

以碳化矽(SiC)功率電晶體為基礎之全橋式微逆變器(Micro-inverter)

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大綱

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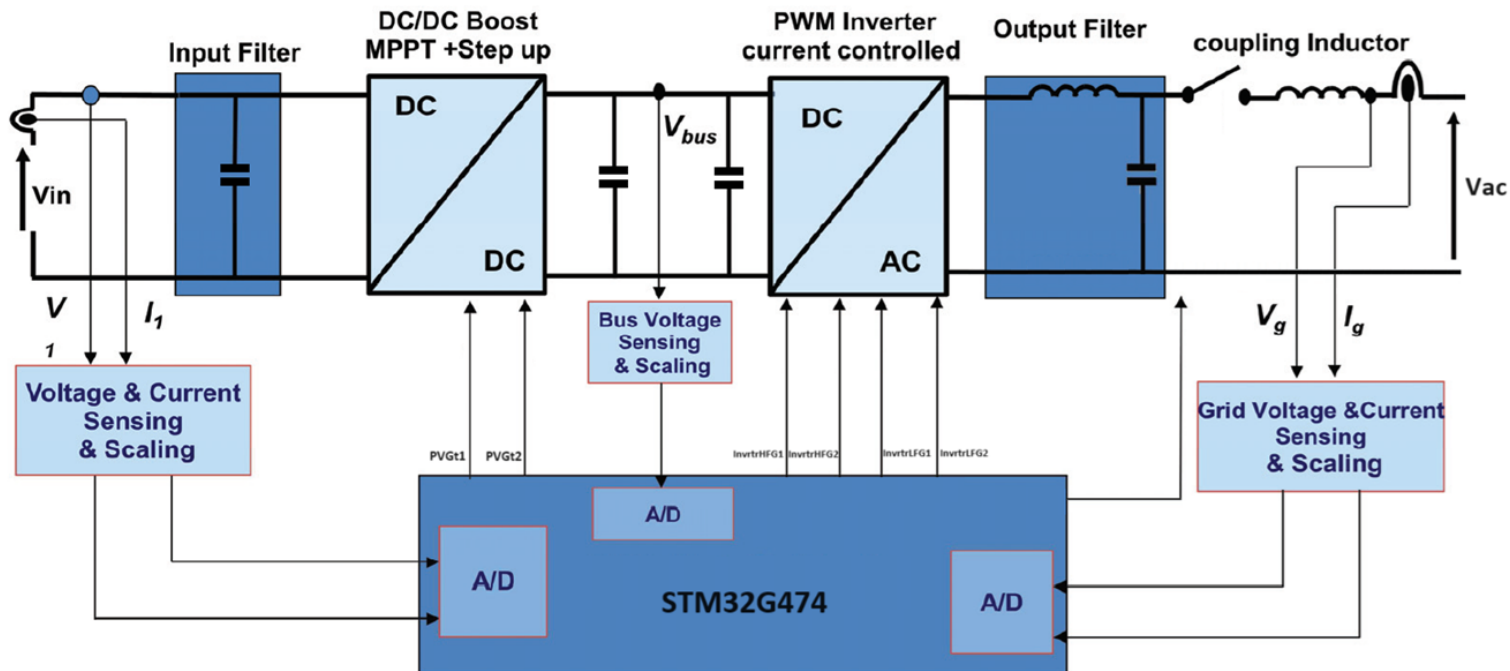
1. 方案規格 (MPPT)

Parameter	Value
Vin_nominal (額定輸入電壓)	36V
Vin_max (最大輸入電壓)	55V
Vin_min (最小輸入電壓)	18V
MPPT_DC input range (MPPT DC 輸入電壓範圍)	20V to 40V
Iin (額定輸入電流)	12A
I _{max} (最大輸入電流)	18A

1. 方案規格(Inverter)

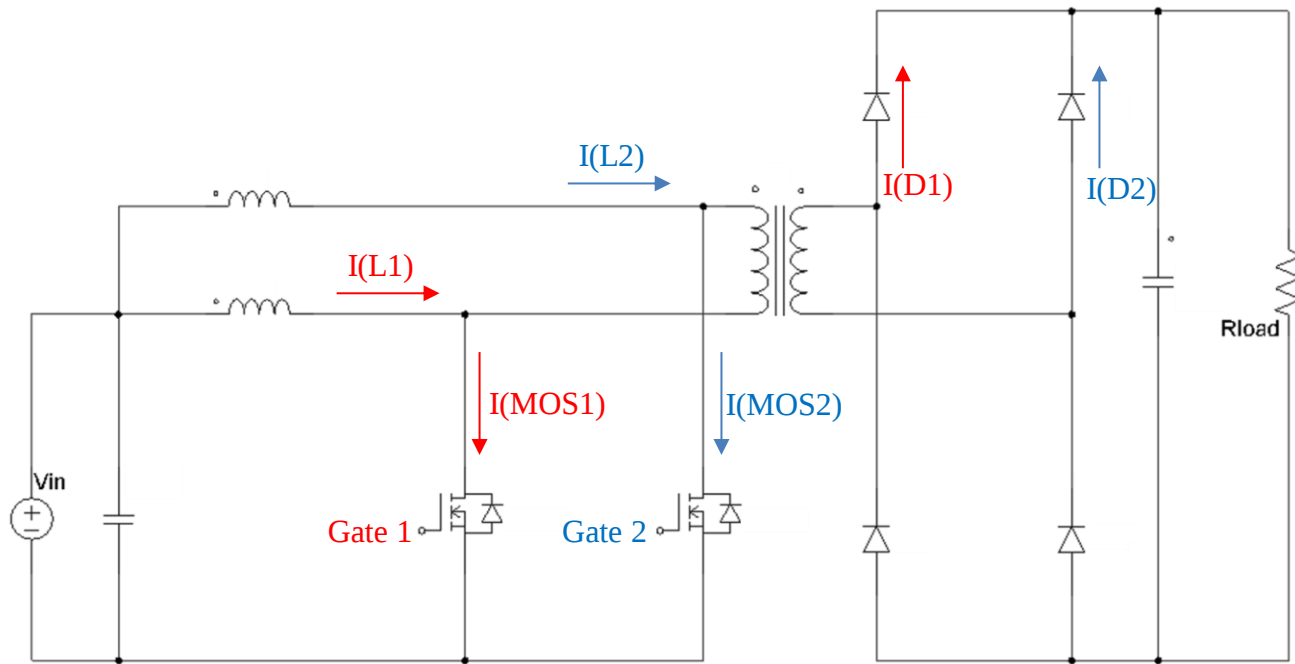
Parameter	Value
Vbus (DC-DC 額定輸出電壓)	380V
Vbus_max (DC-DC 最大輸出電壓)	400V
Vac (AC 額定輸出電壓)	110VAC/60Hz, 220VAC/50Hz
Iac (AC 最大輸出電流)	1.8A/220VAC, 3.6A/110VAC
Pac (最大輸出功率)	400W

2. 系統方塊圖



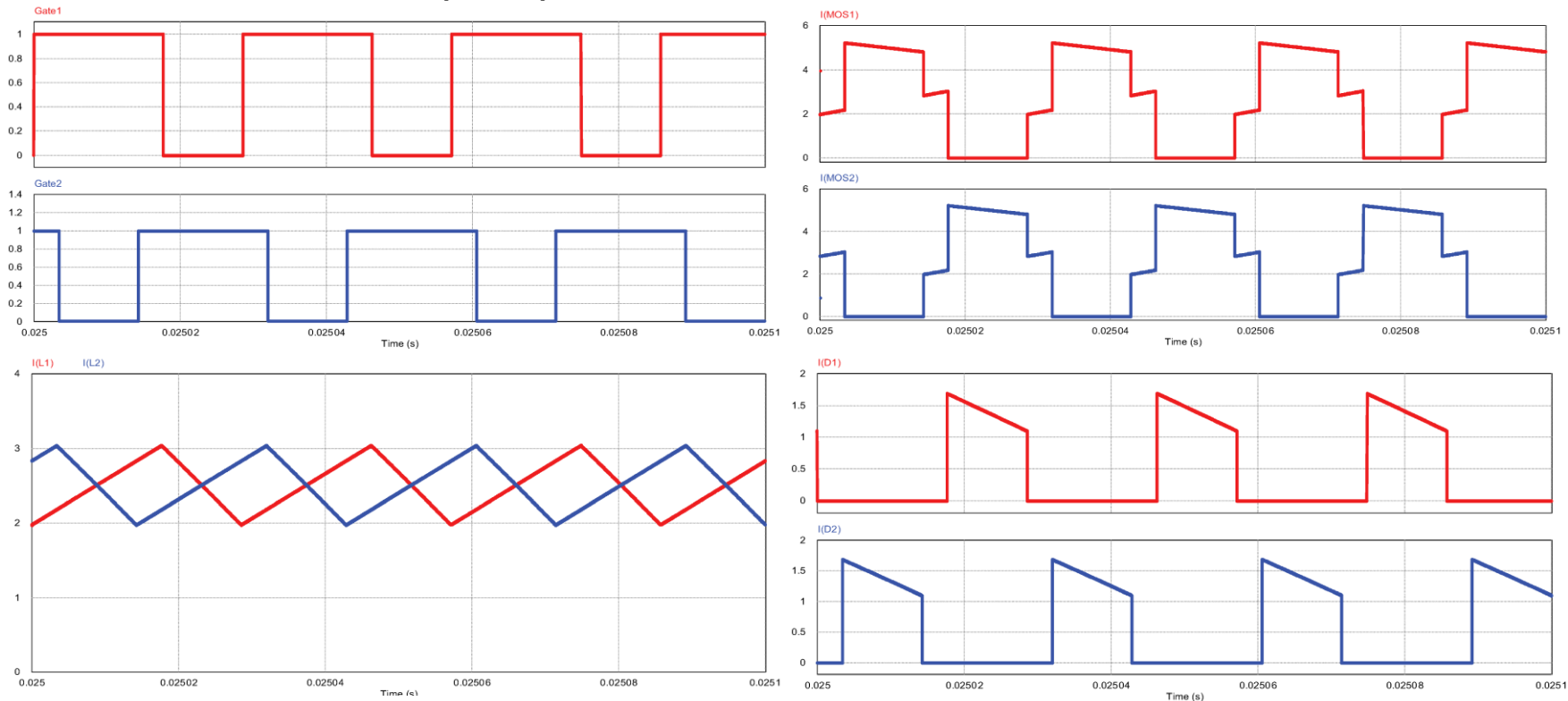
2. 系統方塊圖

DC-DC Converter



2. 系統方塊圖

DC-DC Converter (波形)



2. 系統方塊圖

DC-DC Converter (參數設計)

Calculation of the **maximum duty cycle**: In this topology the switch duty cycle is always >0.5 . Let's call D the time beyond $T_s/2$ for which the MOSFET is still closed:

$$D_{max} = \frac{t_{on,max}}{T_s} - 0.5 = 0.2 \quad (1)$$

$$t_{on,max} = 0.7 \times T_s \quad (2)$$

Calculation of maximum input power:

$$P_{in} = \frac{P_{out}}{\eta} = \frac{400}{0.94} = 425.5W \quad (3)$$

2. 系統方塊圖

DC-DC Converter (參數設計)

Calculation of **maximum average input current**:

$$I_{in,max} = \frac{P_{in}}{V_{in,min}} = \frac{425.5}{18} = 23.6A \quad (4)$$

Calculation of the **maximum switch RMS current**:

$$I_{rms,max} = \frac{\sqrt{2-D}}{2} \times I_{in,max} = \frac{\sqrt{2-0.2}}{2} \times 12.8 = 8.6A \quad (5)$$

Calculation of the **maximum average output current**:

$$I_{out,max} = \frac{P_{out}}{V_{out,min}} = \frac{400}{370} = 1.08A \quad (6)$$

2. 系統方塊圖

DC-DC Converter (參數設計)

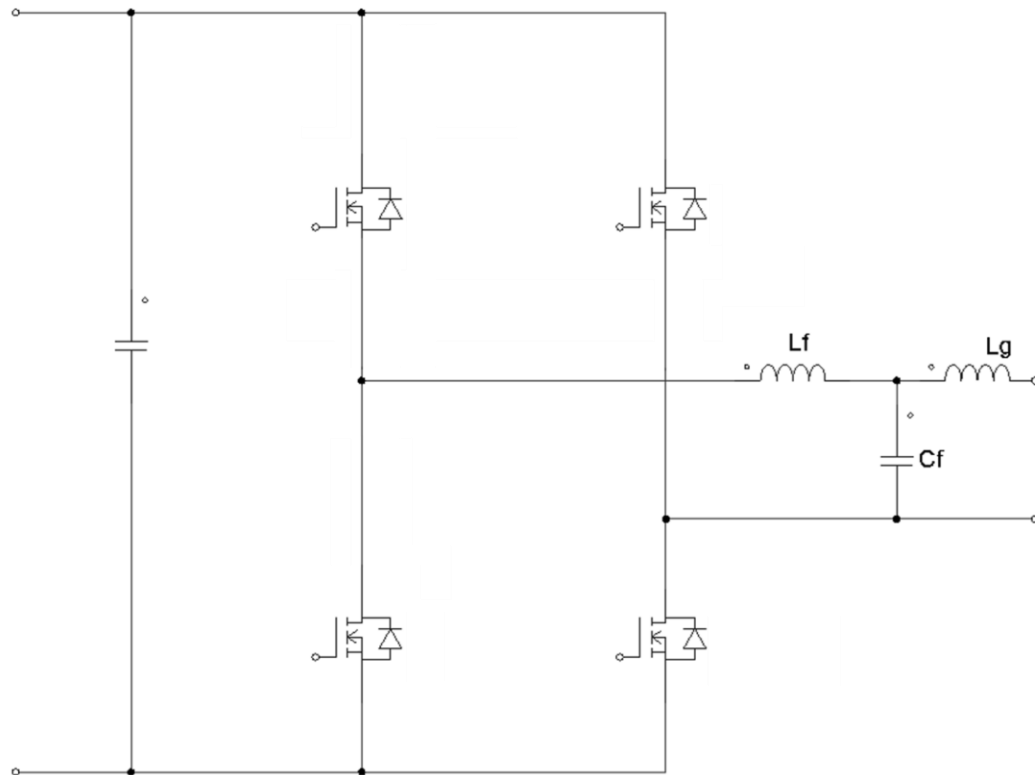
Calculation of transformer **turn ratio**:

$$\frac{N_2}{N_1} = \frac{\frac{V_{out}}{2} \times (1-D)}{2 \times V_{in}} = \frac{\frac{380}{2} \times (1-0.2)}{2 \times 30} = 2.53 \quad (7)$$

where V_{in} is chosen as the average **between the maximum and minimum input voltage value**. The final transformer turn ratio has been chosen equal to 2.6.

2. 系統方塊圖

DC-AC Converter



2. 系統方塊圖

DC-AC Converter (參數設計)

The **minimum value of capacitance required on the DC bus** is calculated according to the following equation:

$$C_{bus} = \frac{4P_{out}}{V_{bus,min}^2} t_1 = \frac{4 \times 400 \times 4.17 \times 10^{-3}}{370^2} = 48.74 \mu F \quad (8)$$

where t_1 is given by

$$t_1 = 4.17 ms = \frac{1}{4 \times f_{grid}} = \frac{1}{4 \times 60} \quad (9)$$

A total capacitance of about twice the calculated value, rated at 450 V and having an operating temperature of 105 °C, is selected for the inverter implementation. The capacitor bank is realized with the parallel connection of **four 22 μ F, 450 V capacitors**.

2. 系統方塊圖

DC-AC Converter (參數設計)

The value of L_f is designed to **limit the current ripple within 20% of the nominal current value**. The following equations have been used to calculate the filtering inductance value:

$$L_f = \frac{1}{n} \frac{(V_{bus} - V_{grid,pk}) \times D}{\Delta i \times f_{sw}} = \frac{1}{3} \frac{(380 - 155) \times 0.75}{0.73 \times 25 \times 10^3} = 3.1mH \quad (10)$$

where n is the number of **inverter levels** ($+V_{bus}$, 0 and $-V_{bus}$) and D is the inverter duty cycle.

2. 系統方塊圖

DC-AC Converter (參數設計)

The filter capacitor value is selected to **limit the exchange of reactive power below 2.5% of nominal active power**:

$$P_{reactive} < 0.05 \times P_{active} \quad (11)$$

$$X_{C_f} \geq \frac{V_{grid}^2}{0.025 \times P_{active}} = \frac{230^2}{10} = -j5290\Omega \quad (12)$$

$$C_f \leq \frac{1}{j\omega X_{C_f}} = \frac{1}{2\pi \times 60 \times 5290} = 501.43nF \quad (13)$$

2. 系統方塊圖

DC-AC Converter (參數設計)

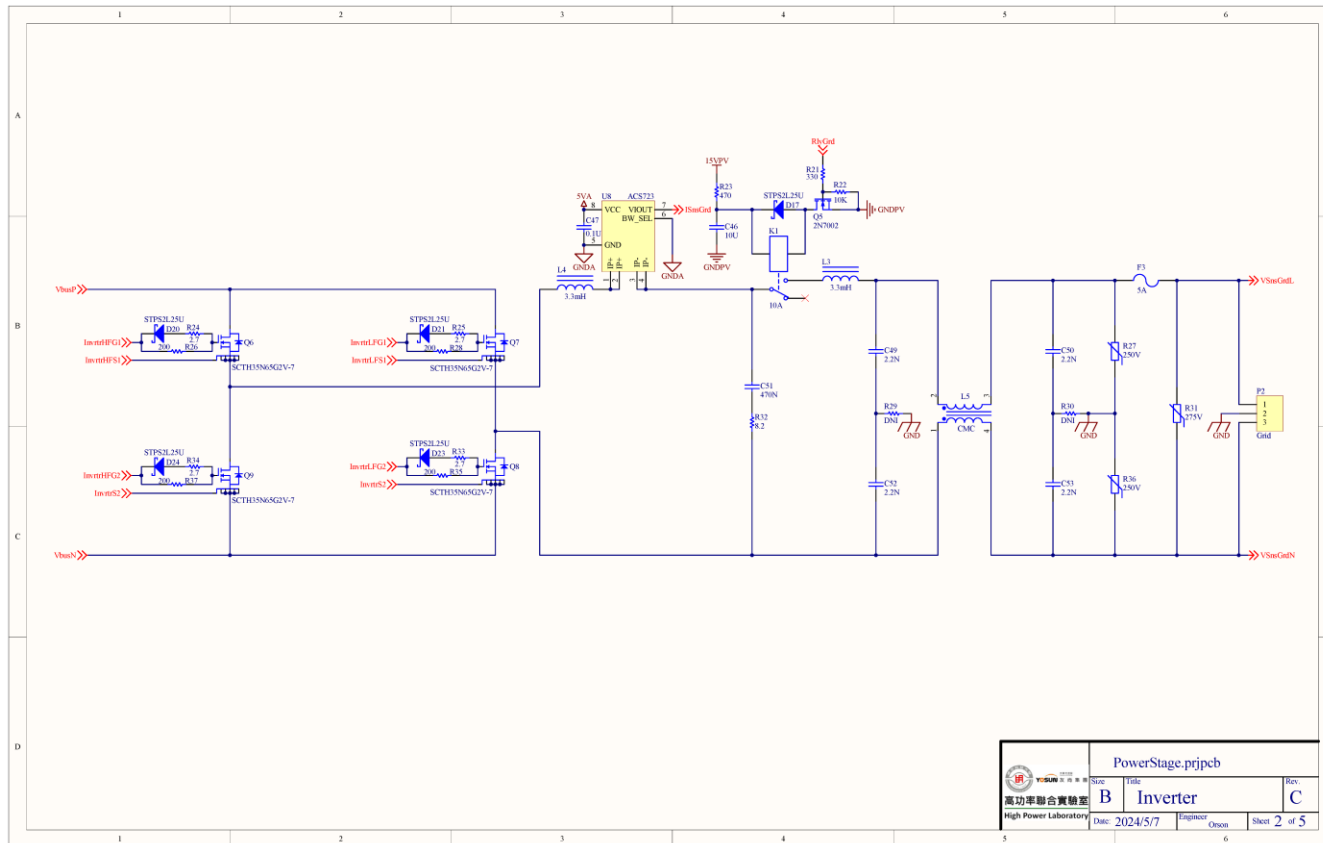
To avoid **resonance problems** for the filter due to low and high order harmonics, the resonant frequency should be chosen in a range between **ten times the line frequency** and **one half of the switching frequency**. The resonant frequency of an LCL filter is given by:

$$f_{res} = \frac{1}{2\pi} \sqrt{\frac{L_f + L_g}{L_f \times L_g \times C_f}} \quad (14)$$

Choosing a filter capacitor value of $470nF$ and a **grid coupling inductor** value equal to the **filtering inductor** value of $3.3mH$, the resulting filter resonant frequency is equal to 5.7 kHz which falls in the frequency range mentioned above.

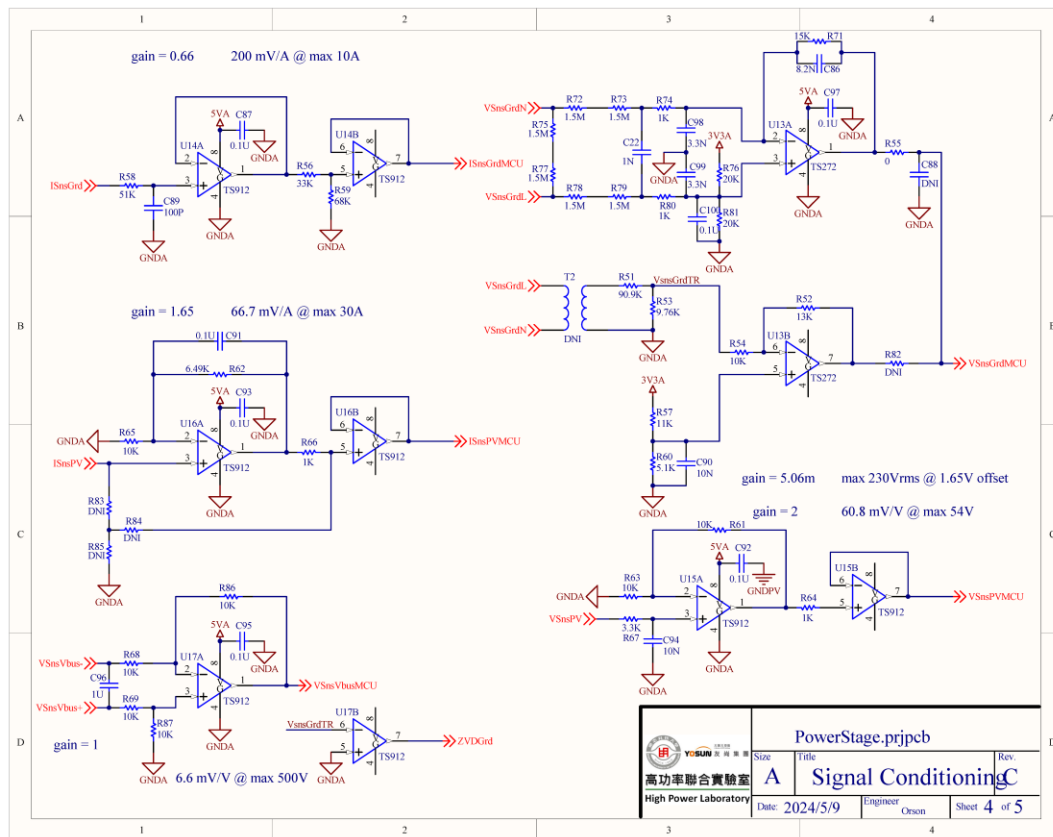


3. 電路圖/PCBA/實體圖

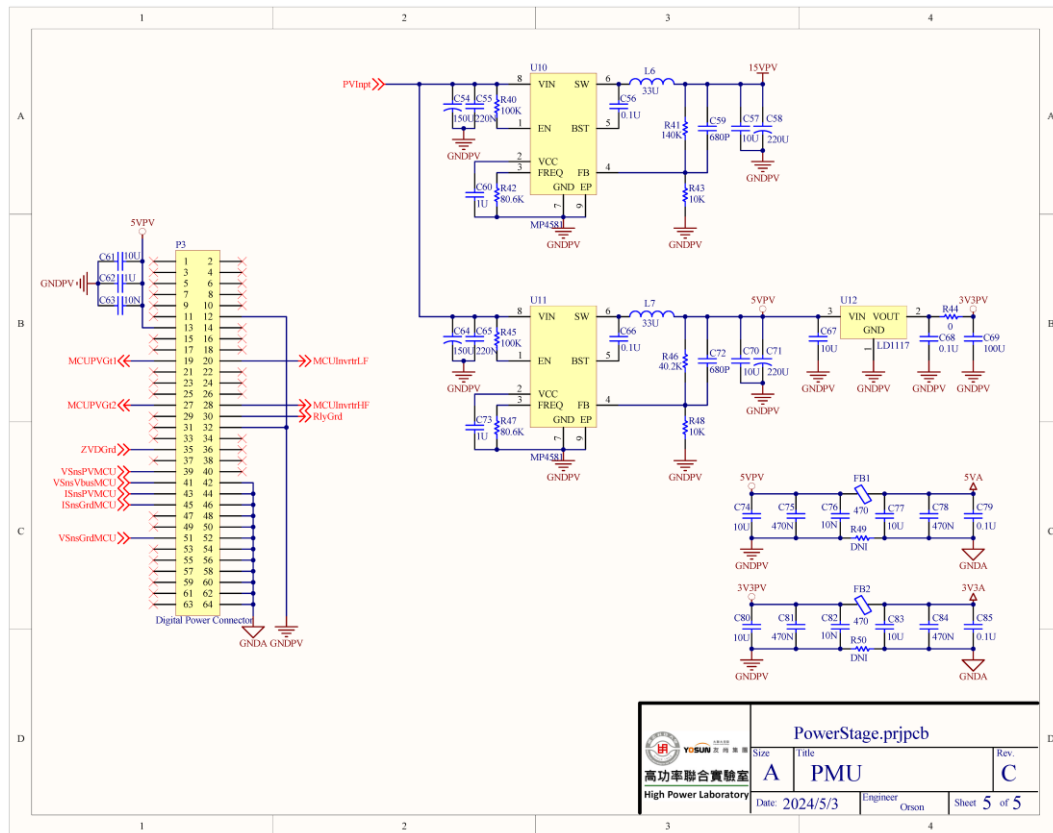




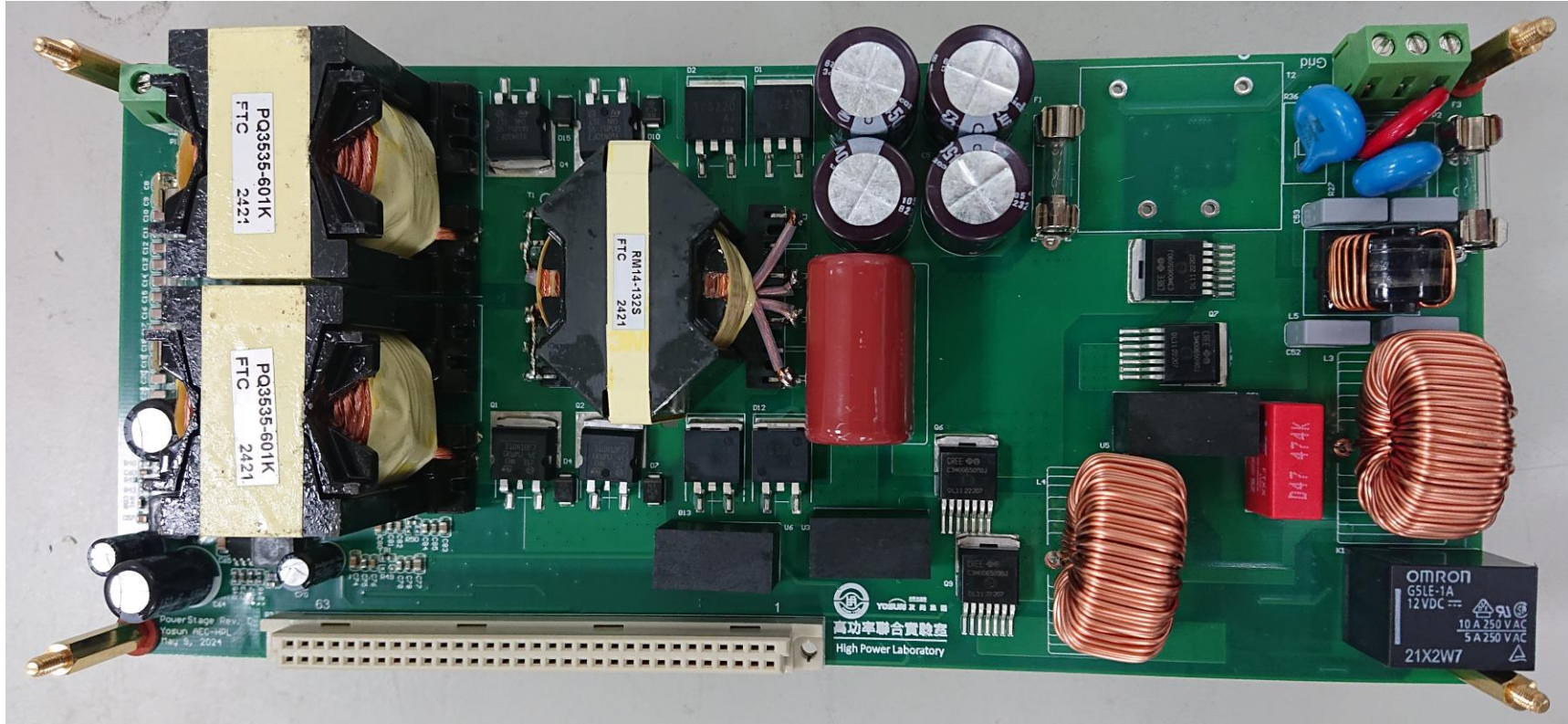
3. 電路圖/PCBA/實體圖



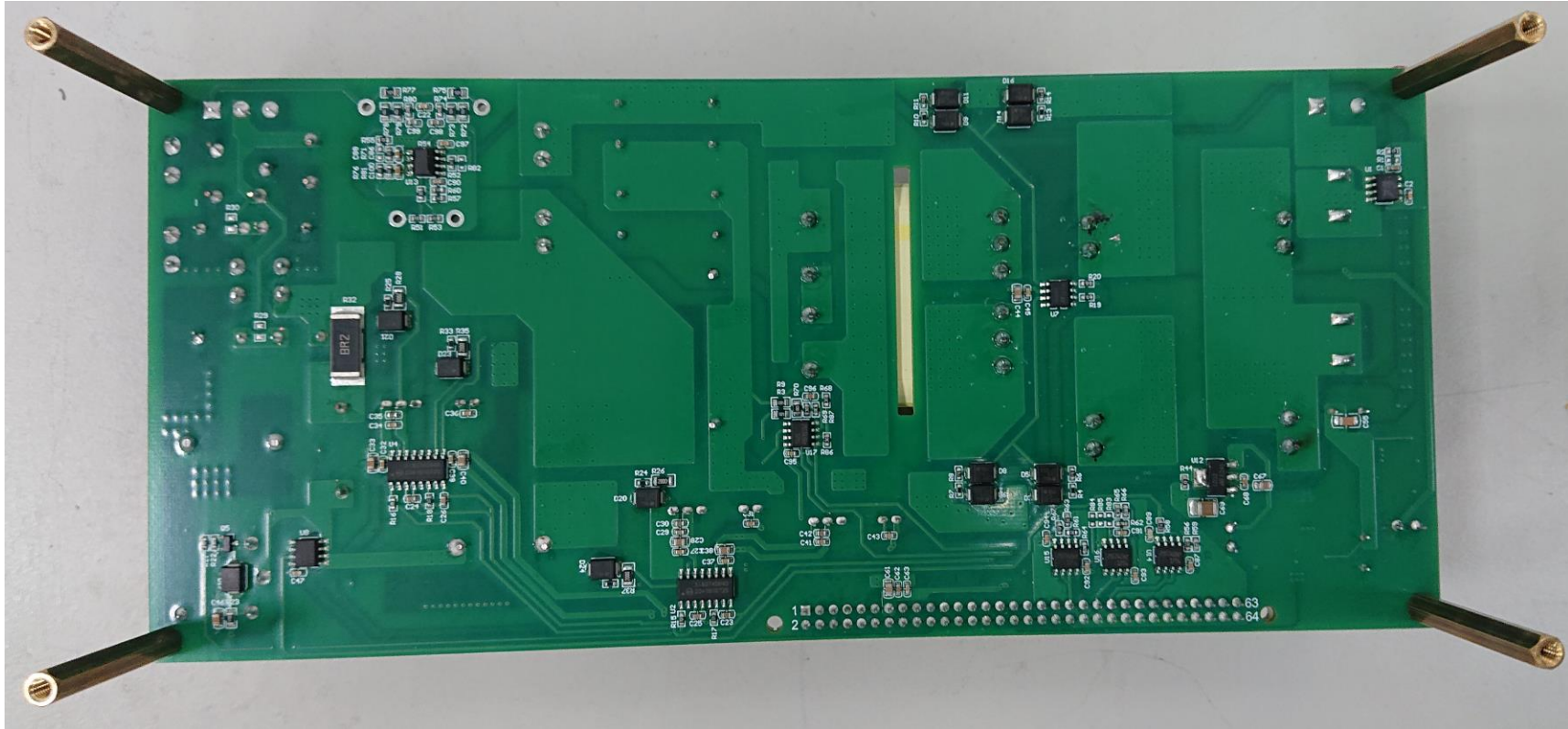
3. 電路圖/PCBA/實體圖



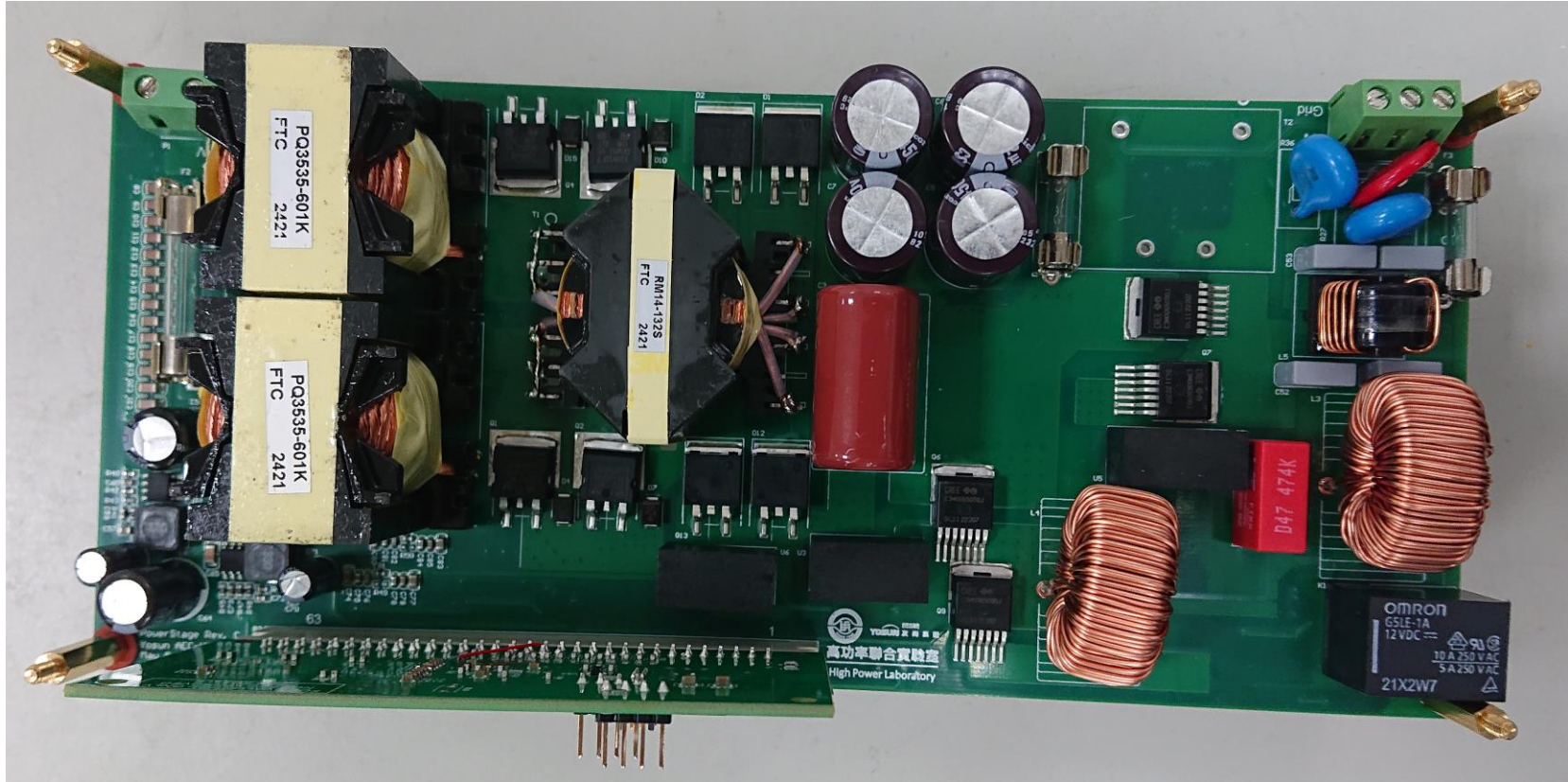
3. 電路圖/PCBA/實體圖



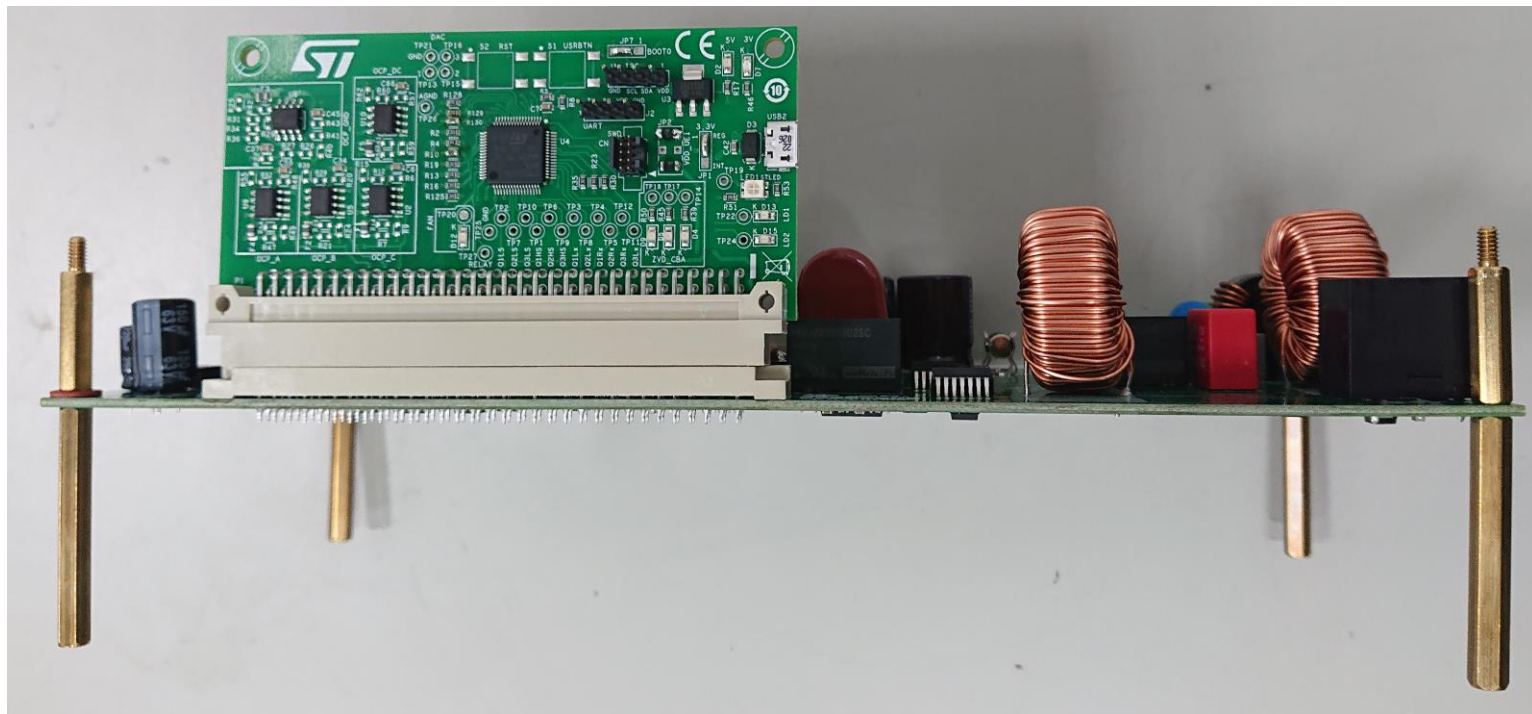
3. 電路圖/PCBA/實體圖



3. Schematic/PCBA/Assembly



3. 電路圖/PCBA/實體圖



4. PLL 架構

Knowing the two voltage components V_β and V_α , the transformation from the **stationary reference frame** to the d-q **rotating frame** is given as follows.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} V_\beta \\ V_\alpha \end{bmatrix} \quad (8)$$

where θ is the angle between the d-q reference frame and the stationary reference frame. The reverse transformation is given by:

$$\begin{bmatrix} V_\beta \\ V_\alpha \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \quad (9)$$

where

$$\begin{bmatrix} V_\beta \\ V_\alpha \end{bmatrix} = \begin{bmatrix} V_m \cos \theta_e \\ V_m \sin \theta_e \end{bmatrix} \quad (10)$$

4. PLL 架構

Then the two components on the d-q reference frame are:

$$V_d = V_m \cos \theta_e \cos \theta + V_m \sin \theta_e \sin \theta = V_m \cos(\theta - \theta_e) \quad (11)$$

$$V_q = -V_m \cos \theta_e \sin \theta + V_m \sin \theta_e \cos \theta = V_m \sin(\theta - \theta_e) \quad (12)$$

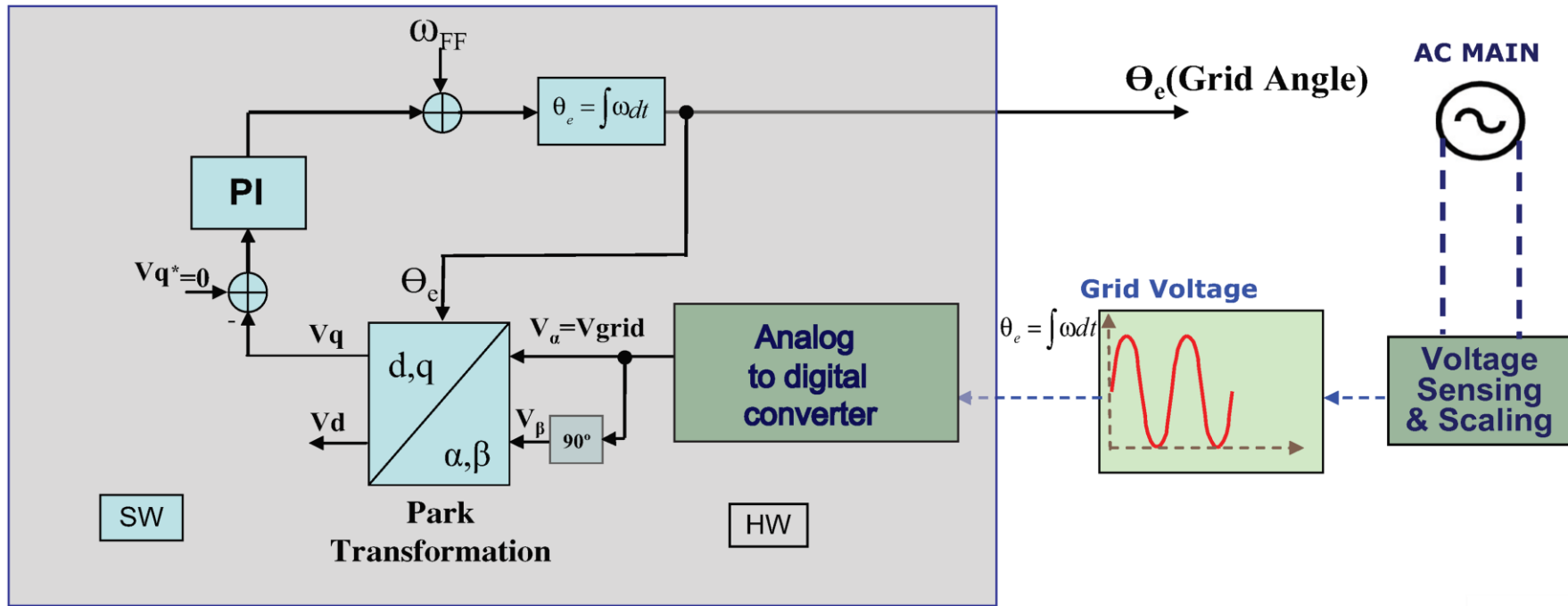
Therefore, if $\theta = \theta_e$, the two components are reduced

$$V_d = V_m \quad (13)$$

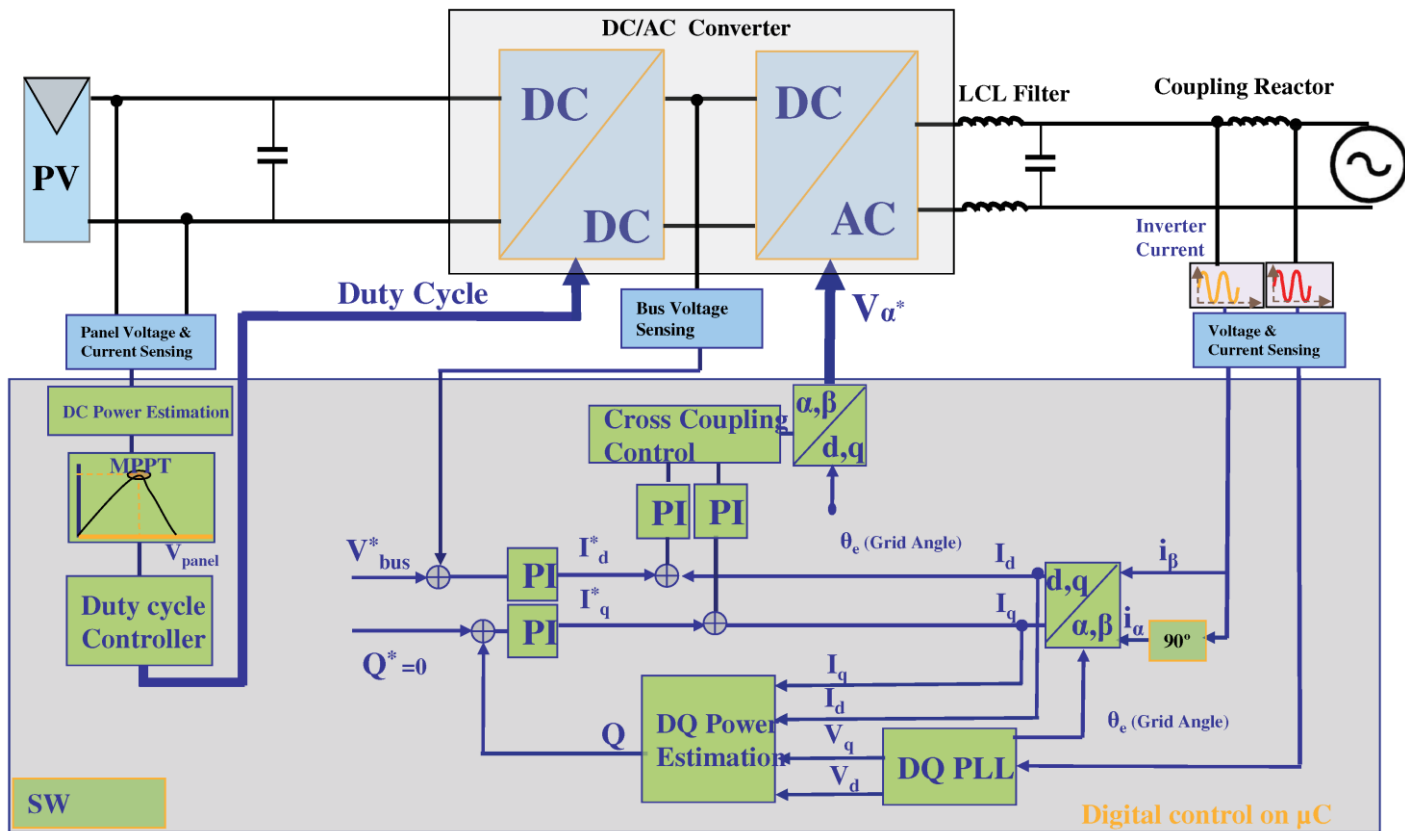
$$V_q = 0 \quad (14)$$

The **grid voltage angle** is detected using PLL structure.

4. PLL 架構



5. 控制演算法



6. 軟件

STM32CubeIDE - MicroInverter/Core/Src/main.c - STM32CubeIDE

File Edit Source Refactor Navigate Search Project Run Window Help myST

Project Explorer ×

- MicroInverter
 - Binaries
 - Includes
 - Core
 - Inc
 - Csrc
 - ControlLayer.c
 - DataSensing.c
 - DCACInverter.c
 - DCDCConverter.c
 - DQPhaseLockedLoop.c
 - HWConfigure.c
 - main.c
 - PIRegulator.c
 - PLLRegulator.c
 - SolarMPPT.c
 - SolarMulDiv.c
 - stm32g4xx_hal_msp.c
 - stm32g4xx_it.c
 - syscalls.c
 - systemem.c
 - system_stm32g4xx.c
 - Startup
 - Drivers
 - Debug
 - MicroInverter.ioc
 - MicroInverter.launch
 - STM32G474RBTX_FLASH.Id
 - STM32G474RBTX_RAM.Id

main.c ×

```
1  /* USER CODE BEGIN Header */
2  /**
3   *
4   * @file      : main.c
5   * @brief     : Main program body
6   *
7   * @attention
8   *
9   * Copyright (c) 2024 STMicroelectronics.
10  * All rights reserved.
11  *
12  * This software is licensed under terms that can be found in the LICENSE file
13  * in the root directory of this software component.
14  * If no LICENSE file comes with this software, it is provided AS-IS.
15  *
16  */
17  /*
18  /* USER CODE END Header */
19  /* Includes -----*/
20  #include "main.h"
21
22  /* Private includes -----*/
23  /* USER CODE BEGIN Includes */
24  #include "HWConfigure.h"
25  #include "DCDCConverter.h"
26  #include "DCACInverter.h"
27  #include "DataSensing.h"
28  #include "ControlLayer.h"
29  /* USER CODE END Includes */
30
```

Console × Problems Tasks Properties Debug Build Analyzer Static Stack Analyzer Search

No consoles to display at this time.

6. 軟件

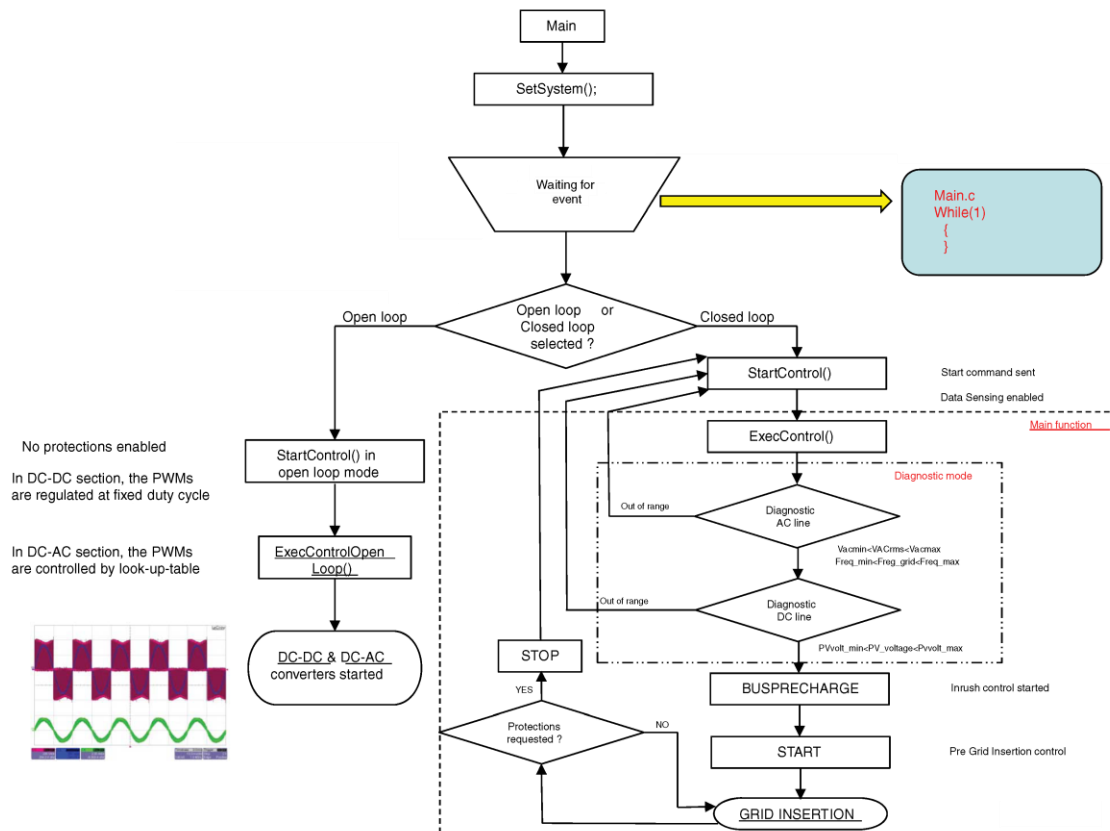
The Src folder contains all .c files that contribute to the power management.

1. **ControlLayer.c**: the core of the firmware. It contains a lot of functions for the **closed and open loop control**;
2. **DataSensing.c**: configures the **data sensing** section for closed loop control;
3. **DCACInverter.c**: contains all functions with regard to the **DC-AC** section;
4. **DCDCConverter.c**: contains all functions with regard to the **DC-DC** section;
5. **DQ_PhaseLockedLoop.c**: contains the DQ-PLL implementation for a **single-phase** and the **anti-islanding protection** routine;

6. 軟件

6. **HWconfigure.c**: configures the **ADC** and **timer** peripherals;
7. **main.c**: includes the main loop function and the system parameters management;
8. **PIRegulator.c**: includes several **PI regulators** for the closed loop control;
9. **PLLRegulator.c**: includes two PI regulators for the closed loop control, the PID_Bus_Voltage and PLL_PID regulator;
10. **SolarMPPT.c**: includes the **maximum power point tracking** algorithm for the DC-DC control;
11. **SolarMulDiv.c**: includes the calculations used for the closed loop control.

6. 軟件



7. 主要元件

Item	Description	P/N	Q'ty	Vendor
1	MCU, LQFP64	STM32G474RE	1	STMicroelectronics
2	Low Dropout Voltage, Voltage Regulator 1.3A, 3.3 V 3+Tab-Pin	LD1117S33CTR	1	STMicroelectronics
3	4 A dual low-side MOSFET driver	PM8834	1	STMicroelectronics
4	Op Amp, 3.5MHz, 5 → 15 V, 8-Pin	TS272IDT	1	STMicroelectronics
5	Low Power, Op Amp, RRIO, 1MHz, 3 → 15 V, 8-Pin	TS912ID	4	STMicroelectronics
6	N-Channel MOSFET, 180 A, 100 V, 3-Pin	STH310N10F7-2	4	STMicroelectronics
7	SiC N-Channel MOSFET, 45 A, 650 V, 7-Pin	SCT055H65G3-7	4	STMicroelectronics
8	650V 20A, Automotive 650 V power Schottky silicon carbide diode	STPSC20065GY-TR	4	STMicroelectronics

7. 主要元件

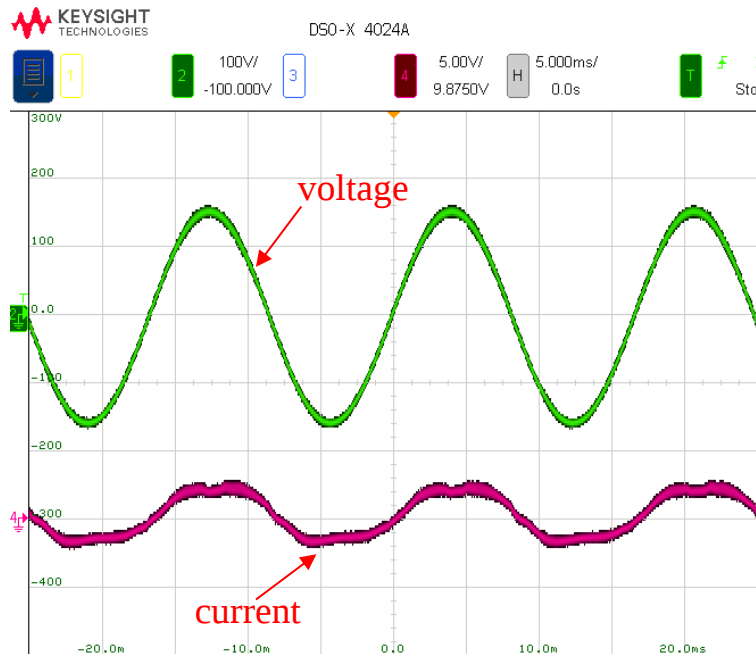
Item	Description	P/N	Q'ty	Vendor
9	25V 2A, Schottky Diode, 2-Pin	STPS2L25U	13	STMicroelectronics
10	DIODE, SMA, ESD Suppressors / TVS Diodes 600W 5.0V Unidirect	SMAJ5.0A-TR	2	STMicroelectronics
11	ESD PROTECTION	ESDA6V1L	1	STMicroelectronics
12	N-Channel MOSFET, 115 mA, 60 V, 3-Pin	2N7002LT1G	1	onsemi
13	100V, 0.8A, High-Efficiency, Synchronous, Step-Down Buck Converter with Integrated Power MOSFETS	MP4581GN	2	MPS
14	Uni-Directional TVS Diode, 600W, 2-Pin	SMBJ100A-13-F	4	DiodesZetex
15	XtremeSense TMR Current Sensor with Ultra-Low Noise and <0.7% Total Error	CT427-HSN830DR	1	CROCUS
16	1 μ F Multilayer Ceramic Capacitor MLCC 50V dc $\pm$ 10% , SMD	UMK107BJ105KA-T	10	Taiyo Yuden

7. 主要元件

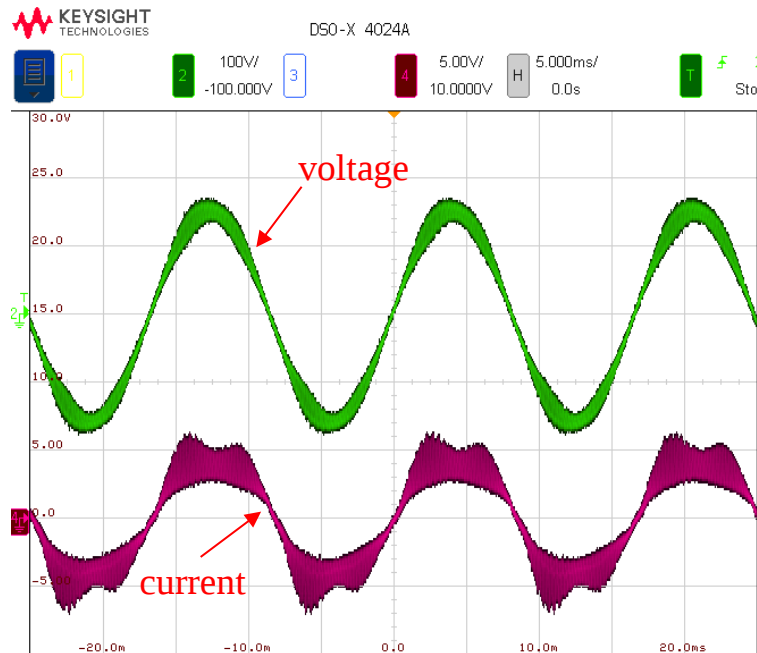
Item	Description	P/N	Q'ty	Vendor
17	1nF MLCC 50V dc $\pm 10\%$, SMD	UMK107B7102KAHT	2	Taiyo Yuden
18	Multilayer Ceramic Capacitors MLCC - SMD/SMT 1206 100VDC 1uF 10% X7R MIDHIGH VOL	HMK316B7105KL-T	14	Taiyo Yuden
19	100nF MLCC 50V dc $\pm 10\%$, SMD	UMJ107BB7104KAHT	26	Taiyo Yuden
20	10 μ F MLCC 25V dc $\pm 10\%$ SMD	TMK212BBJ106KGHT	14	Taiyo Yuden
21	MLCC - SMD/SMT 1206 100VDC 0.22uF 10% X7R MID HIGH VOL	HMK316B7224KL-T	2	Taiyo Yuden
22	680pF Multilayer Ceramic Capacitor MLCC 100V dc $\pm 10\%$, SMD	HMK107SD681KA-T	2	Taiyo Yuden
23	10nF MLCC 50V dc $\pm 10\%$, SMD	UMK107B7103KAHT	5	Taiyo Yuden
24	100 μ F MLCC 16V dc $\pm 20\%$ SMD	EMK325ABJ107MM-P	1	Taiyo Yuden
25	470nF MLCC 25V dc $\pm 10\%$ SMD	TMK107B7474KAHT	4	Taiyo Yuden
26	100pF MLCC 100V dc $\pm 10\%$ SMD	HMK107SD101KA-T	1	Taiyo Yuden

8. 測試報告

Input Voltage and Current



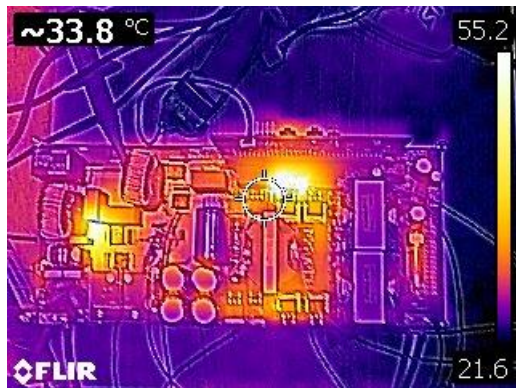
200W output



403W output

8. 測試報告

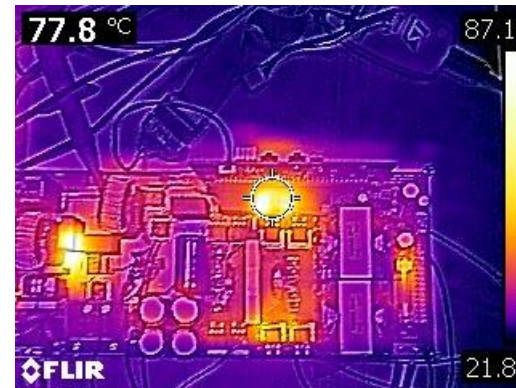
Thermal Image



200W output



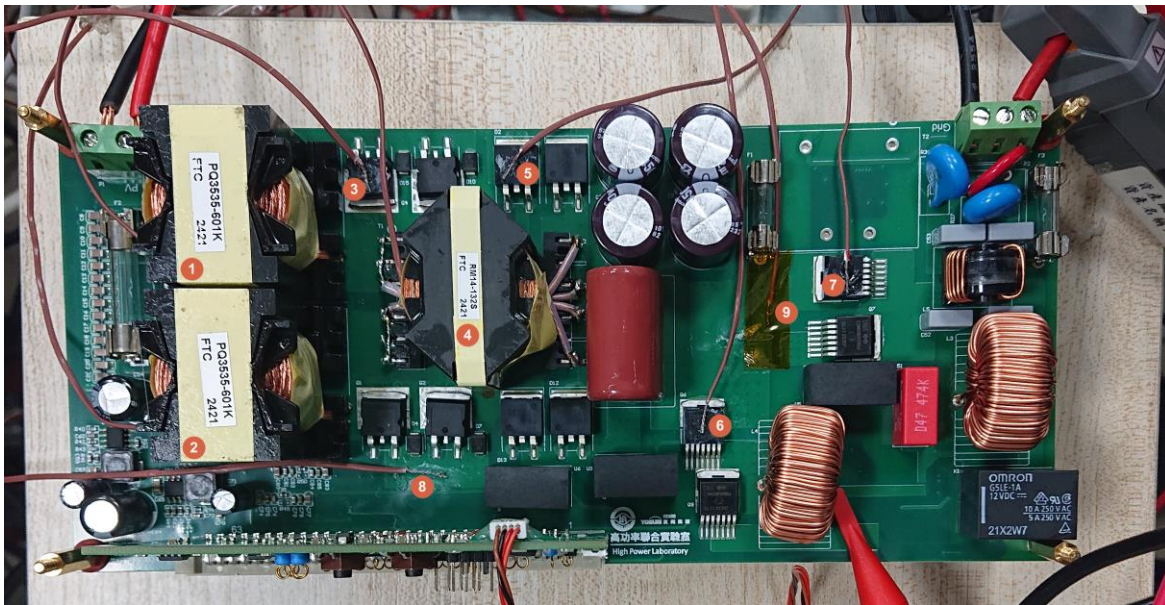
300W output



403W output

8. 測試報告

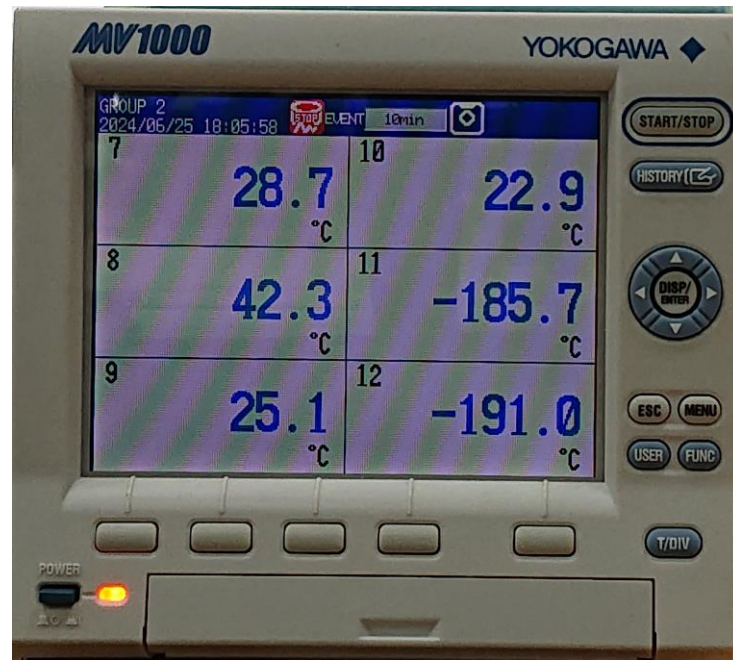
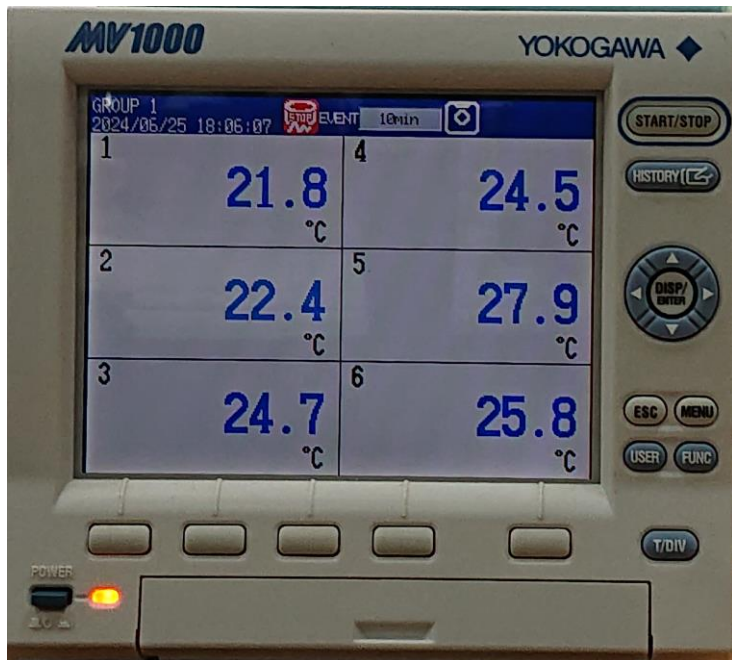
Temperature Probing



Channel No.	Component
1	L1
2	L2
3	Q4
4	T1
5	D2
6	Q6
7	Q7
8	Low Side Copper
9	High Side Copper

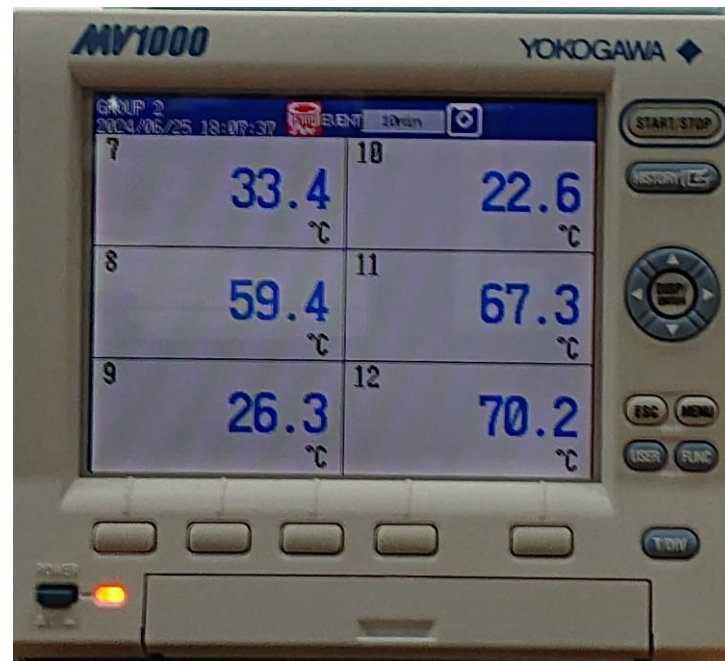
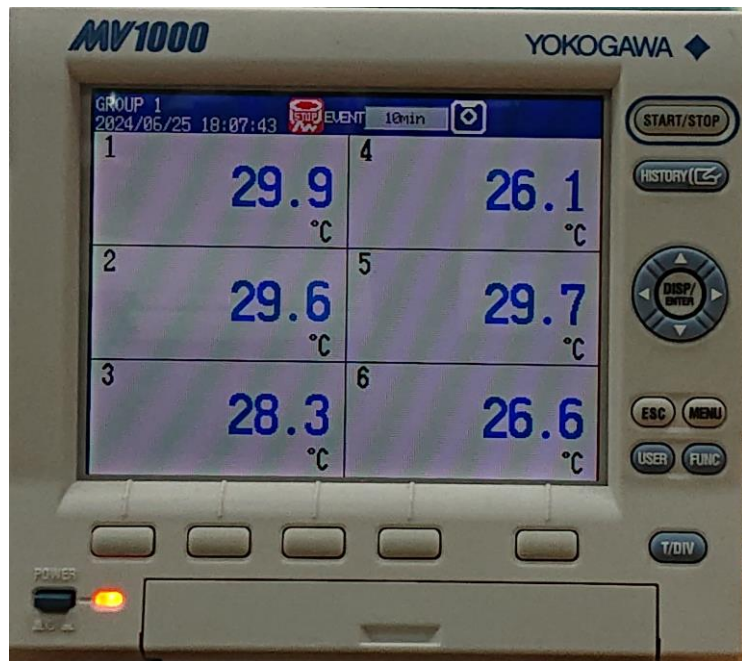
8. 測試報告

Temperature Probing (200W)

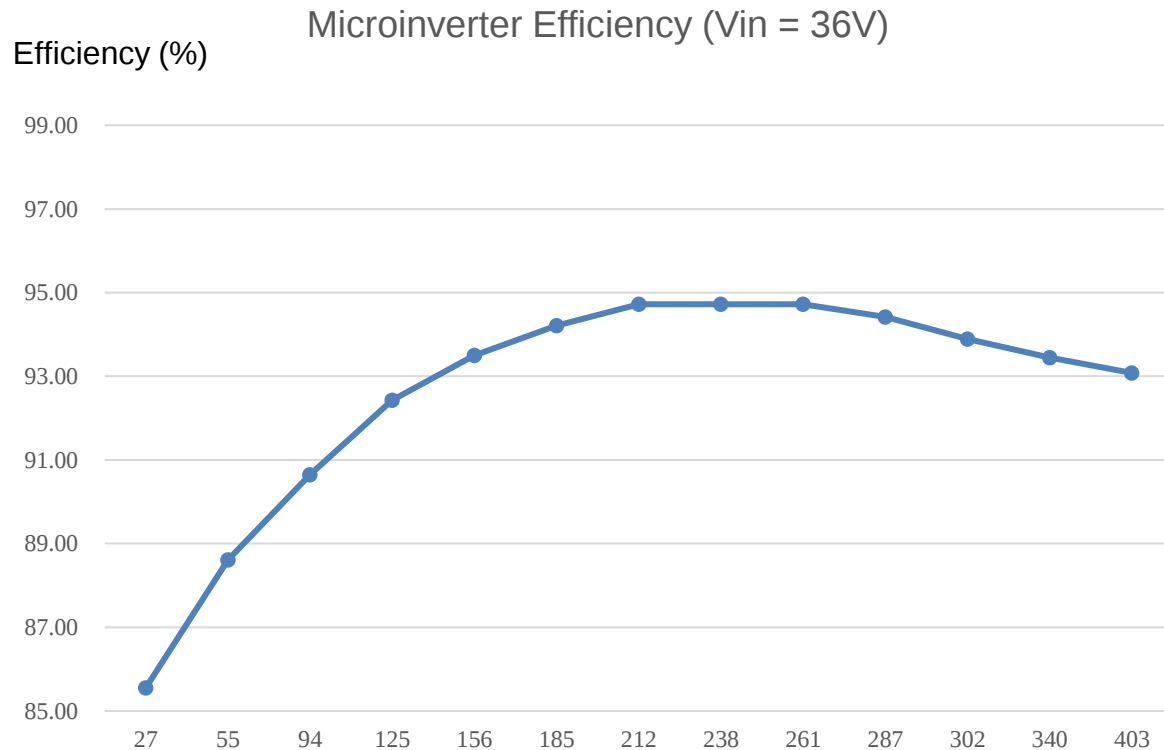


8. 測試報告

Temperature Probing (403W)

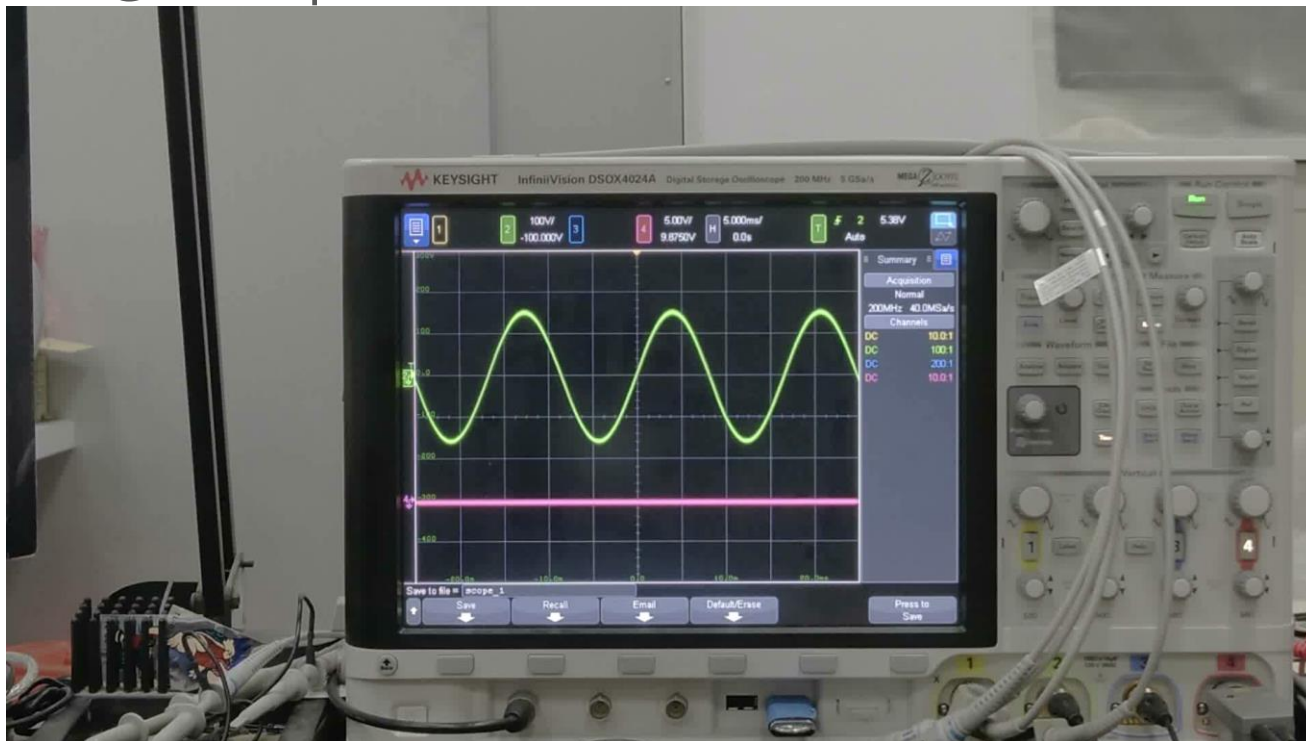


8. 測試報告



8. 測試報告

1. Grid-connected (DC source)
0A~12A@36V input



9. 發佈套件

1. Schematic
2. BOM
3. Gerber File
4. SMD Pick-place Table
5. Firmware (Source Code)

Thank you