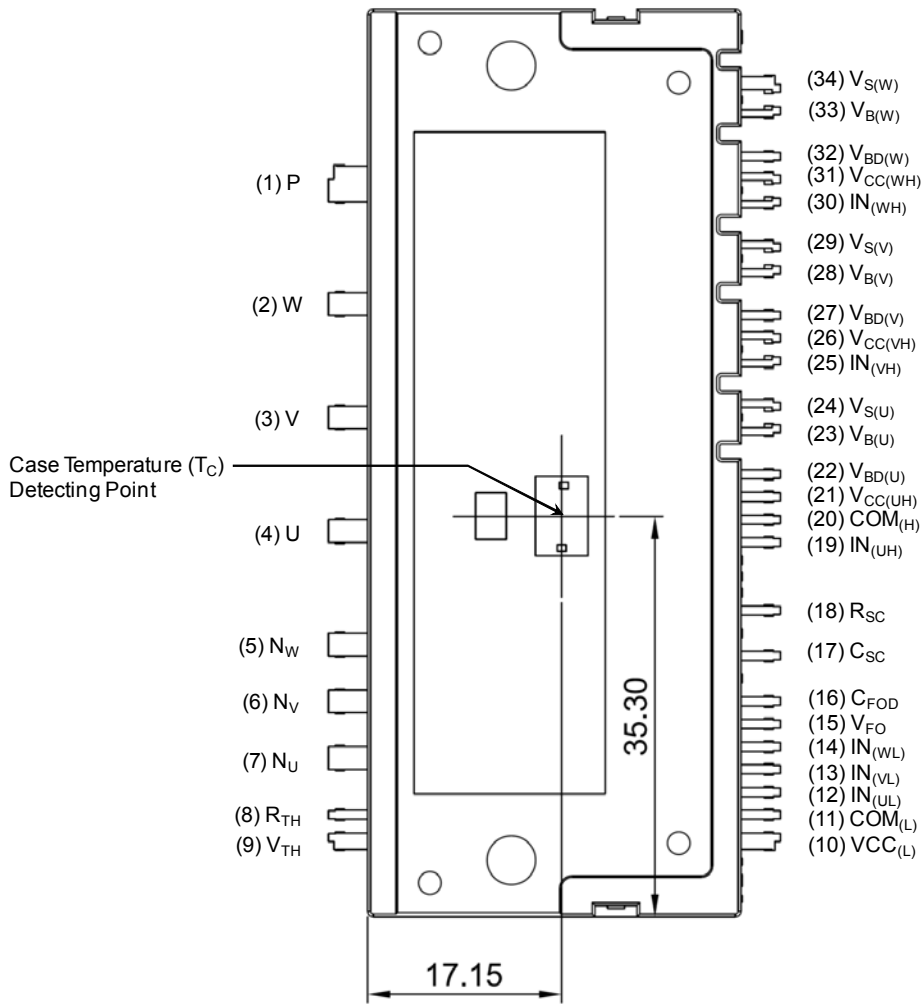


图 2. 俯视图

引脚描述

引脚号	引脚名	引脚描述
1	P	直流输入正端
2	W	W 相输出
3	V	V 相输出
4	U	U 相输出
5	N _W	W 相的直流输入负端
6	N _V	V 相的直流输入负端
7	N _U	U 相的直流输入负端
8	R _{TH}	热敏电阻的串联电阻 (温度检测)
9	V _{TH}	热敏电阻偏压
10	V _{CC(L)}	驱动 IC 和 IGBT 的低端偏压
11	COM _(L)	低端公共电源接地
12	IN _(UL)	低端 U 相的信号输入
13	IN _(VL)	低端 V 相的信号输入
14	IN _(WL)	低端 W 相的信号输入
15	V _{FO}	故障输出
16	C _{FOD}	设置故障输出持续时间的电容
17	C _{SC}	短路电流感测输入电容 (低通滤波器)
18	R _{SC}	短路电流感测电阻
19	IN _(UH)	高端 U 相的信号输入
20	COM _(H)	高端公共电源接地
21	V _{CC(UH)}	U 相 IC 的高端偏压
22	V _{BD(U)}	U 相高端自举电路的自举二极管的阳极
23	V _{B(U)}	U 相 IGBT 驱动的高端偏压
24	V _{S(U)}	U 相 IGBT 驱动的高端偏压接地
25	IN _(VH)	高端 V 相的信号输入
26	V _{CC(VH)}	V 相 IC 的高端偏压
27	V _{BD(V)}	V 相高端自举电路的自举二极管的阳极
28	V _{B(V)}	V 相 IGBT 驱动的高端偏压
29	V _{S(V)}	V 相 IGBT 驱动的高端偏压接地
30	IN _(WH)	高端 W 相的信号输入
31	V _{CC(WH)}	W 相 IC 的高端偏压
32	V _{BD(W)}	W 相高端自举电路的自举二极管的阳极
33	V _{B(W)}	W 相 IGBT 驱动的高端偏压
34	V _{S(W)}	W 相 IGBT 驱动的高端偏压的地

内部等效电路与输入 / 输出引脚

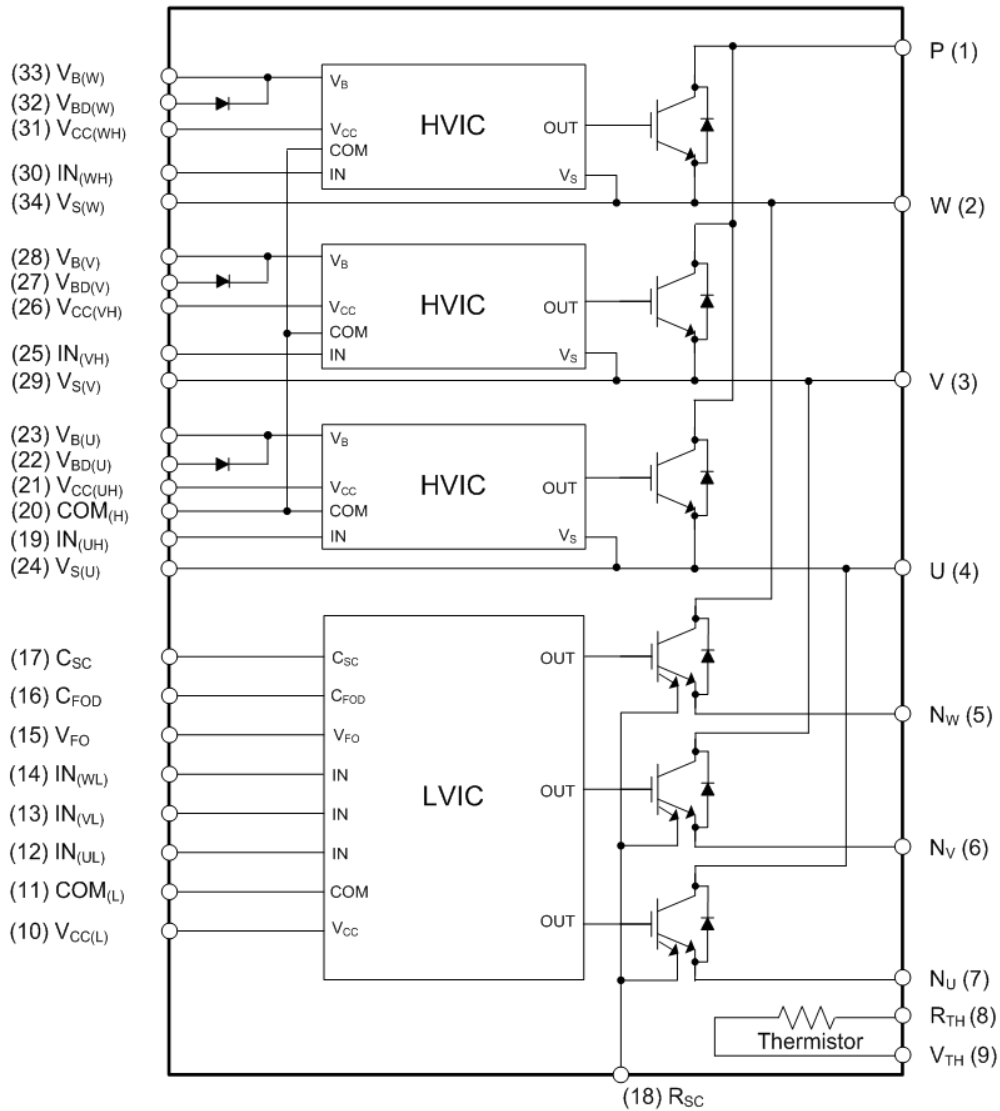


图 3. 内部框图

注:

1. 逆变器高端由三个常规 IGBT 组成，每个 IGBT 包括续流二极管和一个控制 IC。
2. 逆变器高端由三个 sense-IGBT 组成，每个 IGBT 包括续流二极管和一个控制 IC。具有栅极驱动和保护功能。
3. 逆变器的功率端由逆变器的四个直流母线输入端和三个输出端组成。

绝对最大额定值 ($T_J = 25^\circ\text{C}$, 除非另有说明。)**逆变器部分**

符号	参数	工作条件	额定值	单位
V_{PN}	电源电压	施加在 P - N_U 、 N_V 、 N_W 之间	900	V
V_{PN} (浪涌)	电源电压 (浪涌)	施加在 P - N_U 、 N_V 、 N_W 之间	1000	V
V_{CES}	集电极 - 发射极之间电压		1200	V
$\pm I_C$	单个 IGBT 的集电极电流	$T_C = 25^\circ\text{C}$, $T_J \leq 150^\circ\text{C}$ (注 4)	10	A
$\pm I_{CP}$	单个 IGBT 的集电极电流 (峰值)	$T_C = 25^\circ\text{C}$, $T_J \leq 150^\circ\text{C}$, 脉冲宽度小于 1 ms (注 4)	20	A
P_C	集电极功耗	$T_C = 25^\circ\text{C}$ per One Chip (注 4)	93	W
T_J	工作结温		-40 ~ 150	$^\circ\text{C}$

控制部分

符号	参数	工作条件	额定值	单位
V_{CC}	控制电源电压	施加在 $V_{CC(H)}$, $V_{CC(L)}$ - COM 之间	20	V
V_{BS}	高端控制偏压	施加在 $V_{B(U)}$ - $V_{S(U)}$, $V_{B(V)}$ - $V_{S(V)}$, $V_{B(W)}$ - $V_{S(W)}$	20	V
V_{IN}	输入信号电压	施加在 $IN_{(UH)}$, $IN_{(VH)}$, $IN_{(WH)}$, $IN_{(UL)}$, $IN_{(VL)}$, $IN_{(WL)}$ - COM 之间	-0.3 ~ $V_{CC}+0.3$	V
V_{FO}	故障输出电源电压	施加在 V_{FO} - COM 之间	-0.3 ~ $V_{CC}+0.3$	V
I_{FO}	故障输出电流	V_{FO} 引脚处的灌电流	2	mA
V_{SC}	电流感测输入电压	施加在 C_{SC} - COM 之间	-0.3 ~ $V_{CC}+0.3$	V

自举二极管部分

符号	参数	工作条件	额定值	单位
V_{RRM}	最大重复反向电压		1200	V
I_F	正向电流	$T_C = 25^\circ\text{C}$, $T_J \leq 150^\circ\text{C}$ (注 4)	1.0	A
I_{FP}	正向电流 (峰值)	$T_C = 25^\circ\text{C}$, $T_J \leq 150^\circ\text{C}$, 脉冲宽度小于 1 ms (注 4)	2.0	A
T_J	工作结温		-40 ~ 150	$^\circ\text{C}$

整个系统

符号	参数	工作条件	额定值	单位
$V_{PN(Prot)}$	自我保护电源电压限制 (短路保护能力)	$V_{CC} = V_{BS} = 13.5 \sim 16.5 \text{ V}$, $T_J = 150^\circ\text{C}$, 非重复性, $< 2 \mu\text{s}$	800	V
T_C	模块壳体工作温度	见图 2	-40 ~ 125	$^\circ\text{C}$
T_{STG}	存储温度		-40 ~ 125	$^\circ\text{C}$
V_{ISO}	绝缘电压	60 Hz, 正弦波形, 1 分钟, 连接陶瓷基板到引脚	2500	V_{rms}

热阻

符号	参数	工作条件	最小值	典型值	最大值	单位
$R_{th(j-c)Q}$	结点 - 壳体的热阻 (注 5)	逆变器 IGBT 部分 (每 1/6 模块)	-	-	1.33	$^\circ\text{C}/\text{W}$
$R_{th(j-c)F}$		逆变器 FWD 部分 (每 1/6 模块)	-	-	2.30	$^\circ\text{C}/\text{W}$

注:

- 这些值获取了考虑到设计因素的计算结果。
- 关于壳体温度 (T_C) 的测量点, 请参阅图 2。

电气特性 ($T_J = 25^\circ\text{C}$, 除非另有说明。)

逆变器部分

符号	参数	工作条件		最小值	典型值	最大值	单位	
$V_{CE(SAT)}$	集电极 - 发射极间饱和电压	$V_{CC} = V_{BS} = 15\text{ V}$ $V_{IN} = 5\text{ V}$	$I_C = 10\text{ A}, T_J = 25^\circ\text{C}$	-	2.20	2.80	V	
V_F	FWD 正向电压	$V_{IN} = 0\text{ V}$	$I_F = 10\text{ A}, T_J = 25^\circ\text{C}$	-	2.20	2.80	V	
HS	开关时间	$V_{PN} = 600\text{ V}, V_{CC} = 15\text{ V}, I_C = 10\text{ A}$ $T_J = 25^\circ\text{C}$ $V_{IN} = 0\text{ V} \leftrightarrow 5\text{ V}$, 电感负载 见图 5 (注 6)		t_{ON}	0.45	0.85	1.35	μs
				$t_{C(ON)}$	-	0.25	0.55	μs
				t_{OFF}	-	0.95	1.45	μs
				$t_{C(OFF)}$	-	0.10	0.40	μs
				t_{rr}	-	0.25	-	μs
LS		$V_{PN} = 600\text{ V}, V_{CC} = 15\text{ V}, I_C = 10\text{ A}$ $T_J = 25^\circ\text{C}$ $V_{IN} = 0\text{ V} \leftrightarrow 5\text{ V}$, 电感负载 见图 5 (注 6)		t_{ON}	0.35	0.75	1.25	μs
				$t_{C(ON)}$	-	0.20	0.50	μs
				t_{OFF}	-	0.95	1.45	μs
				$t_{C(OFF)}$	-	0.10	0.40	μs
				t_{rr}	-	0.20	-	μs
I_{CES}	集电极 - 发射极间漏电流	$V_{CE} = V_{CES}$		-	-	5	mA	

注:

6. t_{ON} 和 t_{OFF} 包括模块内部驱动 IC 的传输延迟时间。 $t_{C(ON)}$ 和 $t_{C(OFF)}$ 指在内部给定的栅极驱动条件下, IGBT 本身的开关时间。详细信息, 请参见图 4。

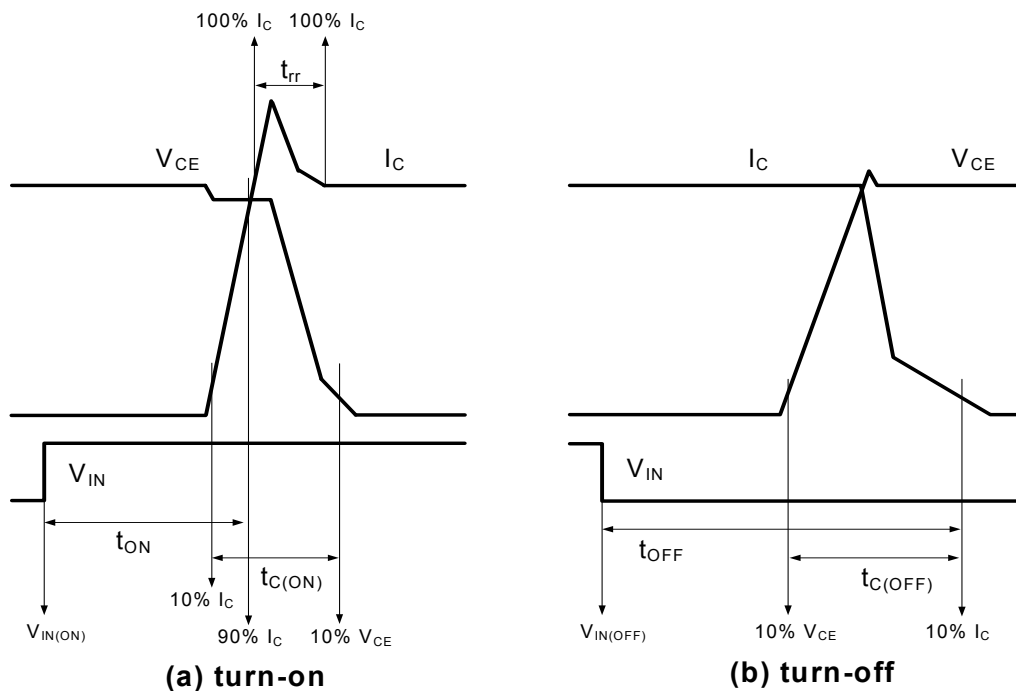


图 4. 开关时间的定义

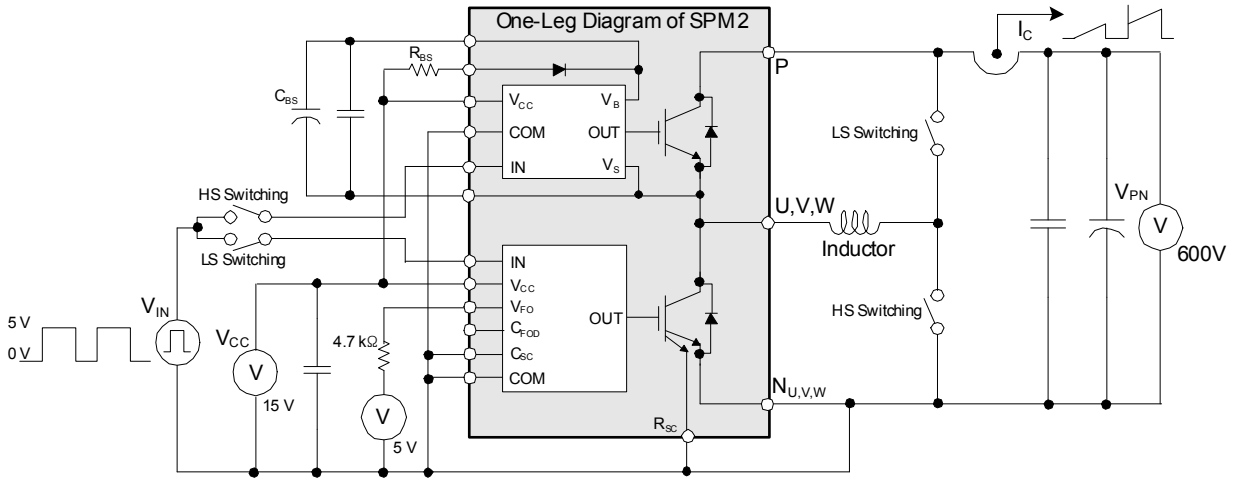


图 5. 开关测试电路实例

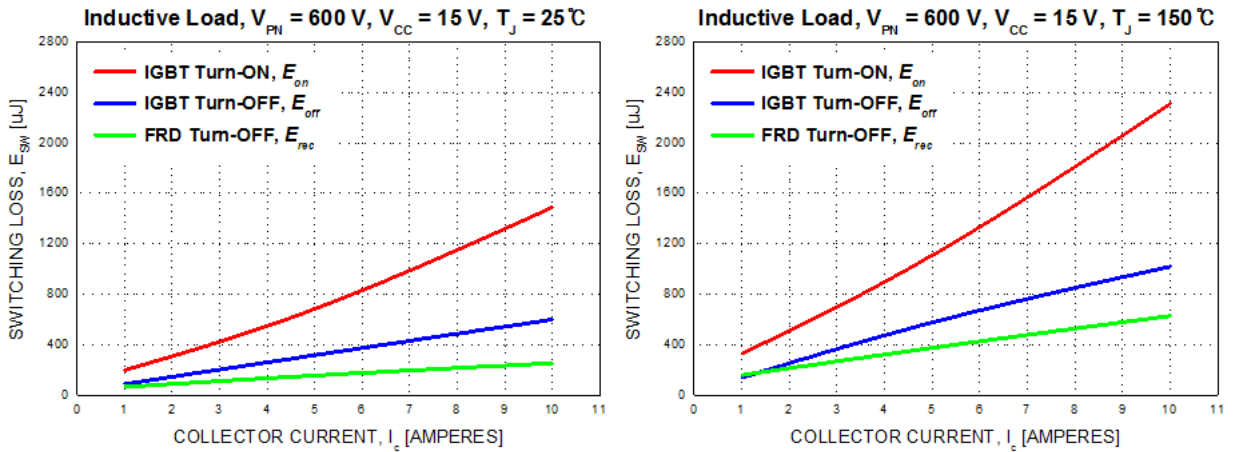


图 6. 开关损耗特性 (典型值)

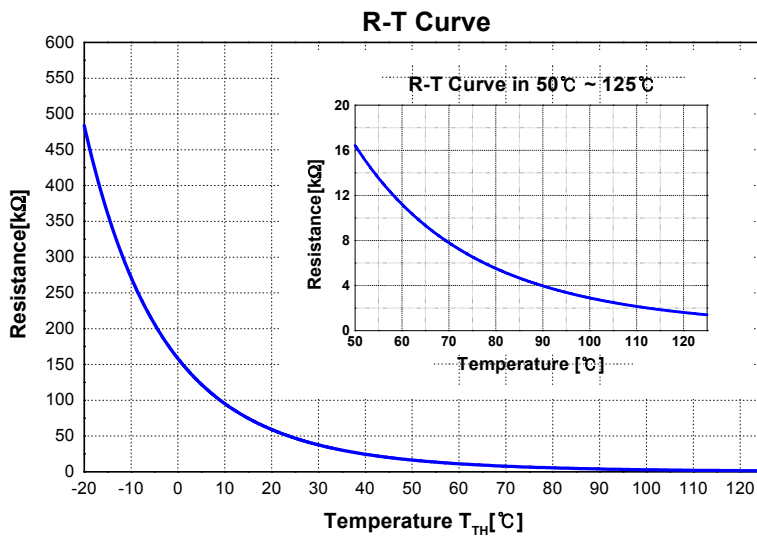


图 7. 内置热敏电阻的 R-T 曲线

自举二极管部分

符号	参数	工作条件	最小值	典型值	最大值	单位
V_F	正向电压	$I_F = 1.0 \text{ A}, T_J = 25^\circ\text{C}$	-	2.2	-	V
t_{rr}	反向恢复时间	$I_F = 1.0 \text{ A}, di_F / dt = 50 \text{ A} / \mu\text{s}, T_J = 25^\circ\text{C}$	-	80	-	ns

控制部分

符号	参数	工作条件	最小值	典型值	最大值	单位	
I_{QCCH}	V_{CC} 静态电源电流	$V_{CC(UH, VH, WH)} = 15 \text{ V},$ $I_{N(UH, VH, WH)} = 0 \text{ V}$	$V_{CC(UH)} - COM_{(H)},$ $V_{CC(VH)} - COM_{(H)},$ $V_{CC(WH)} - COM_{(H)}$	-	-	0.15	mA
I_{QCCL}		$V_{CC(L)} = 15 \text{ V}, I_{N(UL, VL, WL)} = 0 \text{ V}$	$V_{CC(L)} - COM_{(L)}$	-	-	5.00	mA
I_{PCCH}	V_{CC} 电源电流	$V_{CC(UH, VH, WH)} = 15 \text{ V}, f_{PWM} =$ 20 kHz, Duty = 50%, 施加于高端的 一个 PWM 信号输入	$V_{CC(UH)} - COM_{(H)},$ $V_{CC(VH)} - COM_{(H)},$ $V_{CC(WH)} - COM_{(H)}$	-	-	0.30	mA
I_{PCCL}		$V_{CC(L)} = 15 \text{ V}, f_{PWM} = 20 \text{ kHz},$ Duty = 50%, 施加于低端的一个 PWM 信号 输入	$V_{CC(L)} - COM_{(L)}$	-	-	8.50	mA
I_{QBS}	V_{BS} 静态电源电流	$V_{BS} = 15 \text{ V}, I_{N(UH, VH, WH)} = 0 \text{ V}$	$V_{B(U)} - V_{S(U)},$ $V_{B(V)} - V_{S(V)},$ $V_{B(W)} - V_{S(W)}$	-	-	0.30	mA
I_{PBS}	V_{BS} 工作电源电流	$V_{CC} = V_{BS} = 15 \text{ V}, f_{PWM} = 20 \text{ kHz},$ Duty = 50%, 施加于高端的一个 PWM 信号输入	$V_{B(U)} - V_{S(U)},$ $V_{B(V)} - V_{S(V)},$ $V_{B(W)} - V_{S(W)}$	-	-	4.50	mA
V_{FOH}	故障输出电压	$V_{CC} = 15 \text{ V}, V_{SC} = 0 \text{ V}, V_{FO}$ 电路: 4.7 k Ω 至 5 V Pull-up	4.5	-	-	V	
V_{FOL}		$V_{CC} = 15 \text{ V}, V_{SC} = 1 \text{ V}, V_{FO}$ 电路: 4.7 k Ω 至 5 V Pull-up	-	-	0.5	V	
I_{SEN}	每个感测 IGBT 的 感测电流	$V_{CC} = 15 \text{ V}, V_{IN} = 5 \text{ V}, R_{SC} = 0 \Omega,$ 在 N_U, v, w 端没有分流电阻连接	$I_C = 10 \text{ A}$	-	7	-	mA
$V_{SC(ref)}$	短路触发电平	$V_{CC} = 15 \text{ V}$ (注 7)	$C_{SC} - COM_{(L)}$	0.43	0.50	0.57	V
I_{SC}	短路电流触发电平	$R_{SC} = 68 \Omega (\pm 1\%),$ 在 N_U, v, w 端没有分流电阻连接 (注 7)	-	20	-	A	
UV_{CCD}	电源电路欠压保护	检测电平	10.3	-	12.8	V	
UV_{CCR}		复位电平	10.8	-	13.3	V	
UV_{BSD}		检测电平	9.5	-	12.0	V	
UV_{BSR}		复位电平	10.0	-	12.5	V	
t_{FOD}	故障输出脉宽	$C_{FOD} = \text{Open}$	(注 8)	50	-	-	μs
		$C_{FOD} = 2.2 \text{ nF}$		1.7	-	-	ms
$V_{IN(ON)}$	导通阈值电压	施加在 $IN_{(UH, VH, WH)} - COM_{(H)},$ $IN_{(UL, VL, WL)} - COM_{(L)}$ 之 间	-	-	2.6	V	
$V_{IN(OFF)}$	关断阈值电压		0.8	-	-	V	
R_{TH}	热敏电阻的阻值	at $T_{TH} = 25^\circ\text{C}$	见图 7 (注 9)	-	47	-	k Ω
		at $T_{TH} = 100^\circ\text{C}$		-	2.9	-	k Ω

注:

- 短路电流保护功能仅适用于低端, 因为低端 IGBT 中的感测电流已经从主电流中分离出来。如果插入分流电阻来监测 N_U, N_V, N_W 端的相电流, 则短路电流触发电平会改变。
- 故障输出脉宽 t_{FOD} 取决于电容 C_{FOD} 的值, 可采用下面的近似公式进行计算: $t_{FOD} = 0.8 \times 10^6 \times C_{FOD} [\text{s}]$ 。
- T_{TH} 为热敏电阻自身的温度。若需获得壳体温度 (T_C), 请根据具体应用进行实验。

推荐工作条件

符号	参数	工作条件	数值			单位
			最小值	典型值	最大值	
V_{PN}	电源电压	施加在 P - N_U 、 N_V 、 N_W 之间	300	600	800	V
V_{CC}	控制电源电压	施加在 $V_{CC(UH, VH, WH)} - COM_{(H)}$, $V_{CC(L)} - COM_{(L)}$	13.5	15.0	16.5	V
V_{BS}	高端偏压	施加在 $V_{B(U)} - V_{S(U)}$, $V_{B(V)} - V_{S(V)}$, $V_{B(W)} - V_{S(W)}$	13.0	15.0	18.5	V
dV_{CC}/dt , dV_{BS}/dt	控制电源波动		-1	-	1	V / μ s
t_{dead}	防止桥臂直通的死区时间	适用于每个输入信号	2.0	-	-	μ s
f_{PWM}	PWM 输入信号	$-40^\circ\text{C} \leq T_C \leq 125^\circ\text{C}$, $-40^\circ\text{C} \leq T_J \leq 150^\circ\text{C}$	-	-	20	kHz
V_{SEN}	电流感测的电压	施加在 N_U , N_V , $N_W - COM_{(H, L)}$ (包括浪涌电压)	-5	-	5	V
$PW_{IN(ON)}$	最小输入脉宽	$I_C \leq 20\text{ A}$, 线路电感在 N_U, V, W 和直流母线之间为 $N < 10\text{ nH}$ (注 10)	1.5	-	-	μ s
$PW_{IN(OFF)}$			1.5	-	-	
T_J	结温		-40	-	150	$^\circ\text{C}$

注:

10. 若输入脉冲宽度低于推荐值, 本产品可能无输出响应。

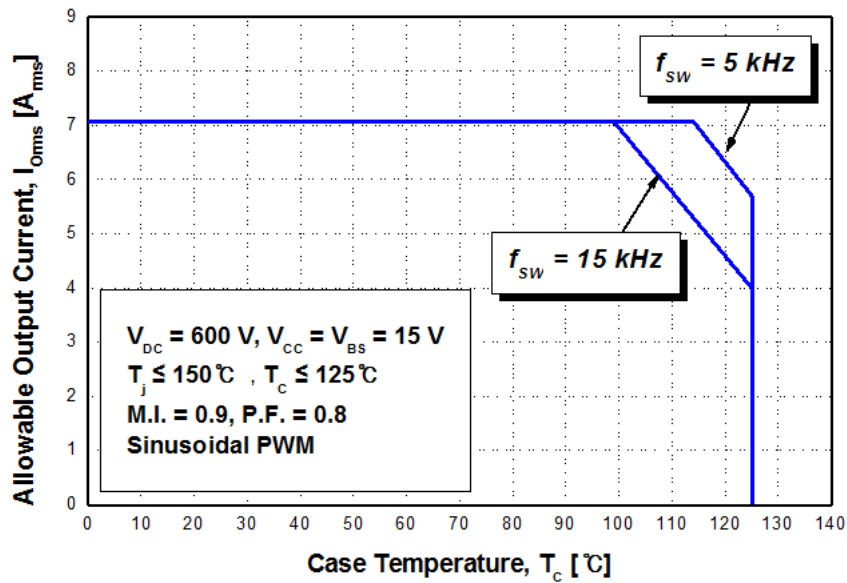


图 8. 允许最大输出电流

注:

11. 这个允许输出电流值是该产品安全工作时的参考值。考虑到实际应用和工作条件, 它可能会改变。

机械特性和额定值

参数	工作条件		最小值	典型值	最大值	单位
器件平面度	见图 9		0	-	+200	μm
安装扭矩	安装螺钉: M4	推荐 1.0 N·m	0.9	1.0	1.5	N·m
	见图 10	推荐 10.1 kg·cm	9.1	10.1	15.1	kg·cm
一端拉力强度	负载 19.6 N		10	-	-	S
一端弯曲强度	负载 9.8 N, 90 度弯曲		2	-	-	次
重量			-	50	-	g

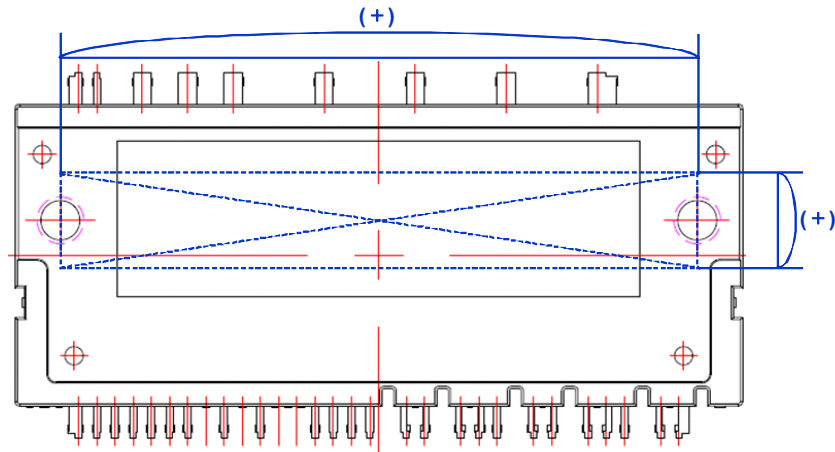


图 9. 平面度测量位置

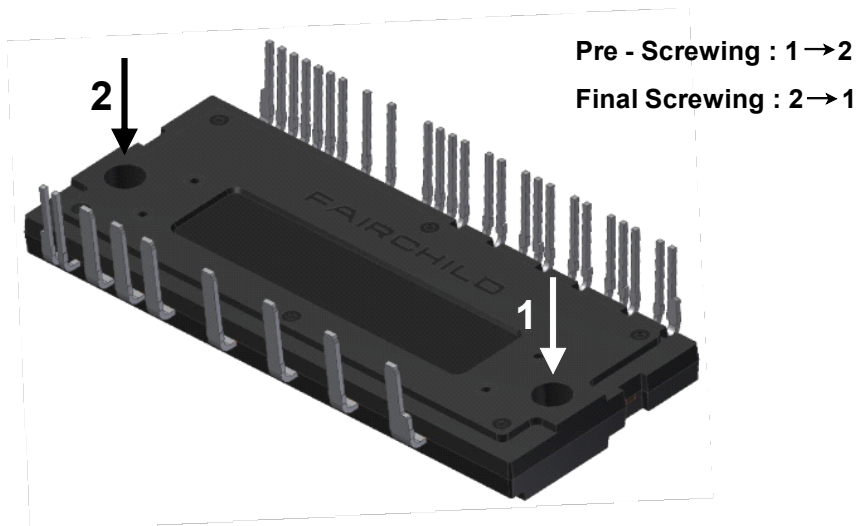


图 10. 安装螺钉时的扭紧顺序

注:

- 12. 安装或扭动螺钉时切勿过分用力。扭力过大会造成 DBC 基底破裂, 产生毛刺并破坏铝质散热片。
- 13. 避免用力不均衡。图 10 显示了安装螺钉时, 推荐的扭紧顺序。安装不全会破坏封装 DBC 基底。预旋紧扭矩约为最大额定扭矩的 20 ~ 30%。

SPM 保护功能时序图

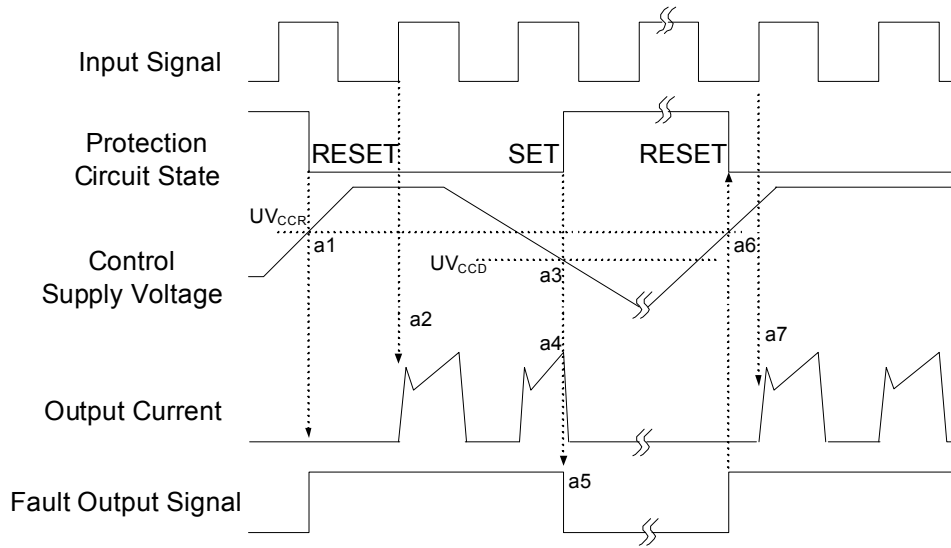


图 11. 欠压保护（低端）

- a1: 控制电源电压上升: 当电压上升到 UV_{CCR} 后, 等到下一个开通信号时, 对应的电路才开始动作。
- a2: 正常工作: IGBT 导通并加载负载电流。
- a3: 欠压检测 (UV_{CCD})。
- a4: 不论控制输入的条件, IGBT 都关断。
- a5: 根据外部电容器 C_{FOD} 的条件, 故障输出工作从一个固定脉冲宽度启动。
- a6: 欠压复位 (UV_{CCR})。
- a7: 正常工作: 当触发下一个低状态到高状态的信号, IGBT 导通并加载负载电流。

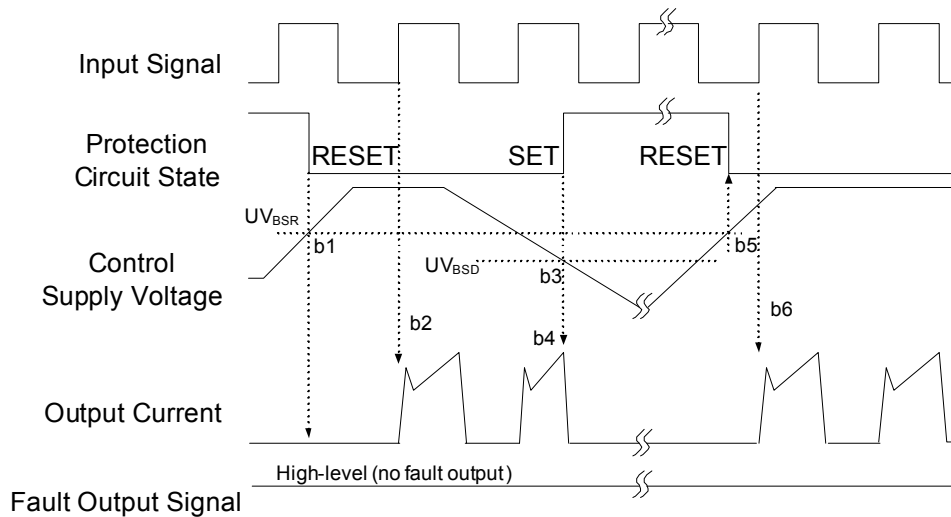


图 12. 欠压保护（高端）

- b1: 控制电源电压上升: 当电压上升到 UV_{BSR} 后, 等到下一个输入信号时, 对应的电路才开始工作。
- b2: 正常工作: IGBT 导通并加载负载电流。
- b3: 欠压检测 (UV_{BSD})。
- b4: 不论控制输入的条件, IGBT 都关闭, 且无故障输出信号。
- b5: 欠压复位 (UV_{BSR})。
- b6: 正常工作: 当触发下一个低状态到高状态的信号, IGBT 导通并加载负载电流。

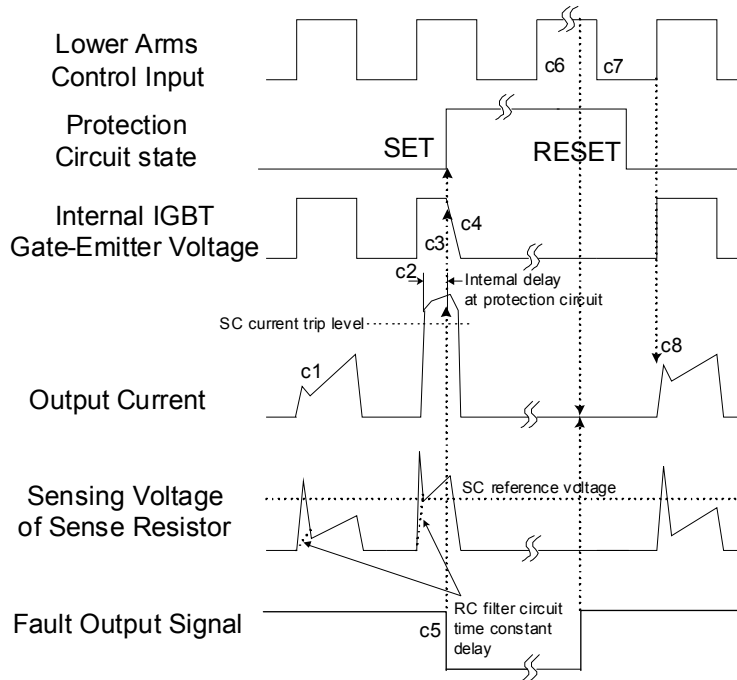


图 13. 短路电流保护（仅适用于低端工作）

（包含外部感测电阻和阻容滤波器连接）

- c1 : 正常工作: IGBT 导通并加载负载电流。
- c2 : 短路电流感测（SC 触发）。
- c3 : 所有的低端 IGBT 都是栅极硬中断。
- c4 : 所有的低端 IGBT 关断。
- c5 : 根据外部电容器 C_{FOD} 的条件, 故障输出工作从一个固定脉冲宽度启动。
- c6 : 输入高状态: IGBT 导通, 但是在故障输出有效的时间内, IGBT 不导通。
- c7 : 故障输出工作结束, 但是 IGBT 不导通直到触发下一个低状态到高状态的信号。
- c8 : 正常工作: IGBT 导通并加载负载电流。

输入 / 输出接口电路

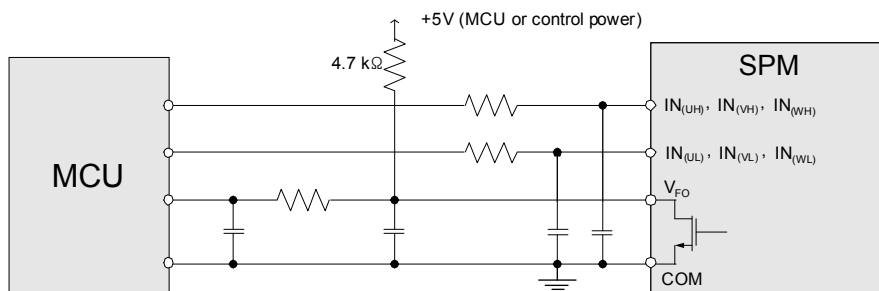


图 14. 推荐的 MCU I/O 接口电路

注:

14. 每个输入端的 RC 耦合（虚线显示部分）可能随着应用程序中使用的 PWM 控制方案和应用程序印刷电路板接线抗阻而改变。Motion SPM 2 产品的输入信号部分集成了一个 $5\text{ k}\Omega$ （典型值）的下拉电阻。因此, 当使用外部的滤波电阻时, 请注意该信号在输入端的压降。

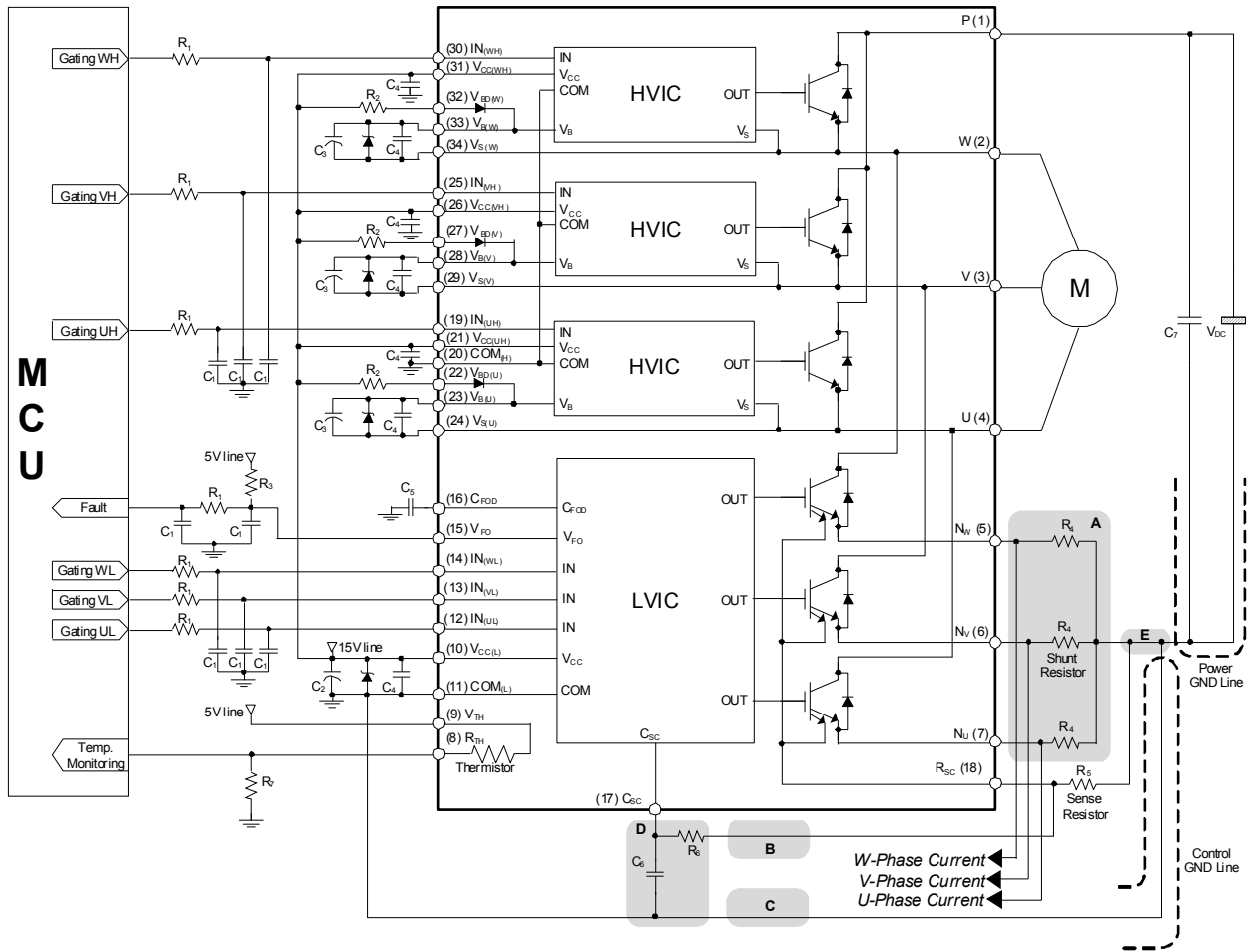
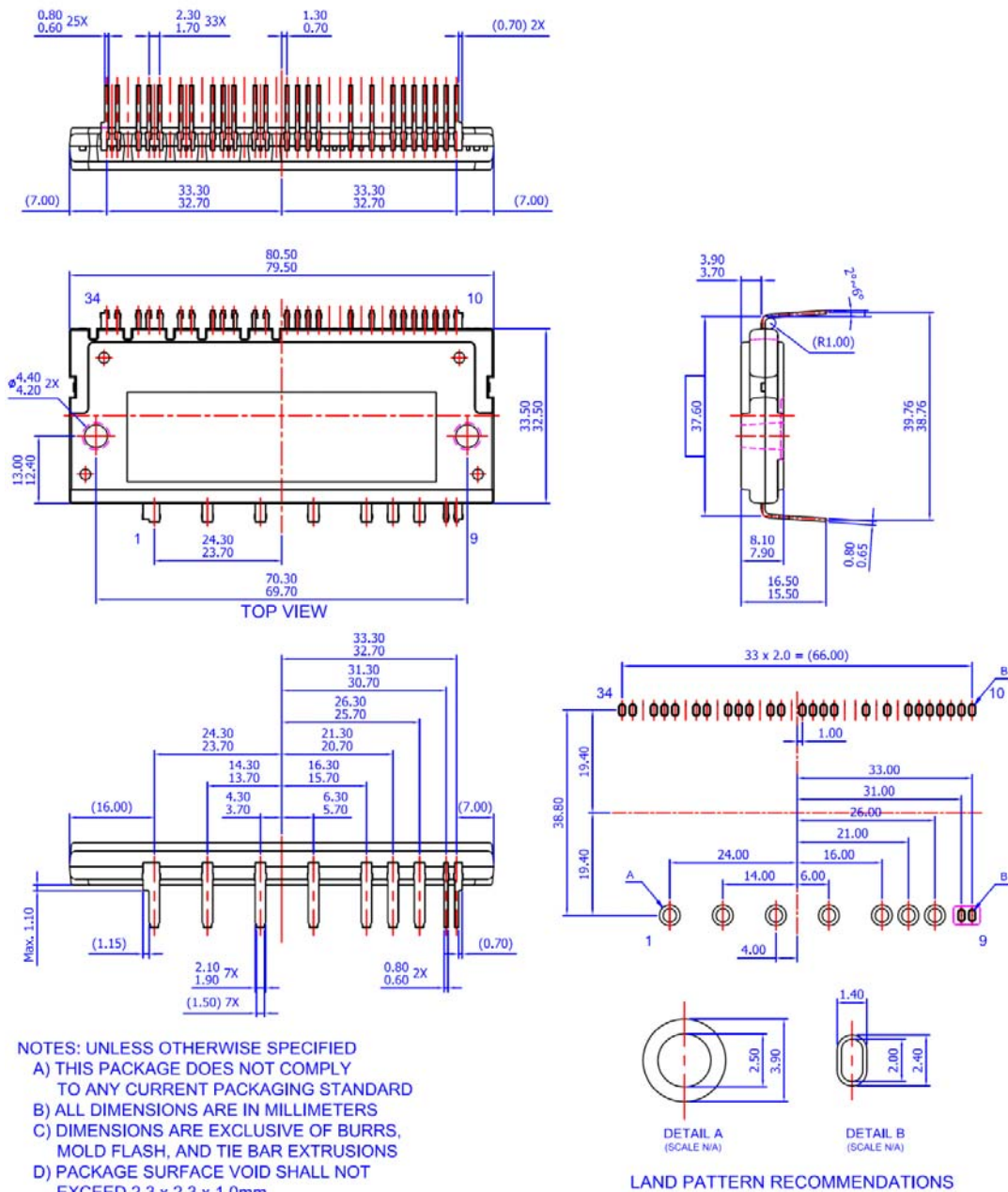


图 15. 典型应用电路

注:

15. 为了避免故障，应尽可能缩短每个输入端的连线（小于 2-3 cm）。
16. V_{FO} 输出是漏极开路型。此信号线应该用电阻上拉至 MCU 或控制电源正极，以使 I_{FO} 达到 2 mA。请参阅图 14。
17. 故障输出脉宽可以被连接到 C_{FOD} 端的电容器 C_5 调节。
18. 输入信号为高电平有效。在 IC 中，有一个 5 k Ω 的电阻将每一个输入信号线下拉接地。应当采用 RC 耦合电路，以避免输入信号振荡。 R_1C_1 时间常数应该选择在 50 ~ 150 ns 范围内，（推荐 $R_1 = 100 \Omega$, $C_1 = 1 \text{ nF}$ ）。
19. 每个 A 点的布线图电感应尽可能的最小化（建议小于 10 nH）。使用表面贴片 (SMD) 类型的分流电阻 R_4 来减少线路电感。为防止发生故障，E 点的线路应尽可能的靠近分流电阻 R_4 端。
20. 插入分流电阻来测量 N_U , N_V , N_W 端的每个相电流，为导致短路电流的触发电平 I_{SC} 改变。
21. 为避免保护功能出错，应尽可能缩短 B, C, D 点周围的连线。在 C_{SC} 滤波器和 R_{SC} 端之间的 B 线应该在靠近感测电阻 R_5 端的点分开。
22. 为了获得稳定的保护功能，请使用电阻值波动在 1% 以内且电感值低的感测电阻 R_5 。
23. 在短路电流保护电路中， R_6C_6 时间常数应该选择在 1.0 ~ 1.5 μs 范围内。 R_6 的电阻值至少应该有感测电阻 R_5 的 10 倍大。请在真实系统中做足够多的评估，因为短路电流保护时间可能根据布线设计图和 R_6C_6 时间常数的值会有所变化。
24. 每个电容都应尽可能地靠近 Motion SPM® 2 产品的引脚安装。
25. 为防止浪涌的破坏，应尽可能缩短滤波电容 C_7 和 P & GND 引脚间的连线。推荐在 P & GND 引脚间使用 0.1 ~ 0.22 μF 的高频无感电容。
26. 在各种工业应用中，几乎都用到了继电器。在这些情况下，CPU 和继电器之间应留有足够的距离。
27. 在每一对控制电源端应该采用齐纳二极管或者瞬态电压抑制器来保护 IC 不受浪涌破坏（推荐 22 V / 1 W，齐纳阻抗特性低于 15 Ω 的齐纳二极管）。
28. 推荐 C_2 的取值应大于自举电容 C_3 的 7 倍左右。
29. 请为 C_3 选择温度特性好的电解电容。同时，为 C_4 选择 0.1 ~ 0.2 μF 温度和频率特性好的 R- 类陶瓷电容。

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