UM3011

User manual

Getting started with the STDES-30KWVRECT 30 kW Vienna PFC rectifier reference design

Introduction

The STDES-30KWVRECT reference design introduces a complete digital power solution for high-power three-phase active front end (AFE) rectifier applications based on the three-level Vienna topology.

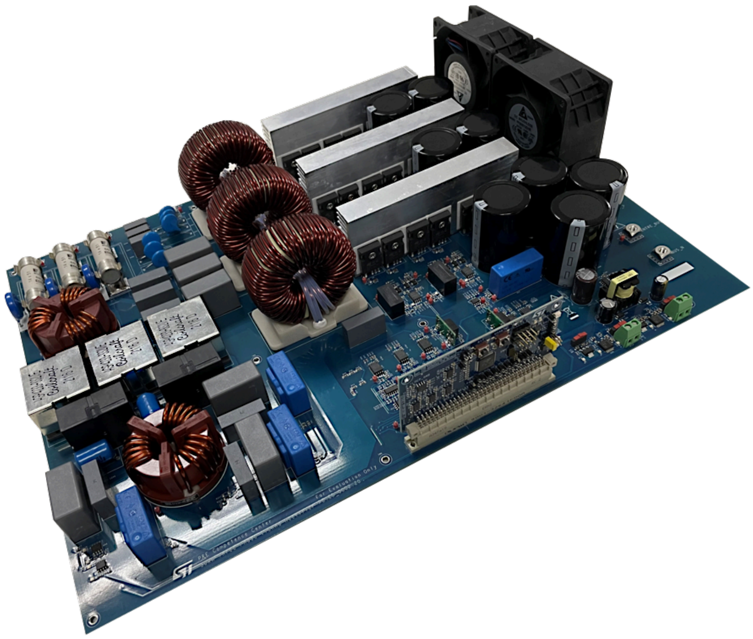
This platform achieves a peak efficiency of more than 98.5% by using the SCTWA90N65G2V-4 and the STPSC40H12CWL.

It features a fully digital control with the STM32G474RET3 mixed-signal high-performance microcontroller, providing the full control of the PF, DC voltage, and soft startup procedure.

The STDES-30KWVRECT achieves a low total harmonic distortion (less than 5% THD at full load) and a high-power factor (higher than 0.99 at full load), providing a high-bandwidth continuous conduction mode (CCM) current regulation.

The STDES-30KWVRECT is a fully assembled kit developed for performance evaluation only, not available for sale.

Figure 1. STDES-30KWVRECT 30 kW Vienna PFC rectifier reference design kit



1 Overview

1.1 Safety instructions

Attention: *This reference design is designed for demonstration purposes only and is not intended for domestic or industrial installations.*

Danger: *The high-voltage levels used to operate this reference design could provoke a serious electrical shock. This reference design has to be used in a suitable laboratory by qualified personnel only, familiar with the installation, use, and maintenance of power electrical systems.*

During operation, do not touch the reference design as some of its components could reach a very high temperature.

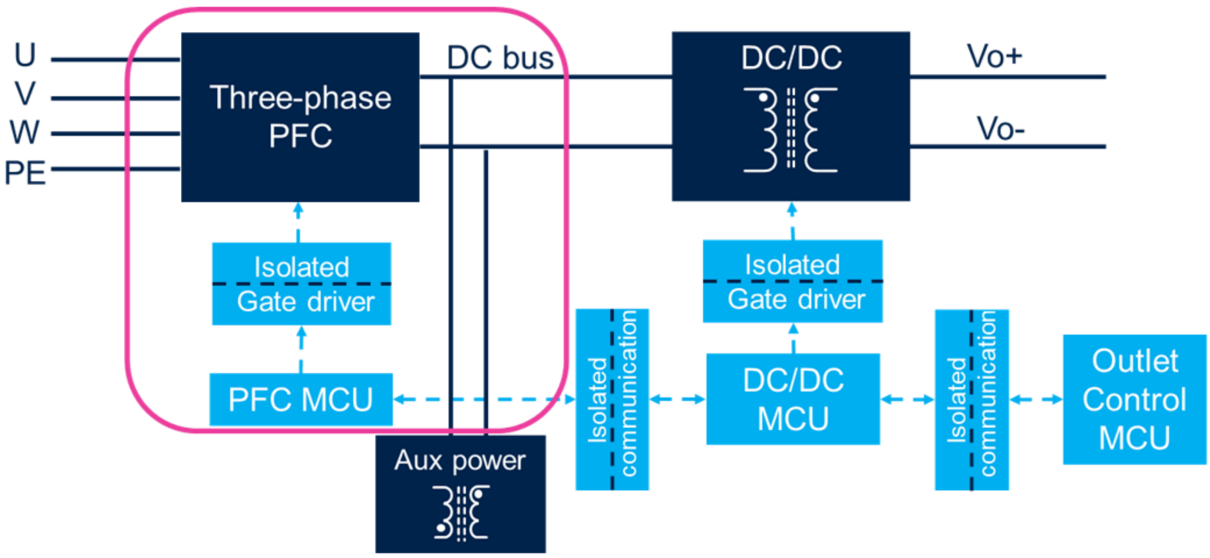
1.2 Features

- Three-phase, three-level AC-DC power converter:
  - Nominal rate for DC voltage: 800 V_{DC}
  - Nominal rate for AC voltage: 400 V_{AC} at 50 Hz
  - Maximum power: 30 kW
  - Power factor: >0.99
  - Inrush current control and soft start-up
  - THD lower than 5% at nominal operation
- Power section based on SiC MOSFETs and SiC diodes:
  - High frequency operation (70 kHz)
  - High efficiency: >98.5%
  - Paralleled SiC MOSFETs for higher power with balanced sharing current
  - Passive element weight and size reduction
- Control section based on the STM32G474RE microcontroller:
  - Control and monitoring interfaces: SWD–UART, I²C, and DACs
  - 64-pin digital power connector
  - LED status as UI
  - Four integrated high-performance op-amps for additional features

1.3 Archictecture

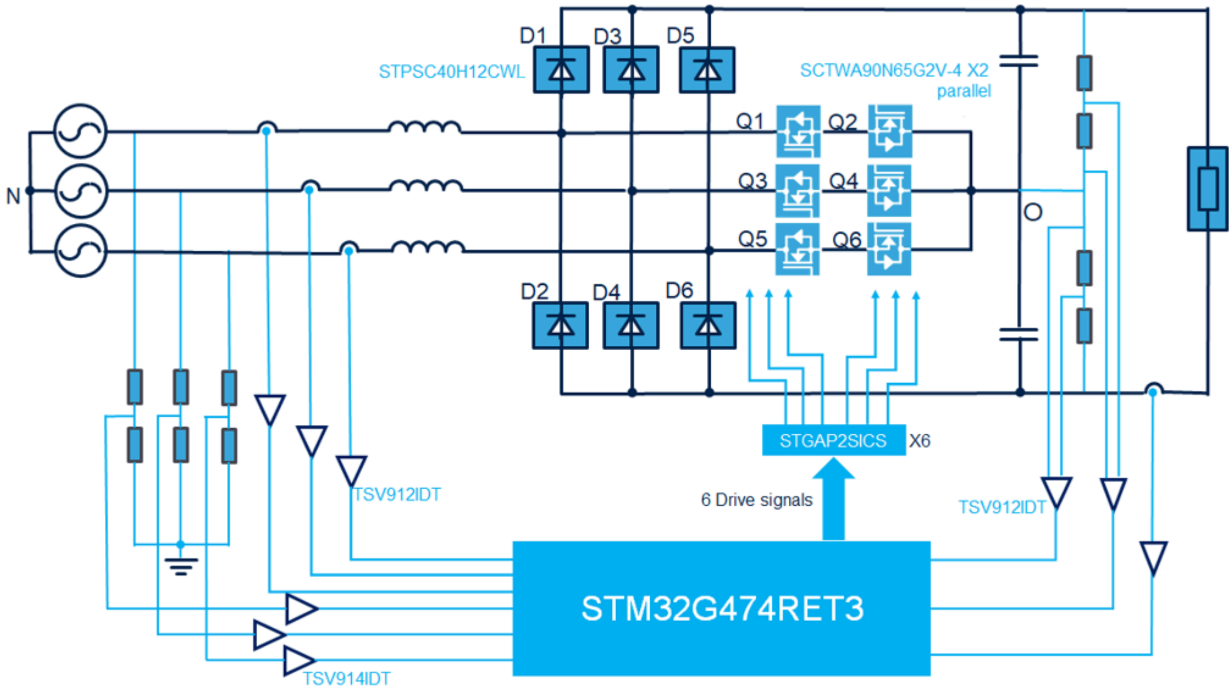
The DC fast charging supply consists of a three-phase active front end (AFE) rectifier, which provides a regulated DC link from a universal three-phase AC input, while it demands a high-quality current from the grid.

Figure 2. Block diagram of a DC fast charging application



The figure below shows the circuit configuration for the three-phase Vienna PFC.

Figure 3. Simplified schematic of the three-phase Vienna PFC



The Vienna rectifier works as a three-phase boost converter that steps up the AC mains input voltage to 800 V_{DC} output while forcing a sinusoidal input current that is in-phase with the input voltage on all three phases.

Each phase consists of a boost inductor, a pair of rectifiers (STPSC40H12C SiC Schottky diodes) and a set of series connected MOSFETs (each position uses two paralleled SCTWA90N65G2V-4 SiC MOSFET). The MOSFETs are connected to the center point of a capacitive divider, which reduces the voltage stress on the SiC MOSFETs. Two SiC Schottky diodes of each phase are used for boosting during the input AC voltage positive and negative alternation.

The driving circuit is an STGAP2SICS galvanic isolated driver IC for SiC MOSFETs. It provides 4 A driving current capability and a common mode transient immunity (CMTI) up to 100 V/ns.

The control of the Vienna PFC is implemented with an STM32G474RE microcontroller, which includes PFC, THD, voltage regulation, input overcurrent protection (OCP), overvoltage protection (OVP), soft-start, and inrush current limit functions.

1.4 Specifications

Table 1. Electrical characteristics

Symbol	Description	Min.	Typical	Max.	Units	Comments
$VAC_{(L-L)}$	Input line-line AC voltage	345	400	460	Vrms	
f_{AC}	Input AC frequency	47	50	63	Hz	
V_{out}	Output voltage	700	800	850	V	
P_{out}	Output power			30	kW	
I_{out}	Output current			37.5	A	VDC=800V
I_{in}	Input current			50	A	$VAC_{(L-L)}$ =350V
η	Peak efficiency			98.56	%	$VAC_{(L-L)}$ =400V, V_{out}=800V
				98.7	%	$VAC_{(L-L)}$ =450V, V_{out}=800V

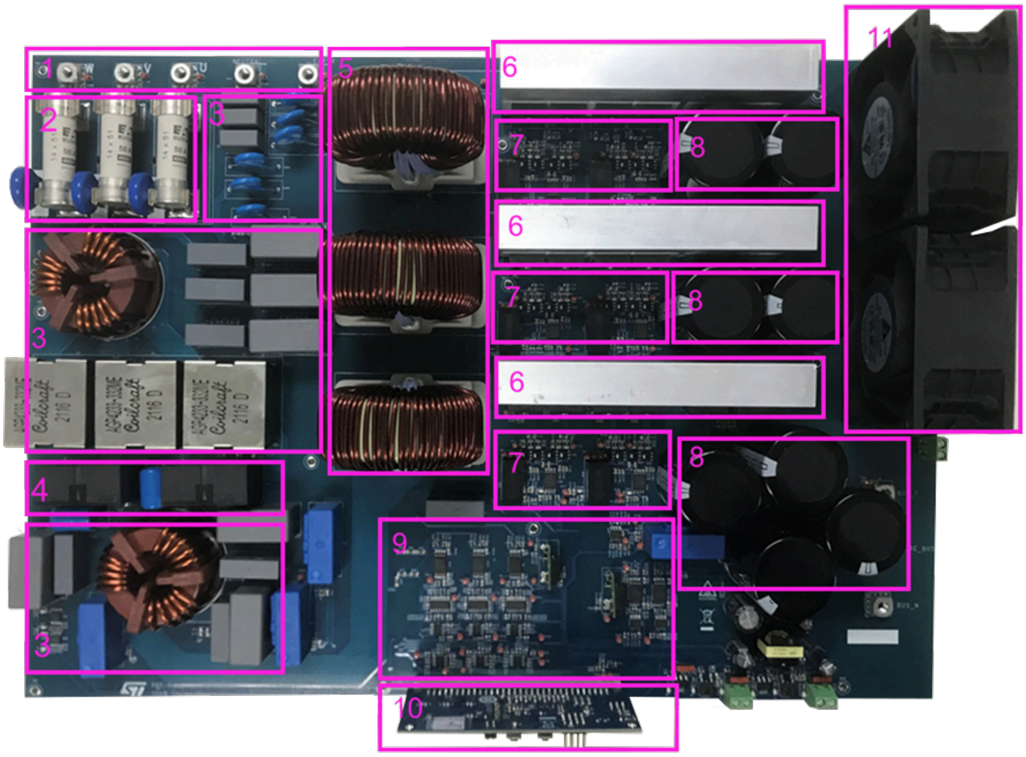
Symbol	Description	Min.	Typical	Max.	Units	Comments
iTHD	Total harmonic distortion			<5	%	At load >50%
PF	Power factor		0.99			At load >50%
I_{inrush}	Inrush current			30	A	$VAC_{(L-L)}$ =450V

1.5 Kit component overview

1.5.1 Power board components

The figure below shows the power board of the STDES-30KWVRECT reference design.

Figure 4. Power board components

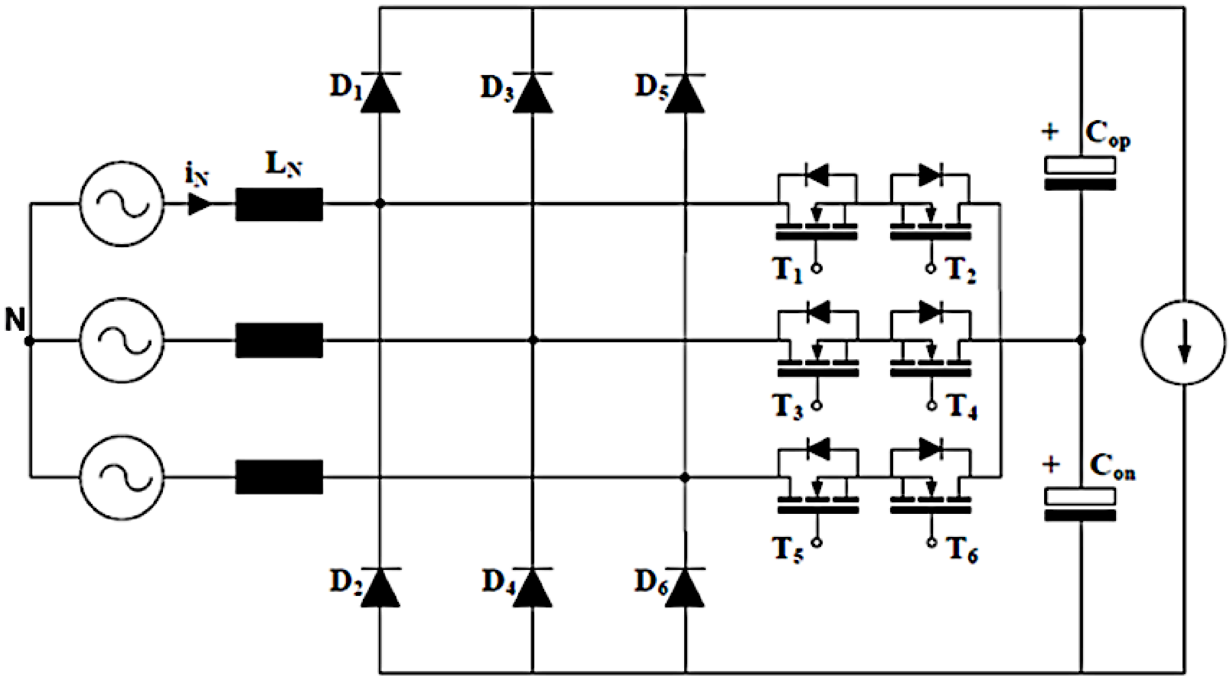


1. AC input connector
2. Fuse
3. EMI filter
4. Inrush current limiter
5. PFC choke
6. SiC MOSFET, diode, and heatsink
7. Drive circuit
8. PFC output capacitors
9. Sensing and amplifier circuit
10. Control board
11. Fans

1.5.2 Power stage

The figure below shows the topology diagram of the three-phase Vienna PFC rectifier and its operation principles.

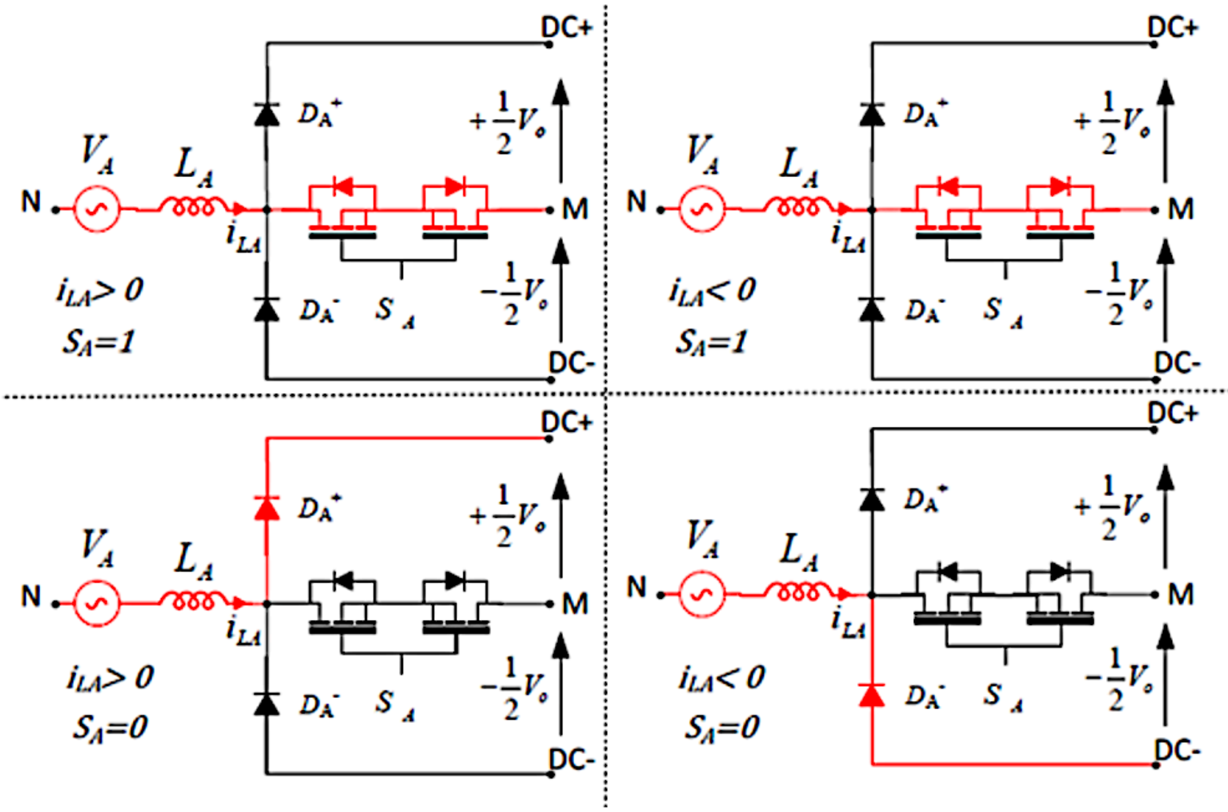
Figure 5. Topology diagram of the Vienna rectifier



The topology input is a set of Y-connected, phase alternate 120-degree three-phase AC voltages, which have equal amplitude and frequency. Each phase consists of a boost inductor, a pair of rectifiers (SiC Schottky diodes), and a set of series-connected SiC MOSFETs. The SiC MOSFETs are connected to the center point of a capacitive divider, which reduces their voltage stress. Since the operation principles of each phase are identical, phase A is shown above as an example.

The figure below shows the single-phase switching principles of the Vienna rectifier.

Figure 6. **Single-phase diagram of the Vienna rectifier**



When $i_{LA}>0$ and $S_A = 1$, the phase node voltage is clamped to the midpoint voltage of the output capacitors. Then, the L_A inductor starts storing the energy.

When $i_{LA}>0$ and $S_A = 0$, the AC current flows into the phase node and the D_A^+ diode is conducting. Then, the phase node is clamped to V_{DC}^+.

Similarly, when the $i_{LA}<0$ and $S_A = 1$ or 0, the phase node is clamped to the midpoint voltage of the output capacitors or V_{DC}^-.

Thus, each phase can be considered as two boost converters in series, sharing the same inductor and switch (SA). The D_A^+ and D_A^- diodes operate, respectively, in the positive and negative half cycles of the input AC voltage.

1.5.2.1 *Power stage calculation*

Since the operation principles of each phase are identical, phase A is used as an example in the calculation process.

The three-phase input voltage can be described as in the following equations.

$$V_A(t) = \frac{\sqrt{2}}{\sqrt{3}} V_{AC(L-L)} \times \sin(\omega_0 t) \quad (1)$$

$$V_B(t) = \frac{\sqrt{2}}{\sqrt{3}} V_{AC(L-L)} \times \sin\left(\omega_0 t - \frac{2\pi}{3}\right) \quad (2)$$

$$V_C(t) = \frac{\sqrt{2}}{\sqrt{3}} V_{AC(L-L)} \times \sin\left(\omega_0 t - \frac{4\pi}{3}\right) \quad (3)$$

Consider the efficiency of the rectifier, the input power is defined as in the following equation.

$$P_{in} = \frac{P_{out}}{\eta} \quad (4)$$

Thus, the phase A input current peak and instantaneous value can be described as in the following equations.

$$I_{APK} = \frac{\sqrt{2} P_{in}}{\sqrt{3} V_{AC(L-L)}} \quad (5)$$

$$I_A(t) = \frac{\sqrt{2}P_{in}}{\sqrt{3}V_{AC(L-L)}} \cdot \sin(\omega_0 t) \quad (6)$$

Assume that the rectifier is operating in the CCM mode, the MOSFET duty cycle in both positive and negative half cycles of the AC input voltage corresponds to the boost circuit as calculated through the following equation.

$$D_A(t) = 1 - \frac{|V_A(t)|}{\frac{V_O}{2}} \quad (7)$$

Define the modulation index (M) as per the following equation.

$$M = \frac{V_O}{\sqrt{2}V_{AC(L-L)}} \quad (8)$$

The MOSFET average and RMS current can be obtained through the following equations.

$$I_{Q\_ave} = \frac{\int_0^{\pi} I_A(t) \cdot D_A(t)dt}{\pi} = I_{APK} \cdot \left(\frac{1}{2} - \frac{1}{\sqrt{3} \cdot M}\right) \quad (9)$$

$$I_{Q\_RMS} = \sqrt{\frac{\int_0^{\pi}\left(I_A(t) \cdot \sqrt{D_A(t)}\right)^2 dt}{\pi}} = I_{APK} \cdot \sqrt{\frac{1}{2} - \frac{8}{3\sqrt{3} \cdot \pi \cdot M}} \quad (10)$$

As the diode DA+ does not operate in the negative cycle of the AC input, the diode average and RMS current can be calculated as follows.

$$I_{d\_ave} = \frac{\int_0^{\pi} I_A(t) \cdot (1 - D_A(t))dt}{2\pi} = I_{APK} \cdot \left(\frac{1}{2\sqrt{3} \cdot M}\right) \quad (11)$$

$$I_{d\_RMS} = \sqrt{\frac{\int_0^{\pi}\left(I_A(t) \cdot \sqrt{1 - D_A(t)}\right)^2 dt}{2\pi}} = I_{APK} \cdot \sqrt{\frac{4}{3\sqrt{3} \cdot \pi \cdot M}} \quad (12)$$

1.5.2.2 *Inductor design*

Boost inductors represent the energy storage elements that allow the converter PFC operation. This is obtained by controlling the inductor current and using a proper conduction pattern in the power device section.

The inductance is related to the desired current ripple, the available converter voltage levels, the switching frequency, and the rated operation voltages.

According to the boost working principle, during the MOSFET conduction, the voltage on the inductor is equal to the input AC voltage. Moreover, the current rises from the bottom to the peak, as the following equation shows.

$$V_A(t) = \frac{\Delta i_{pp}}{D_A(t) \cdot L} \quad (13)$$

Referring to Eq. (1), Eq. (2), Eq. (3), Eq. (7), and Eq. (8), the function of Δi_{pp} can be described as follows.

$$\Delta i_{pp} = \frac{\frac{V_O}{2} \cdot \frac{1}{\sqrt{3}M} \cdot \sin\left(\omega_0 t\right) \cdot \left(1 - \frac{1}{\sqrt{3}M}\sin(\omega_0 t)\right)}{L \cdot f_S} \quad (14)$$

The Δi_{pp} reaches the maximum value when the $\sin\left(\omega_0 t\right) = \frac{\sqrt{3}}{2}M$ condition is satisfied and the Δi_{ppmax} can be expressed as follows:

$$\Delta i_{ppmax} = \frac{V_O}{8 \cdot L \cdot f_S} \quad (15)$$

The inductance can be calculated as follows:

$$L = \frac{V_O}{8 \cdot \Delta i_{ppmax} \cdot f_S} \quad (16)$$

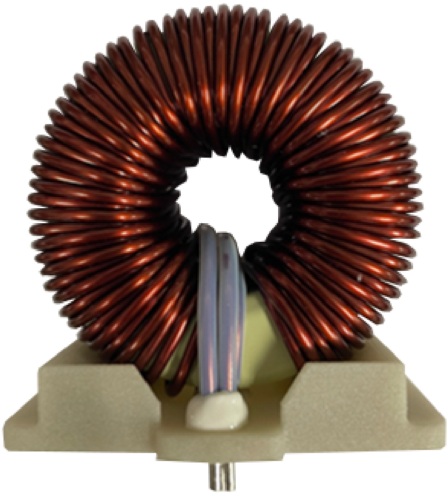


Figure 7. Inductor

Figure 8. DC bias characteristics of the chosen inductor

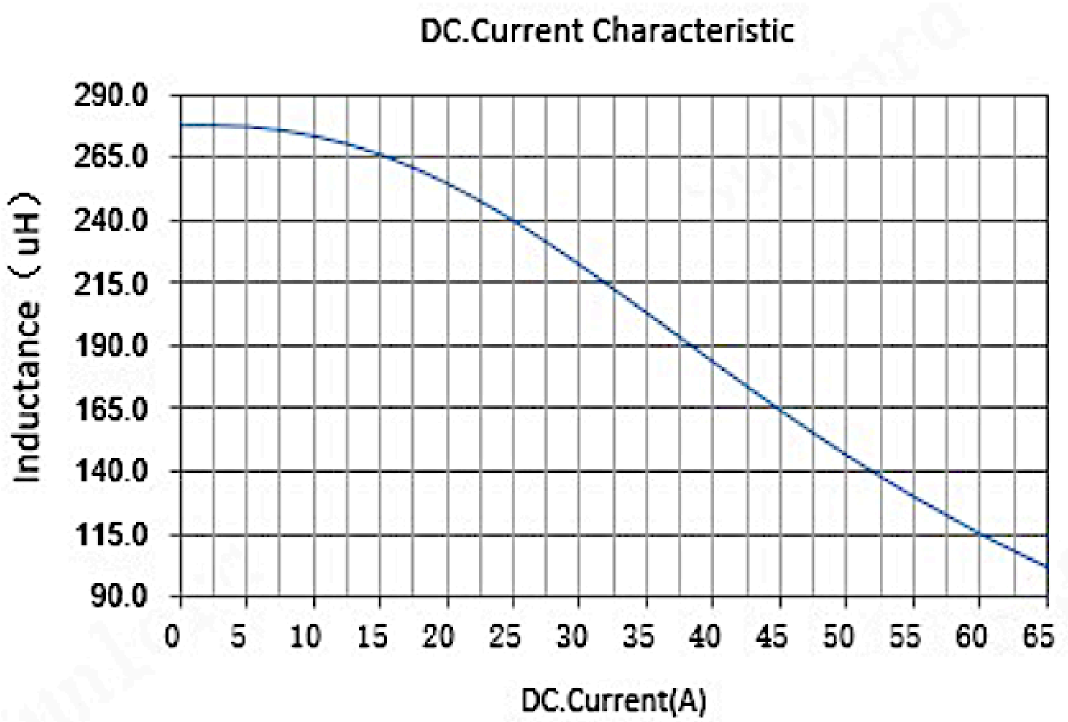


Table 2. Inductor specifications

Parameter	Value
Vendor and order code	Sunlord ARLDC724676C271N1B
Core	Fe-Ni alloy（T62*32*6*25.0 μi = 60)
Winding	Polyester-enameled copper wire（Φ2.1mm*2）
Turns	38
Peak current	65 A
Max current ripple	13 A (20%)
f_s	70 kHz

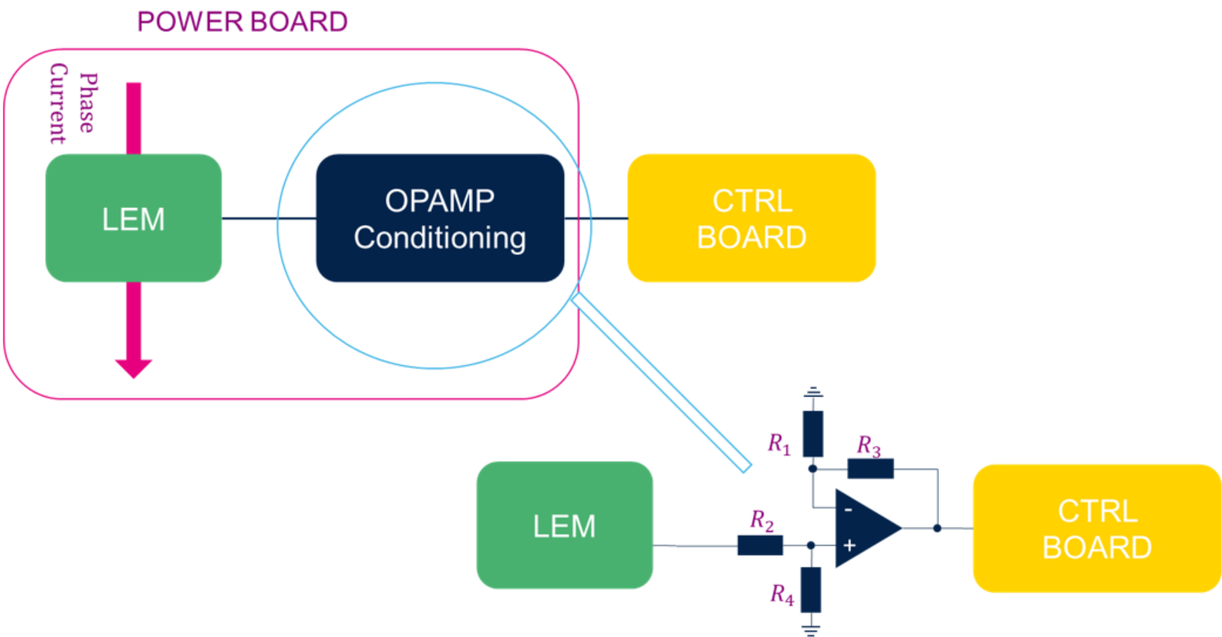
Parameter	Value
Inductance at 0 A	275 µH
Inductance at 65 A	105 µH

1.5.3 Sensing circuit

1.5.3.1 *Inductor current*

To keep the input current in-phase with the input voltage on the three phases, the inductor current isolated sensor is used to measure it. Hall sensors are considered. Since the Hall sensor output contains a DC offset of 2.5 V, and does not match with the ADC input range (0~3.3 V), a conditioning circuit allows obtaining the correct value. The circuit is replicated for each phase and is shown in the figure below.

Figure 9. Inductor current sense circuit

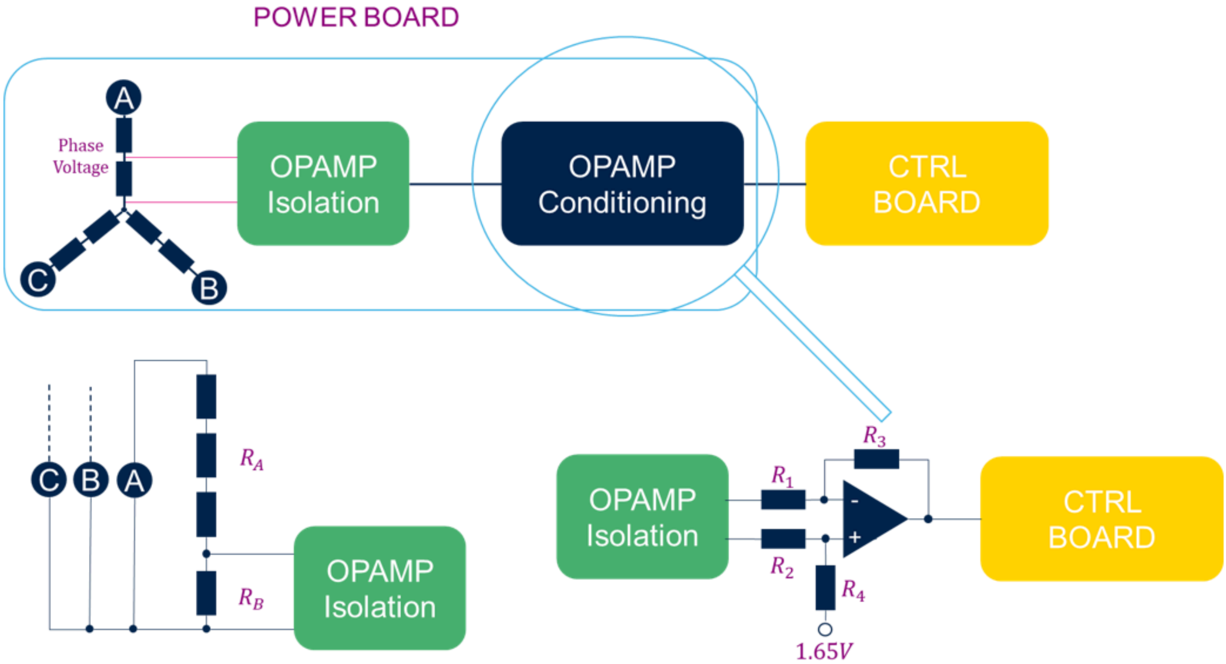


1.5.3.2 *AC voltage sensing*

The three-phase AC voltages are obtained using a two-stage sensor circuit. An isolated op-amp represents the first part. It allows measuring the HV through a voltage divider with an isolation barrier.

The isolated op-amp output is limited in volts and is scaled with a second stage of op-amps with a proper gain and bias. This circuit allows measuring an AC voltage referenced by a virtual or grid neutral point. The circuit is replicated for each phase and is shown in the figure below.

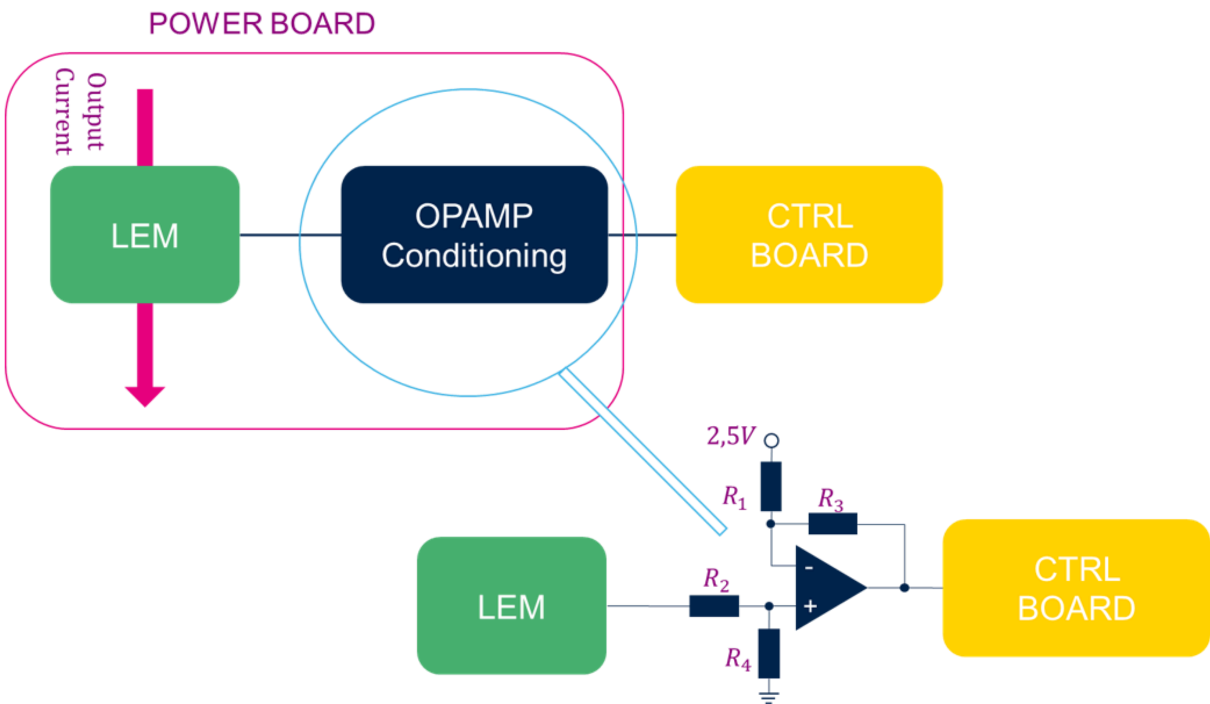
Figure 10. AC voltage sense circuit



1.5.3.3 *DC current sensing*

The DC current sensing also uses the Hall sensors. A conditioning circuit is used to subtract the 2.5 V DC offset from the Hall sensor output and adjust the output to a proper range, as shown below.

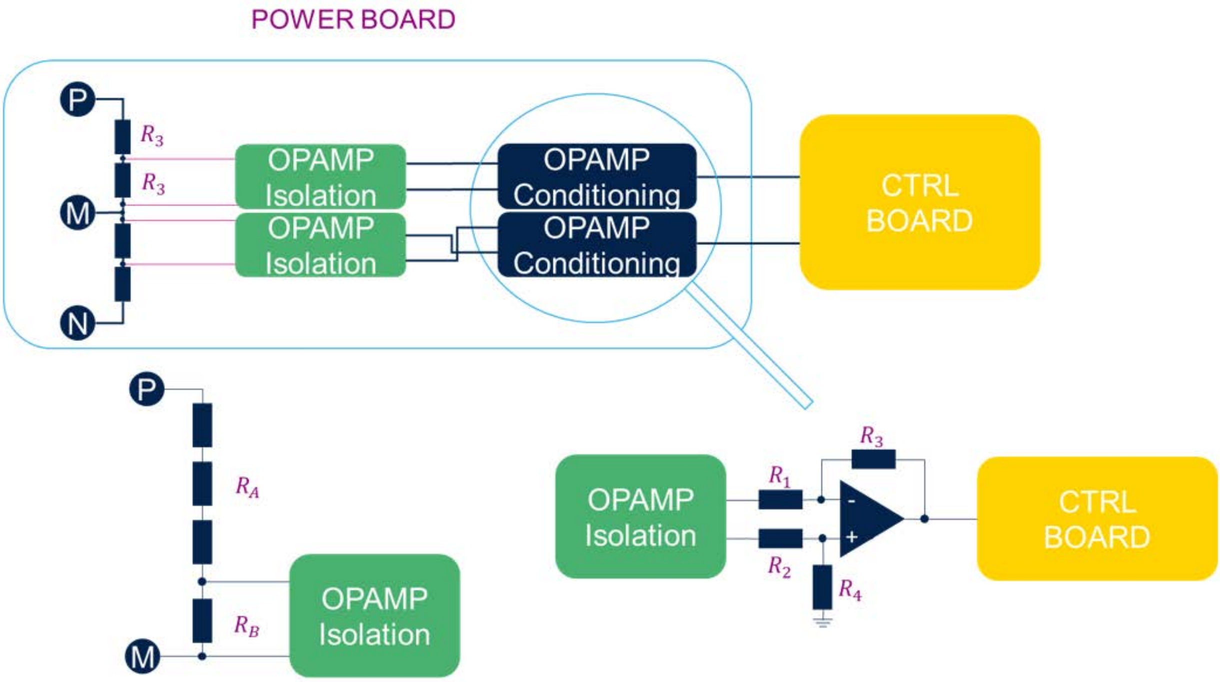
Figure 11. DC current sense circuit



1.5.3.4 *DC voltage sensing*

The DC voltages are obtained using a two-stage sensing. The total DC bus voltage is split, exploiting two voltage dividers. Both voltages are needed to obtain the monitoring of each capacitor to avoid overvoltage, offering independent DC voltages for the control. The circuit is shown in the figure below.

Figure 12. **DC voltage sense circuit**



1.5.4 LEDs

To check the auxiliary power supply status, several LEDs are used as indicators on the power board.

The D8 and D13 green LEDs show the external 7 V and 12 V power supply status. The D11 and D12 green LEDs show the status of VDD_5V and VDD_3.3V, which are used for sensing and control.

For each pair of paralleled MOSFETs, a LED indicates the driving power supply condition of the driving circuit. The LEDs of each phase have the same relative position with respect to the heatsink.

Figure 13. **STDES-30KWVRECT power board LEDs (1 of 2)**

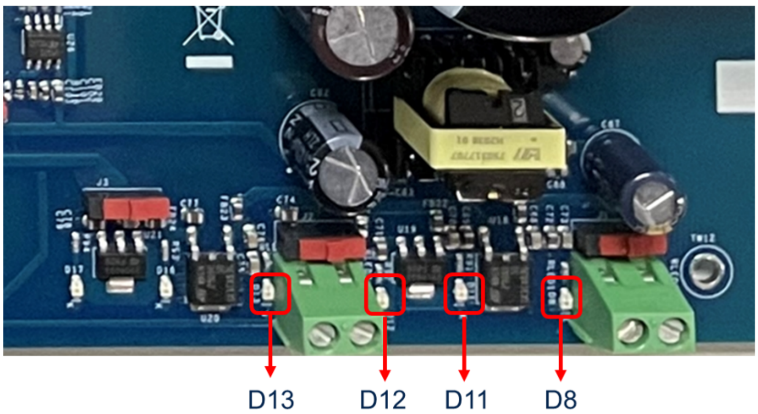


Figure 14. **STDES-30KWVRECT power board LEDs (2 of 2)**

Table 3. **Power board LED definitions**

Reference	Definition	Color	Comments
D8	External 7V	Green	On→normal Blink/off→abnormal
D13	External 12V	Green	
D11	VDD_5V	Green	
D12	VDD_3.3V	Green	
D25, D26	Phase A driving VDD	Green	
D29, D30	Phase B driving VDD	Green	
D33, D34	Phase C driving VDD	Green	

On the PFC control board, two LEDs (D13 and D15) indicate which is the state machine the reference design is working in.

The specific state can be observed on the online debugging interface.

Figure 15. **STDES-30KWVRECT control board LEDs**

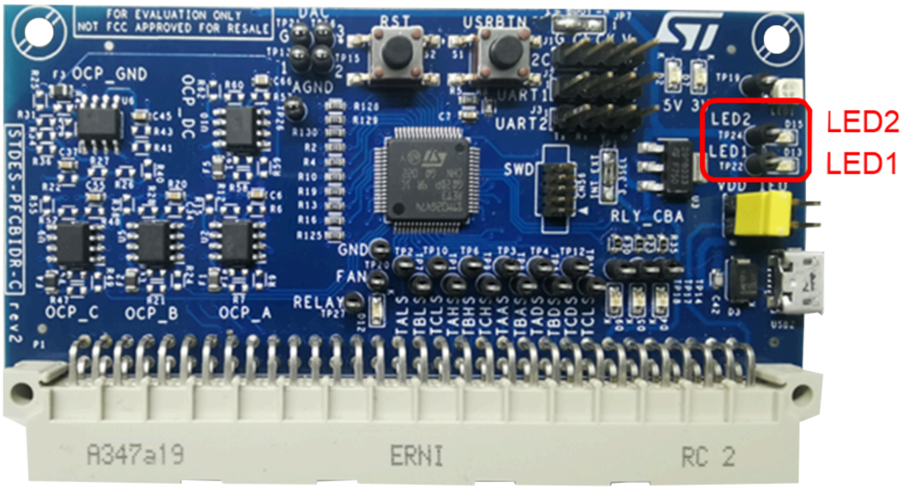


Table 4. Control board LEDs and related state machine

LED status	Definition
D13 on, D15 off	State machine = `Wait, Idle, Init, Start`
D13 on, D15 on	State machine = `Run`
D13 off, D15 off	State machine = `Stop, Error, Fault`

2 AC input wire connection

Connect the line (U, V, W) and earth (PE) wires with J101 connectors as marked on the board to an unpowered main plug.

Figure 16. AC input wire connection

2.1 PFC bus connection

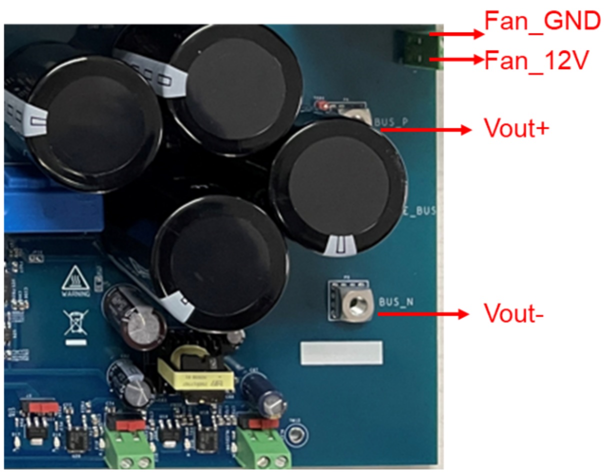
Connect the PFC Vout+ and Vout- output terminals to a resistance box or an electric load.

If using an electronic load, connect the positive and negative terminals of the electronic DC load to the Vout+ and Vout- connectors on the demo board.

2.2 External fan cooling

External fans should be used for cooling during the test (2pcs fans are recommended). The figure below shows the fan power supply wires.

Figure 17. Fan power wire connection



3 Preliminary test procedure

To ensure that each circuit on the power board is operating normally, verify before the signal on each of the test points described in the following sections.

3.1 AC sensing circuit check

To check the proper operation of the AC sensing (Figure 18), measure the test points for voltages (Figure 19) and currents (Figure 20).

Figure 18. AC sensing section on board

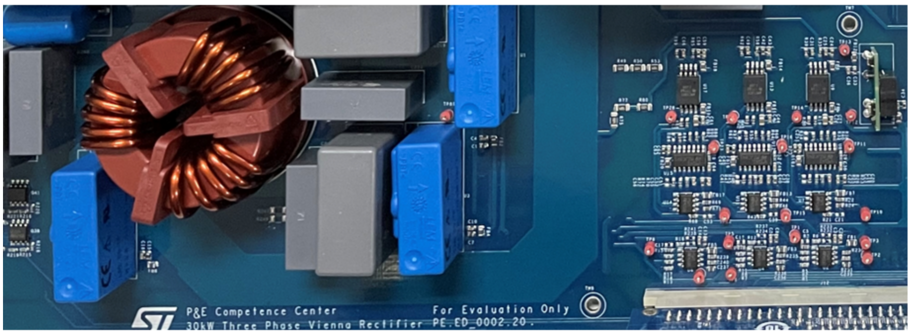


Figure 19. Test procedure for AC voltage sensing

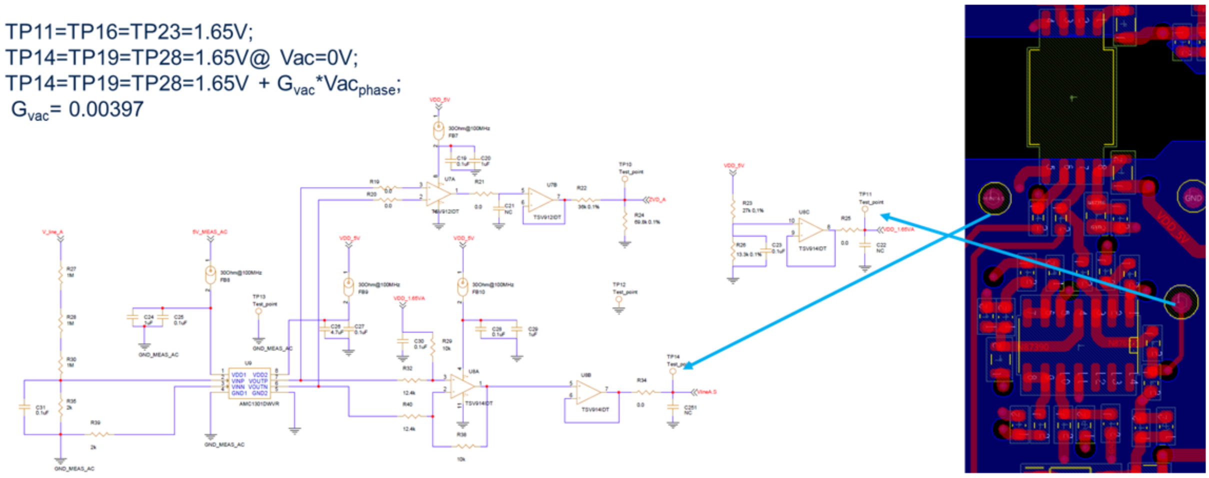
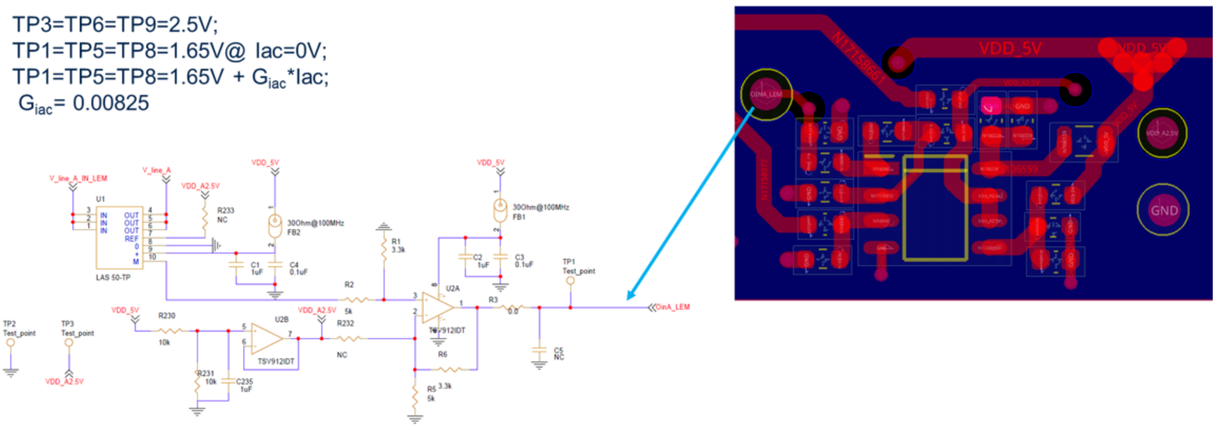


Figure 20. Test procedure for AC current sensing



3.2 DC sensing circuit check

To verify the proper operation of the DC sensing, analyze the test points for voltages (Figure 21) and currents (Figure 22).

Figure 21. Testing procedure for DC voltage sensing

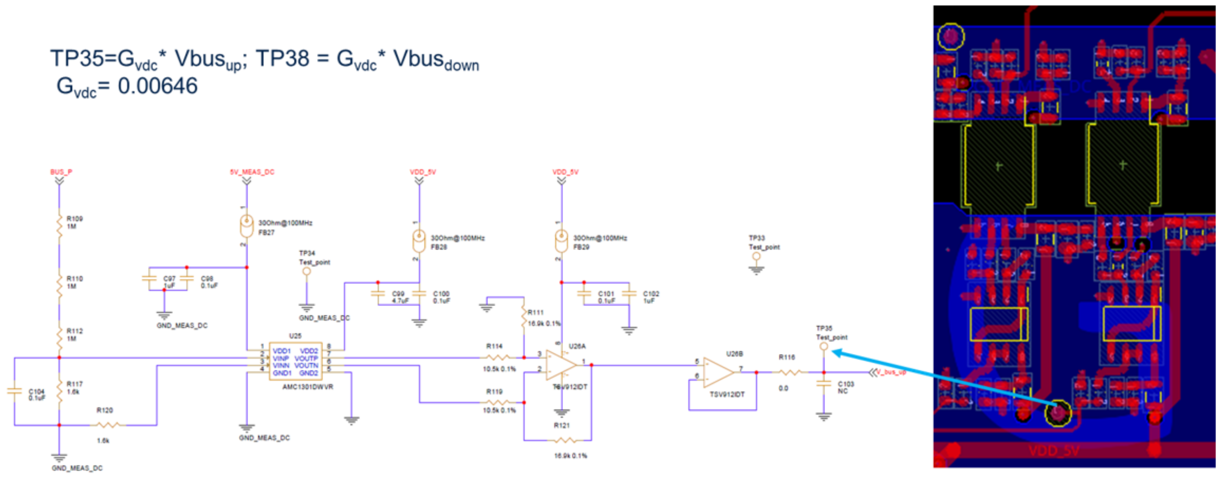
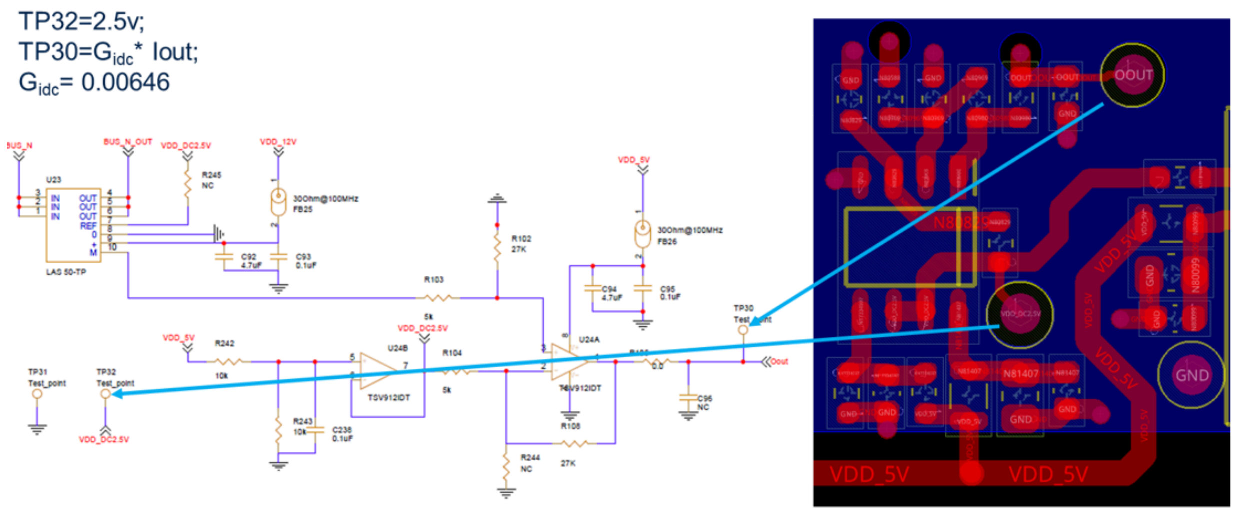


Figure 22. Testing procedure for DC current sensing



4 Power on/off sequence

4.1 Power on

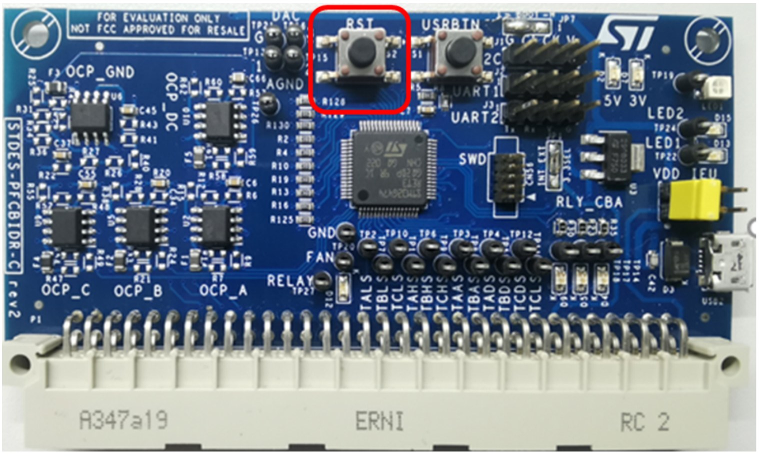
Step 1. Turn on the external auxiliary power supply. Check whether the control LEDs and drive LEDs are lit up.

Step 2. Set the AC source voltage to 20 V_{AC} 50 Hz and turn on. Measure all the sensing circuit test point voltage. Check whether they are operating normally.

Caution: The test probe should be placed before the external auxiliary power and AC source power-on. Do not remove the probe when the board is powered on, as this might cause short-circuit risk and damage the board.

Step 3. Turn off the AC source. Push the reset button on the control board to reset the MCU.
The reset button position is shown in the figure below.

Figure 23. Reset button position on control board



Step 4. The external fan is powered on.

Caution: The demo board might be damaged without fan cooling due to overheat under a heavy load condition.

Step 5. Set the AC source voltage between 350 V_{AC} ~ 450 V_{AC} and 47 Hz ~ 6 3Hz. Ensure that the output load is zero.

Step 6. Turn on the AC source.
Then, the output voltage gradually ramps up to 800 V_{DC}.

Step 7. According to the system specification, set the AC input voltage and the DC output load for test conditions.

Warning: *Do not touch any components when the board is powered on.*

4.2 Power off

After finishing the test, follow the steps below.

Step 1. Remove the load gradually to 0 A.

Step 2. Turn off the AC source.

Warning: *Ensure that the bus capacitors are discharged and the voltage is lower than 60 V before touching the components or metal parts.*

Step 3. Turn off the power supply for the fans and the external power.

5 Control strategy analysis

The voltage-oriented control allows controlling the PFC behavior of the converter in the dq-axis synchronous reference frame.

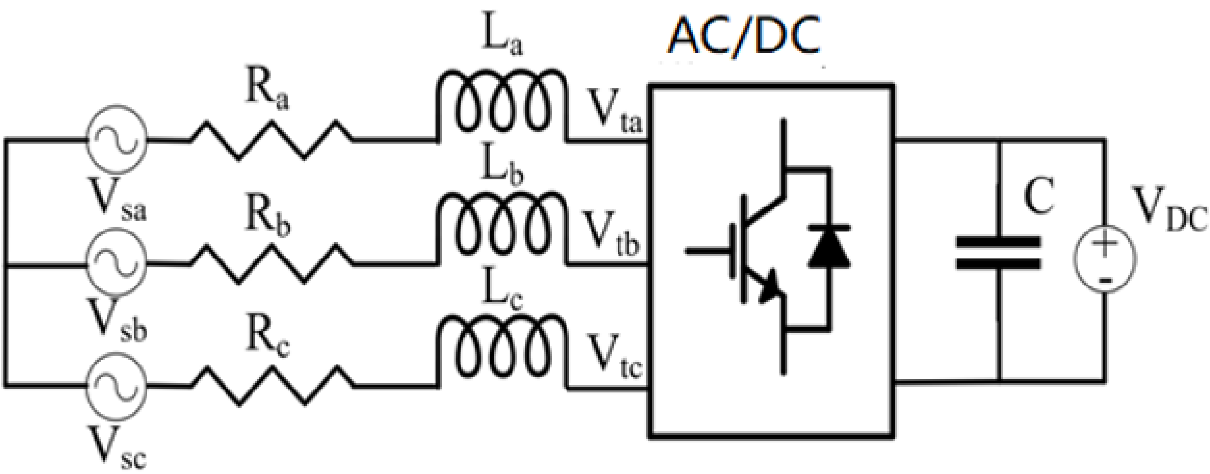
Table 5. Control strategy comparison

Reference frame	Pros	Cons
3-axis stationary reference frame (abc)	• Simple implementation with PI • Avoids effort in the reference transformation • Best results with the PR regulator (no analog) • Best choice for the analog version	• Poor in transient • Phase shifting (lag) • Needs three regulators (three-phase) • Necessary high bandwidth (noise) • Steady state error
2-axis stationary reference frame (αβ)	• Use two regulators instead of three • Simple implementation with PI • Best results with the PR regulator (no analog)	• Poor in transient • Phase shifting (lag) • Digital version only • Necessary high bandwidth (noise)
2-axis synchronous reference frame (dq)	• Zero steady state error (DC reference) • Use of a simple PI (simple structure of the regulator) • Low bandwidth is allowed (robust) • Best in transient (first order behavior)	• Effort frame transformation • Digital version only • Necessary high bandwidth (noise) • Implementation

5.1 Control model

Considering the generic three-phase rectifier converter of the figure below and assuming that the system is balanced as Eq. (17), the relationship of the electrical quantities is Eq. (18).

Figure 24. Topology modeling of a three-phase Vienna rectifier



$$\begin{cases} e_a + e_b + e_c = 0 \\ i_a + i_b + i_c = 0 \end{cases} \quad (17)$$

$$\begin{cases} L\dfrac{di_a}{dt} + Ri_a = V_{sa} - V_{ta} \\ L\dfrac{di_b}{dt} + Ri_b = V_{sb} - V_{tb} \\ L\dfrac{di_c}{dt} + Ri_c = V_{sc} - V_{tc} \end{cases} \quad (18)$$

$$\begin{cases} L\frac{di_\alpha}{dt} + Ri_\alpha = V_{s\alpha} - V_{t\alpha} \\ L\frac{di_\beta}{dt} + Ri_\beta = V_{s\beta} - V_{t\beta} \end{cases} \tag{19}$$

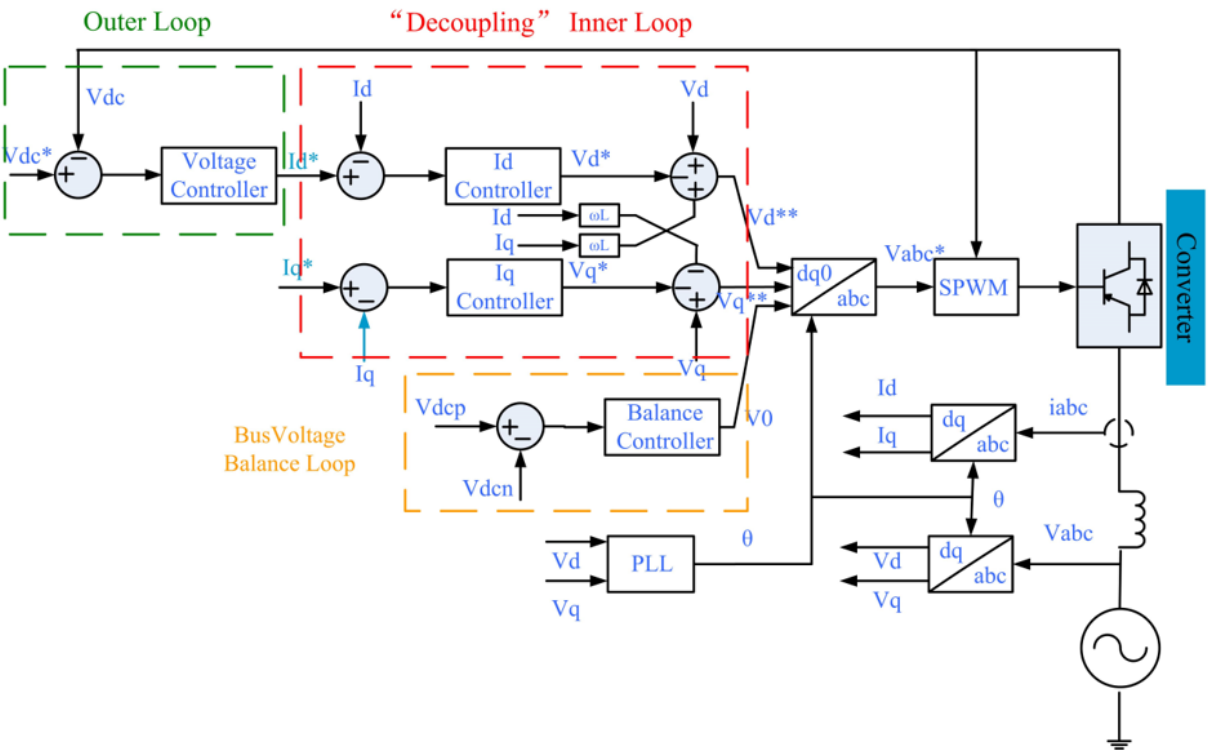
$$\begin{cases} L\frac{di_d}{dt} + Ri_d - \omega(t)Li_q = V_{sd} - V_{ts} \\ L\frac{di_q}{dt} + Ri_q + \omega(t)Li_d = V_{sq} - V_{tq} \\ \frac{d\rho}{dt} = \omega(t) \end{cases} \tag{20}$$

Starting from the 3-axis stationary reference frame (Eq. (18)) and applying the transformation matrices, we obtain the equivalent relationships in the stationary reference frame (Eq. (19)) and in the synchronous reference frame to the fundamental pulsation (Eq. (20)). The active and reactive currents are coupled in the dq-axis synchronous reference frame.

5.2 Control strategy

This reference design power converter can be represented as a second order dynamic system, which consists of inductors and capacitors. The theoretical different dynamic behavior of this two-system element allows considering two fully decoupling first order systems. For this reason, a current control and a voltage control are considered.

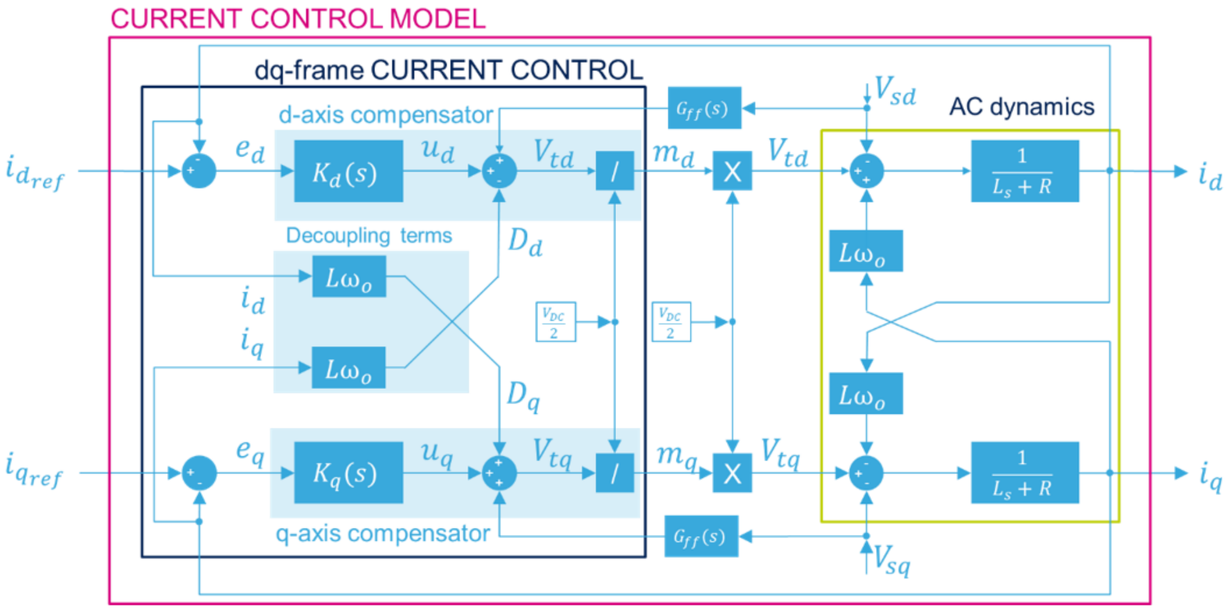
Figure 25. Cascaded control



5.2.1 Current decoupling control strategy

The figure below shows the schematic block of the current decoupling control.

Figure 26. Current decoupling control of the three-phase Vienna rectifier



Considering the general model, the active and reactive currents are coupled in a synchronous reference frame.

$$\begin{cases} L\frac{di_d}{dt} = \omega_0 L i_q - R i_d + V_{sd} - V_{td} \\ L\frac{di_q}{dt} = \omega_0 L i_d - R i_q + V_{sq} - V_{tq} \end{cases} \tag{21}$$

Simple and robust PI current regulators can be used to track references.

$$\begin{cases} u_d = \left(k_p + \frac{k_i}{s}\right)\left(i_{dref} - i_{dfeed}\right) \\ u_q = \left(k_p + \frac{k_i}{s}\right)\left(i_{qref} - i_{qfeed}\right) \end{cases} \tag{22}$$

Adding the current feedforward to obtain a current decoupling control, the control terms and the controlled model are represented in Eq. (22). Combining Eq. (21) and Eq. (22), we obtain Eq. (23), in which the active and reactive currents are full.

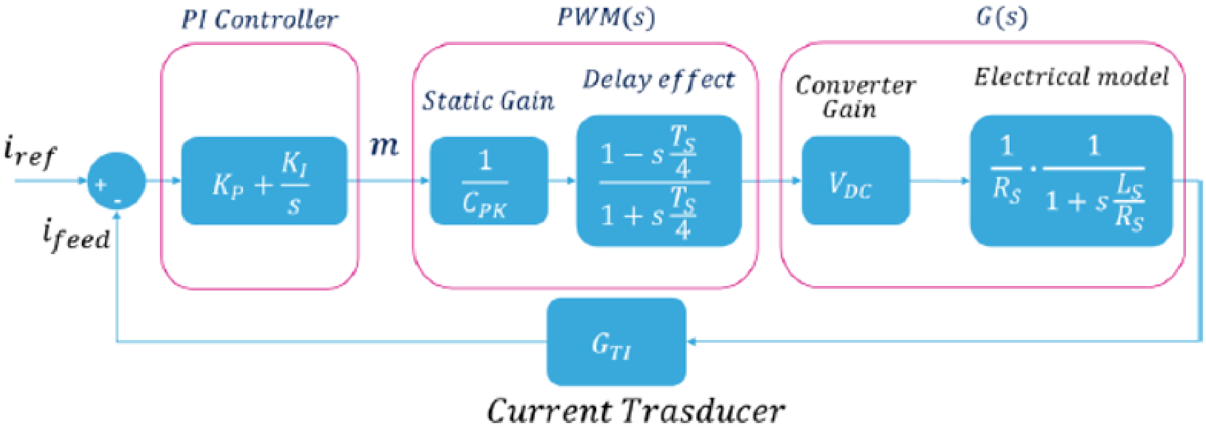
$$\begin{cases} V_{td} = -\left(k_p + \frac{k_i}{s}\right)\left(i_{dref} - i_{dfeed}\right) + \omega_0 L i_q + V_{sd} \\ V_{tq} = -\left(k_p + \frac{k_i}{s}\right)\left(i_{qref} - i_{dfeed}\right) + \omega_0 L i_d + V_{sd} \end{cases} \tag{23}$$

$$\begin{cases} L\frac{di_d}{dt} + R i_d = \left(k_p + \frac{k_i}{s}\right)\left(i_d^* - i_d\right) \\ L\frac{di_q}{dt} + R i_q = \left(k_p + \frac{k_i}{s}\right)\left(i_q^* - i_q\right) \end{cases} \tag{24}$$

$$\begin{cases} (Ls + R) i_d = \left(k_p + \frac{k_i}{s}\right)\left(i_d^* - i_d\right) \\ (Ls + R) i_q = \left(k_p + \frac{k_i}{s}\right)\left(i_q^* - i_q\right) \end{cases} \tag{25}$$

The figure below shows the closed loop representation of the above model.

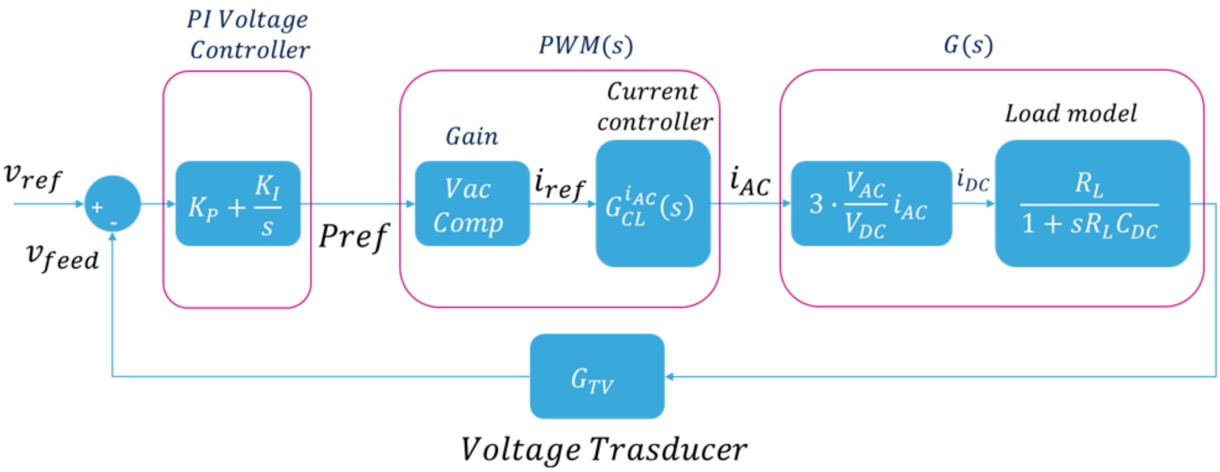
Figure 27. Equivalent closed loop representation of the current control



Thanks to the high switch frequency that the 30 kW Vienna rectifier can operate with a small value inductor, the decoupling term is very small. You can then obtain a good control performance even if the decoupling term is disabled.

5.2.2 Voltage control strategy

Figure 28. Equivalent closed loop representation of the voltage control



5.2.3 Neutral point potential balance control

Referring to Figure 28, the AC current injects into the neutral point in the operation case 1 and case 3 (S_x = 1, x = a, b, c). Define i_{NP} as follows: $i_{NP} = \sum_{x\,=\,a,\,b,\,c} s_x \cdot i_x$

The PWM control essence is to control the switch state. Thus, the output average effect is equivalent to the reference voltage within a control cycle.

$$i_{NP} = (1 - abs(V_a))i_a + (1 - abs(V_b))i_b + (1 - abs(V_c))i_c \quad (26)$$

$$i_{NP} = -abs(V_a)i_a - abs(V_b)i_b - abs(V_c)i_c \quad (27)$$

To control the current i_{NP}, inject the zero sequence voltage into the modulation wave as shown in the following equation.

$$i_{NP} = -abs(V_a + V_0)i_a - abs(V_b + V_0)i_b - abs(V_c + V_0)i_c \quad (28)$$

$$V_0 = \left(V_{dcp} - V_{dcn}\right)k_0 \quad (29)$$

The coefficient K_0 is set according to the actual situation and experience.

5.2.4 Phase locked loop

The aim of the phase locked loop is to get the AC voltage phase used in the converter control. Define the three-phase AC voltage as follows:

$$\begin{cases} V_{sa} = V_m\cos(\omega_0 t + \theta_0) \\ V_{sb} = V_m\cos\left(\omega_0 t + \theta_0 - \frac{2\pi}{3}\right) \\ V_{sc} = V_m\cos\left(\omega_0 t + \theta_0 - \frac{2\pi}{3}\right) \end{cases} \quad (30)$$

After the Clark and Park transformation, it can be expressed as follows:

$$\begin{cases} V_{sd} = V_m\cos(\omega_0 t + \theta_0 - \rho) \\ V_{sq} = V_m\sin(\omega_0 t + \theta_0 - \rho) \\ \frac{d\rho}{dt} = \omega(t) \end{cases} \quad (31)$$

$\omega(t)$ is the angular frequency of the rotating coordinate system. Usually, $\omega(t) = \omega_0$. If we consider $\rho = \omega_0 t + \theta_0$, we obtain:

$$\{V_{sd} = V_m \quad V_{sq} = 0 \quad (32)$$

If the above consideration is guaranteed, we obtain:

$$\begin{cases} L\frac{di_d}{dt} = -Ri_d + \omega(t)Li_q + V_m - V_{td} \\ L\frac{di_q}{dt} = -Ri_q + \omega(t)Li_d - V_{tq} \\ \frac{d\rho}{dt} = \omega(t) \end{cases} \quad (33)$$

To regulate = 0, consider a compensator as follows.

$$\omega(t) = H(s)V_{sq} \quad (34)$$

Then, consider this compensator equation expanded as follows.

$$\frac{d\rho}{dt} = H(s)V_m\sin(\omega_0 t + \theta_0 - \rho) \quad (35)$$

This compensator represents the PLL that allows tracking $\rho = \omega_0 t + \theta_0$.

As $s\sin(\omega_0 t + \theta_0 - \rho) \approxeq (\omega_0 t + \theta_0 - \rho)$, the PLL can obtain:

$$\frac{d\rho}{dt} \approxeq H(s)V_m(\omega_0 t + \theta_0 - \rho) \approxeq H(s)V_{sq} \quad (36)$$

Figure 29. PLL internal regulator diagram

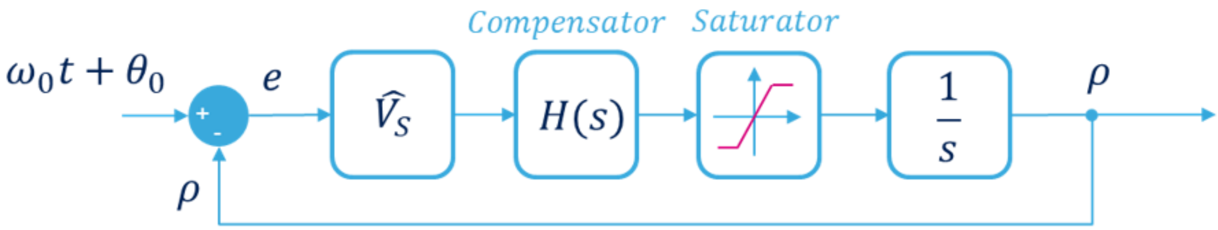
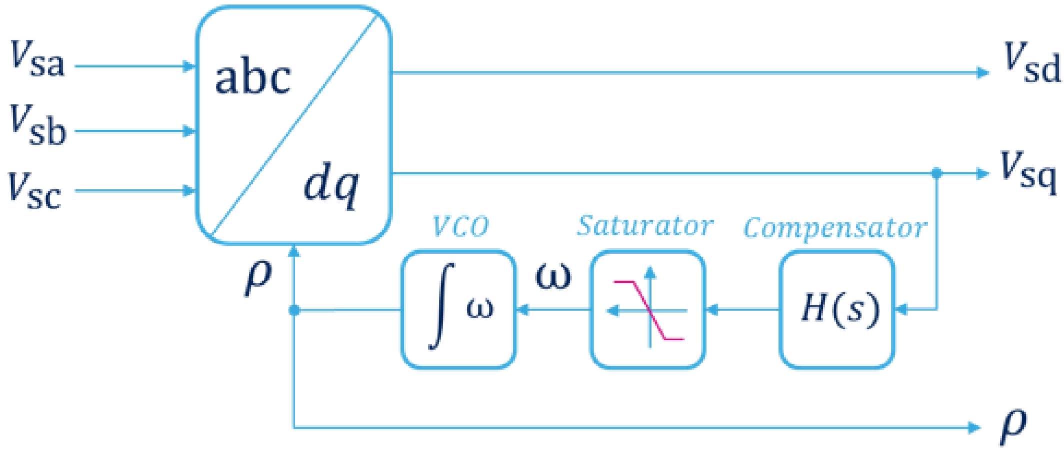


Figure 30. PLL in AC main voltage



6 Firmware implementation

6.1 Firmware ecosystem

The STM32G474RET3 MCU controls the STDES-30KWVRECT.

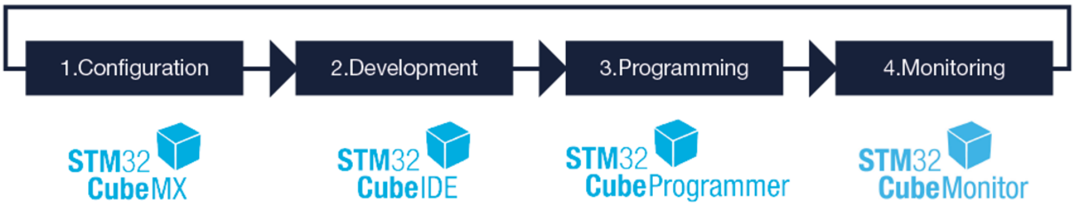
The firmware package is based on the STM32Cube ecosystem. Starting from the STM32CubeMX, all the peripherals and pins used are activated and configured according to the basic project.

The application firmware is supported and tested using STM32CubeIDE, IAR, and Keil development environments.

After the development, the MCU can be programmed through the IDE or STM32CubeProgrammer.

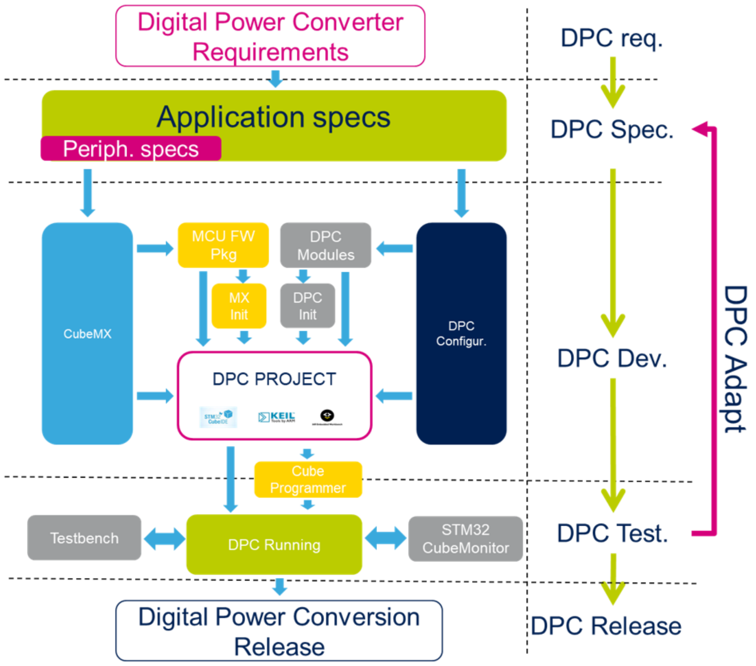
To monitor and control the application, you can use a GUI based on STM32CubeMonitor.

Figure 31. STM32Cube ecosystem development flow



An extensive range of generic and specific firmware modules is available to support the digital power conversion. The figure below shows the generic development flow to get the power conversion used for the STDES-30KWVRECT firmware development.

Figure 32. DPC development flow



This workflow starts from power conversion requirements. This information is then reinterpreted in the application specs that contain information linked to the MCU peripheral and the DPC application configuration.

On the basis of this information, an STM32CubeMX project, properly configured and initialized, is provided. Then, the needed DPC module is included and configured.

The STM32CubeMX generates the development IDE project. The MCU is directly flashed through the IDE or STM32CubeProgrammer. At the end of this operation, the DPC application is tested and debugged through STM32CubeMonitor. The digital power converter firmware is then released, if compliant, and the DPC is adapted.

6.2 MCU pin definition and configuration

The table below shows the MCU pin definition for key function.

Table 6. MCU pin definition for key functions

Signal	Port	MCU pin	MCU function
ADC_IA	PC0	8	ADC_1_IN6
ADC_IB	PC1	9	ADC_1_IN7
ADC_IC	PC2	10	ADC_1_IN8
ADC_bus_down	PA0	12	ADC_2_IN1
ADC_bus_up	PA1	13	ADC_2_IN2
ADC_Iout	PA2	14	ADC_1_IN3
ADC_VA	PA3	17	ADC_1_IN4
ADC_VB	PA7	21	ADC_2_IN4
ADC_VC	PC4	22	ADC_2_IN5
ADC_Temp	PB2	26	ADC_2_IN12
DAC1	PA4	18	DAC1_OUT1
DAC2	PA5	19	DAC1_OUT2
DAC3	PA6	20	DAC2_OUT1
Phase_A_T1	PA9	43	HRTIM1_CHA2
Phase_A_T2	PA11	45	HRTIM1_CHB2
Phase_B_T3	PB13	35	HRTIM1_CHC2
Phase_B_T4	PB15	37	HRTIM1_CHD2
Phase_C_T5	PC7	39	HRTIM1_CHE2
Phase_C_T6	PC9	41	HRTIM1_CHF2
Relay_BP_COIL2	PF1	6	GPIO_Output
Relay_BP_COIL1	PC12	54	GPIO_Output
LED1	PC14	3	GPIO_Output
LED2	PC15	4	GPIO_Output

All the used pins can be activated and configured with STM32CubeMX as shown in the following figure.

Figure 33. **STM32CubeMX configuration pin mapping**

Pin Name	Signal on Pin	GPIO outpu...	GPIO mode	GPIO Pull-u...	Maximum o...	Fast Mode	User Label	Modified
PA2	ADC1_IN3	n/a	Analog mode	No pull-up ...	n/a	n/a	ADC_Iout	☑
PA3	ADC1_IN4	n/a	Analog mode	No pull-up ...	n/a	n/a	ADC_VA	☑
PC0	ADC1_IN6	n/a	Analog mode	No pull-up ...	n/a	n/a	ADC_IC	☑
PC1	ADC1_IN7	n/a	Analog mode	No pull-up ...	n/a	n/a	ADC_IB	☑
PC2	ADC1_IN8	n/a	Analog mode	No pull-up ...	n/a	n/a	ADC_IA	☑

Pin Name	Signal on Pin	GPIO outpu...	GPIO mode	GPIO Pull-u...	Maximum o...	Fast Mode	User Label	Modified
PA0	ADC2_IN1	n/a	Analog mode	No pull-up ...	n/a	n/a	V_bus_down	☑
PA1	ADC2_IN2	n/a	Analog mode	No pull-up ...	n/a	n/a	V_bus_up	☑
PA7	ADC2_IN4	n/a	Analog mode	No pull-up ...	n/a	n/a	ADC_VB	☑
PB2	ADC2_IN12	n/a	Analog mode	No pull-up ...	n/a	n/a	Temp	☑
PC4	ADC2_IN5	n/a	Analog mode	No pull-up ...	n/a	n/a	ADC_VC	☑

Pin Name	Signal on Pin	GPIO outp...	GPIO mode	GPIO Pull-...	Maximum o...	Fast Mode	User Label	Modified
PC10	n/a	Low	Output Pus...	No pull-up ...	Low	n/a	GPIO_2	☑
PC11	n/a	Low	Output Pus...	No pull-up ...	Low	n/a	GPIO_1	☑
PC12	n/a	Low	Output Pus...	Pull-down	Very High	n/a	RELAY_B...	☑
PC13	n/a	n/a	Input mode	No pull-up ...	n/a	n/a	USR_BTN	☑
PC14-OSC...	n/a	Low	Output Pus...	No pull-up ...	Low	n/a	LED_1	☑
PC15-OSC...	n/a	Low	Output Pus...	No pull-up ...	Low	n/a	LED_2	☑
PF1-OSC_...	n/a	Low	Output Pus...	Pull-down	Very High	n/a	RELAY_B...	☑
PG10-NRST	n/a	n/a	Input mode	No pull-up ...	n/a	n/a	NRST	☑

PA9	HRTIM1_C...	n/a	Alternate F...	No pull-up ...	Very High	n/a		☐
PA11	HRTIM1_C...	n/a	Alternate F...	No pull-up ...	Very High	n/a		☐
PB13	HRTIM1_C...	n/a	Alternate F...	No pull-up ...	Very High	n/a		☐
PB15	HRTIM1_C...	n/a	Alternate F...	No pull-up ...	Very High	n/a		☐
PC7	HRTIM1_C...	n/a	Alternate F...	No pull-up ...	Very High	n/a		☐
PC9	HRTIM1_C...	n/a	Alternate F...	No pull-up ...	Very High	n/a		☐

6.3 Timers

The STDES-30KWVRECT uses the peripheral timer of the STM32G474RE to obtain the PWM signal and to define the timed function. Two types of timers are defined for the application: application timer and actuator timer.

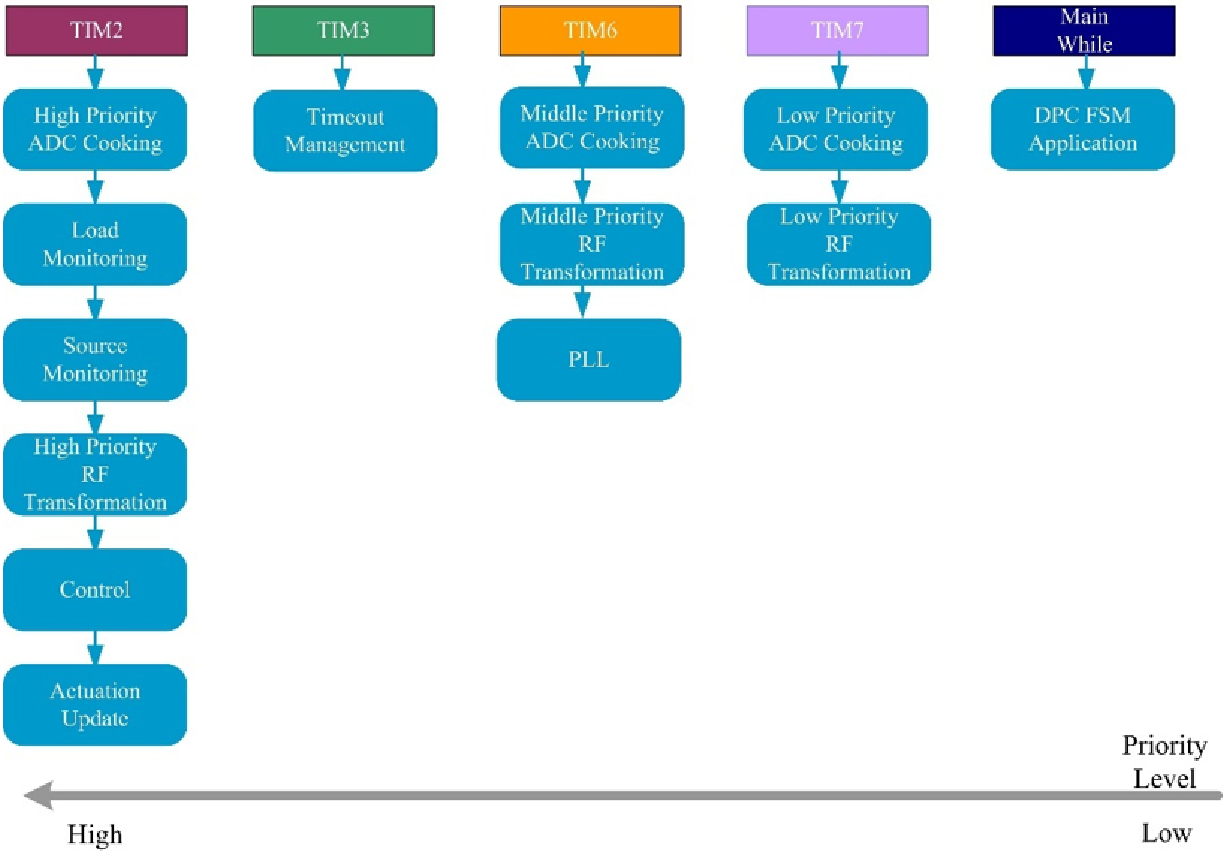
6.3.1 Application timer

The STDES-30KWVRECT needs some time-critical tasks to operate properly.

The outer voltage regulator and the inner current control need to be executed at a fixed period. The other monitoring tasks are scheduled in time, etc. For this reason, exploiting four basic timer ISRs, these tasks are executed periodically.

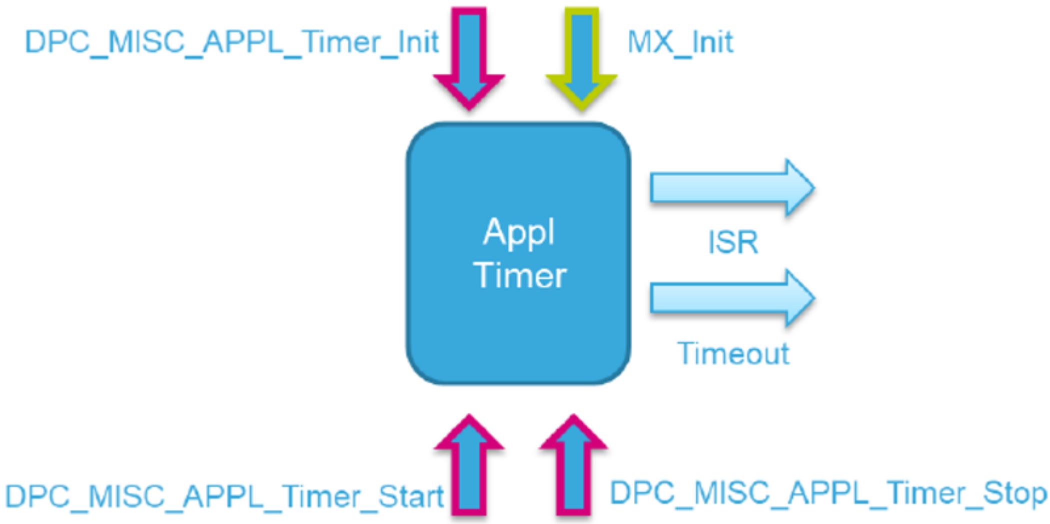
To guarantee the proper operation of the application, the NVIC parameters are settled as shown below.

Figure 34. **Overview of the application timer tasks with priority**



Each application timer is set according to the application timing request. The figure below shows the application timer configuration.

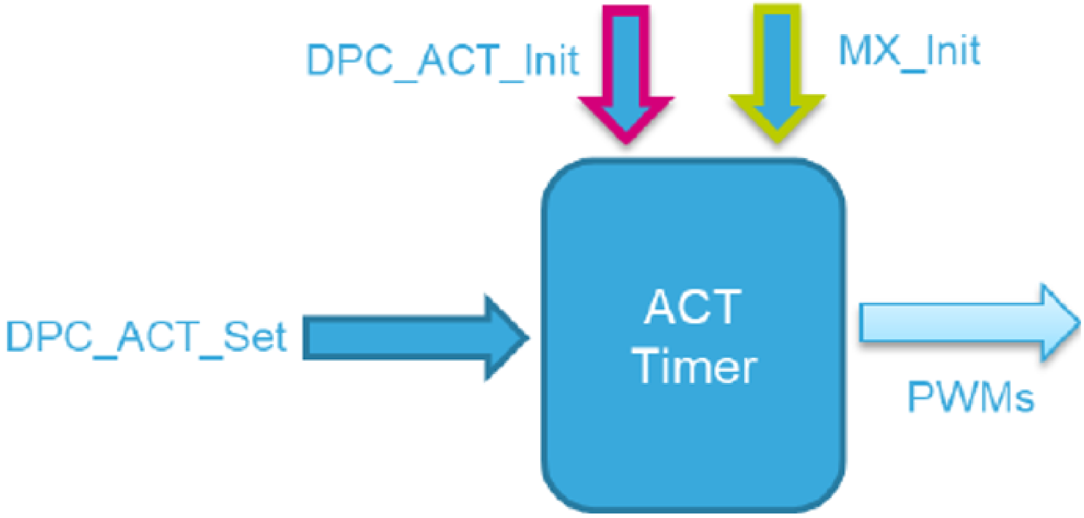
Figure 35. **Application timer graphical representation**



6.3.2 Actuator timer

The STDES-30KWVRECT needs six PWM signals. Exploiting the embedded HRTIM peripheral of the STM32G474RE MCU, we obtain a full controlled PWM setup for the power converter.

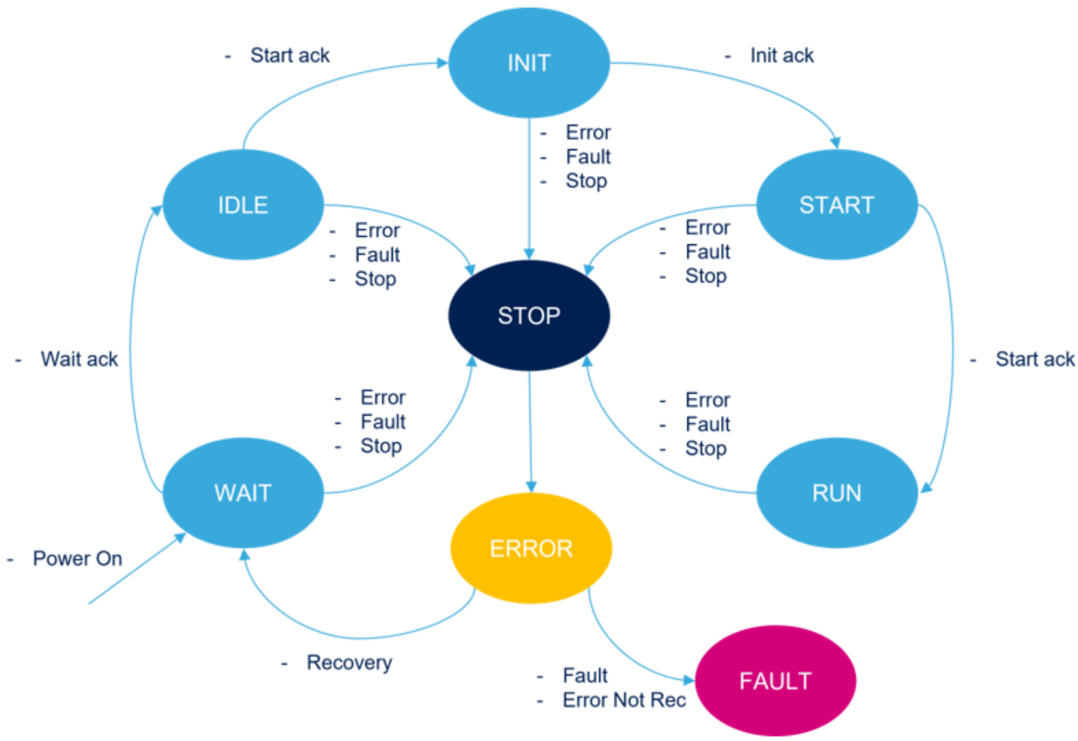
Figure 36. **Actuator timer graphical representation**



6.4 Finite state machine

The STDES-30KWVRECT control supervisor is developed via a passthrough implementation of the finite state machine with events and status.

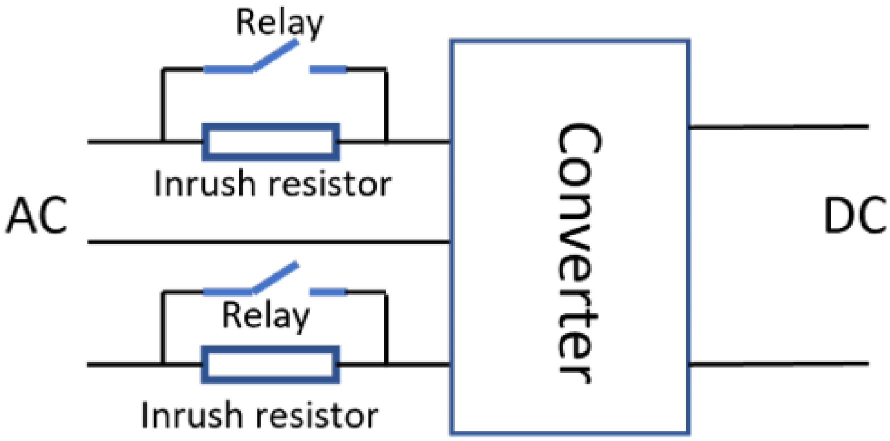
Figure 37. **Finite state machine bubble representation**



6.5 Relay and inrush current control

To avoid a current spike and protect the AC capacitor, the inrush resistors and relays are used in phase A and C as shown below.

Figure 38. **Relay and inrush resistor schematic**



When the AC power is on, the relays are off and the AC current flows through the inrush resistors to charge the capacitor.

After the inrush state is completed, the converter enters the soft-start state followed by the normal run state. Then, the relays turn on and the inrush resistors are shorted. The relays are off when the converter shuts down or fails.

The relay used in the AC side is the EW60 power-latching relay. It features polarized bistable (latching) with two coils and three terminals. The relay coil operation is shown in the figure below.

Figure 39. **Relay coil operation**

Coil operation	1 coil		2 coils		
coil terminals	A1	A2	A1	A2	A3
Set	-	+	-	+	
Reset	+	-	-		+

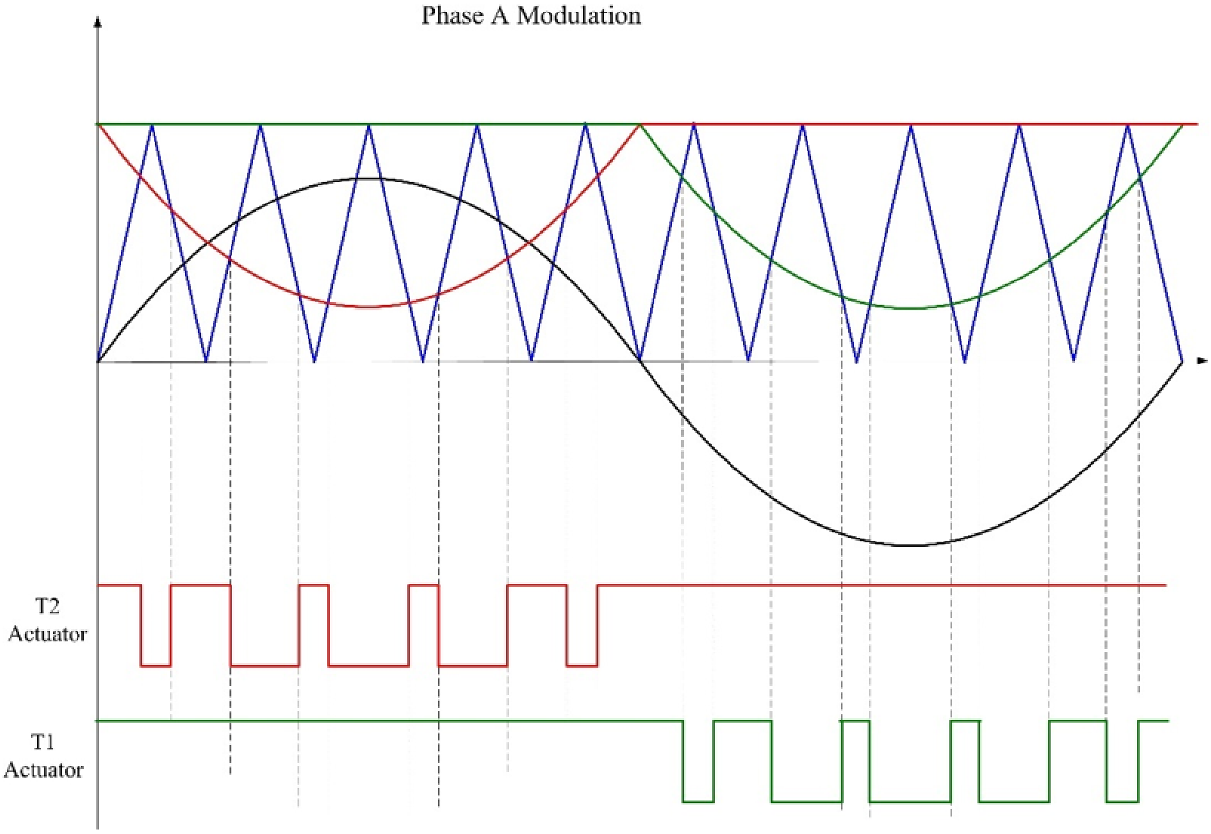
Contact position not defined at delivery

The A1 terminal is connected to the ground, while the MCU controls the potential of the A2 and A3 terminals. The relay control key is that the on/off operation is divided into two steps. The first step is to set the coil terminal (turn on→A2, turn off→A3) potential high level. 100 ms after the first step, the second step is to set the terminal potential low level, so that the efficiency can be improved.

6.6 Modulation

Taking phase A as an example, the figure below shows the STDES-30KWVRECT modulation.

Figure 40. **Phase A modulation**



6.7 Protection

The STDES-30KWVRECT detects the voltage and current value in real-time and compares them with the preset protection thresholds to prevent the converter from damage.

The STDES-30KWVRECT protections include: overvoltage protection, undervoltage protection, overcurrent protection, inrush fault protection and so on.

Table 7. **STDES-30KWVRECT protections**

Item	Description	Threshold	Behavior
Fault OVS	AC source overvoltage protection	DPC_VAC_RMS_OV 270 DPC_VAC_PK_OV 270*$\sqrt{2}$	Turn into stop (→ error→ fault) state Turn off PWM and relays
Fault OCS	AC source overcurrent protection	DPC_IAC_MAX 75	Turn into stop (→ error→ fault) state Turn off PWM and relays
Fault OVL	Loads overvoltage protection	DPC_VDC_OV 800*1.1 (when the output voltage is 800)	Turn into stop (→ error→ fault) state Turn off PWM and relays
Fault OVC	DC capacitor overvoltage protection	DPC_VCAP_LIM 800*0.65 (when the output voltage is 800)	Turn into stop (→ error→ fault) state Turn off PWM and relays
Fault OCL	Loads overcurrent protection	DPC_OVER_LOAD_CURR 48	Turn into stop (→ error→ fault) state Turn off PWM and relays

Item	Description	Threshold	Behavior
Fault INR	Inrush state→ the output voltage is out of range of the diode uncontrolled rectification	DPC_VAC 230 INRUSH_VREF_V 230*$\sqrt{6}$ Range (230*$\sqrt{6}$-80, 30*$\sqrt{6}$+100)	Turn into stop (→ error→ fault) state Turn off PWM and relays
Fault BRS	Start state→the output voltage is out of the preset range	• STARTBURST_VREF_V 800 • Range (790, 810) • (When the output voltage is 800)	Turn into stop (→ error→ fault) state Turn off PWM and relays
Fault PLL OR	Error PLL OR happened. PC_State is FSM_Run	/	Turn into fault state Turn off PWM and relays
Fault AC UVLO	Error AC UVLO happened. PC_State is FSM_Run or FSM_StartUp_burst	/	Turn into fault state Turn off PWM and relays
Fault AC UV	Error AC UV happened, and PC_State is FSM_Run or FSM_StartUp_burst	/	Turn into fault state Turn off PWM and relays
Fault AC OFF	Error AC OFF happened, and PC_State is FSM_Run or FSM_StartUp_burst	/	Turn into fault state Turn off PWM and relays
Error IDLE	Idle state→ the load is not NO_LOAD status	• /	Turn into stop (→ error) state
Error AC UV	AC source undervoltage protection	DPC_VAC_RMS_UV 150 DPC_VAC_PK_UV 150*$\sqrt{2}$	Turn into stop (→ error) state
Error AC UVLO	AC source undervoltage lock-out protection	DPC_VAC_RMS_UVLO 170 • DPC_VAC_PK_UVLO 170*$\sqrt{2}$	Turn into stop (→ error) state
Error PLL OR	Frequency is out of the preset range	PLL_FF_Hz 50 PLL_DELTA_F 20 Range (50-20, 50+20)	Turn into stop (→ error) state
Error AC OFF	AC source voltage is less than the minimum voltage threshold	DPC_VAC_MIN 40	Turn into stop (→ error) state

7 Schematic diagrams

Figure 41. STDES-30KWVRECT power board circuit schematic (1 of 9)

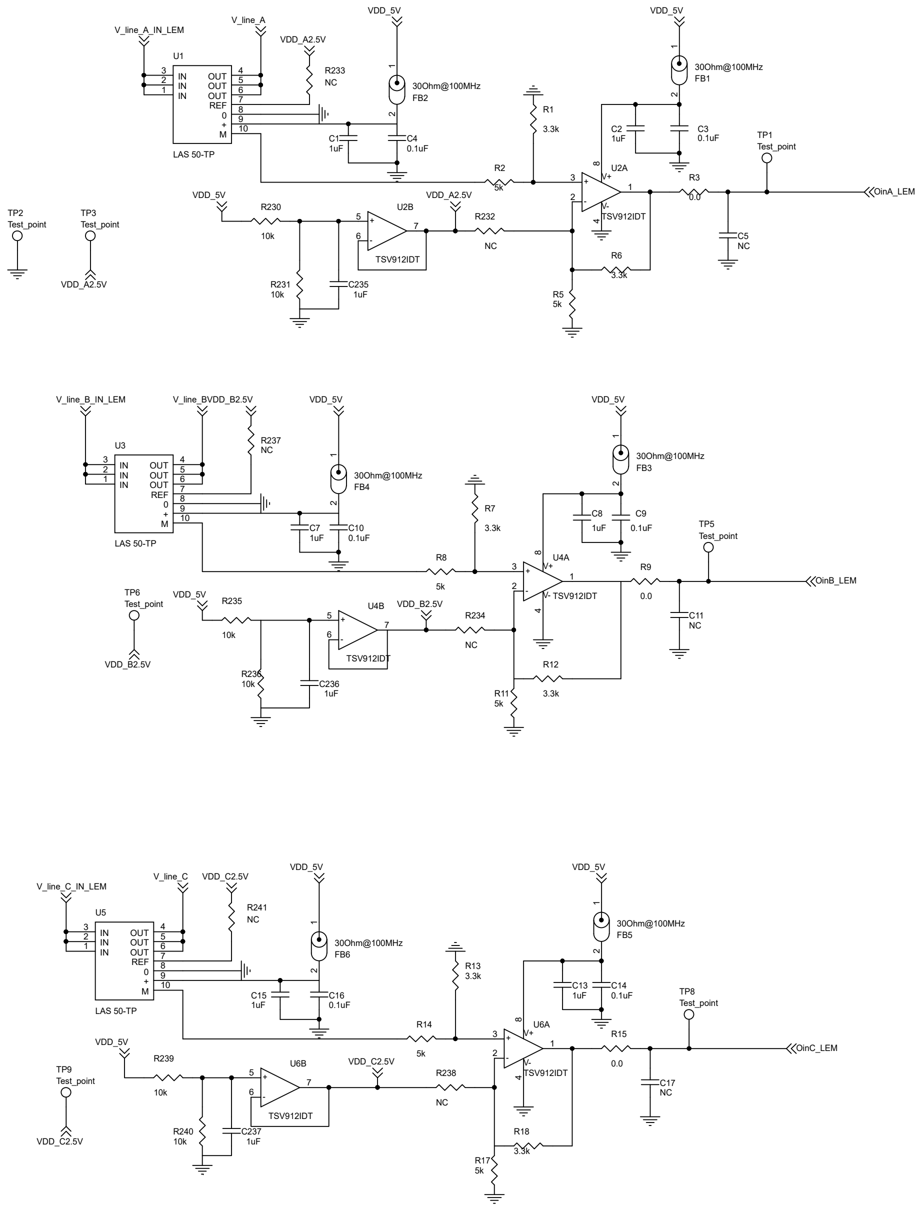


Figure 42. STDES-30KWVRECT power board circuit schematic (2 of 9)

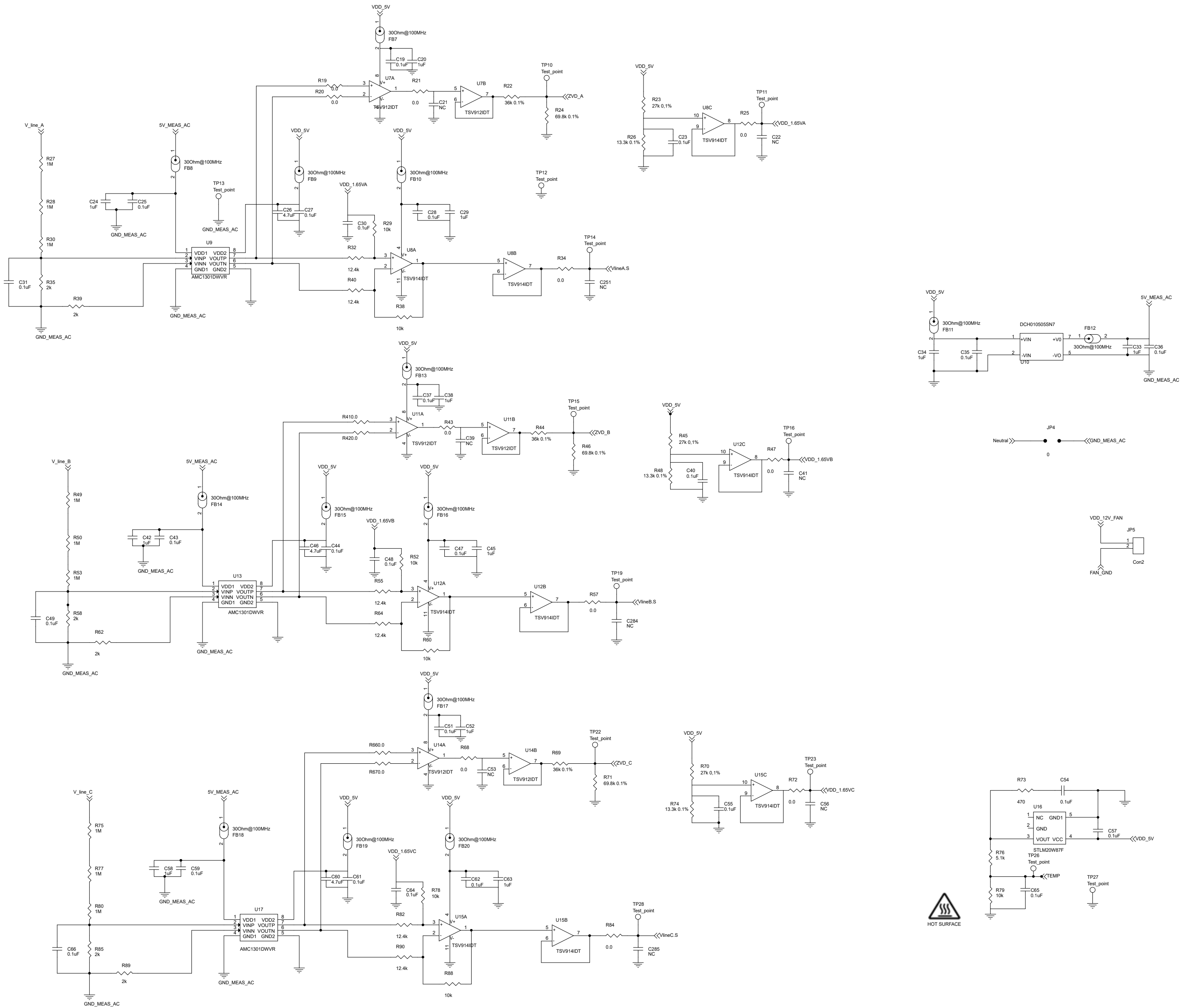


Figure 43. STDES-30KWVRECT power board circuit schematic (3 of 9)

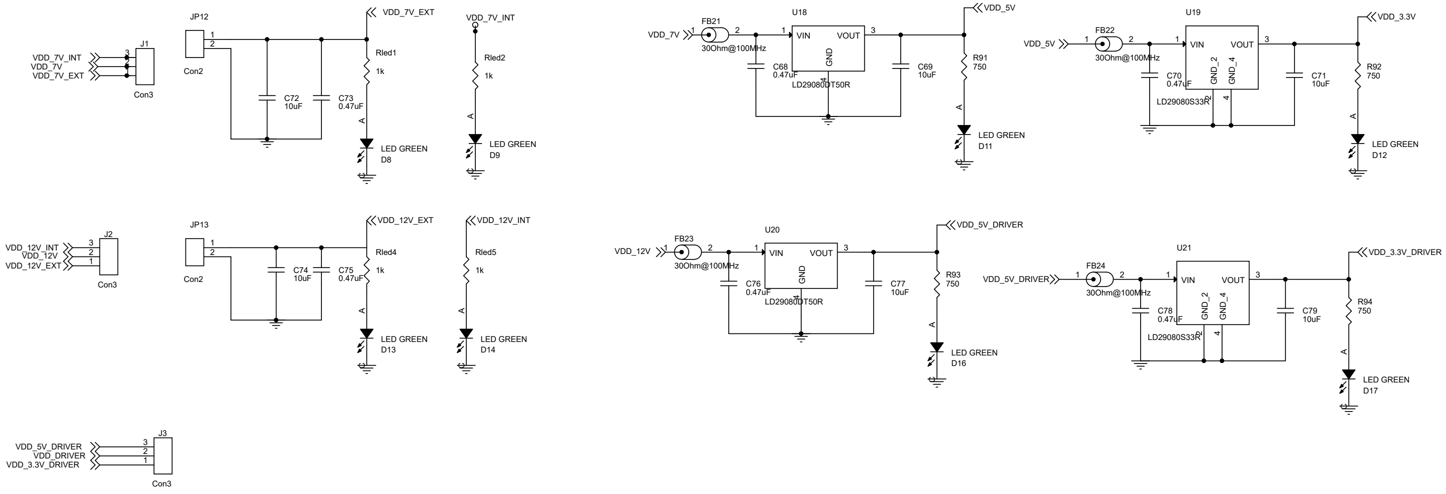


Figure 44. STDES-30KWVRECT power board circuit schematic (4 of 9)

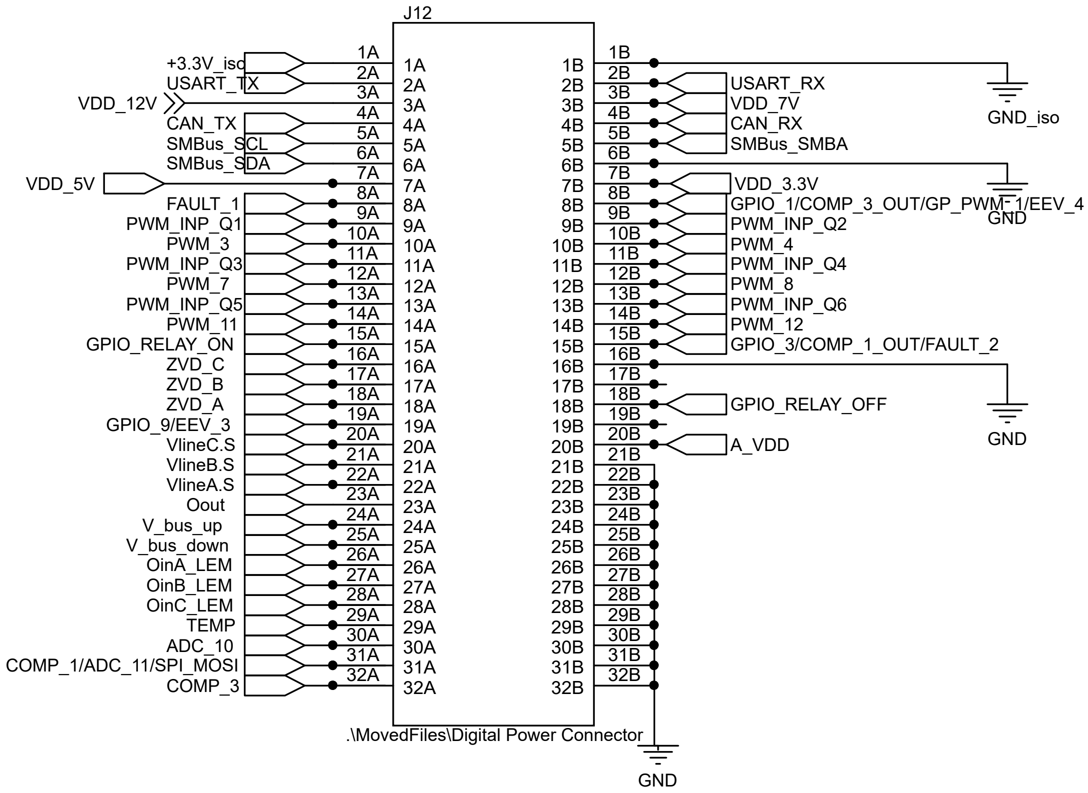


Figure 45. STDES-30KWVRECT power board circuit schematic (5 of 9)

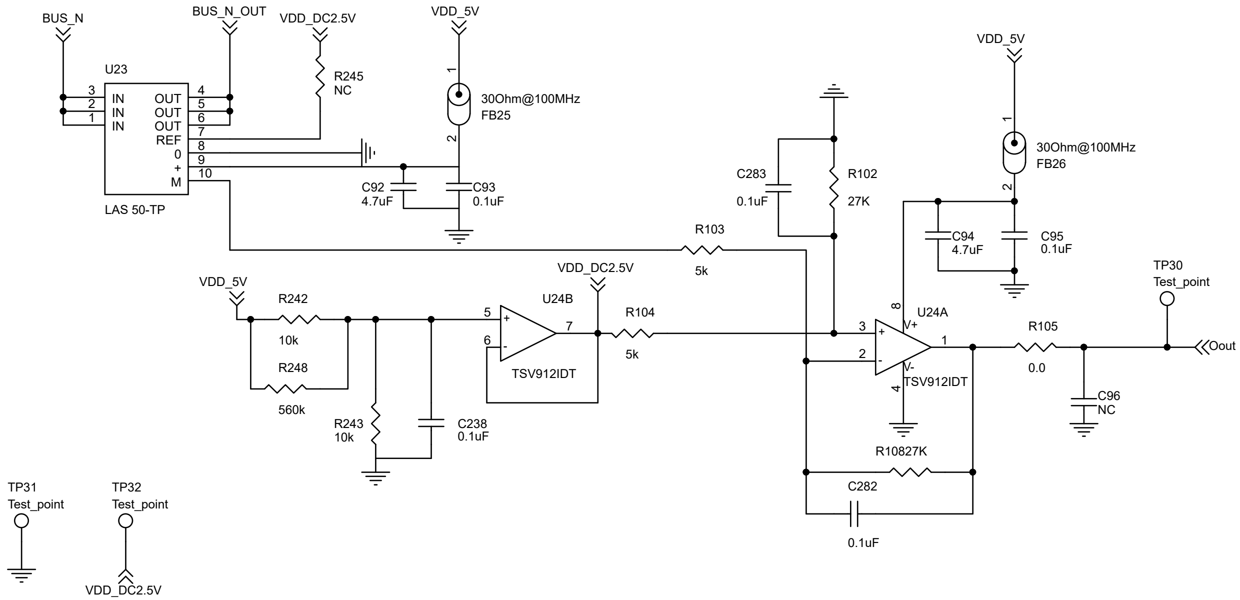


Figure 46. STDES-30KWVRECT power board circuit schematic (6 of 9)

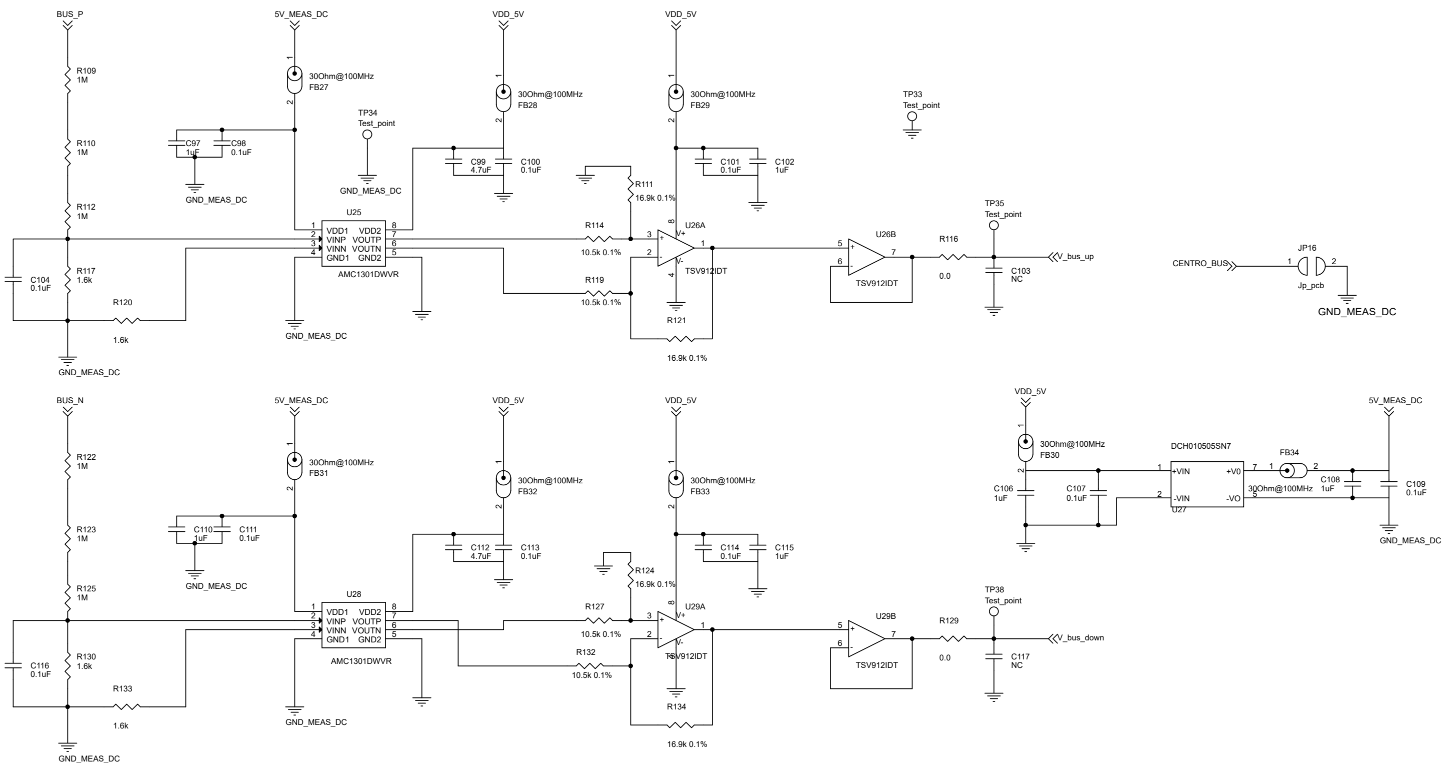


Figure 47. STDES-30KWVRECT power board circuit schematic (7 of 9)

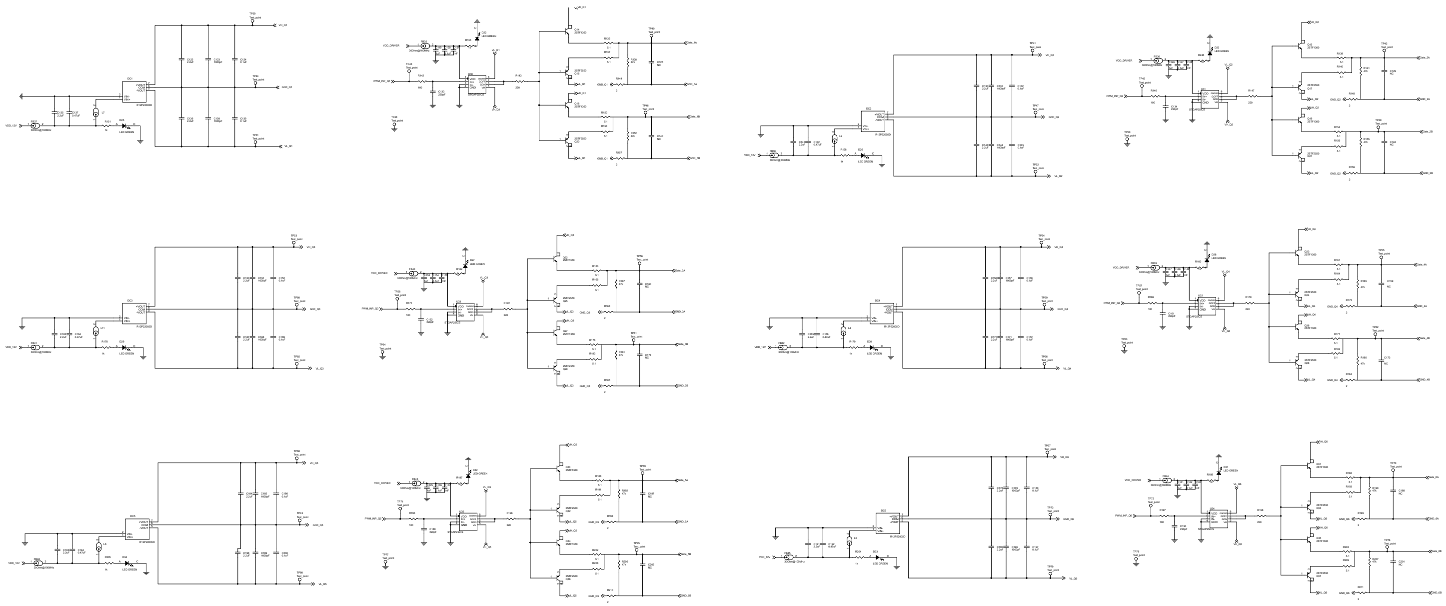


Figure 48. STDES-30KWVRECT power board circuit schematic (8 of 9)

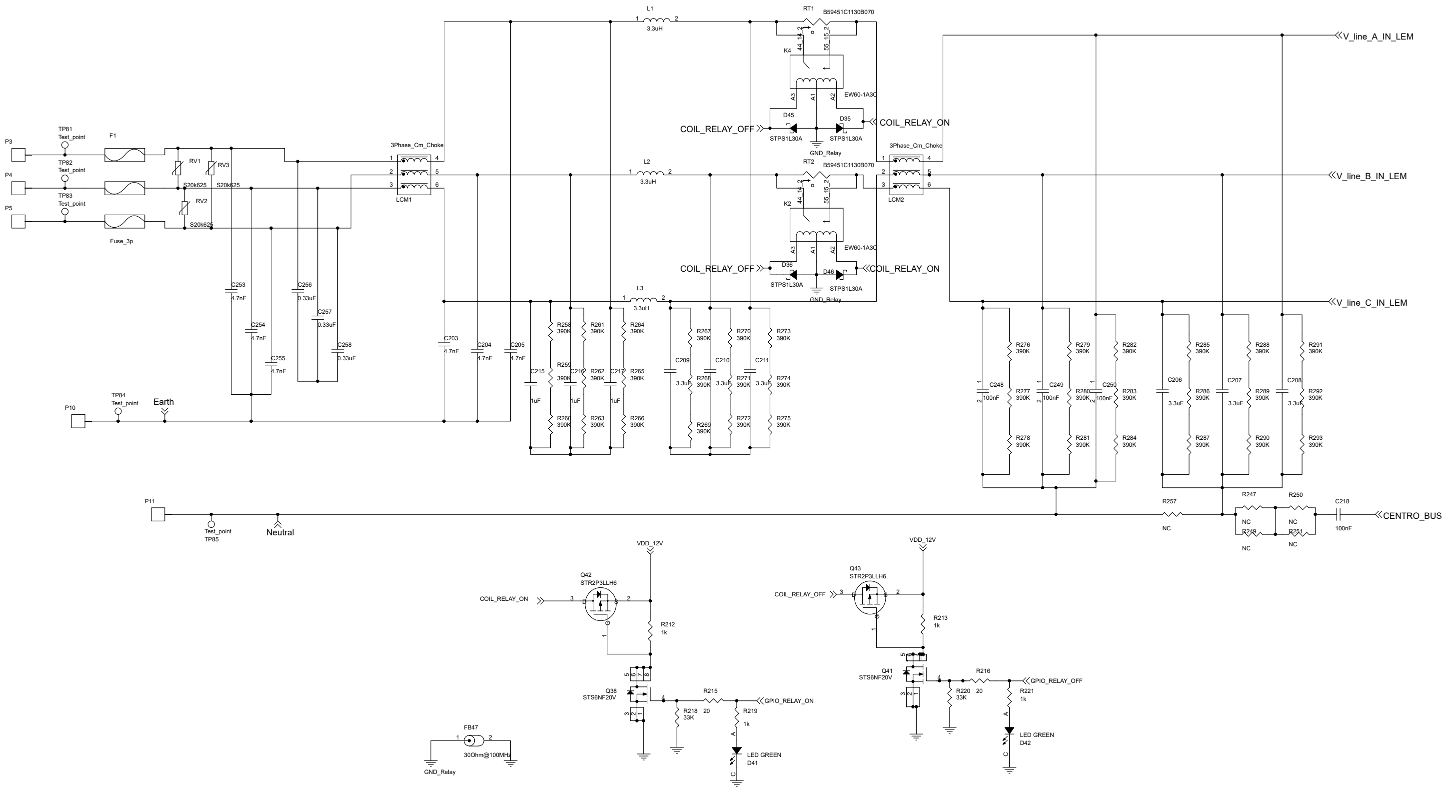


Figure 39. STDES-30KWVRECT power board circuit schematic (9 of 9)

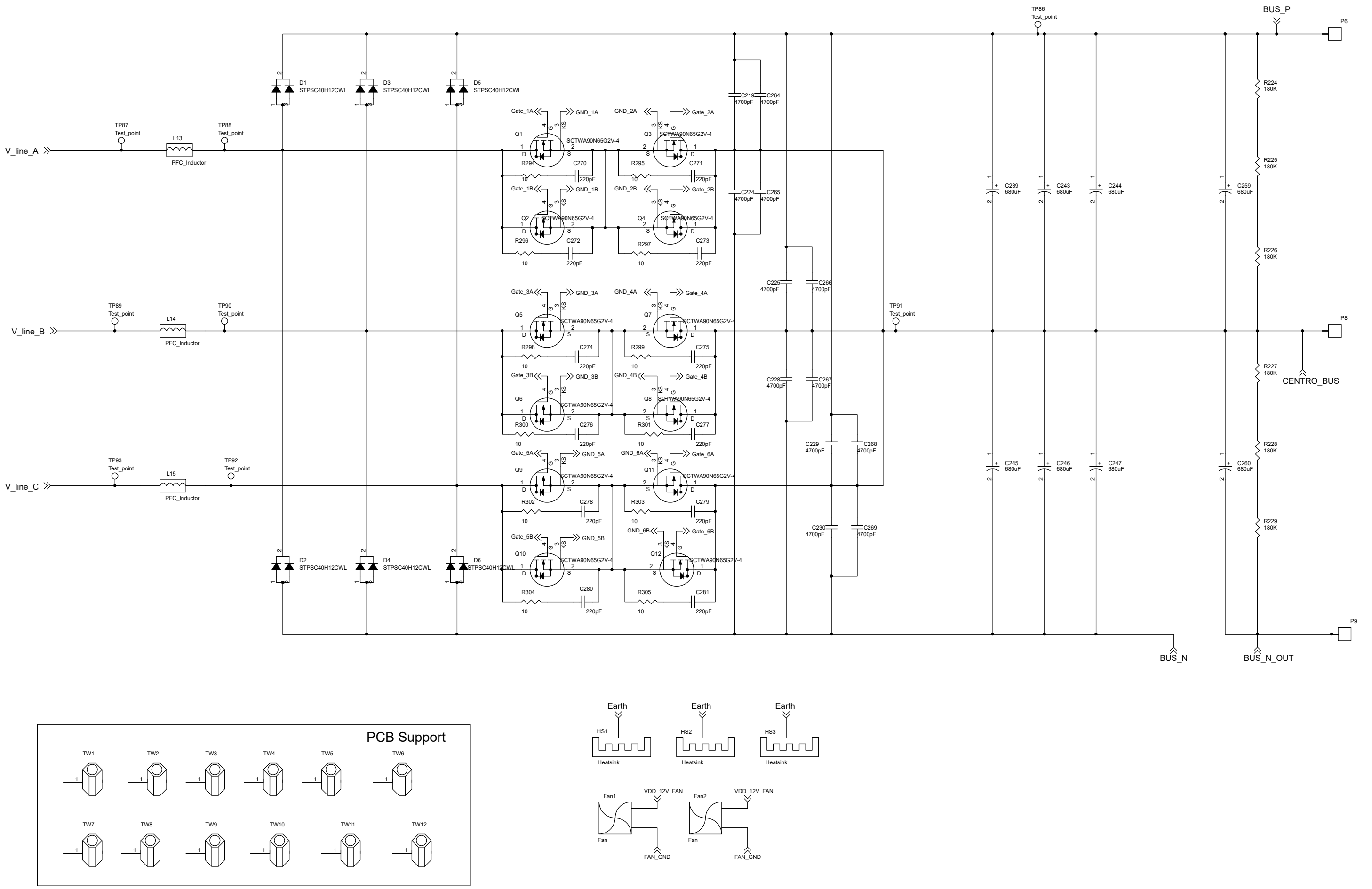
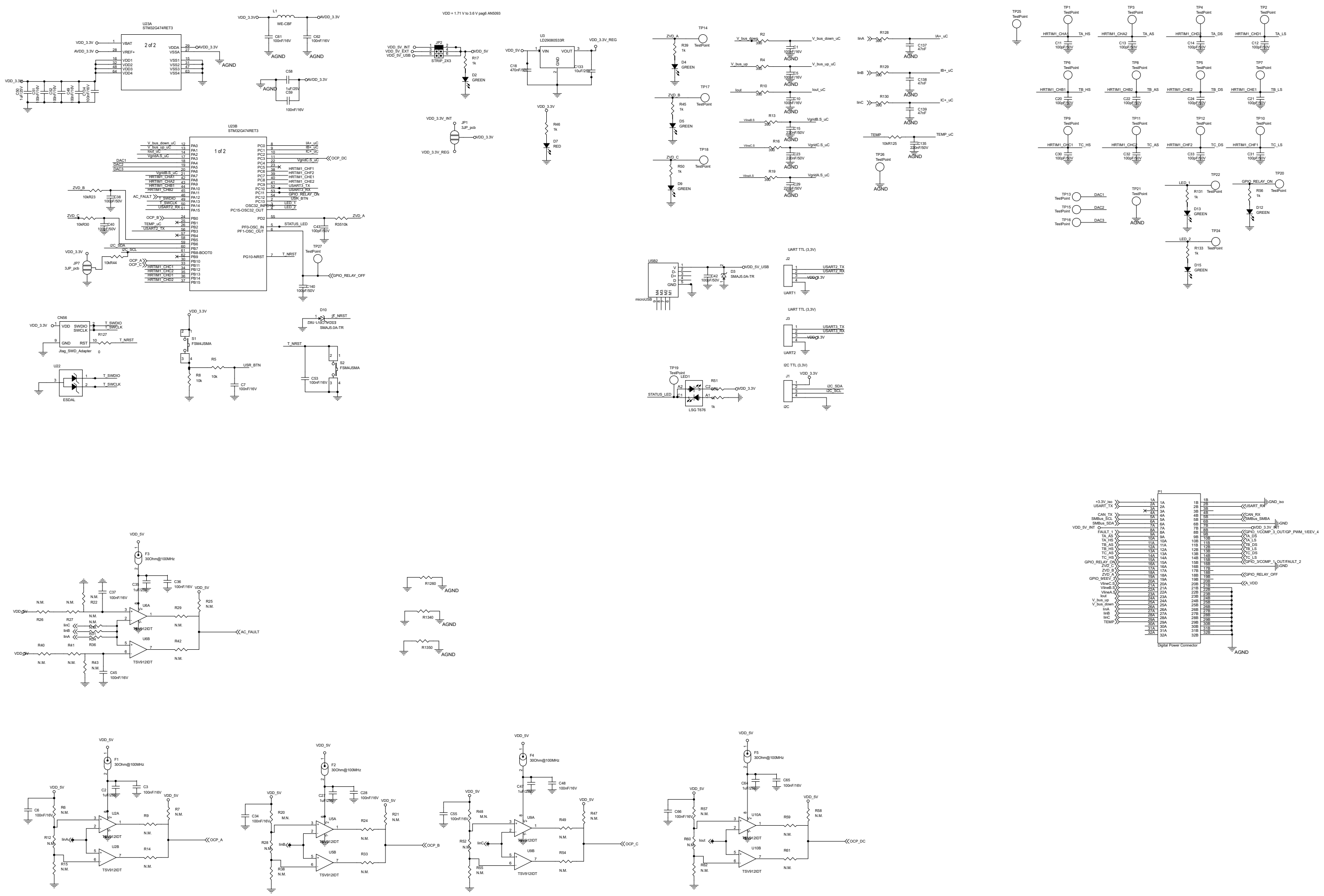


Figure 50. STDES-30KWVRECT control board circuit schematic



8 Bill of materials

Table 8. STDES-30KWVRECT bill of materials

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
1	1	Table 9. Power board bill of materials	-	Power board	ST	Not available for separate sale
2	1	Table 10. Control board bill of materials	-	Control board	ST	Not available for separate sale

Table 9. Power board bill of materials

Item	Qty.	Ref.	Part/value	Description	Manufacturer	Order code
1	32	C1,C2,C7, C8,C13,C15,C20,C24, C29,C33,C34,C38,C42,C45,C52, C58,C63,C97,C102,C106,C108, C110,C115,C119,C126,C147,C153,C175,C181,C235, C236,C237	1uF,0603 (1608 Metric),25V,10%	Ceramic capacitor	Wurth Electronics Inc.	885012206076
2	51	C3,C4,C9, C10,C14,C16,C19,C23,C25,C27, C28,C30,C31,C35,C36,C37,C40, C43,C44,C47,C48,C49,C51,C54, C55,C57,C59,C61,C62,C64,C65, C66,C93,C95,C98,C100,C101,C104,C107, C109,C111,C113,C114,C116,C120,C127,C148,C154, C176,C182,C238	0.1uF,0603 (1608 Metric),16V,10%	Ceramic capacitor	Wurth Electronics Inc.	885012206046
3	7	C26,C46,C60,C92,C94,C99,C112	4.7uF,0805 (2012 Metric),25V,10%	Ceramic capacitor	TDK Corporation	C2012X5R1E475K125AB
4	12	C68,C70,C73,C75,C76,C78,C137,C142,C164,C166,C192,C194	0.47uF,0805 (2012 Metric),50V,10%	Ceramic capacitor	AVX Corporation	08055C474KAT2A

Item	Qty.	Ref.	Part/value	Description	Manufacturer	Order code
5	7	C69,C71,C72,C74,C77,C79	10uF,0805 (2012 Metric),35V,10%	Ceramic capacitor	Taiyo Yuden	GMK212BBJ106KG-T
6	7	C133,C134,C161,C162,C189,C190	220pF,0603 (1608 Metric),50V,10%	Ceramic capacitor	Samsung Electro-Mechanics America, Inc.	CL10B221KB8NNNC
7	15	C124,C132,C139,C145,C152,C158,C169,C172,C180, C186,C197,C200,C282,C283	0.1uF,0603 (1608 Metric),50V,10%	Ceramic capacitor	Wurth Electronics Inc.	885012206095
8	6	C121,C128,C149,C155,C177,C183	1nF,0603 (1608 Metric),25V,10%	Ceramic capacitor	Samsung Electro-Mechanics	CL10B102KA8NNNC
9	18	C122,C130,C135,C136,C141,C143,C150,C156,C163, C165,C167,C170,C178,C184,C191,C193,C195,C198	2.2uF,0805 (2012 Metric),50V,10%	Ceramic capacitor	TDK Corporation	C2012X7R1H225K125AC
10	12	C123,C131,C138,C144,C151,C157,C168,C171,C179, C185,C196,C199	1000pF,0603 (1608 Metric),50V,10%	Ceramic capacitor	AVX Corporation	06035C102KAT2A
11	6	C203,C204,C205,C253,C254,C255	4.7nF,Radial, Disc, 440VAC Y5U	Ceramic capacitor	KEMET	ERK610Z472MCRU
12	6	C206,C207,C208,C209,C210,C211	3.3uF,Radial, Disc,305VAC,20%	Film capacitor	FARA	C42Q2335MBBC000
13	3	C215,C216,C217	1uF,Radial, Disc,305VAC,20%	Film capacitor	FARA	C42Q2105K9SC000
14	1	C218	100nF,Radial, Disc,1KVDC,10%	Film capacitor	KEMET	R474N310050A1K
15	12	C219,C224,C225,C228,C229,C230,C264,C265,C266, C267,C268,C269	4700pF, 1206 (3216 Metric), 630V C0G	Ceramic capacitor	TDK Corporation	CGA5F4C0G2J472J085AA
16	8	C239,C243,C244,C245,C246,C247,C259,C260	680uF,Radial, Can - Snap-In,450V,20%	Alum-electrolytic capacitor	EPCOS (TDK)	B43601A5687M000

Item	Qty.	Ref.	Part/value	Description	Manufacturer	Order code
17	3	C248,C249,C250	100nF,Radial, Disc,440VAC Y5U	Ceramic capacitor	KEMET	ERK610Z472MCRU
18	3	C256,C257,C258	0.33uF,Radial,305 VAC,20%	Film capacitor	EPCOS (TDK)	B32922C3334M000
19	12	C270,C271,C272,C273,C274,C275,C276,C277,C278, C279,C280,C281	220pF,1206 (3216 Metric),1KV C0G/NP0	Ceramic capacitor	Murata Electronics	GRM31A5C3A221JW01D
20	6	DC1,DC2, DC3,DC4, DC5,DC6	CONV DC/DC 2W ,0.77" L x 0.39" W x 0.49" H (19.5mm x 9.8mm x 12.5mm)	DC/DC Converter, 12VIN +20/-5VOUT	Recom Power	R12P22005D
21	6	D1,D2,D3, D4,D5,D6	STPSC40H12CWL, TO-247 long leads	1200 V, 40 A high surge silicon carbide power Schottky diode	ST	STPSC40H12CWL
22	22	D8,D9,D11, D12,D13,D14,D16,D17,D22,D23, D25,D26,D27,D28,D29,D30,D31, D32,D33,D34,D41,D42	SMD,0805 (2012 Metric)	Green Leds	Lite-On Inc.	LTST-C171GKT
23	4	D35,D36,D45,D46	STPS1L30A, SMA	30 V, 1 A low drop power Schottky rectifier	ST	STPS1L30A
24	53	FB1,FB2,FB3,L4,FB4, L5,FB5,L6, FB6,L7,FB7,FB8,L9,FB9,FB10,L11,FB11,FB12,FB13, FB14,FB15,FB16,FB17,FB18,FB19,FB20,FB21,FB22, FB23,FB24,FB25,FB26,FB27,FB28,FB29,FB30,FB31, FB32,FB33,FB34,FB35,FB36,FB37,FB38,FB39,FB40, FB41,FB42,FB43,FB44,FB45,FB46,FB47	Bead,0805,30Ohm	Ferrite beads	TDK Corporation	MPZ2012S300AT000
25	2	Fan1,Fan2	PFB0812DHE,12v,3.3a	FAN	Delta	PFB0812DHE

Item	Qty.	Ref.	Part/value	Description	Manufacturer	Order code
26	3	F1,F2,F3	50A 400VAC, 15mm x 51mm	Fuse	Eaton	C14G50
27	3	HS1,HS2,HS3	TO-247,130mm x 50mm x 18mm	Heatsink	-	-
28	3	JP5,JP12,JP13	CONN TERM BLOCK 2POS 5.08mm	Connector	Phoenix Contact	1715721
29	3	J1,J2,J3	Switch,SPDT,500mA,12V,10mmx2.5mm,opposite side connect	Straight mini slide switch	Wurth Electronics Inc.	450301014042
30	1	J12	CON32x2, R/A 64POS 2.54 mm,	Digital power connector	Erni	284166
31	2	K2,K4	Relay,power latching, 60A,277VAC	Relay	TE Connectivity	EW60-1A3C
32	2	LCM1,LCM2	T60405-S6123-X140	Three-phase CM chock	VACUUMSCHMELZE	T60405-S6123-X140
33	3	L1,L2,L3	AGP4233-332ME	DM inductor	Coilcraft	AGP4233-332ME
34	3	L13,L14,L15	ARLDC724676C271N1B	PFC inductor	Sunloard	ARLDC724676C271N1B
35	8	P3,P4,P5,P6,P8,P9,P10,P11	PowerCon,9mmx 9.5mmx 3.5mm, M5	Power connector	Wurth	7460408
36	12	Q1,Q2,Q3, Q4,Q5,Q6, Q7,Q8,Q9, Q10,Q11,Q12	SCTWA90N65G2V-4, HiP247-4	Silicon carbide power MOSFET 650 V, 18 mOhm typ., 119 A in an HiP247-4 package	ST	SCTWA90N65G2V-4
37	12	Q14,Q15,Q18,Q19,Q22,Q23,Q26, Q27,Q30,Q31,Q34,Q35	2STF1360, SOT-89	Low voltage fast-switching NPN power transistor	ST	2STF1360
38	12	Q16,Q17,Q20,Q21,Q24,Q25,Q28, Q29,Q32,Q33,Q36,Q37	2STF2550, SOT-89	Low voltage high performance PNP power transistor	ST	2STF2550
39	2	Q38,Q41	STS6NF20V, SO-8	N-channel 20 V, 30 mOhm typ., 6 A, 2.7 V drive STripFET II power MOSFET in an SO-8 package	ST	STS6NF20V
40	2	Q42,Q43	STR2P3LLH6, SOT-23	P-channel 30 V, 0.048 Ohm typ., 2 A STripFET H6 power MOSFET in a SOT-23 package	ST	STR2P3LLH6
41	2	RT1,RT2	B59451C1130B070,±25%	PTC thermistors	TDK Electronics Inc.	B59451C1130B070

Item	Qty.	Ref.	Part/value	Description	Manufacturer	Order code
42	3	RV1,RV2,RV3	S20k625, DISC 14mm,625V,6.5KA	Varistor	EPCOS (TDK)	B72220S0621K101
43	16	Rled1,Rled2,Rled4,Rled5,R136,R151,R158,R160,R162,R178,R179,R187,R189,R204,R205,R246	1k,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	RC0603FR-071KL
44	6	R1,R6,R7,R12,R13,R18	3.3k,0603 (1608 Metric),1/10W,1%	Resistor	Panasonic Electronic Components	ERA-3AEB332V
45	8	R2,R5,R8,R11,R14,R17,R103,R104,R76	5.1k,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	RC0603FR-075K1L
46	21	R3,R9,R15,R19,R20,R21,R25,R34,R41,R42,R43,R47,R57,R66,R67,R68,R72,R84,R105,R116,R129	0,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	RC0603JR-070RL
47	3	R22,R44,R69	36k,0603 (1608 Metric),1/10W,0.1%	Resistor	Yageo	RC0603BR-0736KL
48	3	R23,R45,R70	27k,0603 (1608 Metric),1/10W,0.1%	Resistor	Yageo	RT0603BRE0727KL
49	3	R24,R46,R71	69.8k,0603 (1608 Metric),1/10W,0.1%	Resistor	Yageo	RT0603BRE0769K8L
50	3	R26,R48,R74	13.3k,0603 (1608 Metric),1/10W,0.1%	Resistor	Yageo	RT0603BRE0713K3L
51	15	R27,R28,R30,R49,R50,R53,R75,R77,R80,R109,R110,R112,R122,R123,R125	1M,1206 (3216 Metric),1/4W,1%	Resistor	Yageo	RT1206FRE071ML
52	16	R29,R38,R52,R60,R78,R79,R88,R230,R231,R235,R236,R239,R240,R242,R243	10k,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	RC0603FR-0710KL
53	6	R32,R40,R55,R64,R82,R90	12.4k,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	RT0603FRE0712K4L

Item	Qty.	Ref.	Part/value	Description	Manufacturer	Order code
54	6	R35,R39,R58,R62,R85,R89	2k,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	RC0603FR-072KL
55	1	R73	470,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	RC0603FR-07470RL
56	4	R91,R92,R93,R94	750,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	RC0603FR-07750RL
57	4	R102,R108	27K,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	RC0603FR-0727KL
58	4	R111,R121,R124,R134	16.9k,0603 (1608 Metric),1/10W,0.1%	Resistor	Yageo	RT0603BRE0716K9L
59	4	R114,R119,R127,R132	10.5k,0603 (1608 Metric),1/10W,0.1%	Resistor	Yageo	RT0603BRE0710K5L
60	4	R117,R120,R130,R133	1.6k,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	RC0603FR-071K6L
61	24	R135,R137,R139,R140,R150,R153,R154,R156,R161,R163,R164,R166,R176,R177,R182,R183,R186,R188,R191,R193,R202,R203,R208,R209	5.1,1210 (3225 Metric),1/2W,1%	Resistor	Yageo	RC1210FR-075R1L
62	12	R138,R141,R152,R155,R165,R167,R180,R181,R190,R192,R206,R207	47k,1206 (3216 Metric),1/4W,1%	Resistor	Yageo	RC1206FR-0747KL
63	6	R142,R146,R169,R171,R195,R197	100,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	AT0603FRE07100RL
64	6	R143,R147,R170,R172,R196,R198	220,1210 (3225 Metric),1/2W,1%	Resistor	Yageo	RC1210FR-07220RL
65	12	R144,R148,R157,R159,R168,R173,R184,R185,R194,R199,R210,R211	2,1206 (3216 Metric),1/4W,1%	Resistor	Yageo	RC1206FR-072RL
66	4	R212,R213,R219,R221	1k,0603 (1608 Metric),1/10W,1%	Resistor	Yageo RC0603FR-071KL	RC0603FR-071KL
67	2	R215,R216	20,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	RC0603FR-0720RL

Item	Qty.	Ref.	Part/value	Description	Manufacturer	Order code
68	3	R218,R220,R306	33K,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	RC0603FR-0733KL
69	6	R224,R225,R226,R227,R228,R229	180K,1206 (3216 Metric),1/4W,0.1%	Resistor	Panasonic Electronic Components	ERA-8AEB184V
70	1	R248	560k,0603 (1608 Metric),1/10W,1%	Resistor	Yageo	RT0603FRE07560KL
71	36	R258,R259,R260,R261,R262,R263,R264,R265,R266,R267,R268,R269,R270,R271,R272,R273,R274,R275,R276,R277,R278,R279,R280,R281,R282,R283,R284,R285,R286,R287,R288,R289,R290,R291,R292,R293	390K,1206 (3216 Metric),1/4W,1%	Resistor	Yageo	RC1206FR-07390KL
72	12	R294,R295,R296,R297,R298,R299,R300,R301,R302,R303,R304,R305	10,1206 (3216 Metric),1/4W,0.1%	Resistor	Yageo	RT1206BRD0710RL
73	1	R307	330,0805 (2012 Metric),1/10W,0.01%	Resistor	Susumu	RG2012L-331-L-T05
74	82	TP1,TP2,TP3,TP5,TP6,TP8,TP9,TP10,TP11,TP12,TP13,TP14,TP15,TP16,TP19,TP22,TP23,TP26,TP27,TP28,TP30,TP31,TP32,TP33,TP34,TP35,TP38,TP39,TP40,TP41,TP42,TP43,TP44,TP45,TP46,TP47,TP48,TP49,TP50,TP51,TP52,TP53,TP54,TP55,TP56,TP57,TP58,TP59,TP	Test_point,0.100" Dia x 0.180" L (2.54mm x 4.57mm)	Test point	Keystone Electronics	5000

Item	Qty.	Ref.	Part/value	Description	Manufacturer	Order code
		60,TP61,TP62,TP63,TP64,TP65,TP66,TP67,TP68,TP69,TP70,TP71,TP72,TP73,TP74,TP75,TP76,TP77,TP78,TP79,TP80,TP81,TP82,TP83,TP84,TP85,TP86,TP87,TP88,TP89,TP90,TP91,TP92,TP93				
75	12	TW1,TW2,TW3,TW4,TW5,TW6,TW7,TW8,TW9,TW10,TW11,TW12	Support M3X40	PCB support M3 High 40mm	Essentra	TCBN-T1-M3-8-40
76	4	U1,U3,U5,U23	LAS 50-TP	Current Hall sensor	LEM	LAS 50-TP
77	9	U2,U4,U6,U7,U11,U14,U24,U26,U29	TSV912IDT, SO-8	Wide-bandwidth (8 MHz) rail to rail input/output 5 V CMOS op-amps, dual	ST	TSV912IDT
78	3	U8,U12,U15	TSV914IDT, SO-14	Wide-bandwidth (8 MHz) rail to rail input/output 5 V CMOS op-amps, quad	ST	TSV914IDT
79	5	U9,U13,U17,U25,U28	AMC1301DWVR, 8-SOIC (0.295", 7.50mm Width)	IC amplifier	Texas Instruments	AMC1301DWVR
80	2	U10,U27	DCH010505SN7, 7-SIP Module, 4 Leads	DC/DC Converter,5V,1W	Texas Instruments	DCH010505SN7
81	1	U16	STLM20W87F, SOT323-5L	Analog temperature sensor, ultra-low current 2.4 V, high precision	ST	STLM20W87F
82	2	U18,U20	LD29080DT50R, DPAK	800 mA fixed and adjustable output very low drop voltage regulator	ST	LD29080DT50R
83	2	U19,U21	LD29080S33R, SOT-223	800 mA fixed and adjustable output very low drop voltage regulator	ST	LD29080S33R
84	6	U30,U31,U32,U33,U34,U35	STGAP2SICS, SO 8 WIDE 300	Galvanically isolated 4 A single gate driver for SiC MOSFETs	ST	STGAP2SICS

Table 10. Control board bill of materials

Item	Qty.	Ref.	Part/value	Description	Manufacturer	Order code
1	1	CN56	Jtag_SWD_Adapter,10 Way, 2 Row,1.27mm	10 Way, 2 Row, Vertical Pin Header	-	-
2	23	C1,C3,C5, C6,C7,C10 ,C28,C34, C36,C37,C45,C48,C49,C51,C52, C53,C55,C59,C61,C62,C65,C66, C134	100nF,0603 (1608 Metric),16V,10%	Ceramic capacitor	Wurth	885012206046
3	7	C2,C27,C35,C47,C50, C58,C64	1uF,0603 (1608 Metric),25V,10%	Ceramic capacitor	Wurth	885012206076
4	17	C11,C12,C13,C14,C20,C21,C22, C24,C30,C31,C32,C33,C38,C40, C42,C43,C140	100pF,0603 (1608 Metric),50V,10%	Ceramic capacitor	Wurth	885012006057
5	3	C15,C23,C135	220nF,0603 (1608 Metric),50V,10%	Ceramic capacitor	TDK	CGA3E3X7R1H224K080AE
6	1	C18	470nF,0603 (1608 Metric),50V,10%	Ceramic capacitor	Wurth	885012207102
7	1	C29	220pF,0603 (1608 Metric),50V,10%	Ceramic capacitor	Wurth	885012206079
8	1	C133	10uF,0805 (2012 Metric),25V,10%	Ceramic capacitor	Samsung Electro-Mechanics America, Inc.	CL21A106KAYNNNG
9	3	C137,C138 ,C139	47nF,0603 (1608 Metric),50V,10%	Ceramic capacitor	Murata Electronics	GCM188R71H473KA55D
10	7	D2,D4,D5, D9,D12,D13,D15	Green,SMD,0805 (2012 Metric)	Green LED diode	Wurth	150080GS75000
11	2	D3,D10	SMAJ5.0A-TR, SMA	400 W TVS in SMA	ST	SMAJ5.0A-TR
12	1	D7	Red,SMD,0805 (2012 Metric)	Red LED diode	Wurth	150080RS75000
13	5	F1,F2,F3,F4,F5	Bead,0805 (2012 Metric),30Ohm	Ferrite Bead	Wurth	742792021
14	2	JP1,JP7	Solder Jumper Selector	Solder Jumper Selector	ANY	ANY
15	1	JP2	Solder Jumper Selector	Solder Jumper Selector	ANY	ANY
16	1	J1	4 Way, 1 Row, Straight Pin Header,2.54mm	Straight Pin Header	Wurth	61300411121
17	1	J2	4 Way, 1 Row, Straight Pin Header,2.54mm	Straight Pin Header	Wurth	61300411121

Item	Qty.	Ref.	Part/value	Description	Manufacturer	Order code
18	1	J3	4 Way, 1 Row, Straight Pin Header,2.54mm	Straight Pin Header	Wurth	61300411121
19	1	LED1	Green & Red,SMD,0805 (2012 Metric)	Green and red LED PLCC	OSRAM	LSG T676
20	1	L1	Bead,0603 (1608 Metric),120Ohm	Ferrite bead	WE	74279262
21	1	P1	CON32x2, R/A 64POS 2.54 mm,male	Digital power connector	ERNI	533406
22	9	R2,R4,R10,R13,R16, R19,R128, R129,R130	390,0603 (1608 Metric),1/10W,1%	Resistors	Yageo	RC0603FR-07390RL
23	7	R5,R8,R23,R30,R35, R44,R125	10k,0603 (1608 Metric),1/10W,1%	Resistors	Yageo	RC0603FR-0710KL
24	10	R17,R39,R45,R46,R50,R51,R53, R56,R131, R133	1k,0603 (1608 Metric),1/10W,1%	Resistors	Yageo	RC0603FR-071KL
25	4	R126,R127,R134,R135	0,0603 (1608 Metric),1/10W,1%	Resistors	Yageo	RC0603JR-070RL
26	2	S1,S2	SWITCH TACTILE SPST-NO 0.05A 24V	Tactile SPST switch	TE Connectivity	FSM4JSMATR
27	26	TP1,TP2,TP3,TP4,TP5,TP6,TP7, TP8,TP9,TP10,TP11, TP12,TP13,TP14,TP15,TP16,TP17,TP18,TP19,TP20, TP21,TP22,TP24,TP25,TP26,TP27	TestPoint	TestPoint	Keystone Electronics	5001
28	1	USB2	Micro USB 2.0 Molex tipo B	Micro USB 2.0	MOLEX	47346-0001
29	5	U2,U5,U6, U9,U10	TSV912IDT, SO-8	Wide-bandwidth (8 MHz) rail to rail input/output 5 V CMOS op-amps, dual	ST	TSV912IDT
30	1	U3	LD29080S33R, SOT-223	800 mA fixed and adjustable output very low drop voltage regulator	ST	LD29080S33R
31	1	U22	ESDA6V1, SOT23-3L	Dual Transil array for ESD protection	ST	ESDA6V1L

Item	Qty.	Ref.	Part/value	Description	Manufacturer	Order code
32	1	U23	STM32G474RET3, LQFP 64 10x10x1.4 mm	Mainstream Arm® Cortex®-M4 MCU 170 MHz with 512 Kbytes of flash memory, math accelerator, HR timer, high analog level integration	ST	STM32G474RET3

Revision history

Table 11. **Document revision history**

Date	Revision	Changes
13-Apr-2022	1	Initial release.

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