How to use the 15 kW three-level three-phase Vienna rectifier with digital control for power factor correction

Introduction

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

This reference design topology is mostly used for DC fast charging applications related to industrial and electric vehicles.

It features full digital control. The embedded STM32G474RET3 mixed-signal high-performance microcontroller provides the full control of the power factor (PF), the DC voltage, and the auxiliary task to manage the protections and the soft start-up procedure.

The high-bandwidth continuous conduction mode (CCM) current regulation allows the maximum power quality in terms of total harmonic distortion (THD) and power factor (PF).

Figure 1. DC charging station

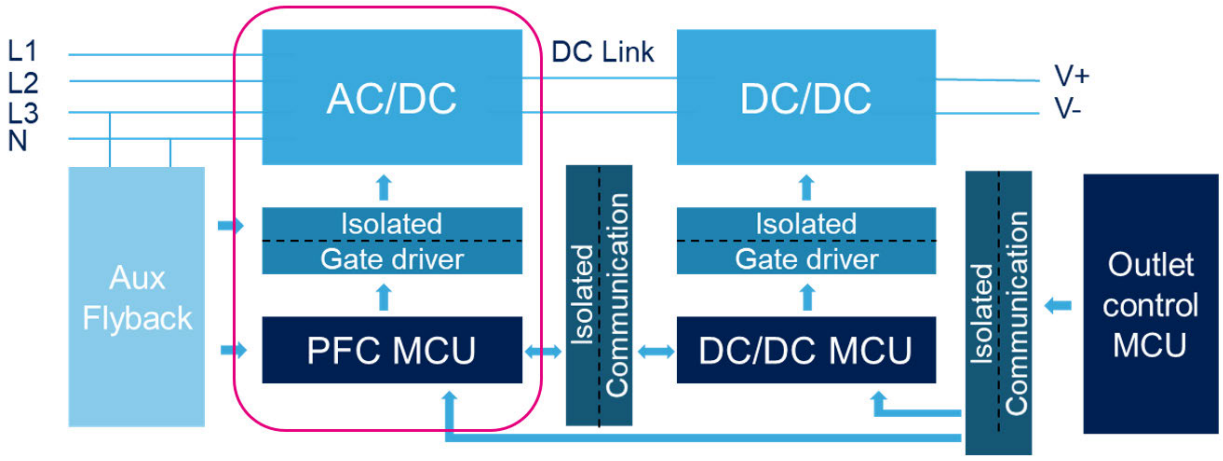
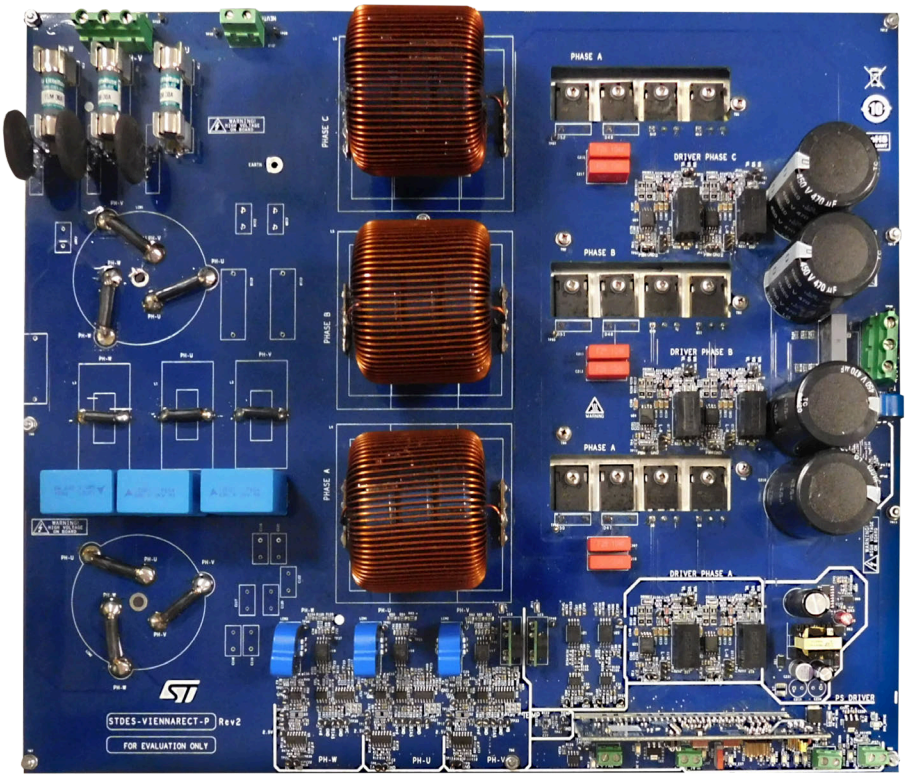
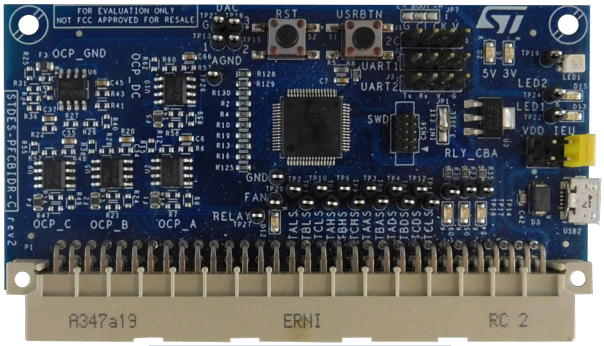


Figure 2. **STDES-VRECTFD reference design - power board**



Fully assembled board developed for performance evaluation only, not available for sale

Figure 3. **STDES-VRECTFD reference design - control board**



Fully assembled board developed for performance evaluation only, not available for sale

The high switching frequency of the SiC MOSFETs (70 kHz) and the multilevel structure allow an efficiency of almost 99% as well as the optimization of passive power components in terms of size and cost.

The high efficiency rectifier is designed for several end applications such as electric vehicle (EV), industrial battery chargers, and industrial equipment, which requires a very high PF and low THD.

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

1 Getting started

1.1 Safety information

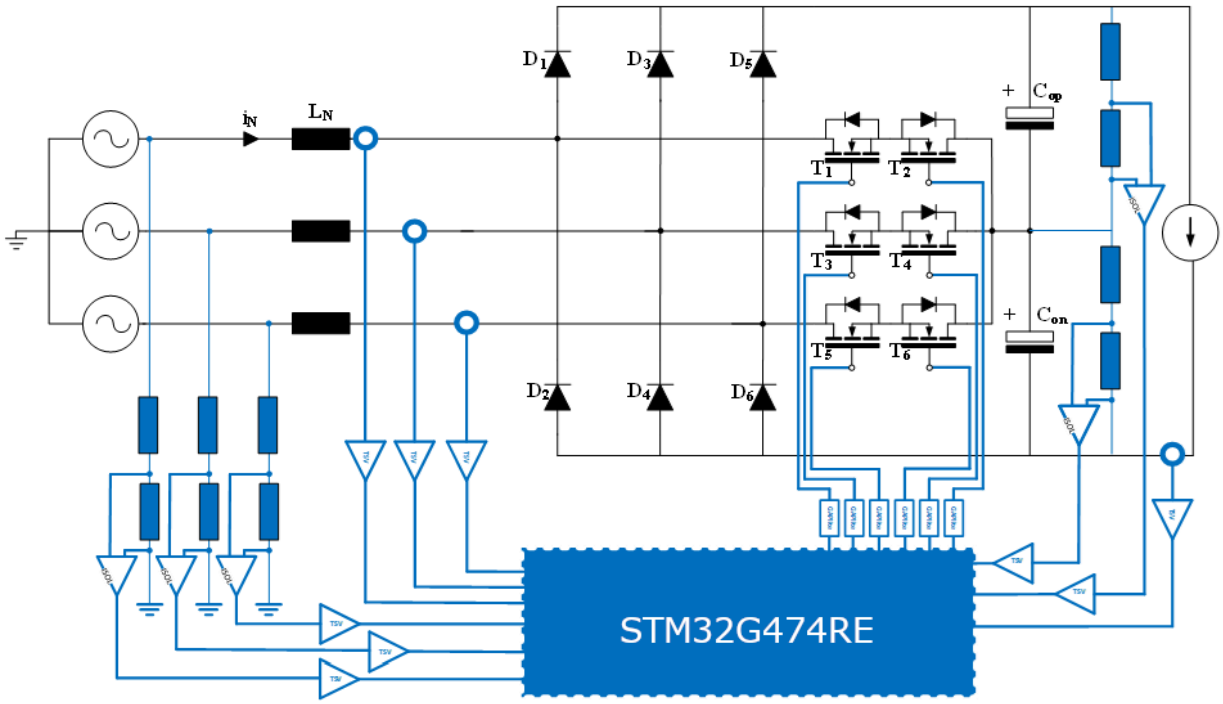
Caution: This reference design is intended for demonstration purposes only and is not for domestic or industrial installations.

Danger: *The high-voltage levels used to operate the reference design can cause serious injury, electrical shock, and even death.*

This reference design is intended for use by experienced power electronics professionals who understand the necessary precautions against potential dangers and risks while operating this board, even when it is not powered. The qualified personnel must be familiar with the installation, use, and maintenance of power electrical systems. During operation, do not touch the board as some of its components could reach a very high temperature.

1.2 Block diagram

Figure 4. STDES-VRECTFD block diagram



1.3 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: 15 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: >98.6%
  - Passive element weight and size reduction
- Control section based on the STM32G474RET3 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

1.4 Main characteristics

Table 1. Main characteristics

Description	Symbol	Min.	Typ.	Max.	Unit	Comments
Three-phase input voltage	V_{AC}	208		480	V_{ACLL}	
AC line frequency	Hz	47		63	Hz	
Maximum output power	P_{OUTmax}		15 7		kW	V_{AC} = 230 V_{RMS} I_{AC} = 21 V_{RMS} V_{AC} = 110 V_{RMS} I_{AC} = 21 V_{RMS}
Output voltage	V_{DC}		800		V	
Power factor	PF		>0.99		-	From 20% of load
Total harmonic distortion	THDi		<5		%	From 20% of load
Switching frequency	f_{sw}		70		kHz	

Table 2. Protection characteristics

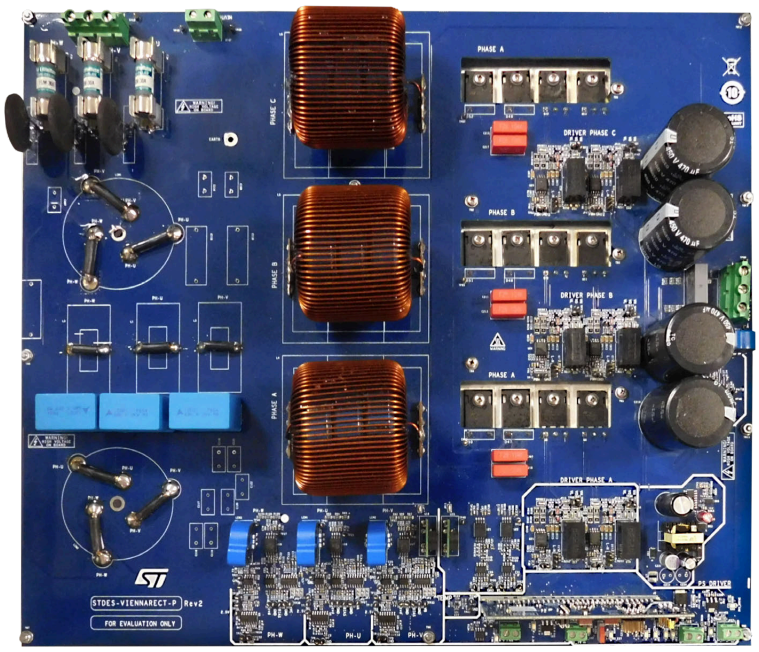
Description	Symbol	Min.	Typ.	Max.	Unit
HVDC overvoltage protection	V_{DCovp}			900	V
HVCAP overvoltage protection	V_{CAPovp}			500	V
AC overcurrent protection	I_{ACovp}			30	A

1.5 Reference design description

1.5.1 Power board

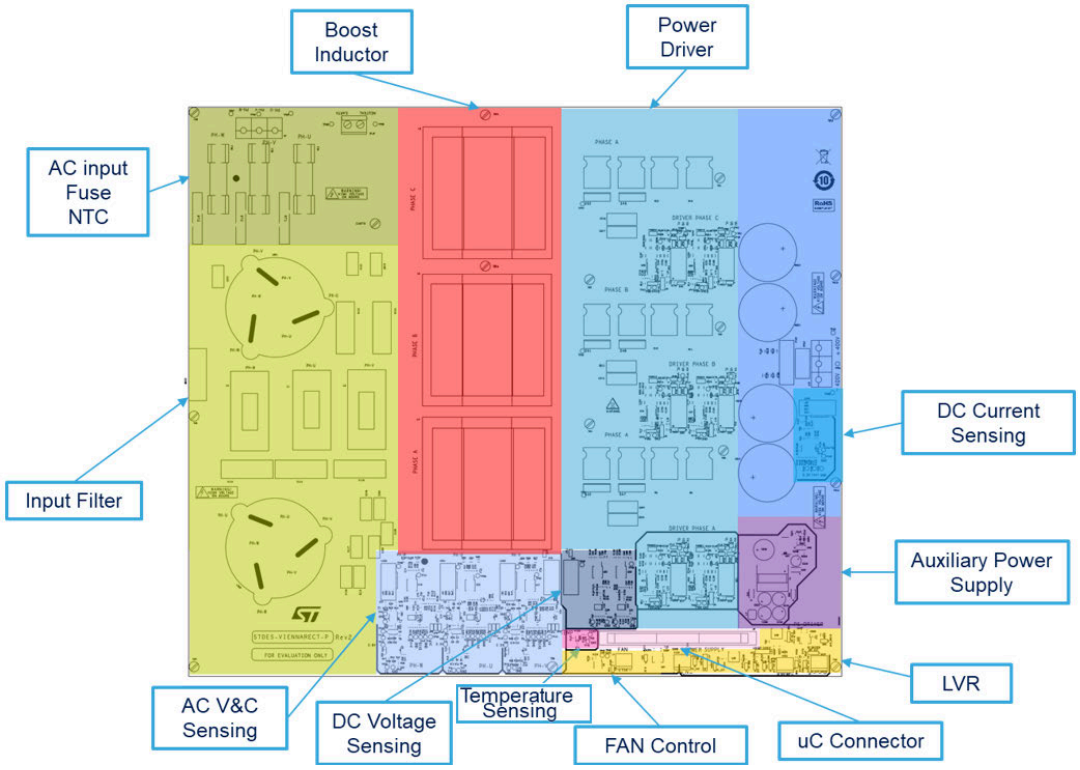
The figure below shows the power board of the STDES-VRECTFD reference design.

Figure 5. **STDES-VRECTFD reference design - power board**



The following figure shows the main sections of the power board.

Figure 6. **STDES-VRECTFD power board sections**



1.5.2 Power stage

1.5.2.1 Boost inductor

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

Continuous conduction mode (CCM) performs the PFC operation of this reference design. The inductance is related to several parameters: the desired current ripple, the available converter voltage levels, the switching frequency, and the rated DC-AC operation voltages.

Table 3. Boost inductor parameters

Parameter	Symbol	Value	Unit
DC voltage	V_0	800	V
Switching frequency	fsw	70	kHz
Rated AC voltage	V_{AC}	230	V_{RMS}
Max. ripple current	$\Delta_{iLppmax}$	10	%
Boost inductance	V_{AC}	470-6	H

1.5.2.2 *Passive current limiter NTC*

Figure 7. Three and four-wire connections

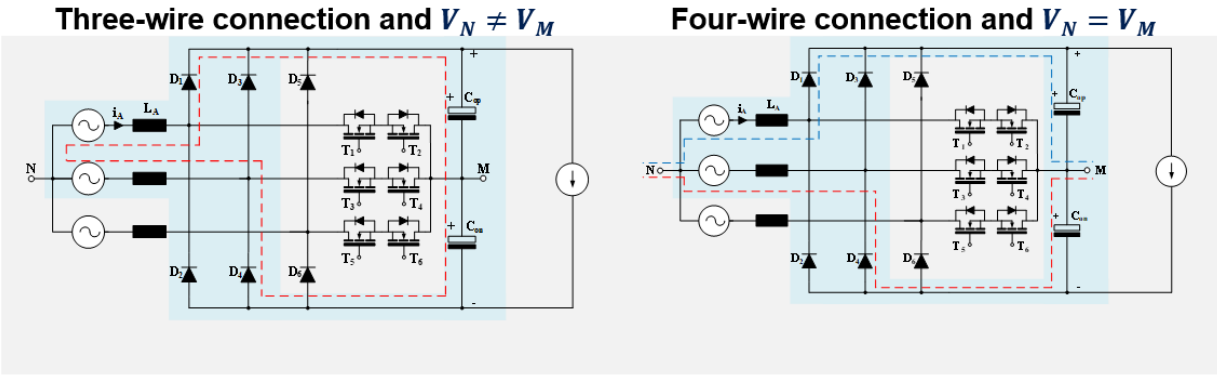


Figure 8. Focus on the STDES-VRECTFD NTC

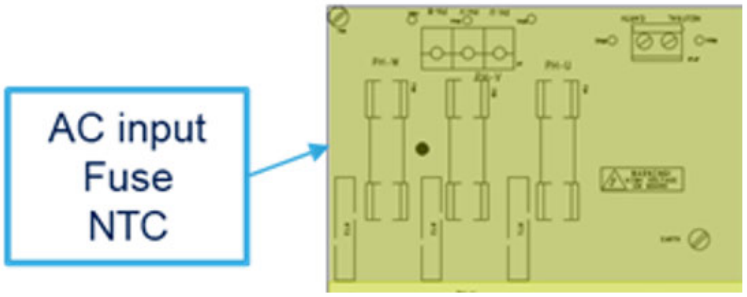


Figure 9. **STDES-VRECTFD NTC specifications**

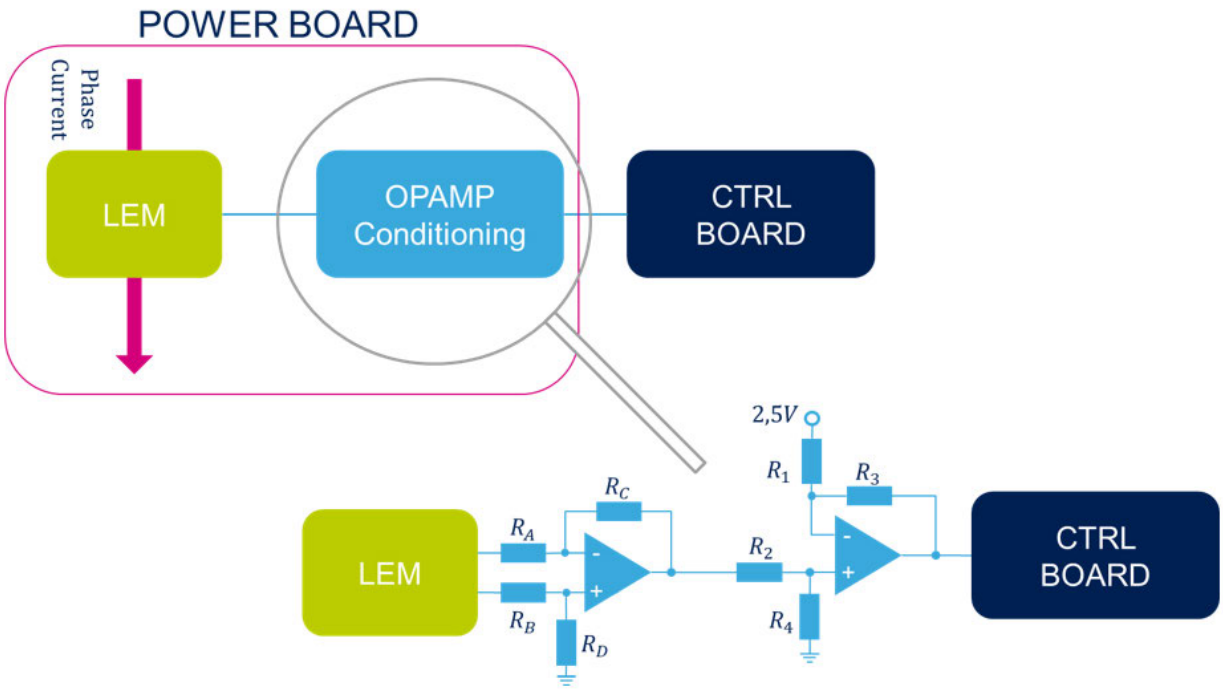
Min Resistance [Ω]	$R_{NTC_{min}} = \frac{\hat{V}_{AC}}{I_{max}}$	$e.g.\ R_{NTC} = \frac{\sqrt{2} \cdot 230}{60} = 5.42\ [\Omega]$
Steady State Current [A]	$I_{NTC_{SS}} = \frac{P_{OUT}}{V_{AC_{rms}}} \cdot \eta$	$e.g. I_{NTC_{SS}} = \frac{4k}{230} \cdot 98\% = 17\ [A]$
Maximum Energy [J]	$E_{NTC} = \frac{C\,\hat{V}_{AC}^{\,2}}{2}$	$e.g.\ E_{NTC} = \frac{313\mu F\ (\sqrt{2} \cdot 230)^2}{2} = 16\ [A]$

1.5.2.3 *Sensing*

1.5.2.3.1 AC current

An isolated sensor measures the AC input current. It represents the boost inductor current to be controlled for the proper operation of the power converter. Hall sensors are taken into consideration. A conditioning circuit allows obtaining the correct value for the ADCs. The circuit shown below is replicated for each phase.

Figure 10. **AC current sensing block diagram**



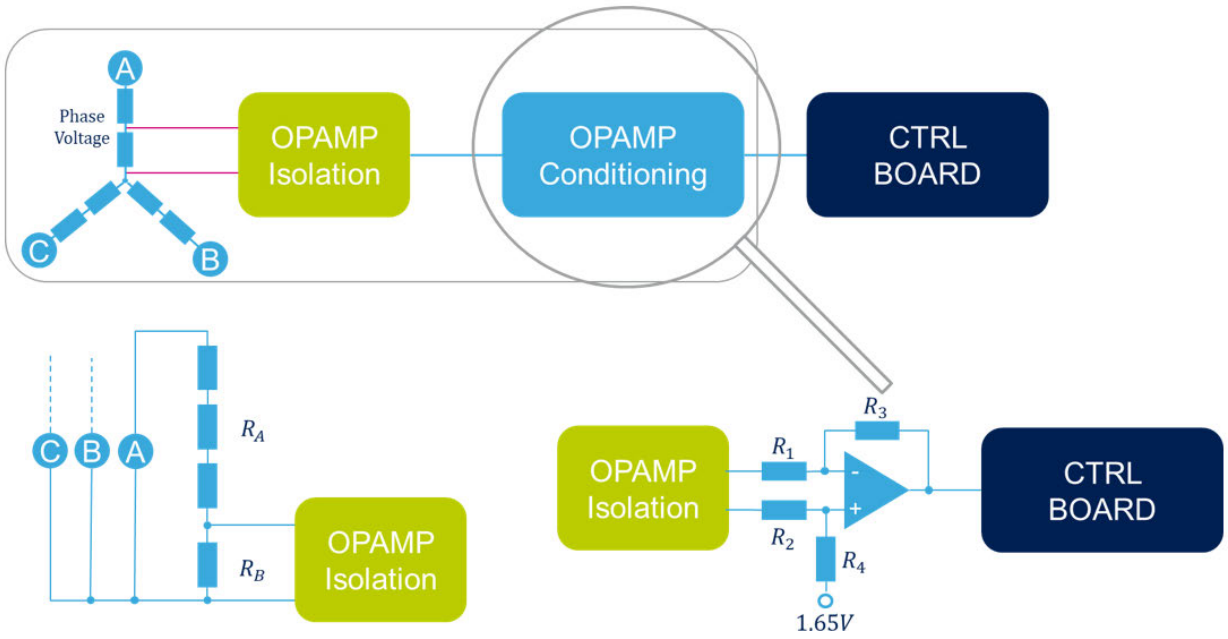
1.5.2.3.2 AC voltage

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

`Isol-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.

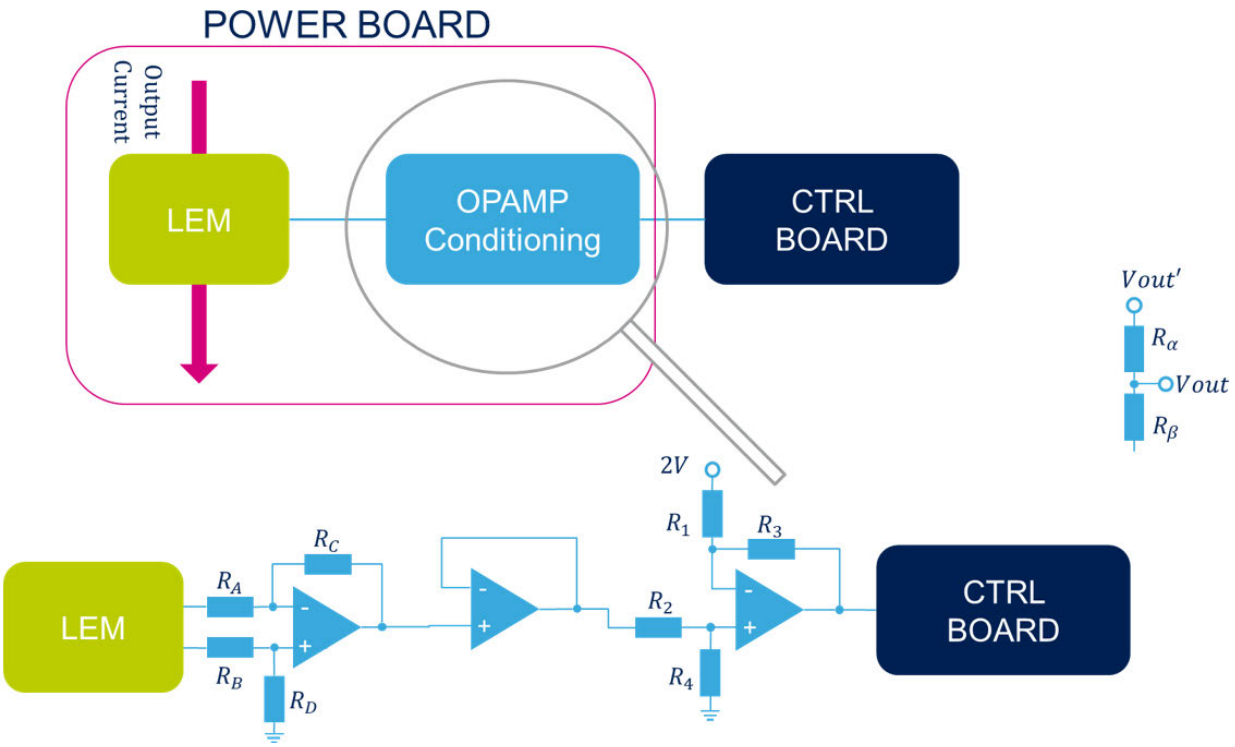
Figure 11. **AC voltage sensing block diagram**



1.5.2.3.3 DC current

An isolated sensor measures the DC output current. Hall sensors are taken into consideration. A conditioning circuit allows obtaining the correct value for the ADCs.

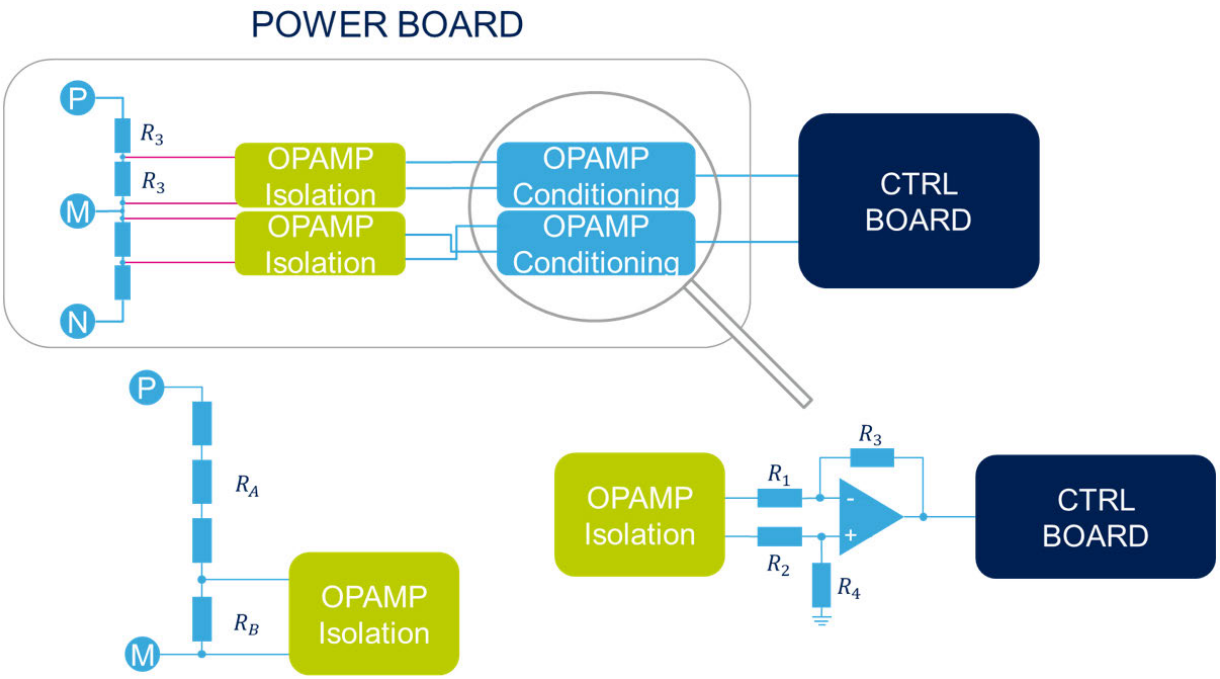
Figure 12. **DC current sensing block diagram**



1.5.2.3.4 DC voltage

The DC voltages are obtained using 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.

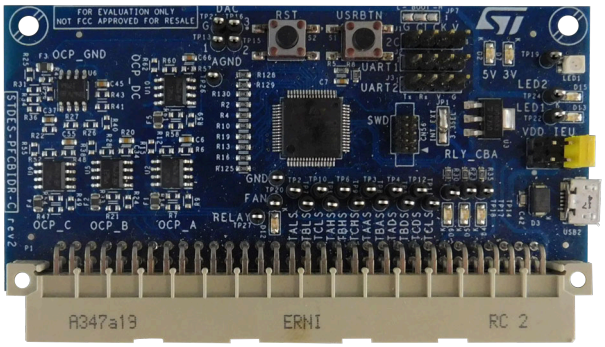
Figure 13. **DC voltage sensing block diagram**



1.5.3 Control board

The figure below shows the control board of the STDES-VRECTFD reference design.

Figure 14. **STDES-VRECTFD reference design - control board**



The following figure shows the main sections of the control board.

Figure 15. **STDES-VRECTFD control board sections**

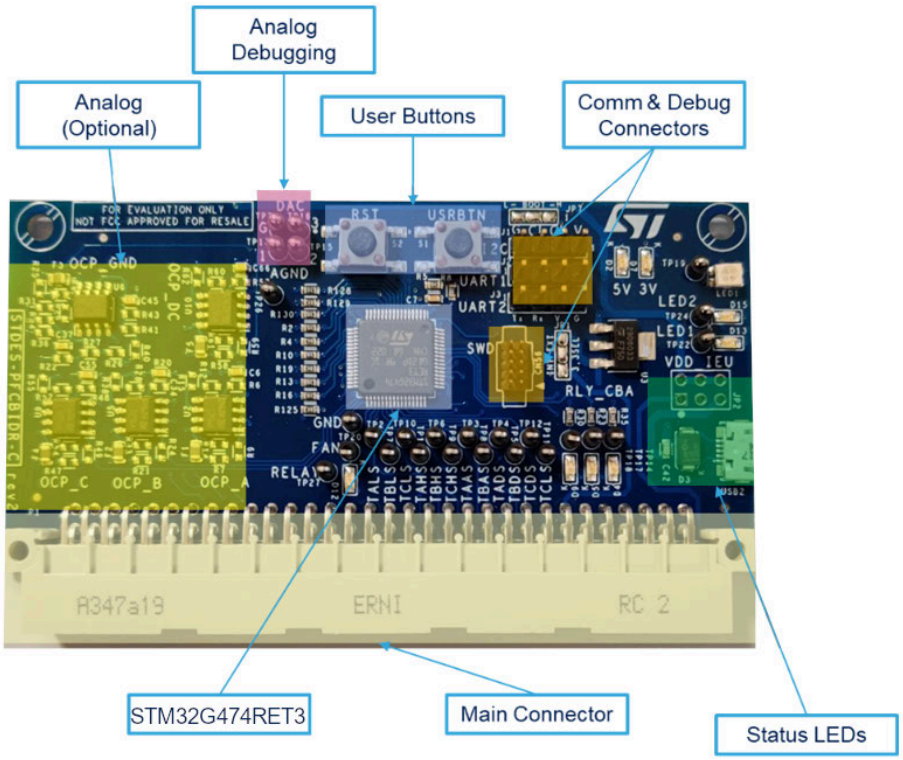
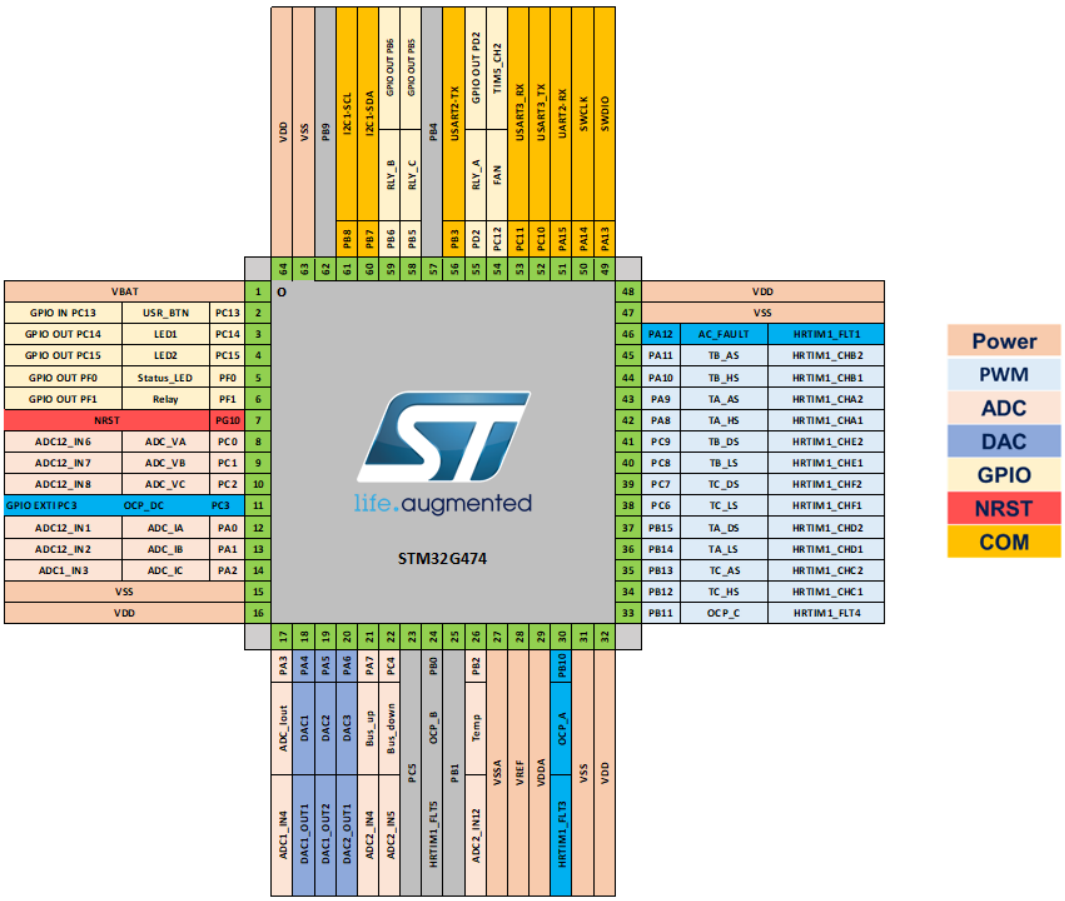


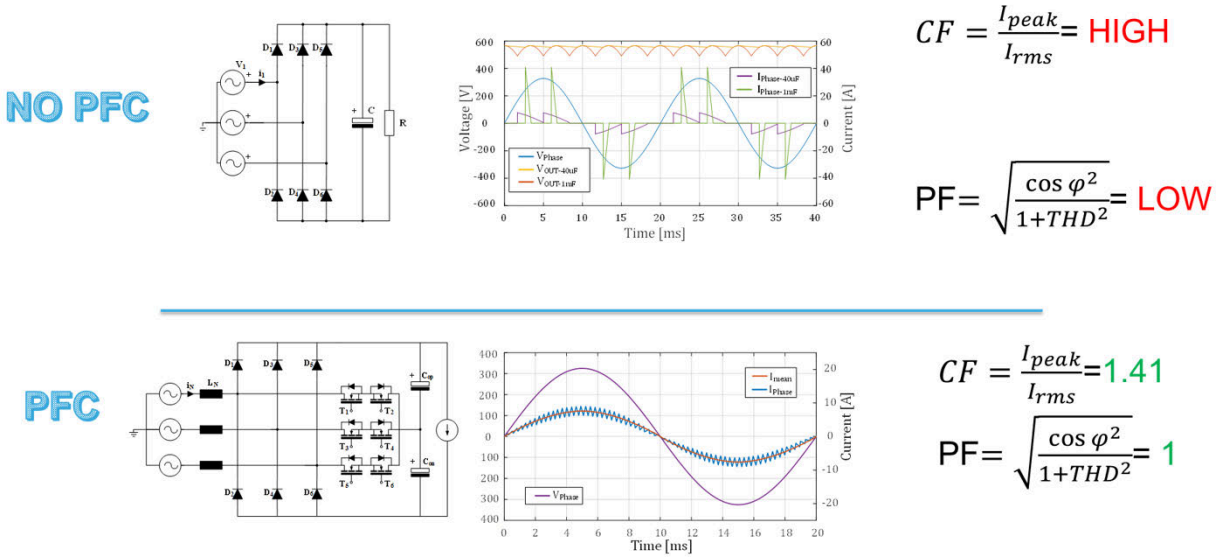
Figure 16. **STDES-VRECTFD MCU pin assignment**



1.6 Power factor correction (PFC) benefits

The figure below highlights the PFC benefits in terms of rest factor and power factor.

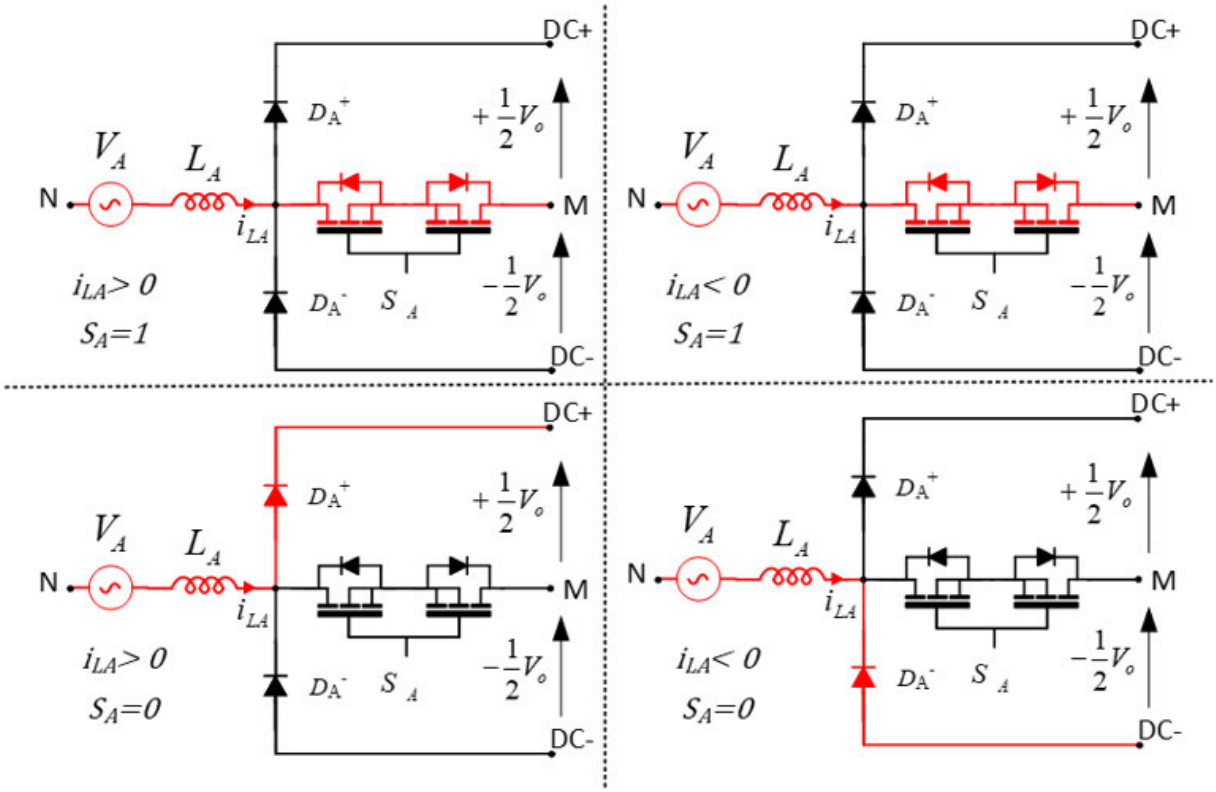
Figure 17. PFC benefits



1.7 Converter operation

The figure below shows the current paths of the Vienna topology. To simplify the scheme, we considered the single phase representation.

Figure 18. Switching paths of the Vienna topology



2 How to use the STDES-VRECTFD reference design

2.1 System setup

To use the STDES-VRECTFD, you need:

- a programmable AC emulator or a programmable AC source;
- a DC electronic load;
- a power analyzer;
- a digital oscilloscope.

You can test the STDES-VRECTFD up to 15 kW at 230 V_{AC} RMS and 6 kW at 110 V_{AC} RMS in a frequency between 47 and 63 Hz.

2.2 How to connect the reference design

To operate the reference design power converter properly, consider the operating limits shown below.

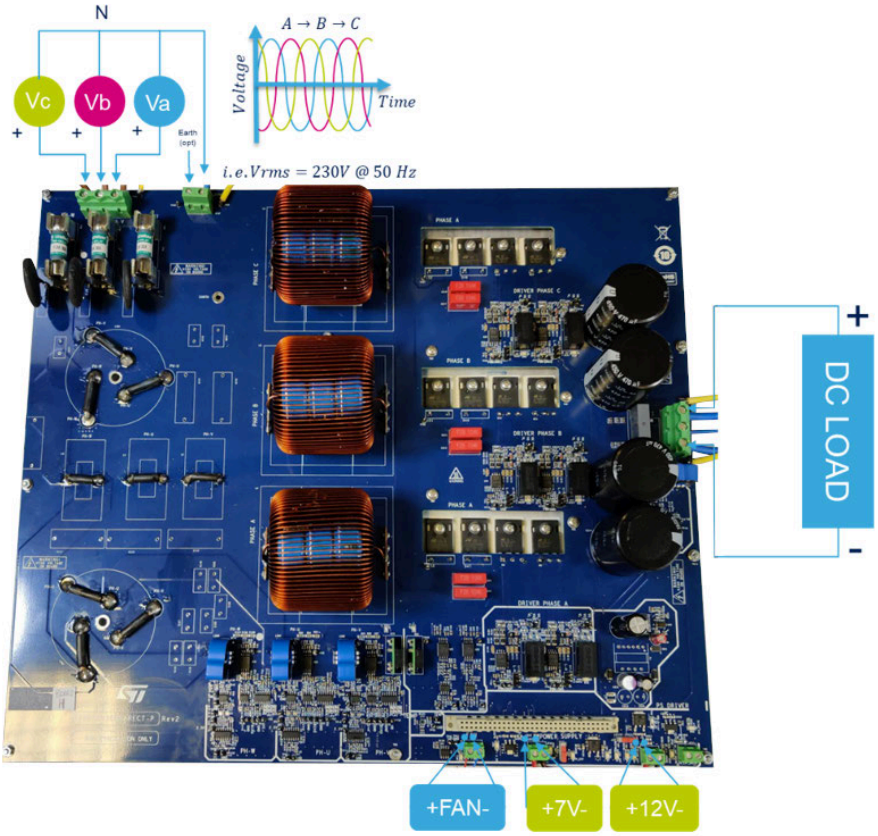
Table 4. Operation condition limits

Description	Value	Unit
Three-phase input voltage range	208-400	V_{AC}
Line frequency range	47-63	Hz
Maximum output power at 230 V_{AC}	15	kW
Voltage limit of the bulk capacitors	500	V

Step 1. Connect the power board as shown in the figure below.

The figure below shows the three-phase connection sequence (A-B-C). The neutral connection is optional. The polarity influences the DC load connection.

Figure 19. STDES-VRECTFD connection



Step 2. Connect an external fan to manage the thermal dissipation.

The auxiliary power supply can be externally provided.

2.3 MCU programming and debugging

You can program and debug the microcontroller unit (MCU) through different tools.

Step 1. Use ST-LINK/V2 and a 20- to 10-pin JTAG adapter to connect the platform to the PC.

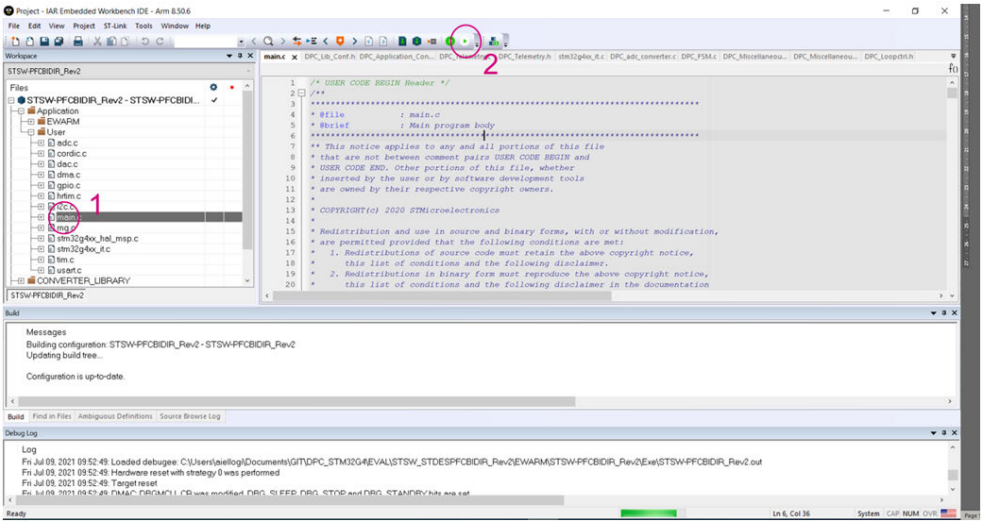
Figure 20. ST-LINK/V2 and adapter

Figure 21. ST-LINK/V2 connected to the control board

Step 2. Select the main.c file in the project/Application/User path.

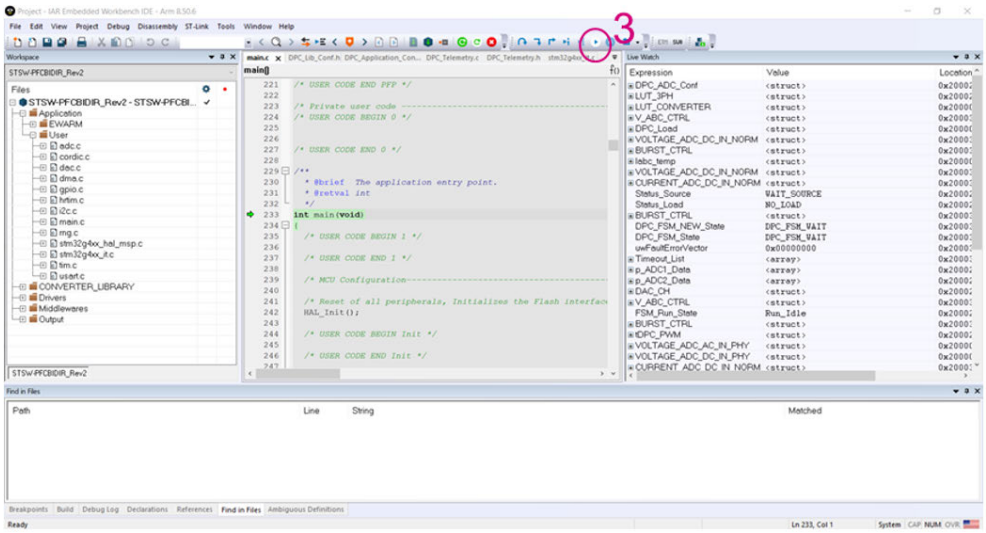
Step 3. Click on the [**Download and debug**] button to start programming and debugging.

Figure 22. IAR EWARM program procedure



Step 4. Click on the [**Run**] button to start the code execution.

Figure 23. IAR EWARM debug procedure

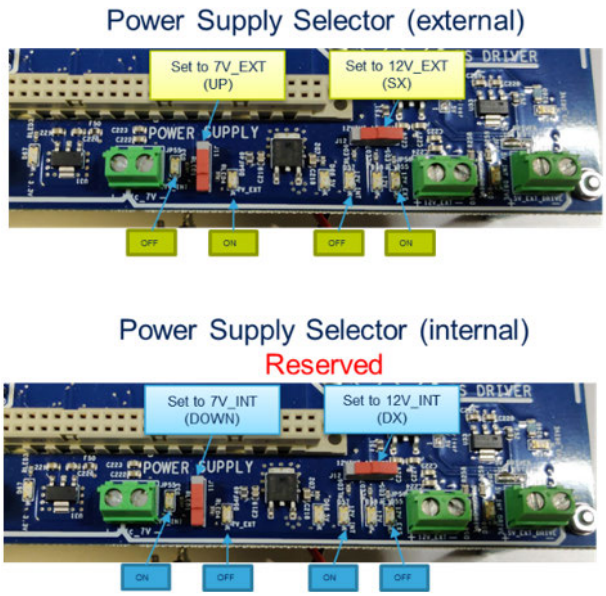


2.3.1 Power supply section

The power supply needs two different input voltages. An embedded SMPS, based on the VIPER26 family, provides self-powering from the DC-link.

As shown in the figure below, you can select either an internal or external supply voltage. Specific LEDs allow identifying the selected configuration.

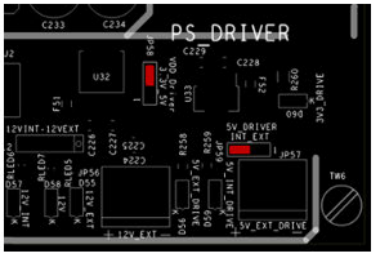
Figure 24. Example of power supply configuration



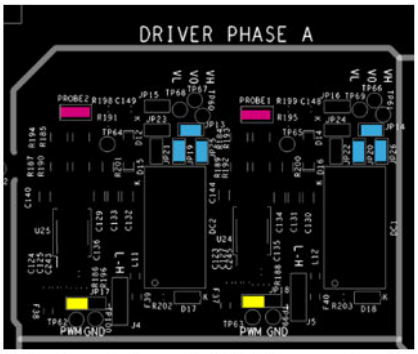
2.3.2 Driver section

The driving section configuration is related to the power switch technology. In this case, we considered the SiC power MOSFETs. The figure below shows this specific configuration.

Figure 25. Example of driver configuration



Driver section power supply selector



Gate driver VH VL selector

2.4 Preliminary test procedure

2.4.1 AC sensing

To verify the proper operation of the AC sensing (Figure 26), analyze the test points for voltages (Figure 27) and currents (Figure 28).

Figure 26. **AC sensing section**

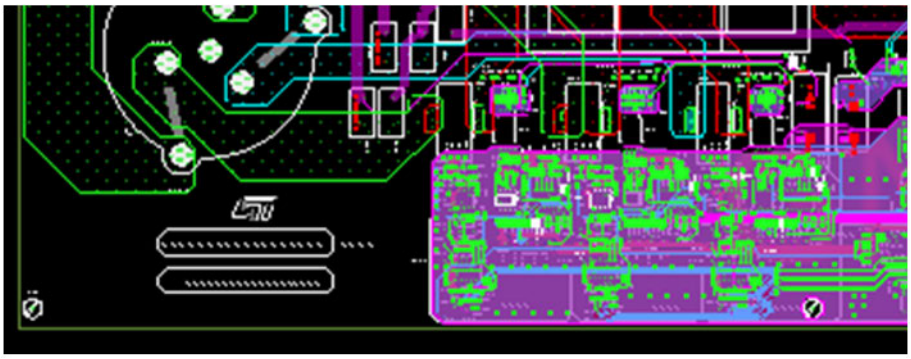


Figure 27. **AC voltage sensing test procedure**

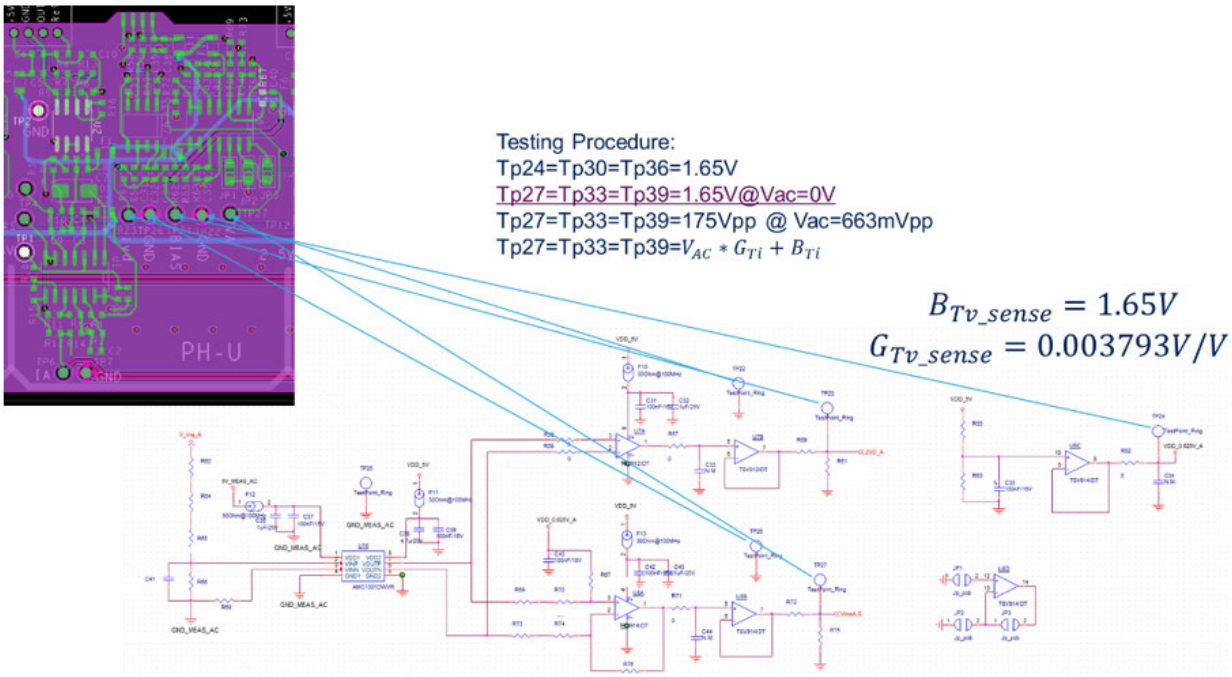
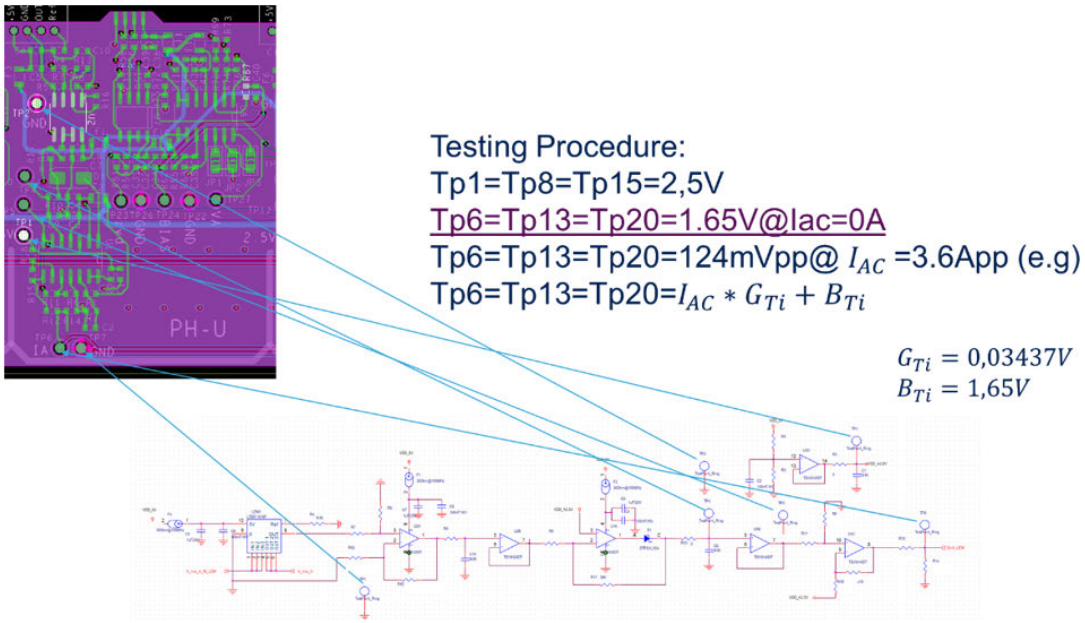


Figure 28. **AC grid current sensing test procedure**



2.4.2 DC sensing

To verify the proper operation of the DC sensing, analyze the test points for voltages (Figure 29) and currents (Figure 30).

Figure 29. **DC voltage sensing test procedure**

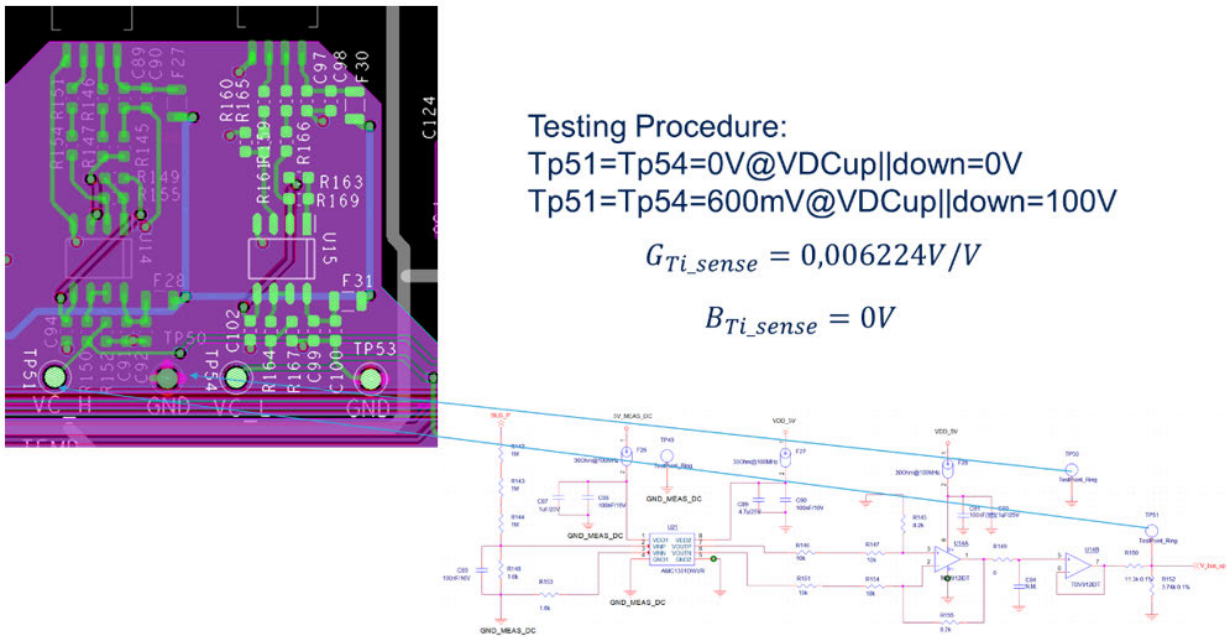
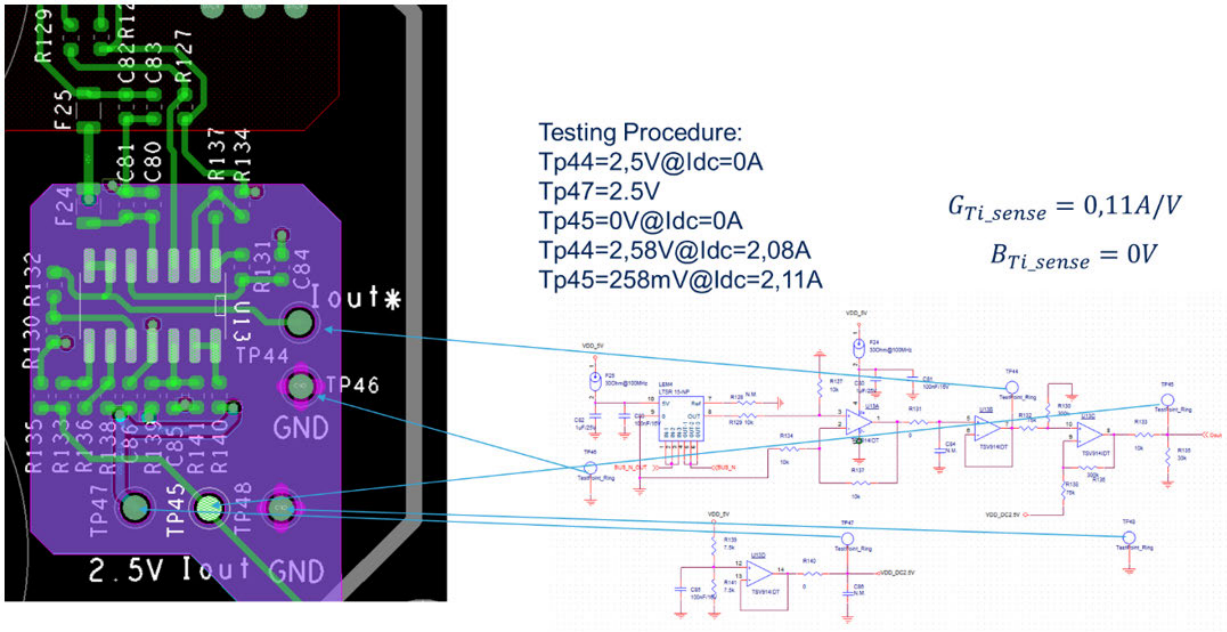


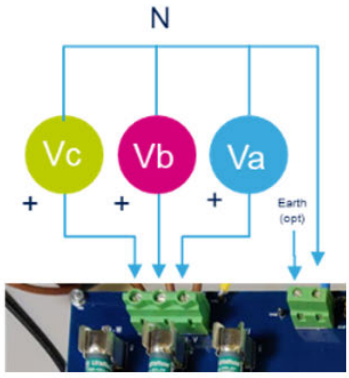
Figure 30. **DC current sensing test procedure**



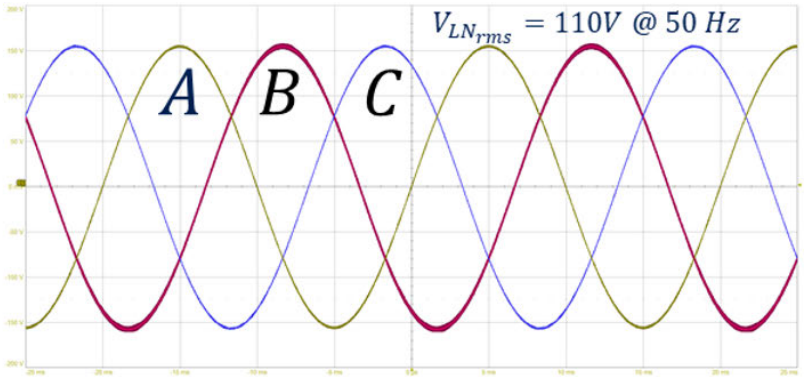
2.4.3 AC connection

Check that the STDES-VRECTFD AC main connection is in line with the figure below.
A three-phase sequence (ABC) is mandatory for the proper operation of the power converter.

Figure 31. **AC connection and sequence**



AC connection

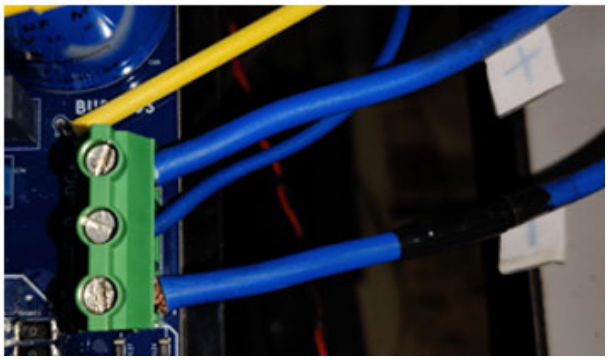


AC sequence

2.4.4 DC connection

The figure below shows the output DC connection. Ensure to apply the correct polarity.

Figure 32. **DC side load connection**



2.5 Startup procedure

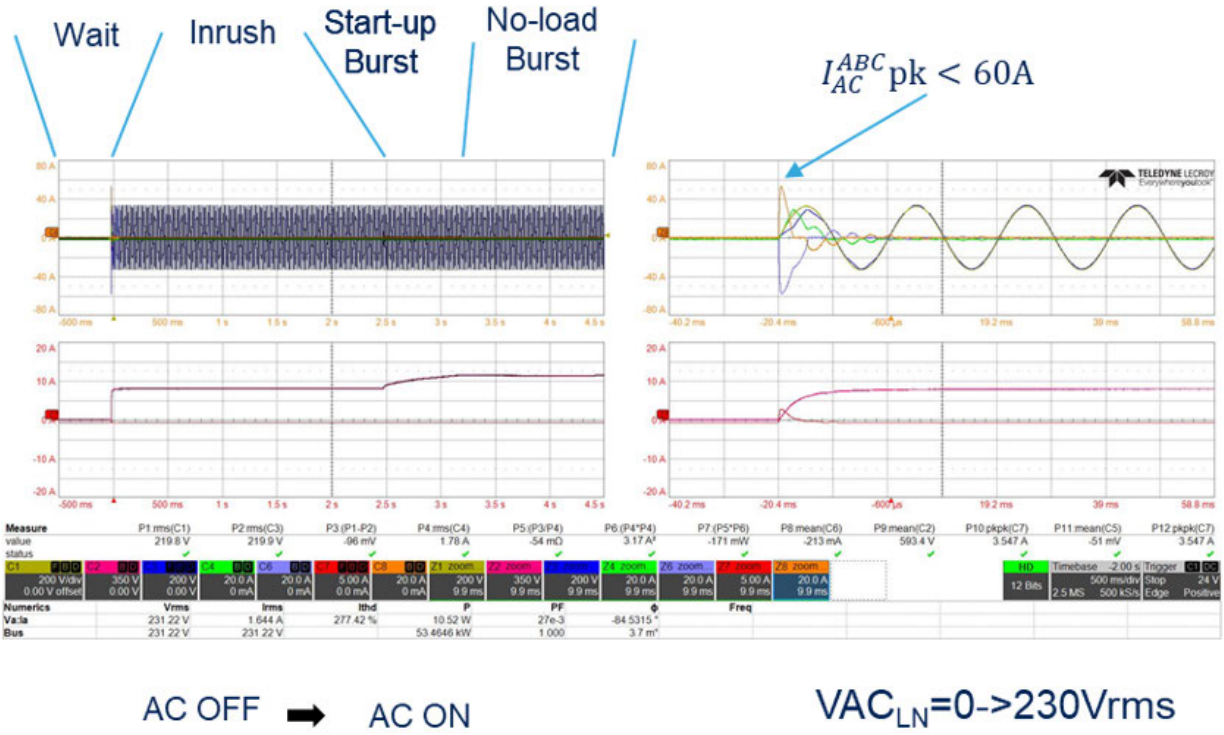
After connection and debugging initialization, you can perform the startup procedure.

An embedded finite state machine handles this procedure. It consists of different states that perform a preliminary check of the converter and the precharge of the capacitor. Then the burst operation boosts the output voltage.

The STDES-VRECTFD reference design allows managing the complete startup procedure.

However, a controlled step-by-step procedure is available. It is useful during the preliminary test or after hardware/sw modification.

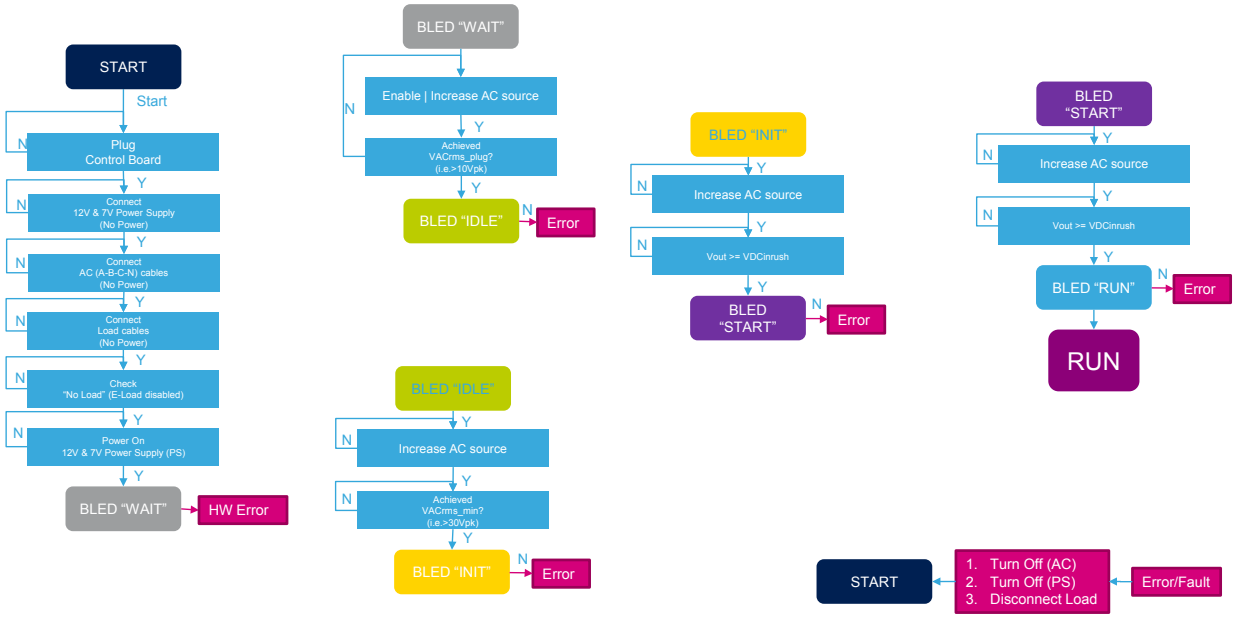
Figure 33. **Startup procedure**



2.5.1 Controlled startup procedure

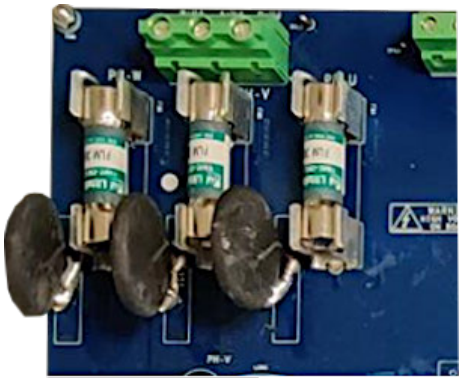
The AC power supply is slowly increased to verify the procedure step step-by-step as shown below.

Figure 34. **Connection and power-on procedure**



This procedure takes the ICL NTCs into consideration.

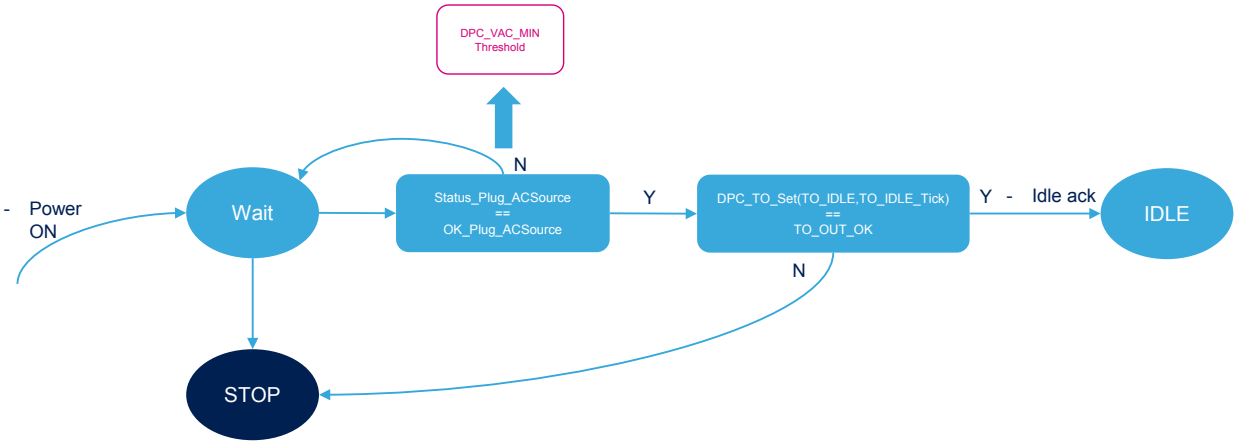
Figure 35. **STDES- VRECTFD ICL NTCs**



The procedure consists of the following steps.

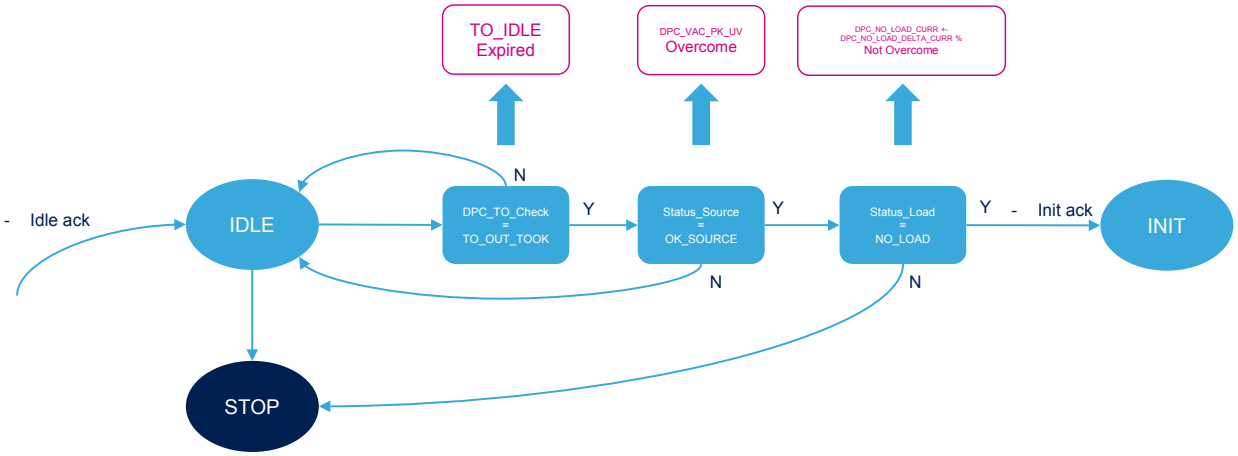
1. `FSM Wait`: PWM signals are in IDLE state, configured in low state, to force all the MOSFETs in off state. The AC main voltage is already under monitoring. This state is maintained until AC main reaches a lower AC voltage threshold (`OK_Plug_ACSource`), that is 30 V_{AC}. After that, an internal timeout (`TO_IDLE`) is activated to prevent power converter connection during the first-phase synchronization procedure. FSM moves on to `FSM Idle`.

Figure 36. FSM_Wait block diagram



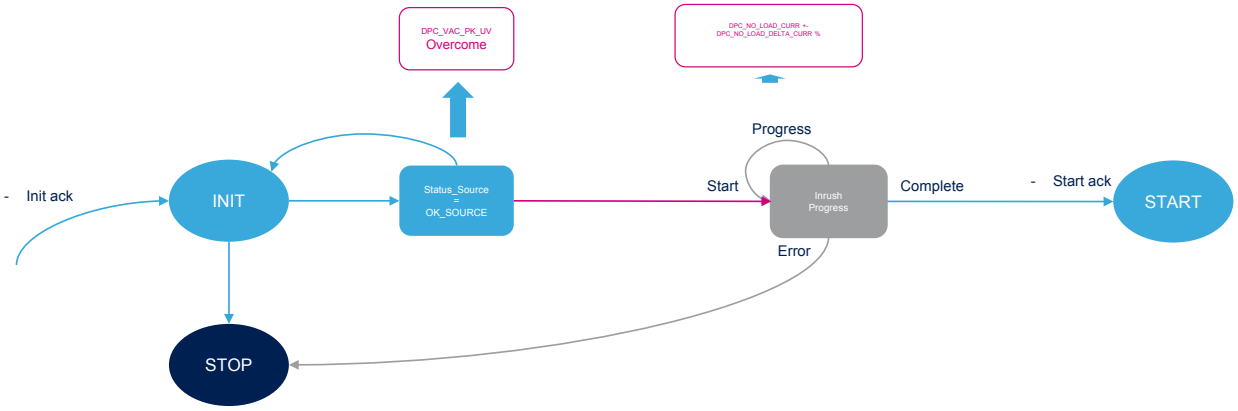
2. `FSM Idle`: after `TO_IDLE` time elapses, wait for the AC mains to reach the uvAC value (`OK_SOURCE`). After checking the load current, a new timeout is set (`TO_INIT`) to prevent PLL instability. FSM moves to `FSM_Init`.

Figure 37. FSM_Idle block diagram



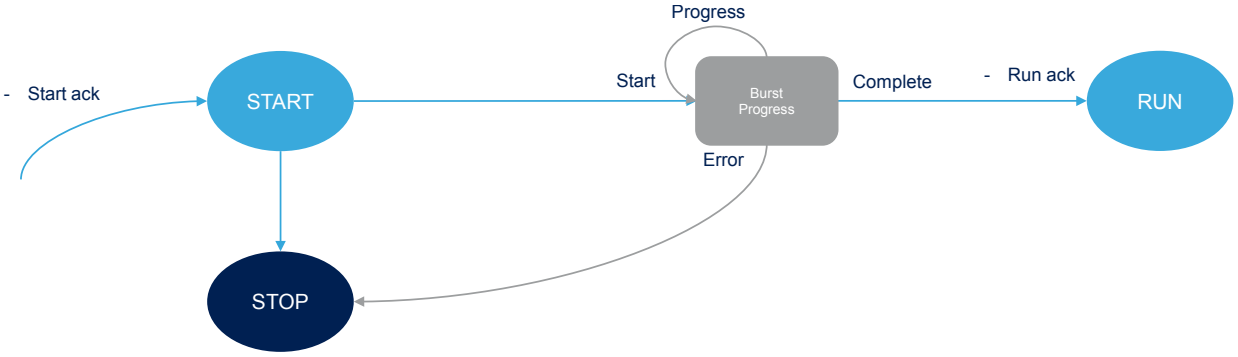
3. `FSM_Init`: handles the inrush current control. If the grid voltage is correct, the status source is equal to `OK_SOURCE`. The bulk capacitors are at low voltage and the inrush current must be limited. For this reason, during this state, the inrush relays are considered in series with a high resistance. On the basis of their values, the inrush is completed. The state machine state is still maintained to stabilize the output voltage according to the grid amplitude. After a configurable time, the FSM moves to start state (`FSM_Start`).

Figure 38. FSM_Init block diagram



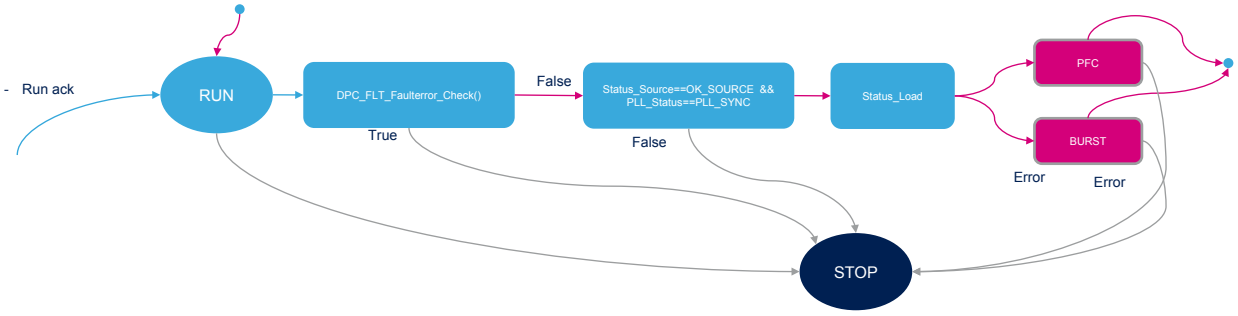
4. `FSM_Start`: is related to the burst mode operation of the power converter. During this procedure, the PWM is activated. The pulse sequence at a fixed duty cycle allows boosting the input voltage and increasing the DC output voltage at a reference voltage. The state machine then moves to `FSM_Run` state.

Figure 39. FSM_Start block diagram



5. `FSM_Run`: if the startup procedure is completed without any issue, `FSM_Start` manages the PFC operation of the power converter. The burst operation still maintains the DC voltage. If a DC load occurs, the PFC modulation and the control loop are activated to handle the load power demand.

Figure 40. FSM_Run block diagram



2.5.2 Direct startup procedure

The finite state machine manages a direct startup procedure. The AC source takes the nominal voltage into consideration. The inrush current limitation and the burst mode operation must be completed after the DC load connection.

3 Control

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

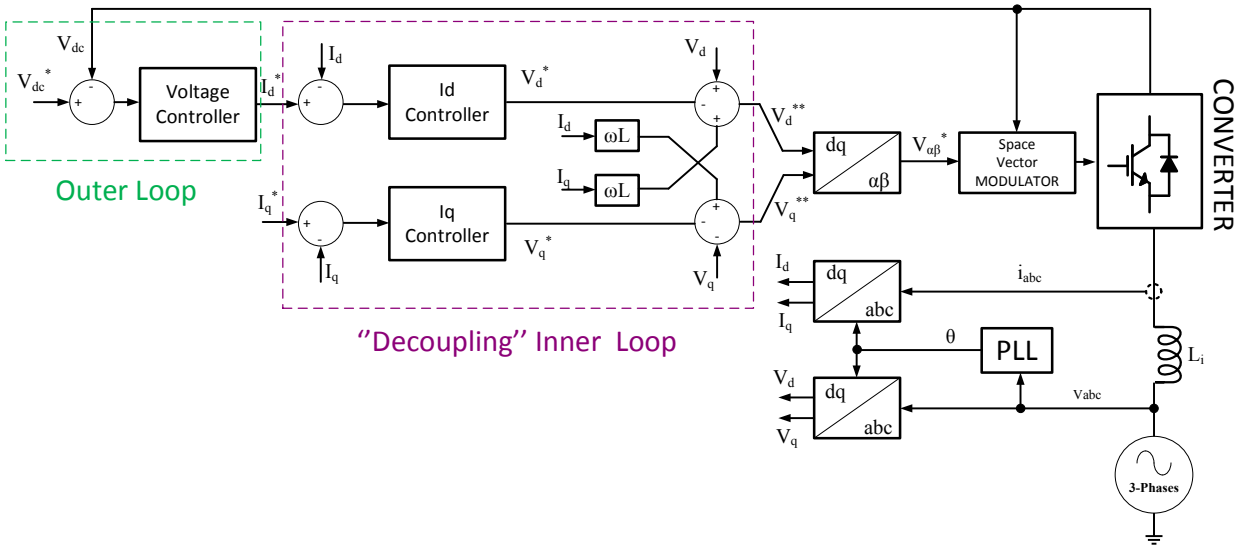
Table 5. Control strategy comparison

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

3.1 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 taken into account.

Figure 41. Cascaded control



3.1.1 Current control strategy

A continuous conduction mode controls the reference design current.

Figure 42. **Continuous conduction mode in current control**

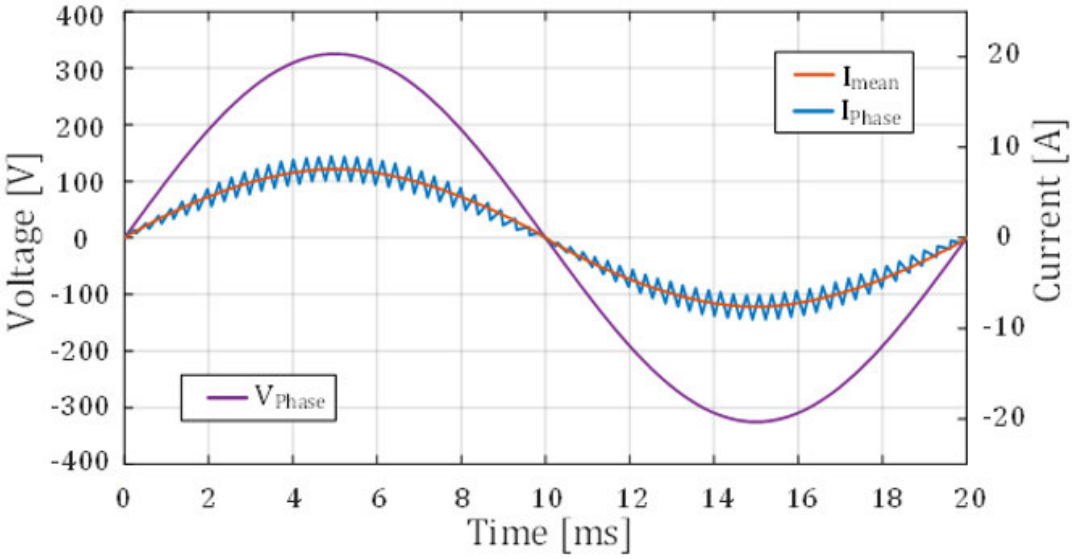


Figure 43. **Current decoupling control of the reference design converter model**

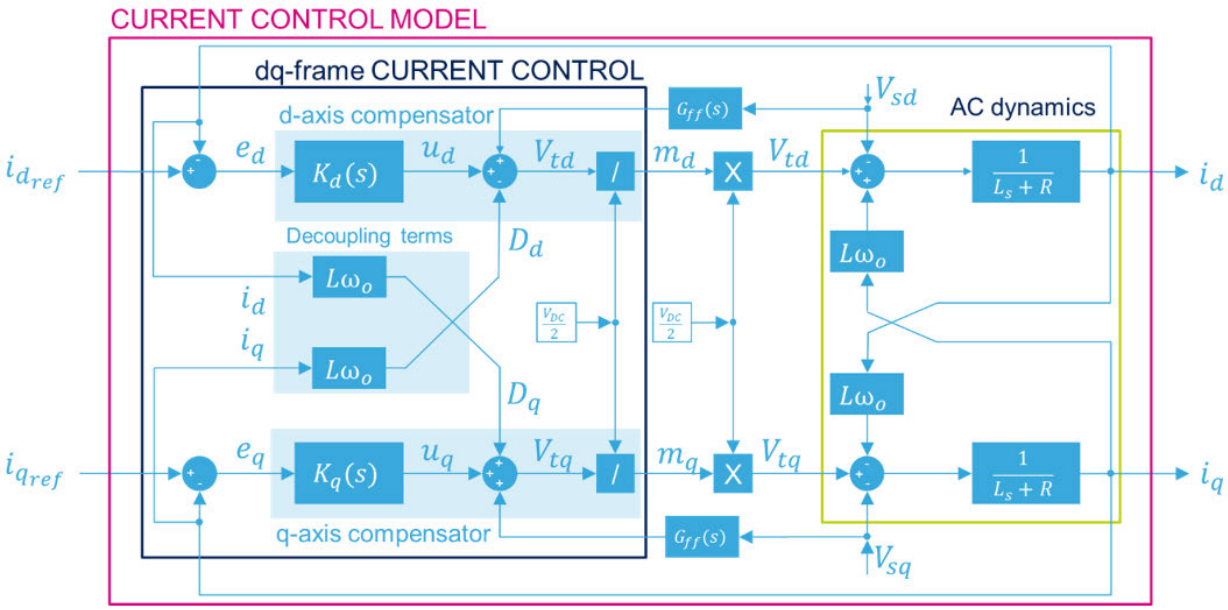
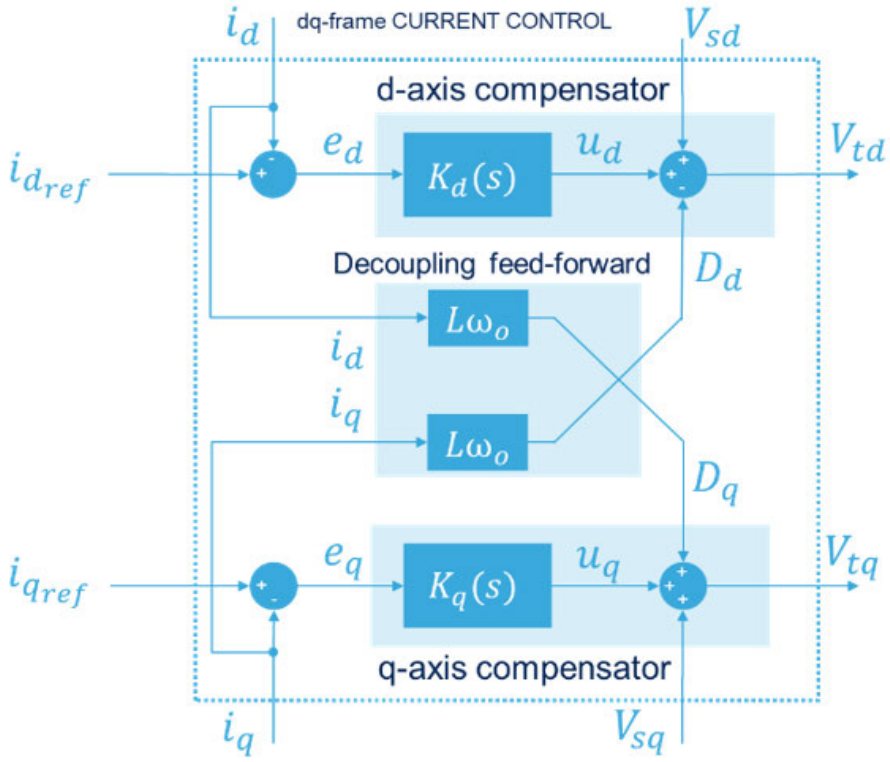


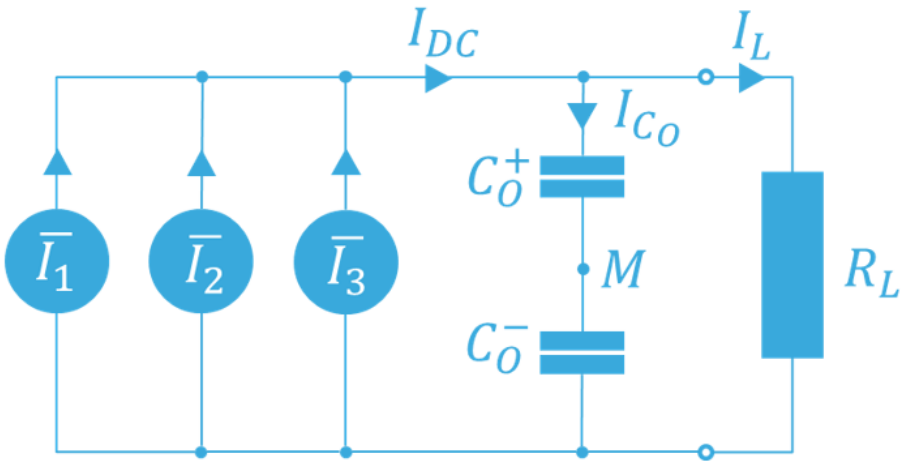
Figure 44. **CDC**



3.1.2 Voltage control strategy

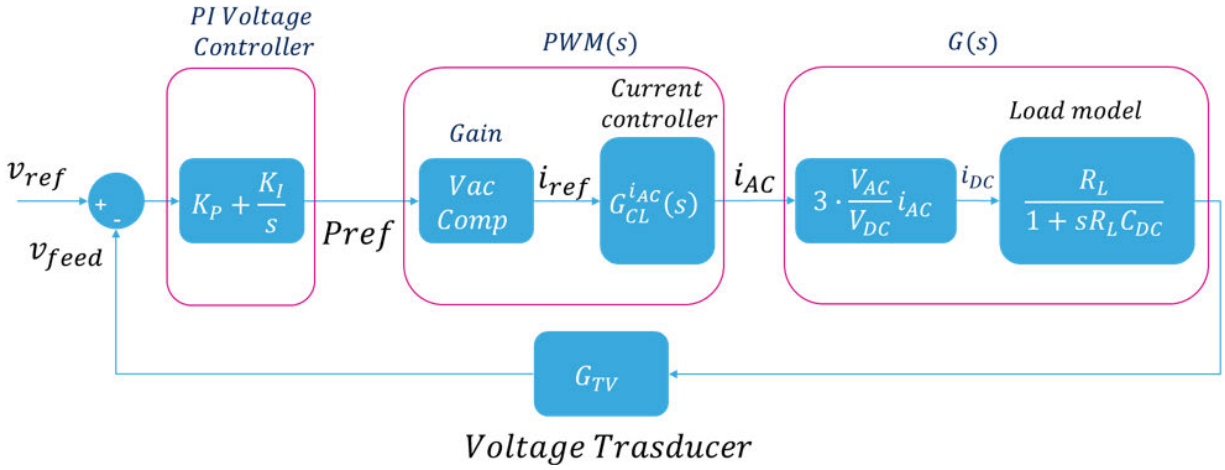
The outer loop of the PFC operation is a voltage control.

Figure 45. **Converter DC side model**



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

Figure 46. **Voltage control diagram**



3.2 Phase locked loop

In converter control, the PI regulators are usually used. This kind of regulator gets the best results when using a DC reference term.

Figure 47. **PLL internal regulator loop**

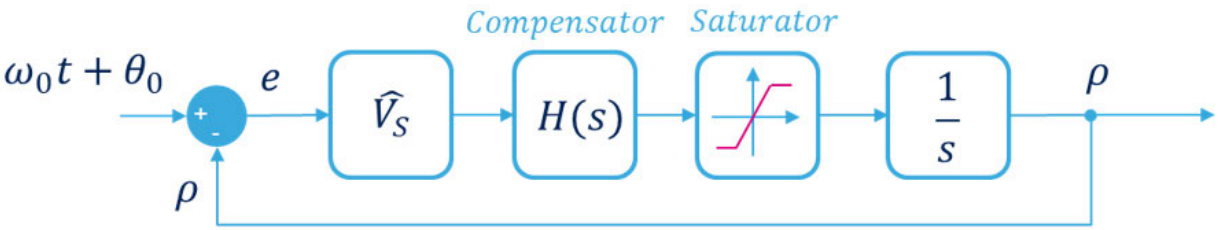
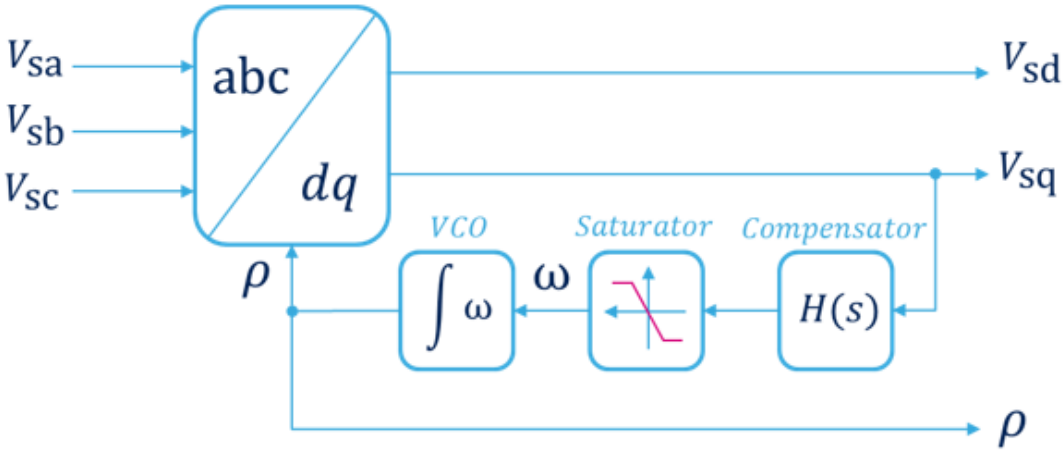


Figure 48. **PLL in AC main voltage**



4 Software implementation

The STM32G474RET3 MCU controls the STDES-VRECTFD.

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.

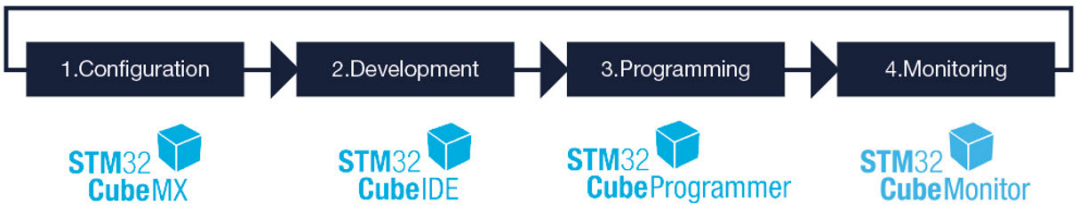
The application firmware is supported and tested using STM32CubeIDE, IAR, and Keil development environments.

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.

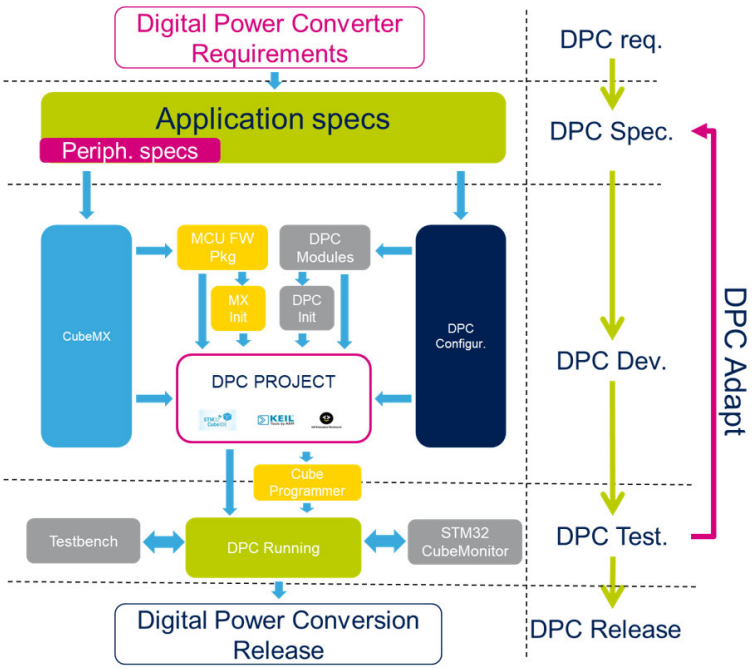
The firmware described in this documentation development is based on the STM32CubeG4 firmware package v1.3.0.

Figure 49. 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-VRECTFD firmware development.

Figure 50. DPC development flow



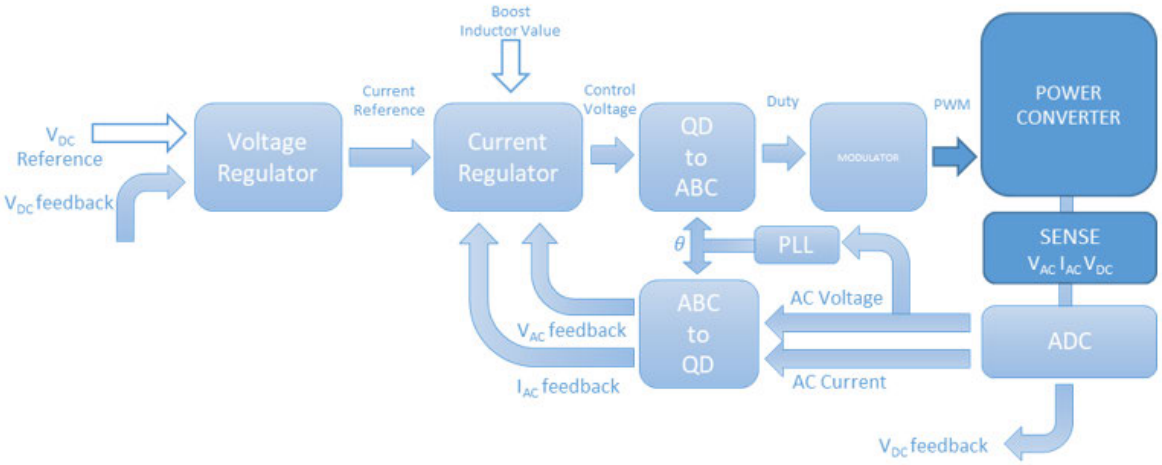
This workflow starts from power conversion requirements. This information is then reinterpreted in the application specs that contain information linked to the MCU peripheral and the DPC application configuration.

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.

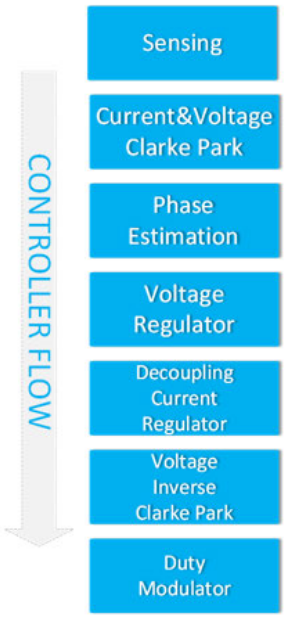
The STDES-VRECTFD reference design power converter allows managing the energy flow. The figure below shows the algorithm schematic diagram of the implementation in the AC-DC rectifier application.

Figure 51. AC-DC rectifier application



The figure below shows the basic representation of the execution flow. A current decoupling control well fitted for this application is used. This allows managing the energy flow in terms of AC current.

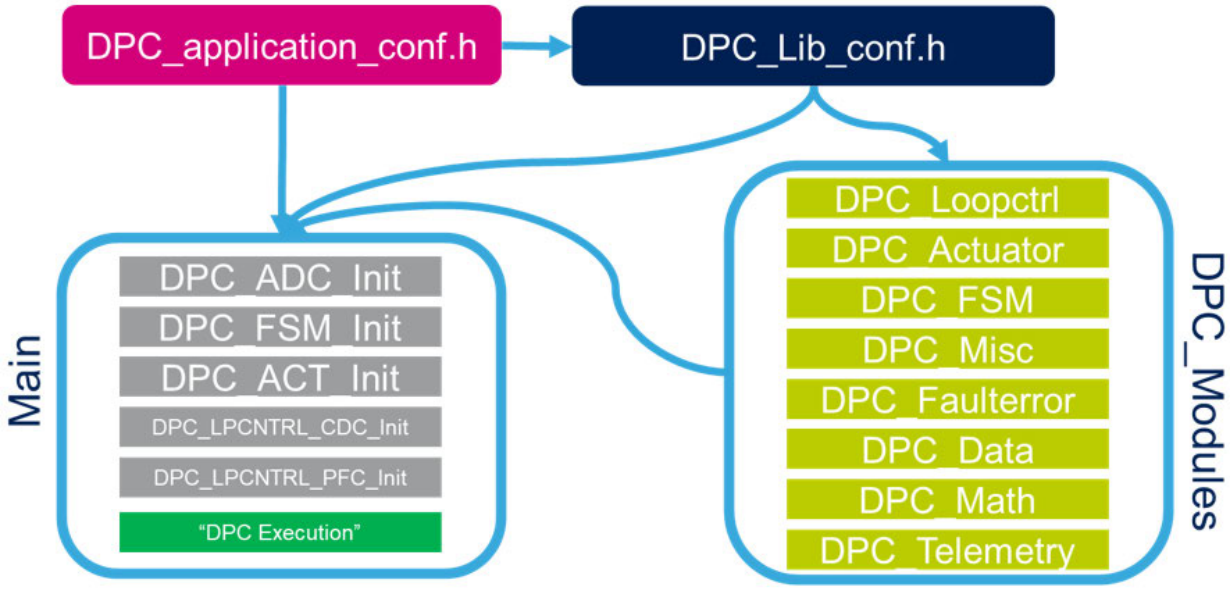
Figure 52. Simplified execution task of the control in AC-DC



4.1 Configuration files

The STDES-VRECTFD power converter configuration is based on two main configuration files.

Figure 53. **STDES-VRECTFD configuration files**



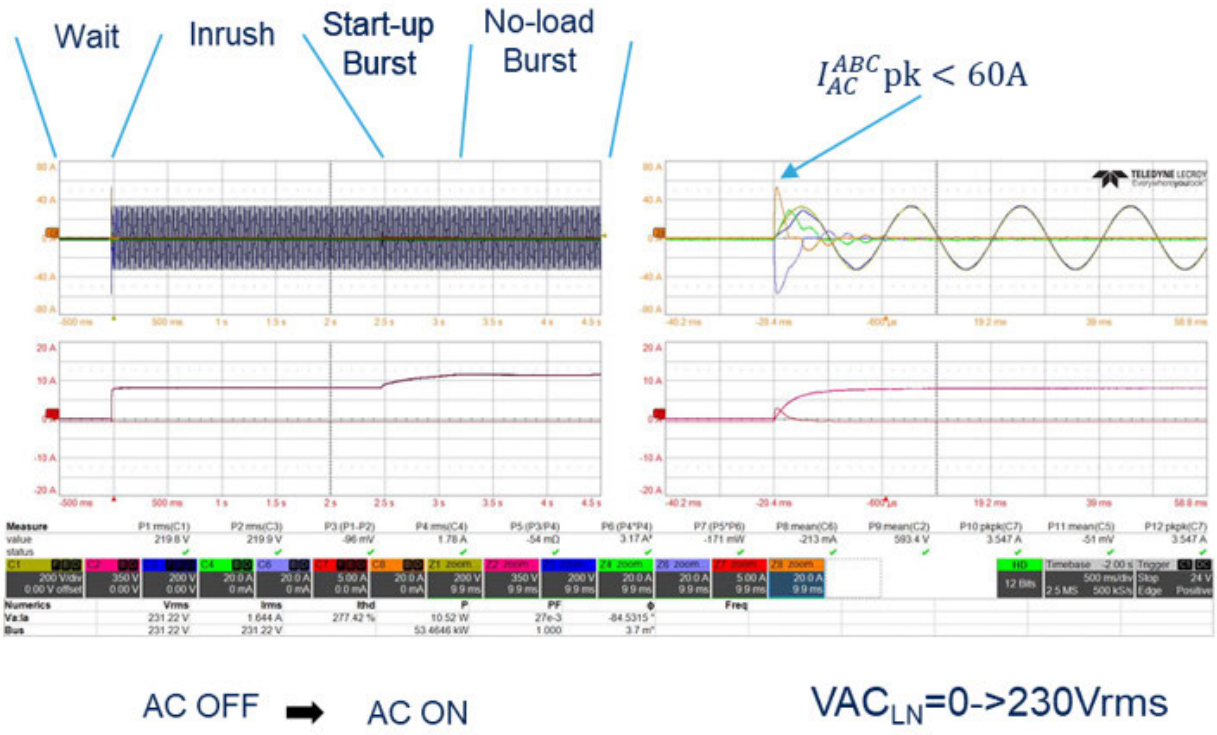
The “DPC_application_conf” header file contains the application specific `DEFINE` (that is the ADC gain factor PI regulator gain, FSM configuration, control reference value, etc.).

The “DPC_Lib_conf” header file contains the configuration parameters linked to the MCU peripheral configuration.

5 Measurements

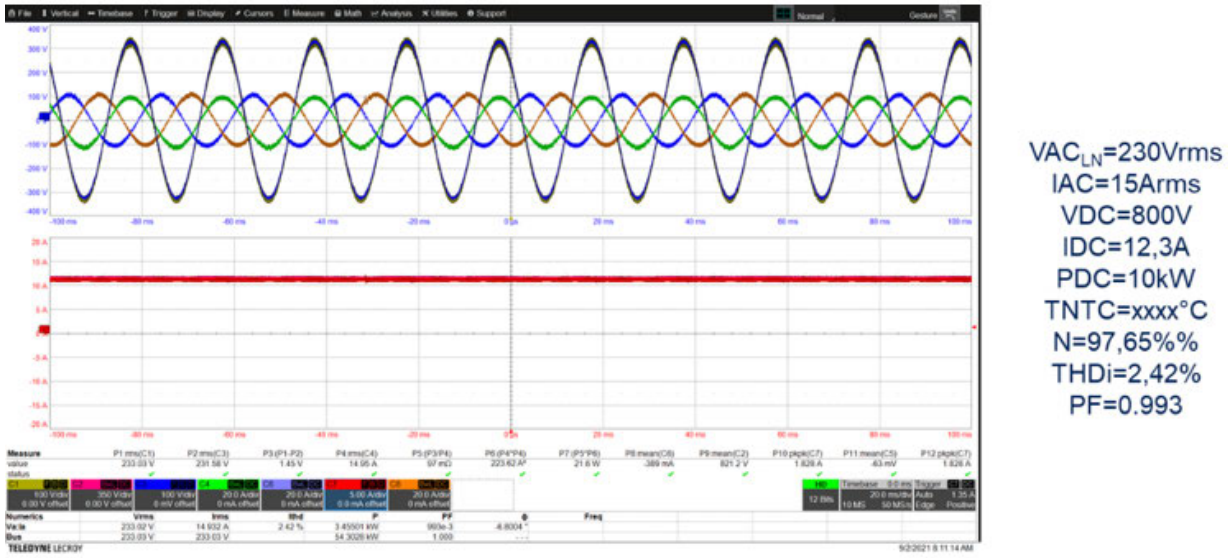
5.1 Startup procedure

Figure 54. **Startup procedure**



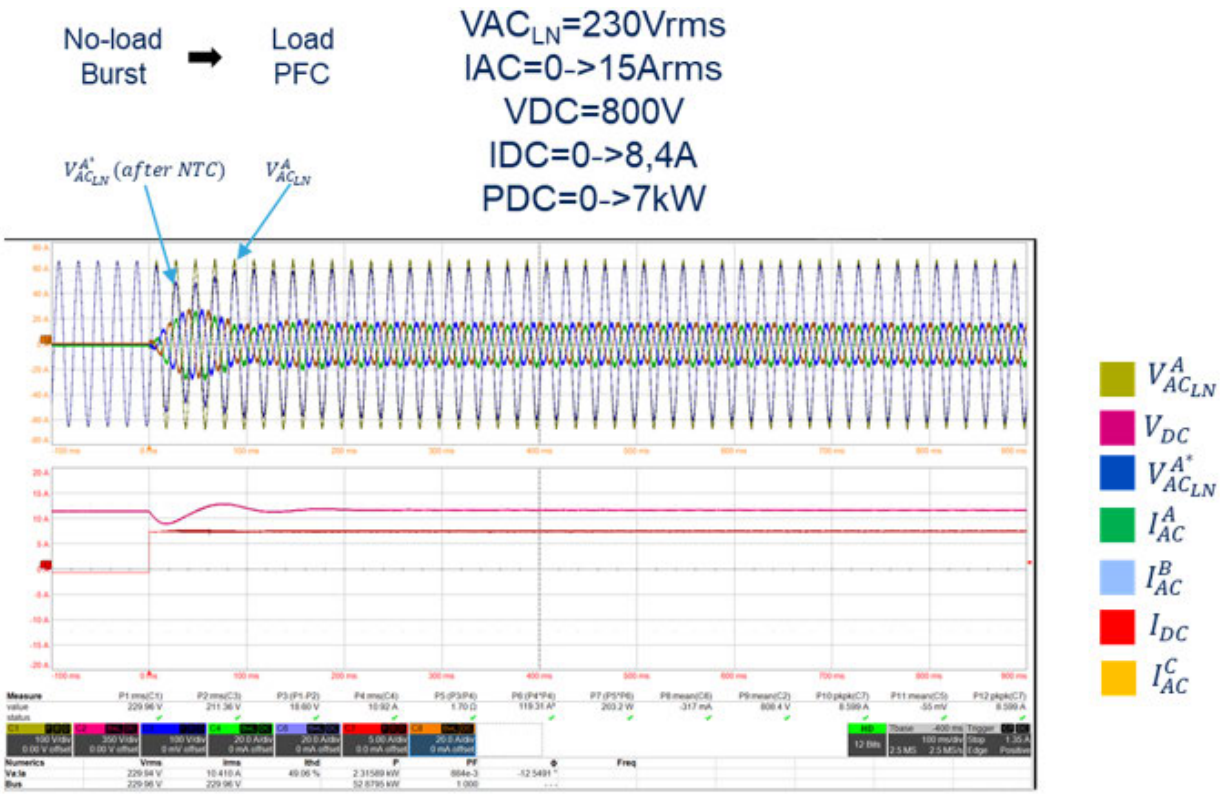
5.2 PFC operation

Figure 55. **PFC operation**



5.3 Step load

Figure 56. **Step load**



5.4 Power factor, efficiency, and THDi

The table below shows the power factor (PF column), efficiency (n column), and THD (THDi column).

Table 6. **STDES-VRECTFD power factor, efficiency, and THDi**

VAC_{LN} [Vrms]	IAC [Arms]	V_{DC} [V]	I_{DC} [A]	P_{DC} [kW]	S_{AC} [kVA]	P_{AC} [kW]	n [%]	PF	f_{sw}[kHz]	THDi [%]
230	1.64	800	1.24	1	1.1360	1.0277	97.53	0.922	70	18.24
	3.03		2.49	2	2.0984	2.0353	98.32	0.949		13.72
	4.46		3.73	3	3.0839	3.0403	98.493	0.976		9.72
	5.92		4.99	4	4.0919	4.0593	98.618	0.986		6.46
	7.39		6.23	5	5.1078	5.0801	98.569	0.991		4.87
	8.85		7.47	6	6.110	6.0877	98.491	0.994		4.57
	10.27		8.67	7	7.096	7.0759	98.461	0.995		3.69
	11.82		9.97	8	8.1639	8.1456	98.34	0.997		3.29
	13.29		11.21	9	9.1716	9.1547	98.25	0.997		3.07
	14.77		12.44	10	10.1935	10.1778	98.08	0.998		2.50
	16.21		10.94	11	11.186	11.1719	97.99	0.998		2.42
	17.76		14.96	12	12.27	12.26	97.86	0.999		2.31
	19.29		16.2	13	13.30	13.29	97.74	0.999		1.99
	20.74		17.39	14	14.31	14.29	97.59	0.999		2.01
	22.26		18.66	15	15.357	15.345	97.49	0.999		2.01

Figure 57. **STDES-VRECTFD power factor plot**

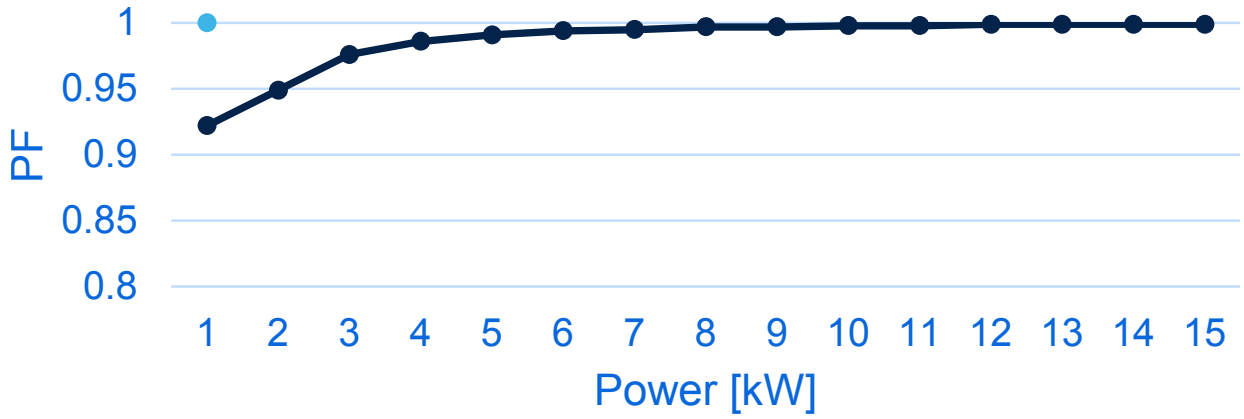


Figure 58. **STDES-VRECTFD efficiency plot**

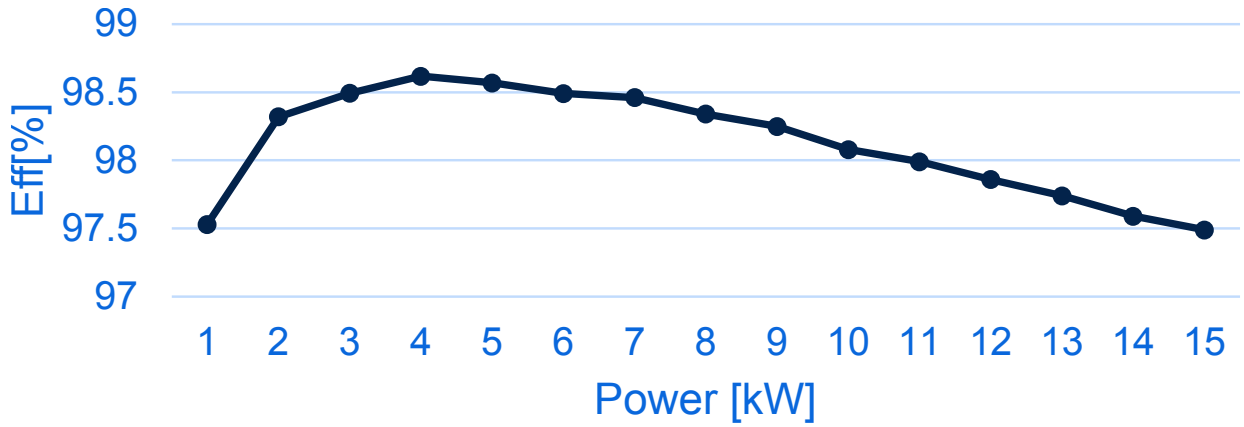
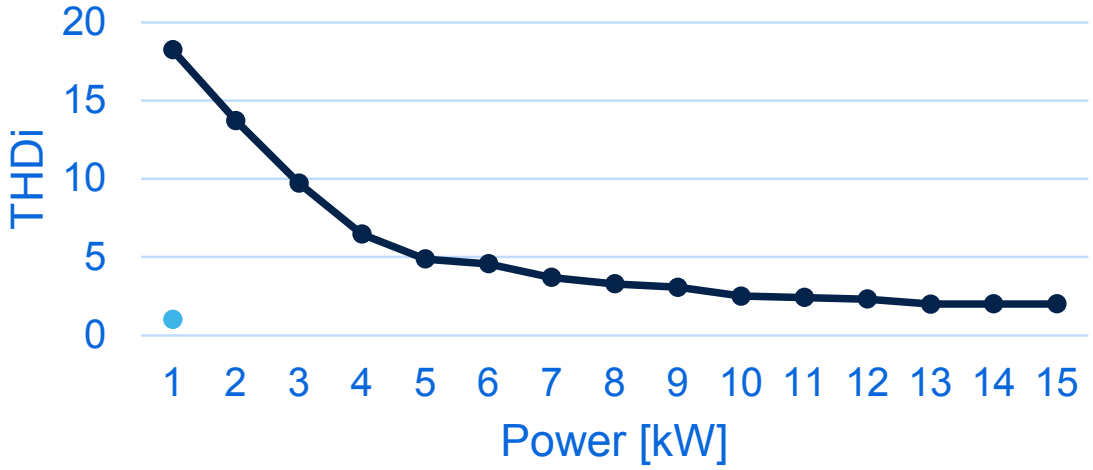


Figure 59. **STDES-VRECTFD THDi plot**



6 Schematic diagrams

Figure 60. **STDES-VRECTFD circuit schematic - power board (1 of 11)**

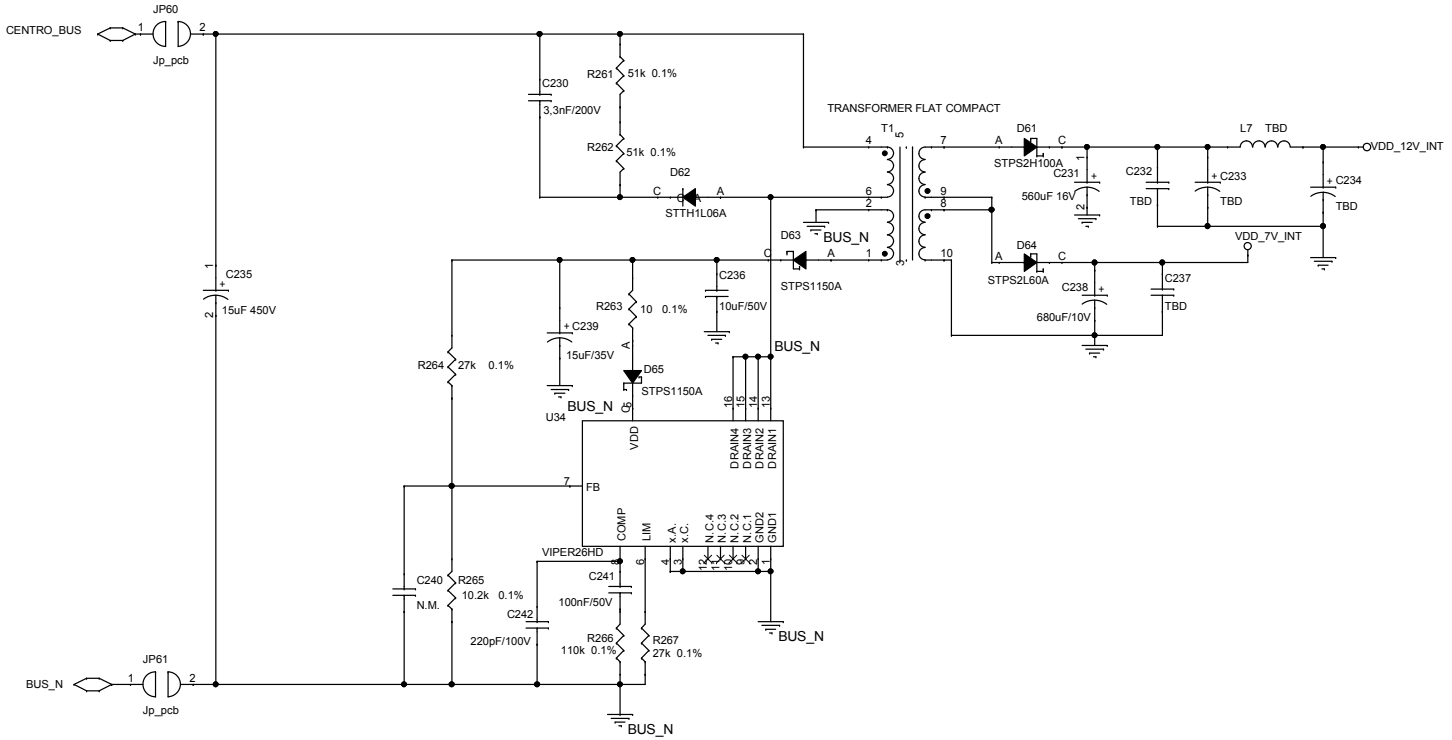


Figure 61. STDES-VRECTFD circuit schematic - power board (2 of 11)

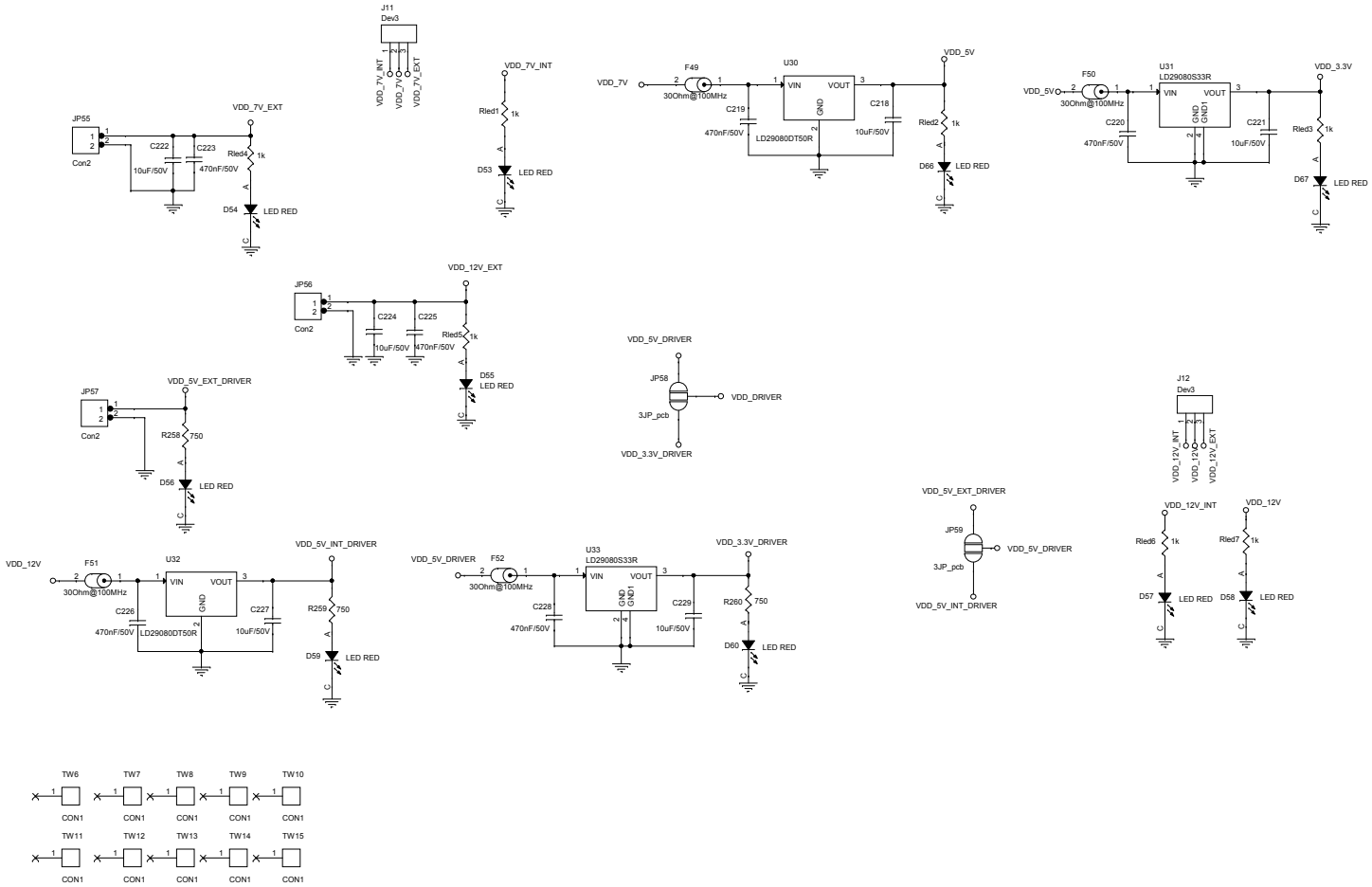
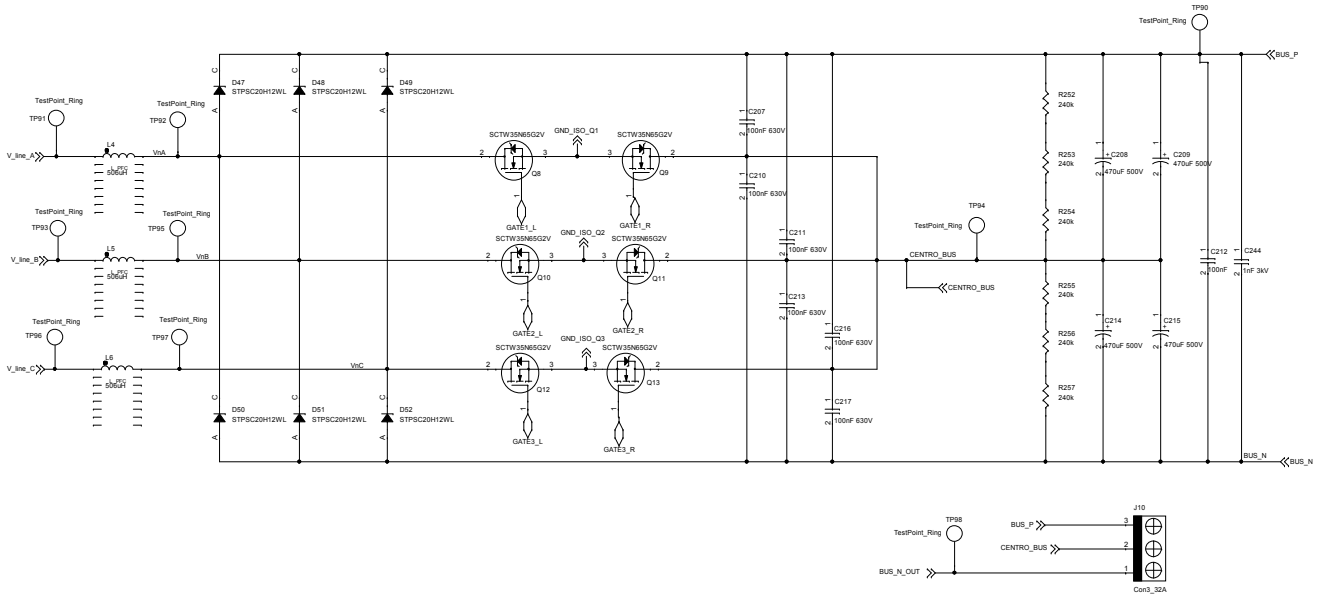


Figure 62. STDES-VRECTFD circuit schematic - power board (3 of 11)



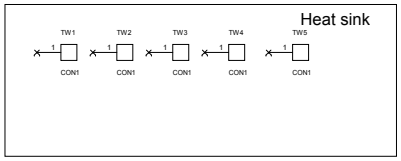


Figure 63. STDES-VRECTFD circuit schematic - power board (4 of 11)

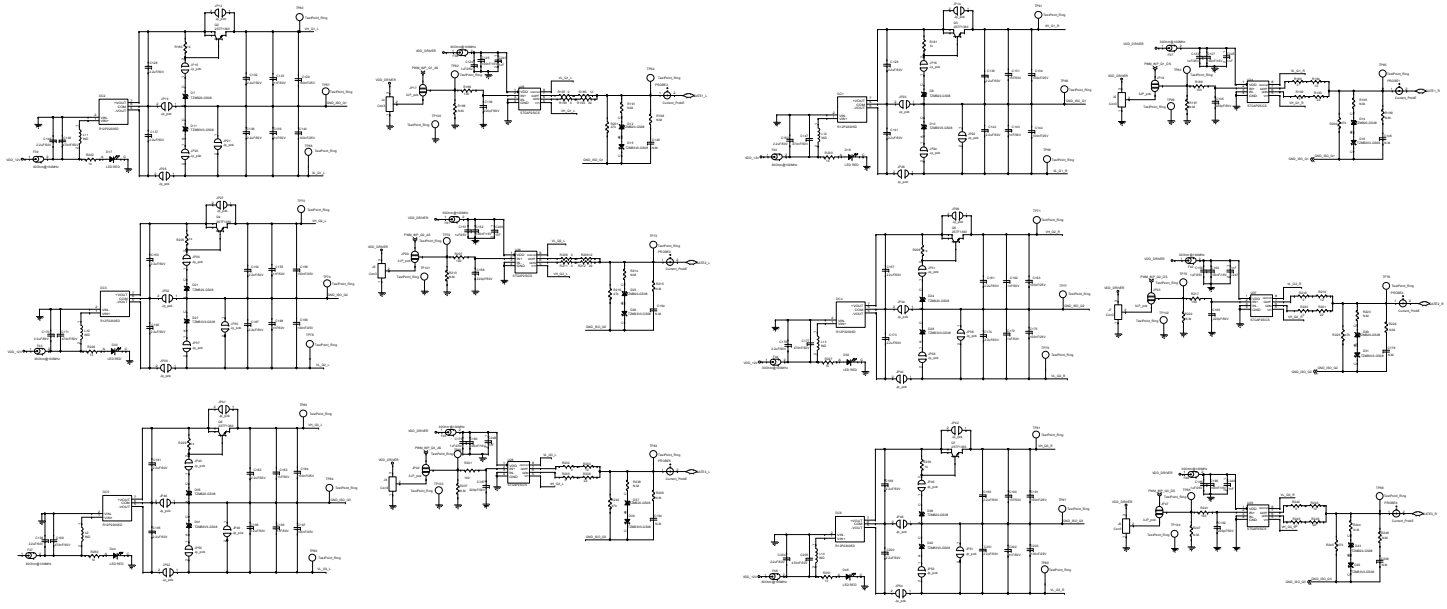


Figure 64. STDES-VRECTFD circuit schematic - power board (5 of 11)

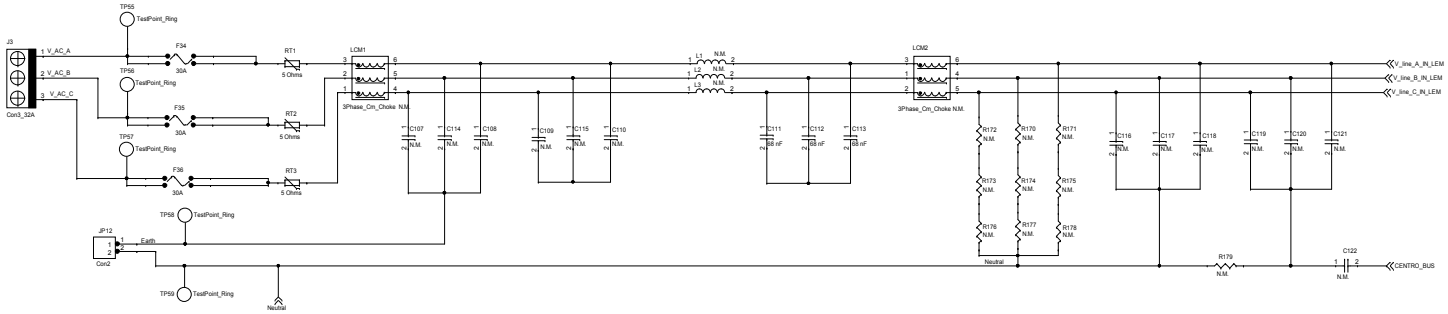


Figure 65. STDES-VRECTFD circuit schematic - power board (6 of 11)

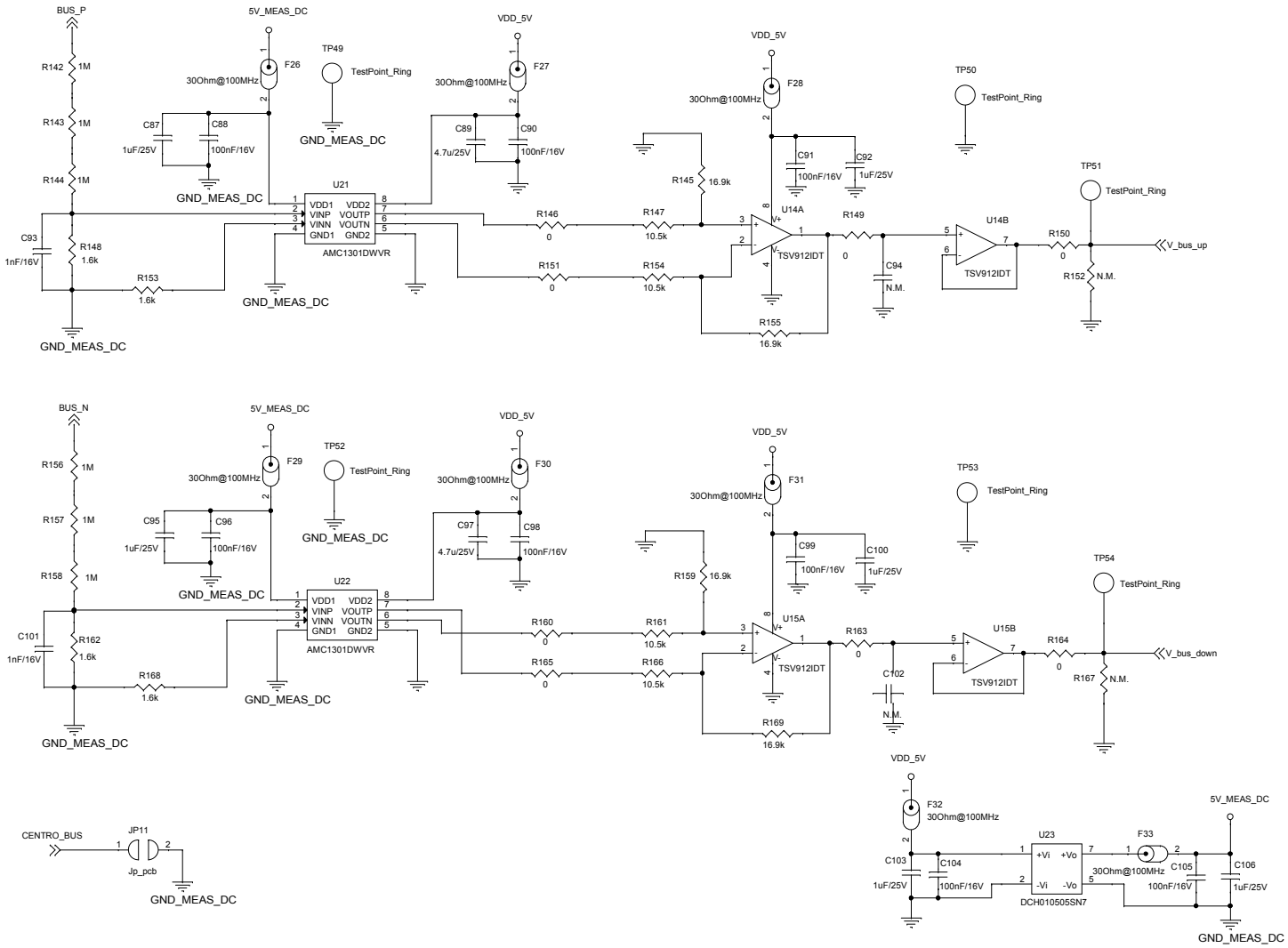


Figure 66. STDES-VRECTFD circuit schematic - power board (7 of 11)

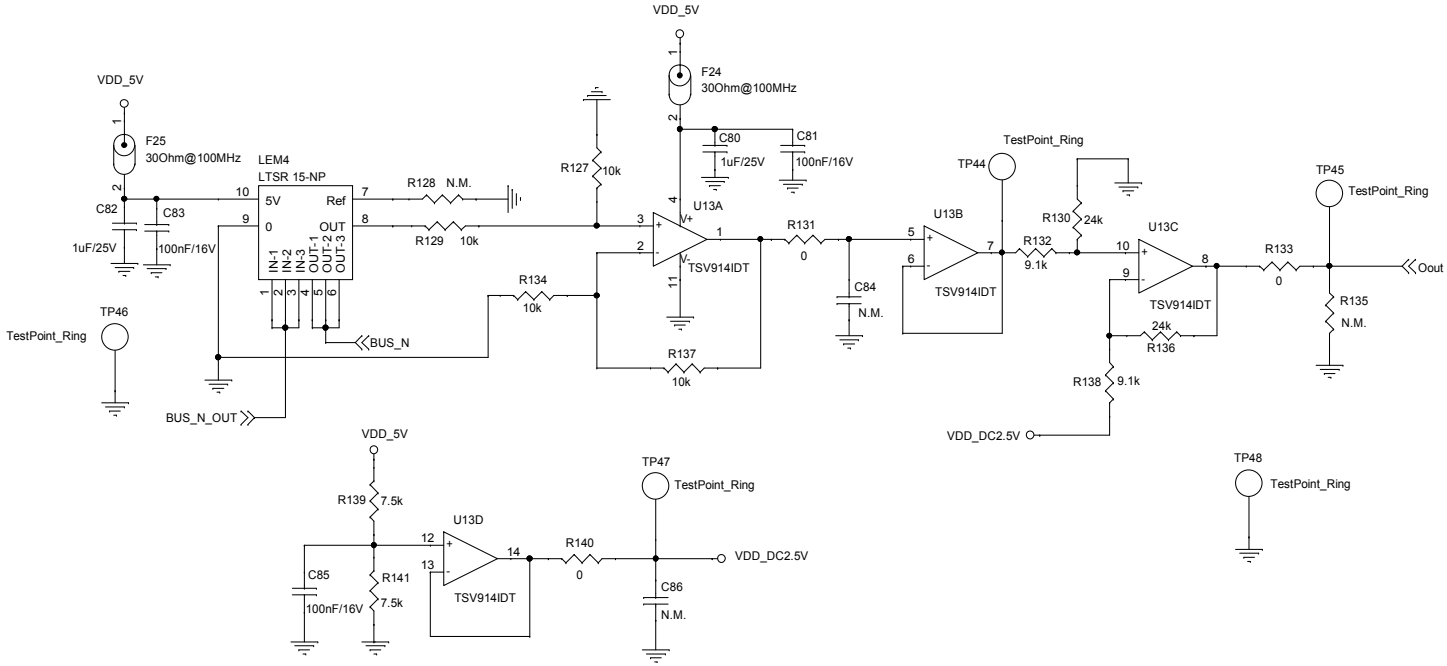


Figure 67. **STDES-VRECTFD circuit schematic - power board (8 of 11)**

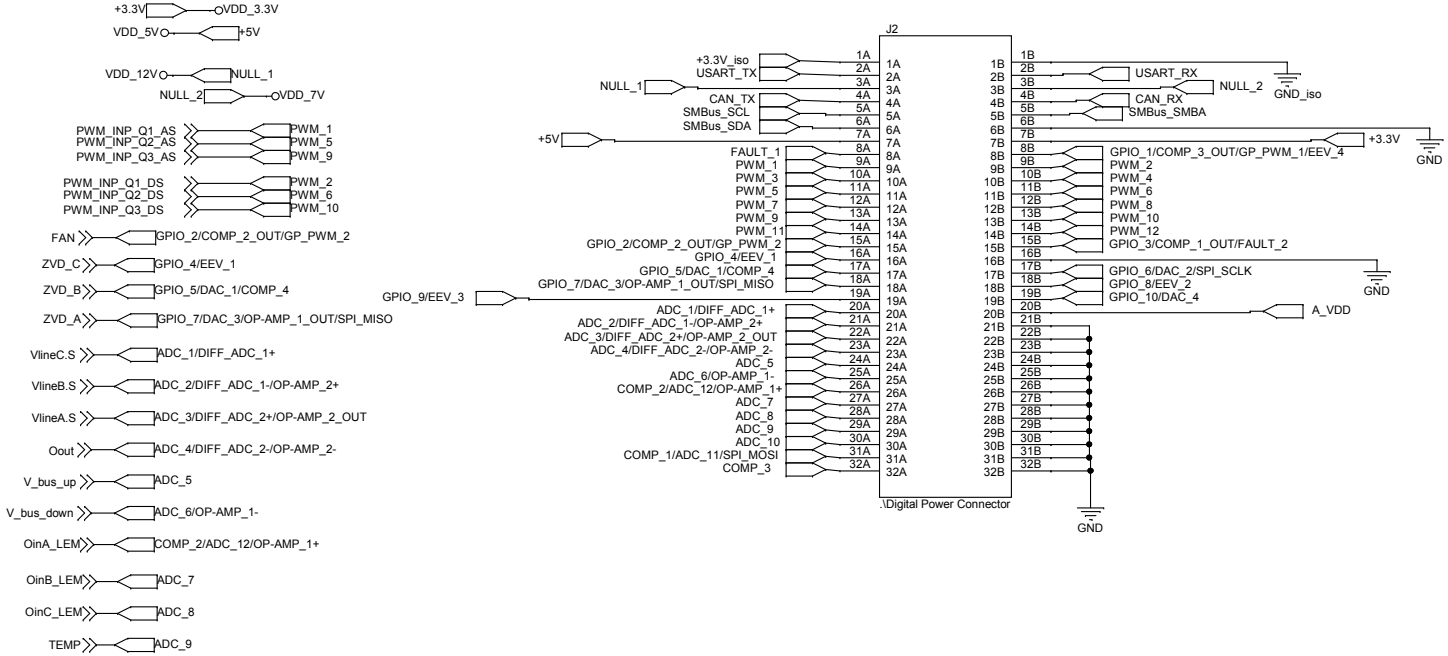


Figure 68. **STDES-VRECTFD circuit schematic - power board (9 of 11)**

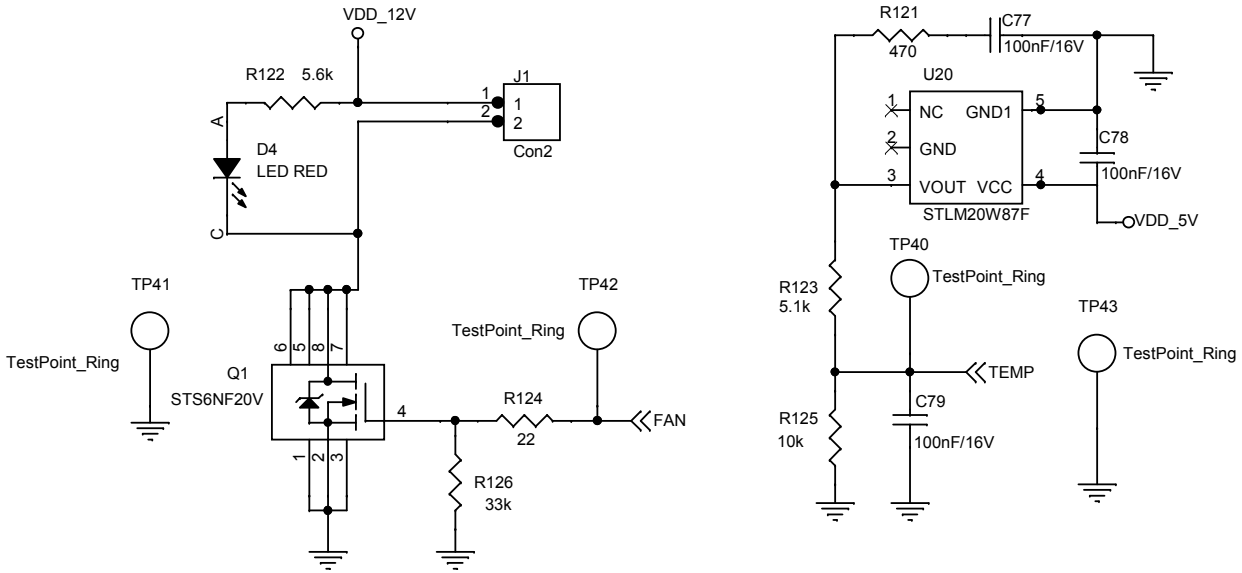


Figure 69. STDES-VRECTFD circuit schematic - power board (10 of 11)

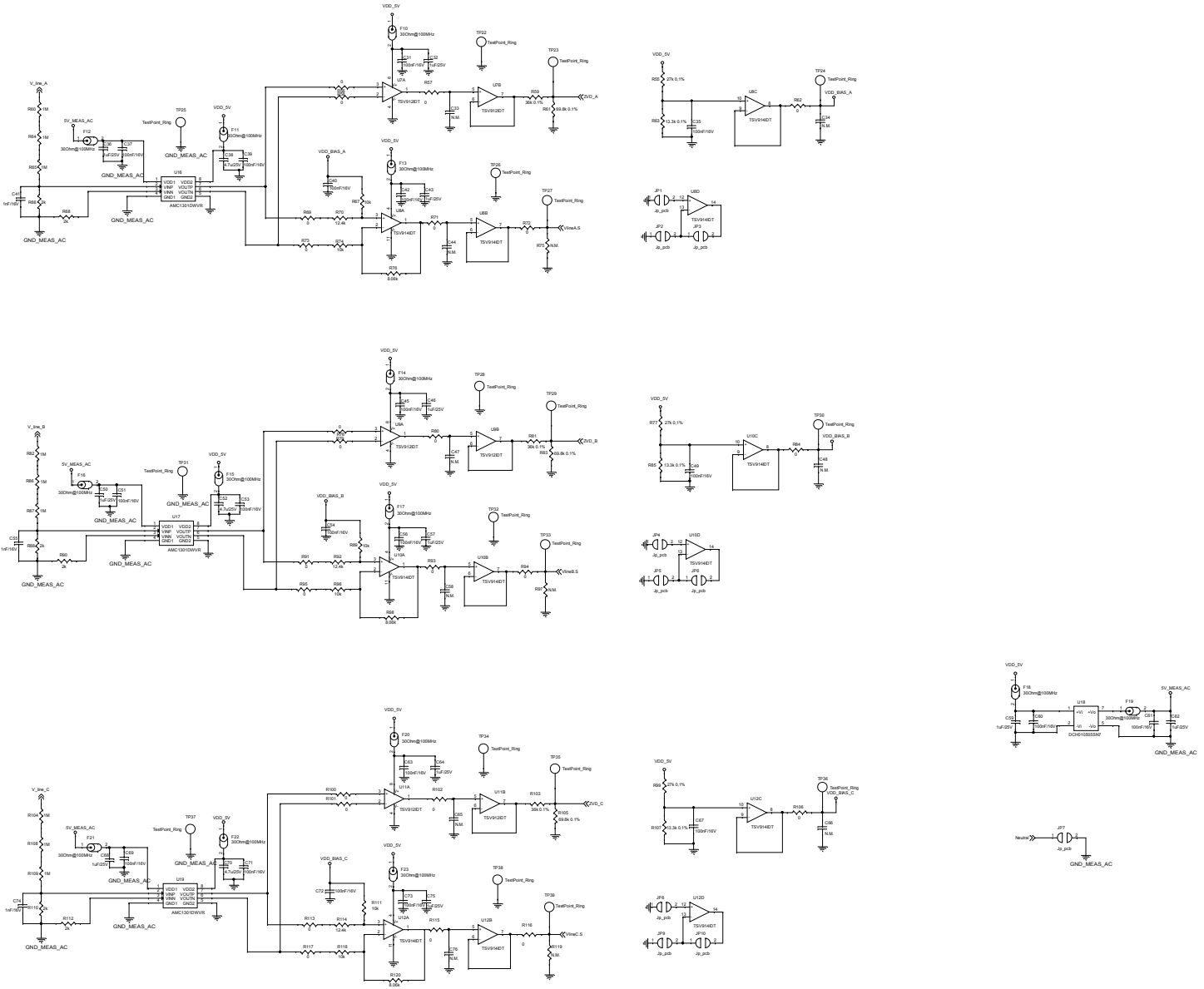


Figure 70. STDES-VRECTFD circuit schematic - power board (11 of 11)

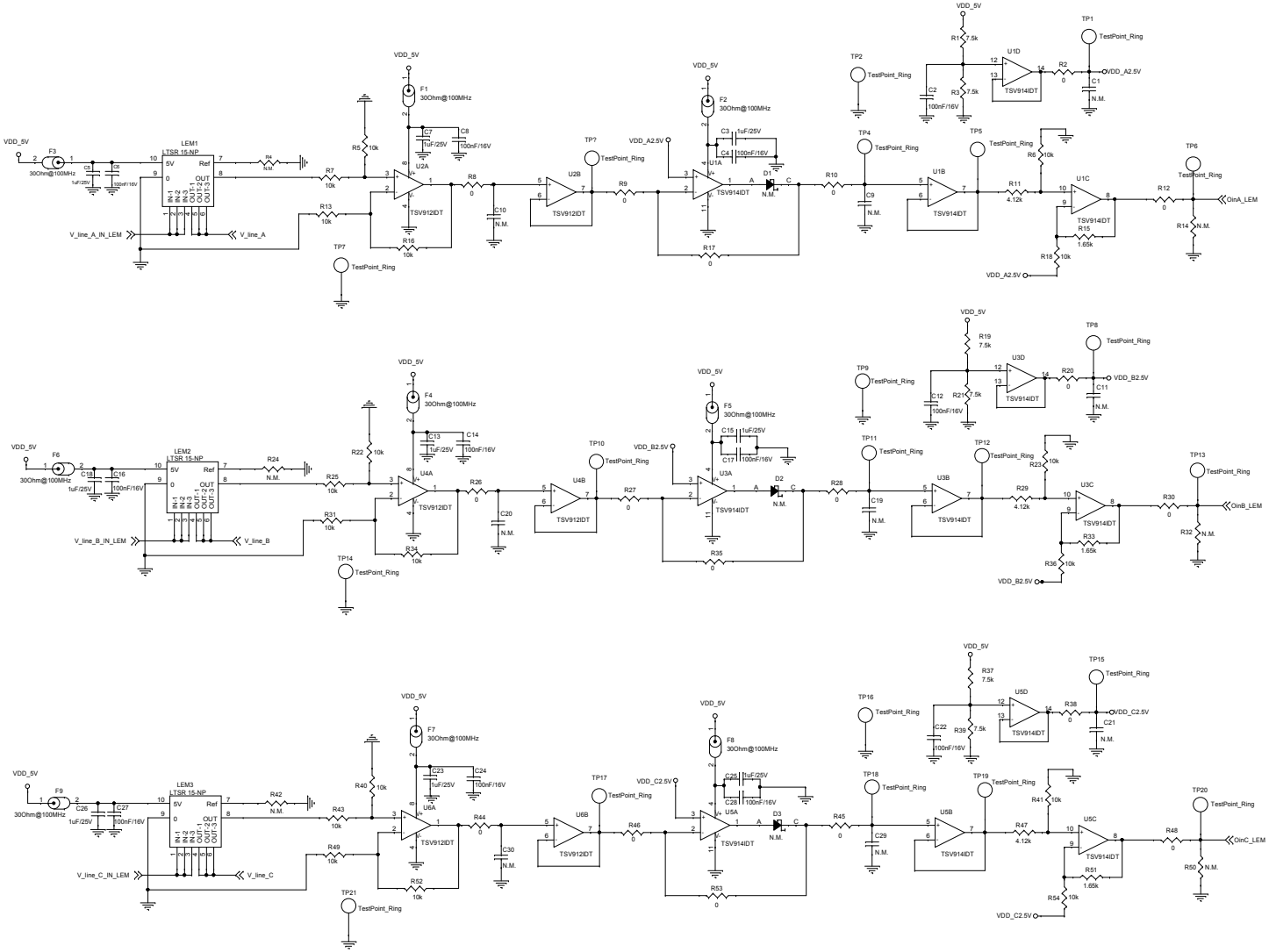
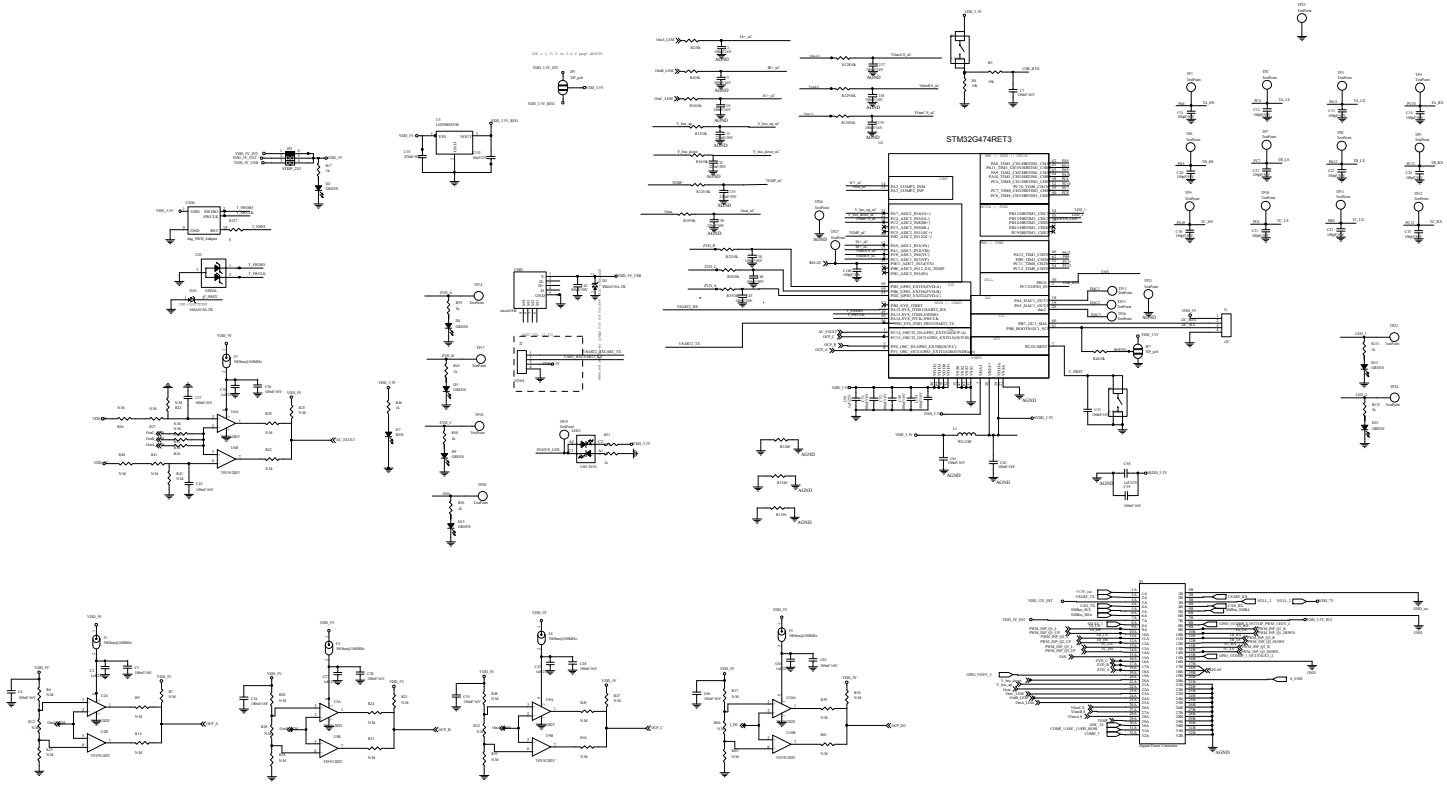


Figure 71. **STDES-VRECTFD circuit schematic - control board**



7 Bill of materials

Table 7. STDES-VRECTFD bill of materials

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
1	1	Table 8. Power board	-	Power board	ST	Not available for separate sale
2	1	Table 9. Control board	-	Control board	ST	Not available for separate sale

Table 8. Power board bill of materials

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
1	28	C1, C9, C10, C11, C19, C20, C21, C29, C30, C33, C34, C44, C47, C48, C58, C65, C66, C76, C84, C86, C94, C102, C148, C149, C164, C178, C194, C206	SMD 0603 (1608)	Multilayer ceramic capacitors (not mounted)	-	-
2	1	C240	SMD 0805 (2012)	Multilayer ceramic capacitor (not mounted)	-	-
3	2	C8, C14	100 nF, SMD 0603 (1608), 16 V, ±10 %	Multilayer ceramic capacitors (not mounted)	Wurth Elektronik	885012206046
4	5	C41, C55, C74, C93, C101	1 nF, SMD 0603 (1608), 25 V, ±10 %	Multilayer ceramic capacitors	Wurth Elektronik	885012006044
5	50	C2, C4, C6, C12, C16, C17, C22, C24, C27, C28, C31, C35, C37, C39, C40, C42, C45, C49, C51, C53, C54, C56, C60, C61, C63, C67, C69, C71, C72, C73, C77, C78, C79, C81, C83, C85, C88, C90, C91, C96, C98, C99, C104, C105, C125, C127, C152, C160, C180, C186	100 nF, SMD 0603 (1608), 25 V, ±10 %	Multilayer ceramic capacitors	Wurth Elektronik	885012206046
6	1	C7	1 µF, SMD 0603 (1608), 440 V_{AC}, ±20 %	Multilayer ceramic capacitor (not mounted)	Wurth Elektronik	885012206076

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
7	33	C3, C5, C13, C15, C18, C23, C25, C26, C32, C36, C43, C46, C50, C57, C59, C62, C64, C68, C75, C80, C82, C87, C92, C95, C100, C103, C106, C123, C124, C151, C159, C179, C185	1 µF, SMD 0603 (1608), 305 V_{AC}, ±20 %	Multilayer ceramic capacitors	Wurth Elektronik	885012206076
8	5	C38, C52, C70, C89, C97	4.7 µF, SMD 0603 (1608), 50 V, ±10 %	Multilayer ceramic capacitors	Any	Any
9	10	C107, C108, C114, C116, C117, C118, C119, C120, C121, C122	Radial, Disc, 25 V, ±5 %	Multilayer ceramic capacitors (not mounted)	-	-
10	6	C109, C110, C111, C112, C113, C115	Radial, 50 V, ±10 %	Multilayer ceramic capacitors (not mounted)	-	-
11	30	C126, C128, C130, C132, C137, C138, C141, C142, C145, C150, C153, C154, C157, C161, C166, C167, C170, C173, C174, C176, C181, C182, C188, C189, C195, C196, C198, C200, C201, C204	2.2 µF, SMD 1206 (3216), 50 V, ±5 %	Multilayer ceramic capacitors	Any	Any
12	12	C129, C134, C140, C144, C156, C163, C169, C175, C184, C191, C197, C203	100 nF, SMD 1206 (3216), 50 V, ±10 %	Multilayer ceramic capacitors	Wurth Elektronik	885012208058
13	12	C131, C133, C139, C143, C155, C162, C168, C172, C183, C190, C193, C202	1 nF, SMD 1206(3216), 630 V_{DC} V, ±10 %	Multilayer ceramic capacitors	Wurth Elektronik	885012208075
14	6	C135, C136, C158, C165, C187, C192	220 pF, SMD 0603 (1608), 500 V, ±20 %	Multilayer ceramic capacitors	Wurth Elektronik	885012206079
15	12	C146, C147, C171, C177, C199, C205, C219, C220, C223, C225, C226, C228	470 nF, SMD 0805(2012), 1K V_{DC}, ±10 %	Multilayer ceramic capacitors	Any	Any

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
16	6	C207, C210, C211, C213, C216, C217	100 nF, Radial, 25 V, ±20 %	CAP FILM RADIAL	Wurth Elektronik	890303425004CS
17	4	C208, C209, C214, C215	470 µF, Radial, Can - Snap-In, 200 V, ±10 %	Aluminium capacitors	Vishay BC Components	MAL215759471E3
19	1	C212	100 nF, Radial, 16 V, ±20 %	Film radial capacitor	KEMET	R474N310050A1K
20	7	C218, C221, C222, C224, C227, C229, C236	10 µF, SMD 0805 (2012)	Multilayer ceramic capacitors	Any	Any
21	1	C230	3.3 nF, SMD 1206 (3216), ±20 %	Multilayer ceramic capacitor	Any	Any
22	1	C231	560 µF, Radial, Can, 450 V, ±20 %	Aluminium capacitor	Panasonic Electronic Components	16SEPF560M
23	2	C232, C237	0805 (2012 Metric)	Capacitors (not mounted)	-	-
24	2	C233, C234	0805 (2012 Metric), ±20 %	Capacitors (not mounted)	-	-
25	1	C235	15 µF, Radial, Can, 50 V, ±10 %	Aluminium capacitor	Panasonic Electronic Components	EEU-EE2W150
26	1	C238	680 µF, Radial, Can, 50 V, ±5 %	Aluminium capacitor	Panasonic Electronic Components	EEU--FR1C681L
27	1	C239	15 µF, Radial, Can, 50 V, ±5 %	Aluminium capacitor	Wurth Elektronik	860160572002
28	1	C241	100 nF, 0805 (2012 Metric), 30 V	Multilayer ceramic capacitor	Wurth Elektronik	885012207098
29	1	C242	220 pF, 0805 (2012 Metric)	Multilayer ceramic capacitor	Any	Any
30	6	C243 C245 C246 C247 C248 C249	1 nF, SMD 0603 (1608), 20 V	Multilayer ceramic capacitors	Wurth Elektronik	885012206083
31	3	D1, D2, D3	STPS1L30A, SMA	30 V, 1 A low drop power Schottky rectifiers (not mounted)	ST	STPS1L30A
32	17	D4, D17, D18, D30, D32, D44, D46, D53, D54, D55, D56, D57, D58, D59, D60, D66, D67	LED RED, 1206 (3216 Metric), 20 A	Red LEDs	Lumex Opto/ Components Inc.	SML-LX1206SIC-TR
33	12	D7, D8, D12, D14, D21, D23, D24, D29, D35, D37, D38, D43	TZMB20-GS08, DO-213AC, MINI-MELF, SOD-80, 100 V	Zener diodes	Vishay Semiconductor Diodes Division	TZMB20-GS08

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
34	12	D11, D13, D15, D16, D26, D27, D28, D31, D39, D41, D42, D45	TZMB3V3-GS08, DO-213AC, MINI-MELF, SOD-80, 600 V	Zener diodes	Vishay Semiconductor Diodes Division	TZMB3V3-GS08
35	6	D47, D48, D49, D50, D51, D52	STPSC20H12WL, TO-220AC	1200 V, 20 A high surge silicon carbide power Schottky diode	ST	STPSC20H12WL
36	1	D61	STPS2H100A, SMA	100 V, 2 A power Schottky rectifier	ST	STPS2H100A
37	1	D62	STTH1L06A, SMA	600 V, 1 A low drop ultrafast diode	ST	STTH1L06A
38	2	D63, D65	STPS1150A, SMA	150 V, 1 A power Schottky rectifier	ST	STPS1150A
39	1	D64	STPS2L60A, SMA	60 V, 2 A low drop power Schottky rectifier	ST	STPS2L60A
40	6	DC1, DC2, DC3, DC4, DC5, DC6	R12P22005D, 0.77" L x 0.39" W x 0.49" H (19.5 mm x 9.8 mm x 12.5 mm)	DC-DC converters	Recom Power	R12P22005D
41	49	F1, F2, F3, F4, F5, F6, F7, F8, F9, F10, F11, F12, F13, F14, F15, F16, F17, F18, F19, F20, F21, F22, F23, F24, F25, F26, F27, F28, F29, F30, F31, F32, F33, F37, F38, F39, F40, F41, F42, F43, F44, F45, F46, F47, F48, F49, F50, F51, F52	22 ohm at 100 MHz, 0805 (2012 Metric)	Ferrite beads	Wurth Elektronik	742792021
42	3	F34, F35, F36	Fuse10X38, 2Xclips + Fuse 250 V 30 A	Fuse clip cartridges	Eaton + Littelfuse	BK/1A3400-09-R + OFLM030, T
43	1	JP12	Con2, 2pos 7.62 mm	Connector terminal block	Phoenix Contact	1731721+M46:O46F46M46:N46
44	4	J1, JP55, JP56, JP57	Con2, 2pos 5.08 mm	Connector terminal blocks	Wurth Elektronik	691213510002
45	1	J2	Digital power connector	Connector	ERNI	284166 32X2
46	2	P2 X 2	Male DIN 41612 through hole 90 degree	Adapter digital power connector	ERNI	384241
47	2	J3, J10	Con3_32A, 3P 9.52 mm 90DEG	Fixed terminal blocks	Phoenix Contact	1714984

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
48	6	J4, J5, J6, J7, J8, J9	Con3	Pin headers	Wurth Elektronik	61300311121
49	2	J11, J12	Dev3, 20.5 A	Switches	Wurth Electronics Inc.	450301014042
50	39	JP11, JP13, JP14, JP15, JP16, JP19, JP20, JP21, JP22, JP23, JP24, JP25, JP26, JP27, JP28, JP30, JP31, JP32, JP34, JP35, JP36, JP37, JP38, JP39, JP40, JP41, JP42, JP43, JP45, JP46, JP48, JP49, JP50, JP51, JP52, JP53, JP54, JP60, JP61	Jp_pcb	Jumpers (not mounted)	-	-
51	8	JP17, JP18, JP29, JP33, JP44, JP47, JP58, JP59	3JP_pcb	Jumpers (not mounted)	-	-
52	3	L1, L2, L3	±20 %	Inductors (not mounted)	Pulse electronics	PA0431LNL
53	3	L4, L5, L6	514 µH	Boost inductors	Wurth Electronics Inc.	750344313
54	1	L7		Inductor (not mounted)	-	-
55	6	L9, L10, L11, L12, L13, L14	22 µH 130 mA, 0805 (2012 Metric)	Fixed inductors	Taiyo Yuden	LBC2012T220M
56	2	LCM1, LCM2	3Phase_Cm_Choke	Common mode chokes (not mounted)	-	-
57	4	LEM1, LEM2, LEM3, LEM4	LTSR 15-NP, Ring Opening 0.126" Diam., 6 leads	Hall current sensors	LEM USA Inc.	LTSR 15-NP
58	2	2XP3	CON40A, 2X20, pitch 2.54 mm	Connector	Sullins Connector Solution	PPPC202LJBN-RC
59	13	PROBE1, PROBE2, PROBE3, PROBE4, PROBE5, PROBE6, PROBE8, PROBE9, PROBE10, PROBE11, PROBE12, PROBE13, PROBE14	Current_ProbE	Jumpers (not mounted)	-	-

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
60	1	Q1	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
61	6	Q2, Q3, Q4, Q5, Q6, Q7	2STF1360, SOT-89	Low voltage fast-switching NPN power transistor	ST	2STF1360
62	6	Q8, Q9, Q10, Q11, Q12, Q13	SCTW35N65G2V, HIP247	Silicon carbide power MOSFET 650 V, 55 mOhm typ., 45 A in an HiP247 package	ST	SCTW35N65G2V
63	8	R1, R3, R19, R21, R37, R39, R139, R141	7.5 k, SMD 0603(1608), ±1 %	Resistors	Any	Any
64	31	R2, R8, R10, R20, R26, R28, R38, R44, R45, R56, R57, R58, R62, R71, R78, R79, R80, R84, R93, R100, R101, R102, R106, R115, R131, R140, R149, R163, R12, R30, R48	SMD	Resistors	Any	Any
65	22	R4, R24, R42, R128, R191, R195, R196, R197, R198, R199, R213, R214, R215, R222, R223, R224, R237, R238, R239, R244, R247, R248		Resistors (not mounted)	Any	Any
66	4	R147, R154, R161, R166	10.5k, SMD 0603 (1608), ±0.1 %	Resistors	Any	Any
67	3	R70, R92, R114	12.4k, SMD 0603 (1608), ±0.1 %	Resistors	Any	Any
68	31	R5, R6, R7, R13, R16, R22, R23, R25, R31, R34, R40, R41, R43, R49, R52, R74, R96, R118, R125, R127, R129, R134, R137, R151, R18, R36, R54, R67, R89, R111	10 k, SMD 0603(1608), ±0.1 %	Resistors	Any	Any
69	3	R15, R33, R51		Resistors	Any	Any

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
71	6	R11, R18, R29, R36, R47, R54	18.7 k, SMD 0603 (1608), ±0.1 %	Resistors	Any	Any
72	6	R12, R30, R48, R59, R81, R103	36k, SMD 0603(1608), ±1 %	Resistors	Any	Any
73	3	R14, R32, R50 N.M.	69.8 k, SMD 0603 (1608), ± 0.1 %	Resistors (not mounted)	Any	Any
74	3	R61, R83, R105	69.8 k, SMD 0603 (1608), ±1%	Resistors	Any	Any
75	15	R60, R64, R65, R82, R86, R87, R104, R108, R109, R142, R143, R144, R156, R157, R158	1 M, SMD1206 (3216), ±0.1%	Resistors	Any	Any
76	3	R63, R85, R107	13.3 k, SMD 0603 (1608), ±0.1%	Resistors	Any	Any
77	6	R66, R68, R88, R90, R110, R112	2 k, SMD 0603(1608), ±1 %	Resistors	Any	Any
78	6	R76, R98, R120	8.06k, SMD 0603 (1608), ±1 %	Resistors	Any	Any
79	5	R72, R94, R116, R150, R164	11.3 k, SMD 0603 (1608), ±1%	Resistors	Any	Any
80	5	R75, R97, R119, R152, R167	3.74 k, SMD 0603 (1608)	Resistors (not mounted)	Any	Any
81	1	R121	470, SMD 0603 (1608), ±1 %	Resistors	Any	Any
82	1	R122	5.6k, SMD 0603 (1608), ±1 %	Resistors	Any	Any
83	1	R123	5.1 k, SMD 0603 (1608), ±1%	Resistors	Any	Any
84	1	R124	22, SMD 1206 (3216)	Resistors	Any	Any
85	6	R193, R194, R212, R221, R236, R246	22, SMD1210(3225), ±0.1 %	Resistors	Any	Any
86	1	R126	33 k, SMD 0603 (1608), ± 0.1 %	Resistors	Any	Any
87	2	R130, R136	24 k, SMD 0603 (1608), ±0.1 %	Resistors	Any	Any
88	2	R132, R138	9.1 k, SMD 0603(1608)	Resistors	Any	Any
89	1	R135 N.M.	30 k, SMD 0603(1608), %,	Resistors	Any	Any

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
90	4	R145, R155, R159, R169	16.9 k, SMD 0603 (1608), ±1%	Resistors	Any	Any
91	4	R148, R153, R162, R168	1.6 k, SMD 0603 (1608)	Resistors	Any	Any
92	9	R170 R171 R172 R173 R174 R175 R176 R177 R178	SMD 0805 (2012)	Resistors (not mounted)	Any	Any
93	1	R179	SMD 1206 (3216)	Resistor (not mounted)	Any	Any
94	19	R180, R181, R202, R203, R205, R206, R226, R227, R229, R230, R250, R251, RLED1, RLED2, RLED3, RLED4, RLED5, RLED6, RLED7	1 k, SMD 0603 (1608)	Resistors	Any	Any
95	6	R184, R185, R209, R219, R233, R243	12, SMD 1210 (3225),	Resistors	Any	Any
96	6	R186, R188, R207, R217, R231, R241	100, SMD 0603 (1608)	Resistors	Any	Any
97	33	R9, R17, R35, R46, R53, R69, R72, R73, R91, R94, R95, R113, R116, R117, R133, R146, R149;R151, R160, R163, R165, R187, R189, R190, R192, R208, R211, R218, R220, R232, R235, R242, R245	0, SMD 1210 (3225)	Resistors	Any	Any
98	6	R200, R201, R216, R225, R240, R249	47 k, SMD 1206 (3216)	Resistors	Any	Any
99	6	R252, R253, R254, R255, R256, R257	240 k, SMD 1206 (3216)	Resistors	Any	Any
100	2	R258, R259	750, SMD 0805 (2012)	Resistors	Any	Any
101	1	R260	750, SMD 1206 (3216)	Resistor	Any	Any
102	2	R261, R262	51k, SMD 1206 (3216)	Resistors	Any	Any
103	1	R263	10, SMD 0603(1608), %,	Resistor	Any	Any

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
104	2	R55, R77, R99, R264, R267	27 k, SMD 0603 (1608)	Resistors	Any	Any
105	1	R265	10.2 k, SMD 0603 (1608)	Resistor	Any	Any
106	1	R266	110 k, SMD 0603 (1608)	Resistor	Any	Any
107	3	RT1, RT2, RT3	5 A 32 mm	Inrush current limiters	Ametherm	SL32 5R020-B
108	1	T1	TRANSFORMER FLAT COMPACT	Transformer (not mounted)	Wurth	750317707
109	103	TP1, TP2, TP4, TP5, TP6, TP7, TP8, TP9, TP10, TP11, TP12, TP13, TP14, TP15, TP16, TP17, TP18, TP19, TP20, TP21, TP22, TP23, TP24, TP25, TP26, TP27, TP28, TP29, TP30, TP31, TP32, TP33, TP34, TP35, TP36, TP37, TP38, TP39, TP40, TP41, TP42, TP43, TP44, TP45, TP46, TP47, TP48, TP49, TP50, TP51, TP52, TP53, TP54, TP55, TP56, TP57, TP58, TP59, TP60, 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, TP94, TP95, TP96, TP97, TP98, TP99, TP100, TP101, TP102, TP103, TP104	TestPoint_Ring, 1 mm	Test terminals	Any	Any

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
110	7	U10, U12, U13, U1, U3, U5, U8	TSV914IDT, SO-14	Wide-bandwidth (8 MHz) rail to rail input/output 5 V CMOS Op-Amps, quad	ST	TSV914IDT
111	4	U11, U14, U15, U7	TSV912IDT, SO-8	Wide-bandwidth (8 MHz) rail to rail input/output 5V CMOS Op-Amps, dual	ST	TSV912IDT
112	5	U16, U17, U19, U21, U22	AMC1301DWVR, 8-SOIC (0.295", 7.50 mm Width)	IC op-amp isolation circuits	Texas Instruments	AMC1301DWVR
113	2	U18, U23	DCH010505SN7, SIP,	1-channel DC-DC power supply module 4-pin	Texas Instruments	DCH010505SN7
114	1	U20	STLM20W87F, SOT323-5L	Analog temperature sensor, ultra-low current 2.4 V, high precision	ST	STLM20W87F
115	6	U24, U25, U26, U27, U28, U29	STGAP2SICS, SO-8	Galvanically isolated 4 A single gate driver	ST	STGAP2SICS
116	4	U2, U4, U6, U9	TSV912IDT, SO-8	Wide-bandwidth (8 MHz) rail to rail input/output 5V CMOS Op-Amps, dual	ST	TSV912IDT
117	2	U30, U32	LD29080DT50R, DPAK	800 mA fixed and adjustable output very low drop voltage regulator	ST	LD29080DT50R
118	2	U31, U33	LD29080S33R, SOT-223	800 mA fixed and adjustable output very low drop voltage regulator	ST	LD29080S33R
119	1	U34	VIPER26HD, SO-16	Fixed frequency VIPer plus family	ST	VIPER26HD
120	5	TW1, TW2, TW3, TW4, TW5	M3X10, Male/ Female M3X10 mm	Spacers	Wurth Elektronik	971100351
121	5	Screw M3 X 6mm	M3 Pan Head, M3X6mm	Screws	RS	482-8515
122	10	TW6, TW7, TW8, TW9, TW10, TW11, TW12, TW13, TW14, TW15	M3X40, Brass Hex Standoff	Brass Hex Standoff Male/ Female, 40mm, M3 x M3	Wurth Elektronik	971100354
123	10	M3	Hex Nut, M3	Hex nut	RS	483-0502

Table 9. Control board bill of materials

Item	Q.ty	Ref.	Part / Value	Description	Manufacturer	Order code
1	1	CN56	Jtag_SWD_Adapter	Connector	Samtec	FTSH-105-01-F-D-K
2	26	C1, C3, C5, C6, C7, C10, C28, C34, C36, C37, C45, C48, C49, C51, C52, C53, C55, C59, C61, C62, C65, C66, C134, C137, C138, C139	100nF/16V	CAPACITOR, 603	Any	Any
3	7	C2, C27, C35, C47, C50, C58, C64	1µF/25V	CAPACITOR, 603	Any	Any
4	17	C11, C12, C13, C14, C20, C21, C22, C24, C30, C31, C32, C33, C38, C40, C42, C43, C140	100pF/50V	CAPACITOR, 603	Any	Any
5	3	C15, C23, C135	220nF/50V	CAPACITOR, 603	Any	Any
6	1	C18	470nF/50V	CAPACITOR, 805	Murata	-
7	1	C29	220pF/50V	CAPACITOR, 603	Any	Any
8	1	C133	10µF/25V	CAPACITOR, 805	TDK	-
9	7	D2, D4, D5, D9, D12, D13, D15	GREEN	LED, SMD 0805	Any	Any
10	2	D3, D10	SMAJ5.0A-TR, SMA	400 W TVS in SMA	ST	SMAJ5.0A-TR
11	1	D7	RED	LED, SMD 0805	Any	Any
12	5	F1, F2, F3, F4, F5	30Ω@100MHz	-	TDK Corporation	MPZ2012S300AT000
13	2	JP1, JP7	3JP_pcb	-	-	-
14	1	JP2	STRIP_2X3 (not mounted)	-	-	-
15	1	J1	i2C	CONNECTOR, strip4_100m_v	Any	Any
16	1	J2	CON4	CONNECTOR, strip4_100m_v	Any	Any
17	1	LED1	-	LED	OSRAM	LSG T676
18	1	L1	WE-CBF	FERRITE, 603	WE	74279262
19	1	P1	64 male	Connector	ERNI	533406
20	16	R2, R4, R5, R8, R10, R13, R16, R19, R23, R30, R35, R44, R125, R128, R129, R130	10k	RESISTOR, 603	Any	Any

Item	Q.ty	Ref.	Part / Value	Description	Manufacturer	Order code
21	36	R6, R7, R9, R12, R14, R15, R20, R21, R22, R24, R25, R26, R27, R28, R29, R31, R33, R34, R36, R38, R40, R41, R42, R43, R47, R48, R49, R52, R54, R55, R57, R58, R59, R60, R61, R62	(not mounted)	RESISTOR, 603	Any	Any
22	10	R17, R39, R45, R46, R50, R51, R53, R56, R131, R133	1k	RESISTOR, 603	Any	Any
23	2	R126, R127	0	RESISTOR, 603	Any	Any
24	2	S1, S2	-	None	TE Connectivity	FSM4JSMATR
25	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	Any	Any
26	1	USB2	-	microUSB connector	MOLEX	47346-0001
27	5	U2, U5, U6, U9, U10	TSV912IDT, SO-8	Wide-bandwidth (8 MHz) rail to rail input/output 5V CMOS Op-Amps, dual	ST	TSV912IDT
28	1	U3	LD29080S33R, SOT-223	800 mA fixed and adjustable output very low drop voltage regulator	ST	LD29080S33R
29	1	U4	STM32G474RET3, LQFP64	Mainstream Arm Cortex-M4 MCU 170 MHz with 512 Kbytes of Flash memory, Math Accelerator, HR Timer, High Analog level integration	ST	STM32G474RET3
30	1	U22	ESDA6V1L, SOT23-3L	Dual Transil array for ESD protection	ST	ESDA6V1L

Revision history

Table 10. **Document revision history**

Date	Revision	Changes
18-Jan-2022	1	Initial release.

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