36 W low voltage BLDC ceiling fan reference solution

About this document

Scope and purpose

This application note provides an overview of Infineon's 36 W low voltage (LV) brushless direct current (BLDC) ceiling fan solution including specifications, feature sets, key performance, and test results.

Infineon's 36 W BLDC ceiling fan solution is powered by ICL8810 integrated controller (IC) at the ACDC PFC flyback stage for constant voltage output along with CoolMOS™ IPA80R1K4CE MOSFET. For BLDC sensorless field-oriented control (FOC) motor drive, the XMC1302 microcontroller from the XMC™ series is used. It also includes MOTIX™ 6ED2742S01Q 160 V 6-channel gate driver and IRLML0040TRPBF (SOT23) as the motor inverter MOSFET, which provide a cost-effective, high-performance, and flexible system.

This BLDC ceiling fan solution has provisions for both radio frequency (RF) and infrared (IR) remote control.

Intended audience

This application note is intended for technical specialists and engineers who are interested in understanding ceiling fan control and electronic converters.

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1 Board introduction

1.1 Block diagram

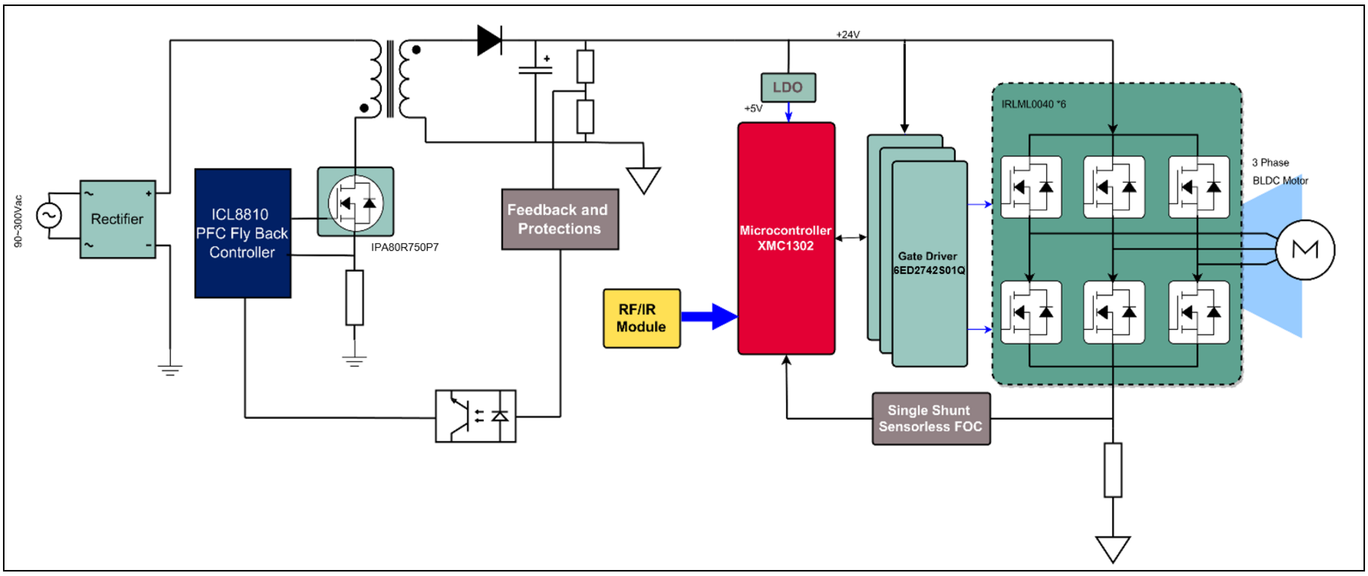


Figure 1 Block diagram of BLDC ceiling fan

Infineon's 36 W reference design is a discrete and configurable BLDC LV single-shunt sensorless FOC motor-control ceiling fan solution. The reference board is designed to provide a highly efficient and robust ceiling fan solution with a smooth and fast start-up of the motor to its maximum speed.

It has a wide operating range from 90 to 300 V_{AC}, a reliable surge protection circuitary with a strong CoolMOS™ 800 V IPA80R750P7 superjunction MOSFET that can safely protect the system from 4 kV of lightning events. This reference solution uses Infineon's ICL8810 controller to ensure a high power factor, low iTHD, and stable outputs and protections such as overcurrent protection (OCP) and overvoltage protection (OVP) for both input and output. Secondary-side regulation (SSR) is adopted for highly reliable regulation.

Two output levels are designed at the secondary side of the flyback stage to provide power to the essential components in the motor drive control circuitary. Low-dropout (LDO) 5 V is used for the secondary side auxiliary output. Infineon's IRLML0040TRPBF three-phase inverter requires 24 V of supply. The 6ED2742S01Q three-phase gate driver can also be supplied by the 24 V main output. The XMC1302 motor microcontroller is powered with +5 V; this controller uses sensorless FOC and single-shunt sensing is integrated to provide accurate speed and angle estimation while reducing component count. Both RF and IR remote control circuits are powered by +5 V supply as well. The three outputs are stably regulated and the power is sufficient for a 400 RPM maximum speed depending on design requirements.

This reference design can support both RF and IR remote control, and allows more convenient control of the system, catering to different design needs. A robust control scheme can reach the maximum speed from the motor stop within 10 s, showing excellent dynamic response of the system.

Multiple protections are integrated, such as flyback input and output OVP, flyback OCP, hardware and software motor OCP, motor DC-link OVP, and stall detection. Faults, if occurred, are monitored; once a fault is cleared, the system attempts restart and resumes the last speed condition.

The catch-free run (CFR) function enables the fan to rotate properly even when it is initially turning in the reverse direction due to external forces.

Sleep-mode function is available to reduce standby power to a minimum level when the fan is not in use – this helps save power consumption costs.

1.2 Design specifications

Table 1 Design specifications

Parameter	Symbol	Value	Unit
Operating AC input voltage	V AC	90~300	V
Normal operational AC input voltage	$V\ AC_{max}$	230	V
Normal operational AC input frequency	F_{line}	47–63	Hz
Maximum input power	$P_{in,\ max}$	37.5	W
PFC FB secondary regulated CV output	V DC	24	V
Steady-state CV output load current	$I_{load,\ max}$	1.28	A
Efficiency at nominal $P_{out,\ full}$	η	86	%
Minimum switching frequency at $P_{out,\ full}$	f_{sw}	61	kHz
Protections			
Primary OCP trigger level	$I_{PFC,OCP}$	3.23	A
CV OVP trigger level	$V_{PFC,OVP}$	35	V
Motor input undervoltage lockout (OVLO) level	V_{UVLO}	18	V
Motor drive hardware overcurrent trigger level	I_{HW_OCP}	4.6	A
Motor drive software overcurrent trigger level	I_{SW_OCP}	4.15	A

1.3 Feature overview

The board is optimized for 230 V AC input BLDC ceiling fan solution. The PFC flyback (FB) stage uses an ICL8810 controller and CoolMOS™ IPA80R750P7 as the switching MOSFET. The motor side contains an XMC1302 gate driver MCU for the FOC sensorless control.

The key features of the 36 W BLDC ceiling fan solution include:

- Input operating range 90-300 V AC, with 230 V AC nominal operating input
- Efficiency at least 85 percent for input 120-300 V AC at full load
- PF at least 0.9 for input 90-230 V AC and 36 W input power, 0.92 at 230 V AC
- iTHD at least 10 percent for 90-300 V AC input and 36 W input power, 4.2 percent at 230 V AC
- Low standby power equal to or less than 0.8 W at input 90-300 V AC
- Thermal rise at the hottest spot is less than 45°C at room temperature for a 230 V AC input
- Sustains 400 V AC input line voltage and surge protection 4 kV differential mode
- Auxiliary supplies from PFC FB include 24 V (motor gate driver and inverter) and 5 V (MCU and remote-control modules)
- Three-phase single-shunt FOC sensorless motor control integrated
- Supports both RF and IR remote interface
- Motor inverter has both software and hardware OCP to better protect the system
- A robust, fast, and smooth motor dynamic performance with a startup time of around 10 s to reach a 350 RPM maximum speed
- Integrated stall detection function for safety purposes
- Auto-retry function included to restart the motor when a fault is cleared
- Last speed memory is captured by the motor MCU
- Sleep mode function of the MCU further reduces standby power when the ceiling fan is turned off
- CFR function allows fan to rotate without hiccups even with initial external force
- Configurable/scalable discrete solution as per requirements

2 Functional description

2.1 Main board functional blocks

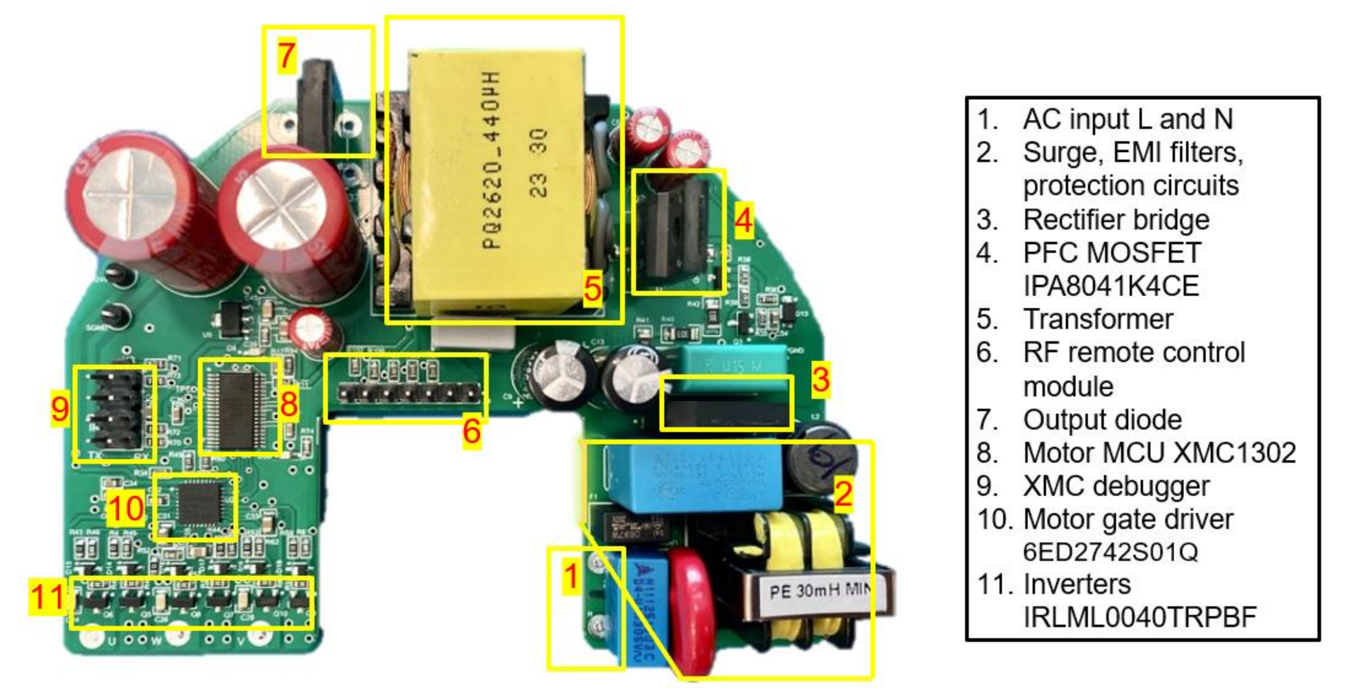


Figure 2 Functional groups on the top side of the main board

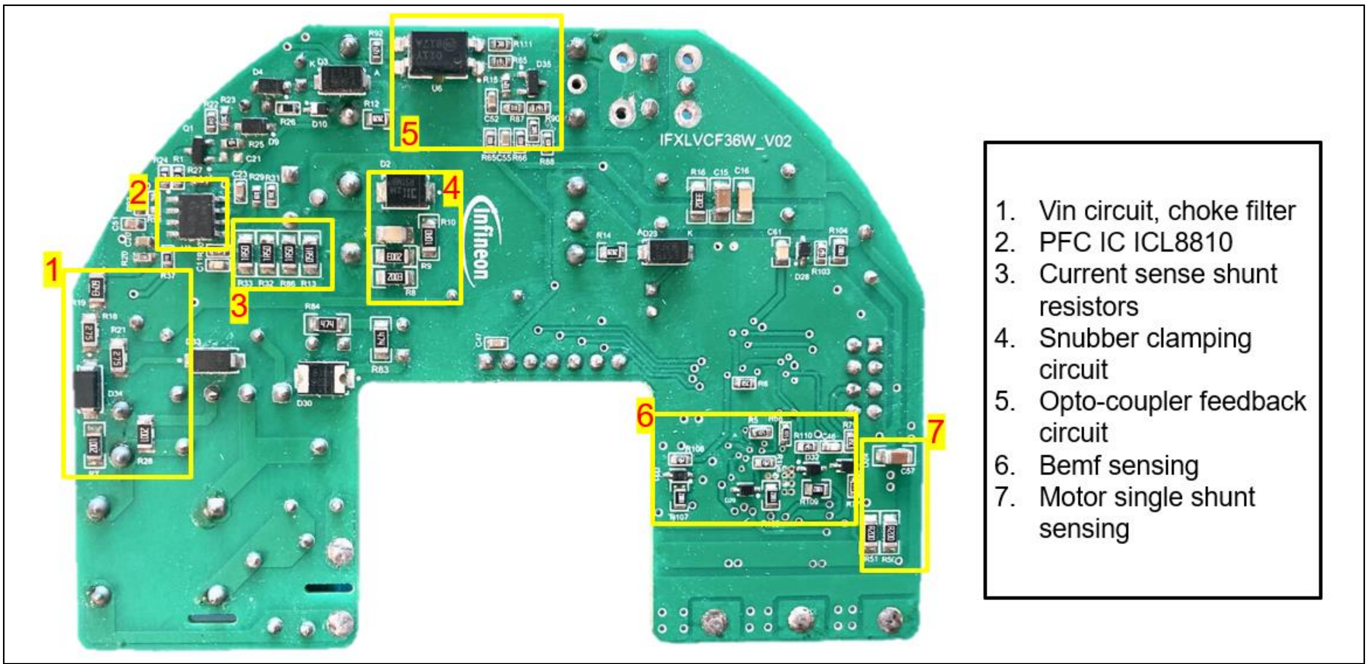


Figure 3 Functional groups on the bottom side of the main board

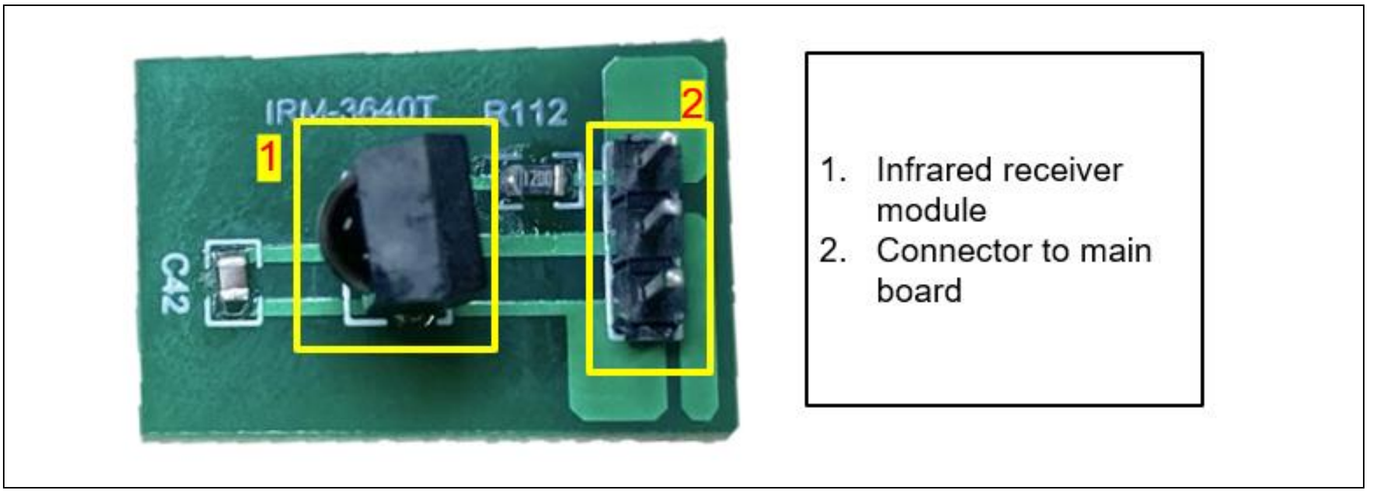


Figure 4 **Functional groups on the daughter board**

2.2 Connection and setup

The connection is simple, as shown in Figure 5: the RF remote receiver module is plugged in for the remote controller, AC source L and N wires are connected to the mains, the output has three wires for three phases U, V, and W of the ceiling fan; the debugger connects with PC for parameter tuning.

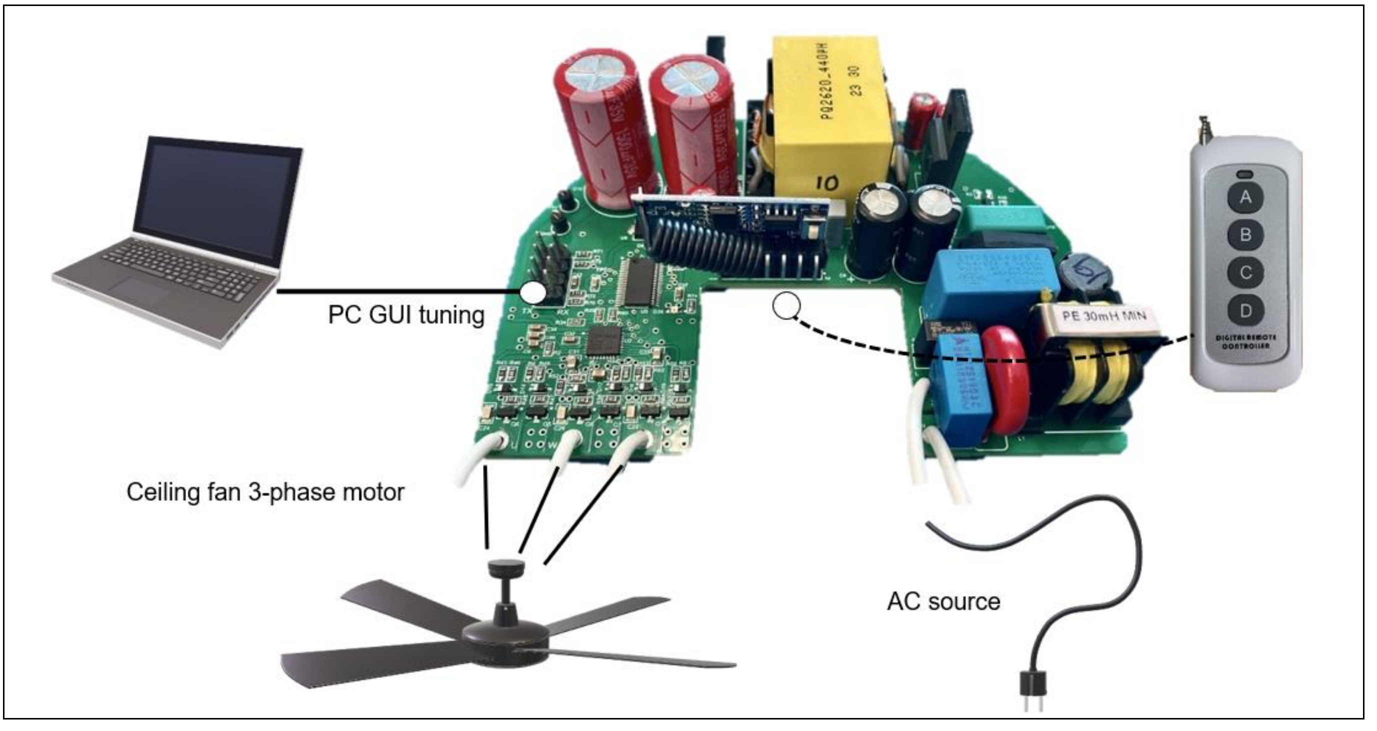


Figure 5 **Setup of board**

2.3 PFC flyback section description

2.3.1 EMI filter and surge protection

Figure 6 shows the surge and EMI protection section schematic. EMI filters include the two X2 capacitors of 100 nF and 220 nF, common-mode choke L1 of 30 mH and a 730 µH differential-mode choke L2.

To protect the system from lightning surge, a 385 V AC metal oxide varistor (MOV) is used across the power supply line along with an RCD snubber circuit after the rectifier bridge.

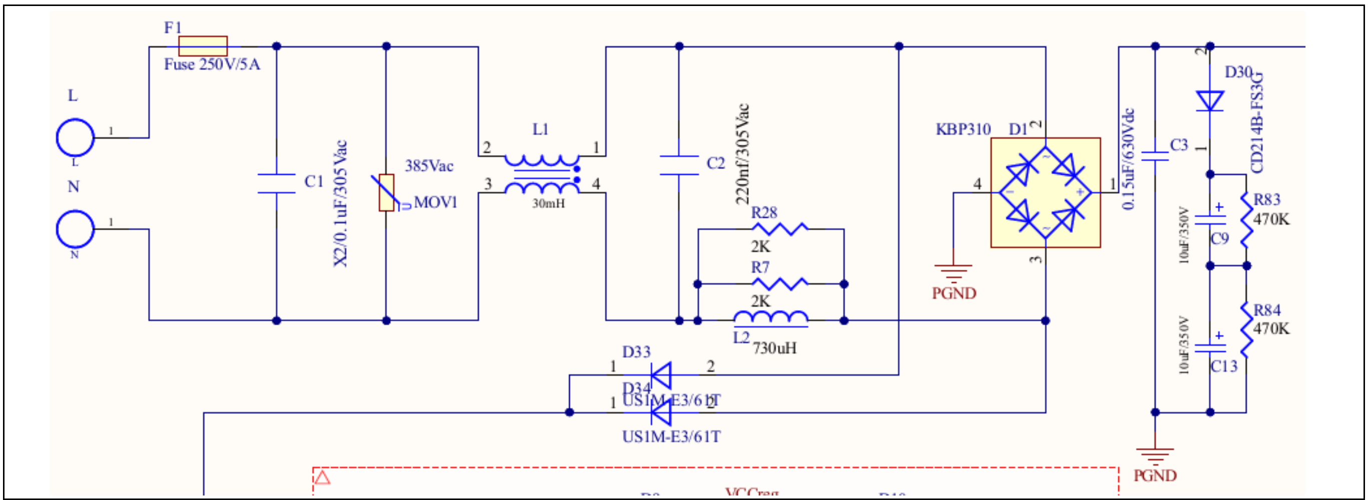


Figure 6 Input EMI filter and surge protection design schematic

2.3.2 Current sensing and overcurrent protection

The ICL8810 controller includes a primary-side OCP feature. The current through the MOSFET at the PFC stage is sensed across resistor R_{CS}, as shown in Figure 7.

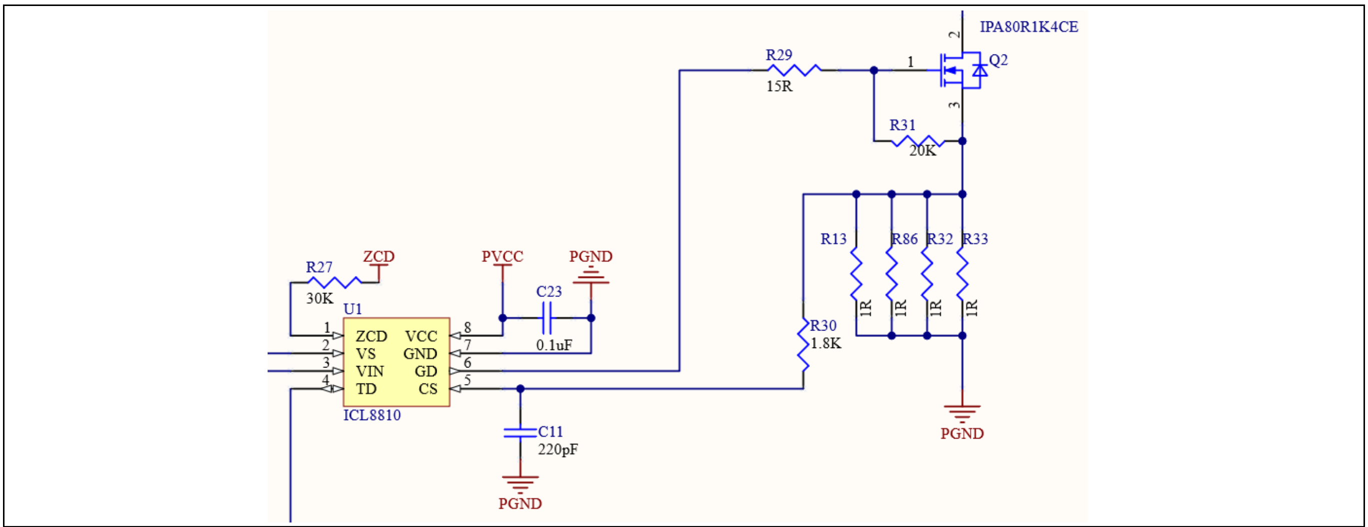


Figure 7 Current sensing circuitry

R_{CS_OCP} consists of four 1.5 Ω resistors (R13, R86, R32, and R33) in parallel for better power handling during lightning surge. In order to limit input power at the low-line to reduce the temperature at the input filters, a larger effective resistance value is used.

The effective resistance is 0.375 Ω; following the OCP design of ICL8810, we have:

$$I_{PRI,OC1} = \frac{V_{OCP1,TYP}}{R_{CS\_OCP}} = \frac{0.61\,V}{0.375\Omega} = 1.63\,A$$

Equation 1

Where $V_{OCP1,TYP}$ refers to the first OCP threshold for ICL8810, as stated in the datasheet. ICL8810 has the second OCP level of $V_{OCP2,TYP}$ = 1210 mV.

$$I_{PRI,OC2} = \frac{V_{OCP2,TYP}}{R_{CS\_OCP}} = \frac{1.21\,V}{0.375\Omega} = 3.23\,A$$

Equation 2

When a PFC primary OCP is triggered, the system would turn off the gate driver for the ongoing switching cycle. The system shuts down and auto-restarts after 200 ms.

2.3.3 Overvoltage protection

The output OVP of the flyback stage is designed together with the current sensing circuit in Figure 9. R30 is R_{CS_OVP}, which is used to set the secondary output OVP level. Setting an output OVP of 35 V, we have:

$$I_{ZCD-OVP} = \frac{\frac{N_{aux}}{Ns} \times V_{outovp} \times 1.05}{R_{ZCD}}$$

Equation 3

$$I_{ZCD-OVP} = \frac{\frac{6}{11} \times 35 \times 1.05}{30K} = 668\,\mu A$$

Equation 4

Where 1.05 refers to an extra 5 percent tolerance.

With this, the current output of the CS pin is calculated:

$$I_{CS\_OVP} = I_{ZCD\_OVP} \times n_{ZCD,OVP} = 668\,\mu A \times 0.484 = 323\mu A$$

Equation 5

Where $n_{ZCD,OVP}$ is the ratio between I_{CS_OVP} and I_{ZCD_OVP} in ICL8810.

$$R_{CS\_OVP} = \frac{V_{OCP1,TYP}}{I_{CS,OVP}} = \frac{0.61\,V}{323\,\mu A} = 1.89\,k\Omega$$

Equation 6

Once an OVP is triggered at the PFC stage, the system shuts down and restarts automatically after 200 ms.

2.4 Motor drive section description

2.4.1 Interface circuit of XMC1302

Figure 8 shows the interface of the XMC1302 motor drive MCU:

- The XMC1302 MCU requires 5 V supply from the PFC output
- UH, UL, VH, VL, WH, and WL drive the high-side and low-side of the gate driver for three phases
- IR is used for IR remote control module connection
- Red LED indicates any fault or protection triggered
- DO1 to DO3 from pin 29 to 32 are the four buttons for RF remote control
- SWIO, SWCLK, PC RXD, and PC TXD are used for debugger connection with the PC GUI
- I_{BUS} is the bus current sensing, pin 37 is for the internal comparator to compare with OC_{th}, and pin 38 is for actual shunt sensing
- DC voltage is the bus voltage sensing signal
- BEMF U, V, and W refer to the back electromagnetic fields generated at respective phases, used for CFR function
- DO3 at pin 6 is a pin dedicated for waking up the system from Deep Sleep mode for RF control
- IU is the phase current sensing

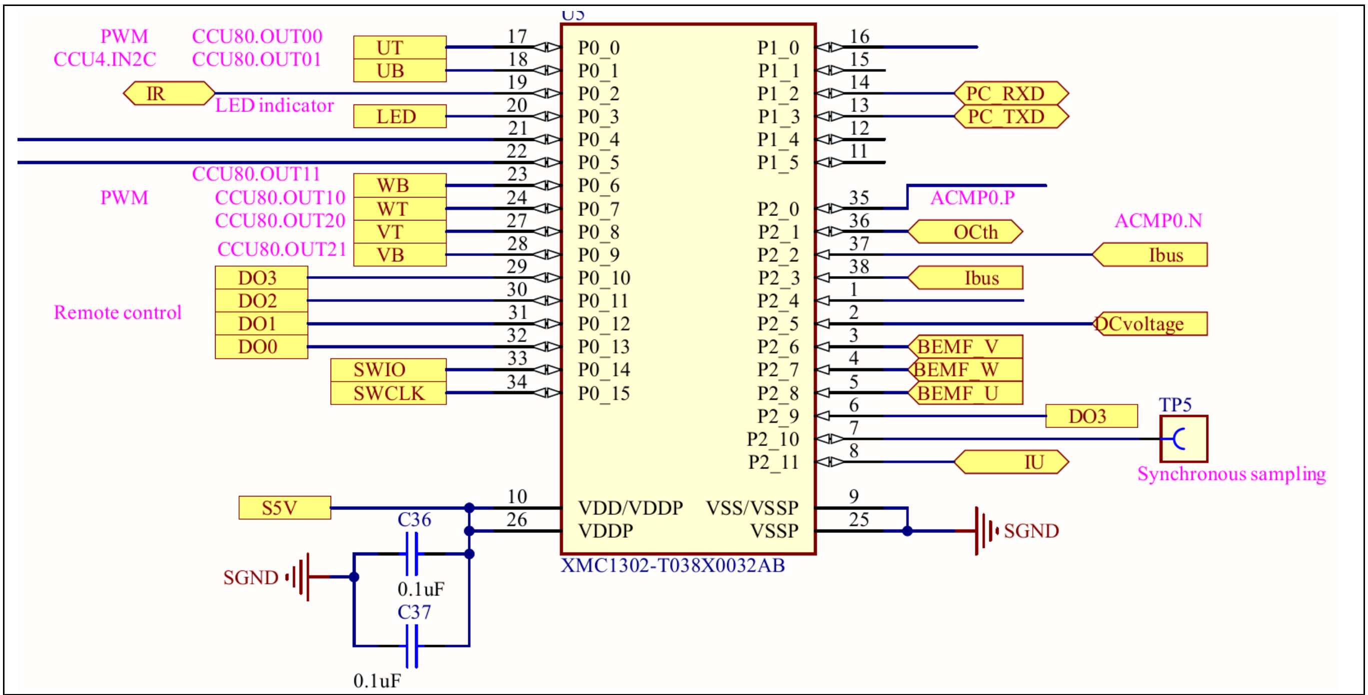


Figure 8 Interface circuit of XMC1302

2.4.2 Motor current sensing

This module is used to measure motor phase currents using the VADC peripheral.

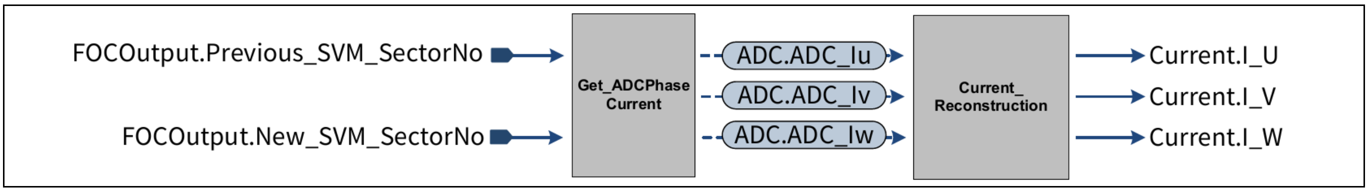


Figure 9 Current sensing and calculation functions

The phase current measurements are synchronized with the PWM space vector modulation(SVM) pattern generation. The fourth slice of the CCU80 module, slice 3, is used to trigger the ADC conversions.

In XMC1302, a gain stage can be applied to all analog channels of the VADC peripheral. This is to compensate for low-amplitude signals. With this feature, an external fast op-amp is not required for the phase current signals. This leads to cost savings in the PCB BOM.

Single-shunt current sensing

The single-shunt current measurement technique measures the power supply current and, with knowledge of the switching states, recreates the three-phase current of the motors.

In the single-shunt current sensing, two different SVMs are used:

- Pseudo-zero vector (PZV) SVM
- four-segment SVM

Pseudo-zero vector SVM

PZV SVM is used to ensure enough time is given for single-shunt current sensing. The CCU80 slice 3 is used as a timer to automatically trigger the ADC conversion at a specific time. The ADC conversions are triggered at both the rising and falling edges of the CCU80 slice 3 signals. When a four-segment SVM is used, the ADC conversion trigger points are also changed.

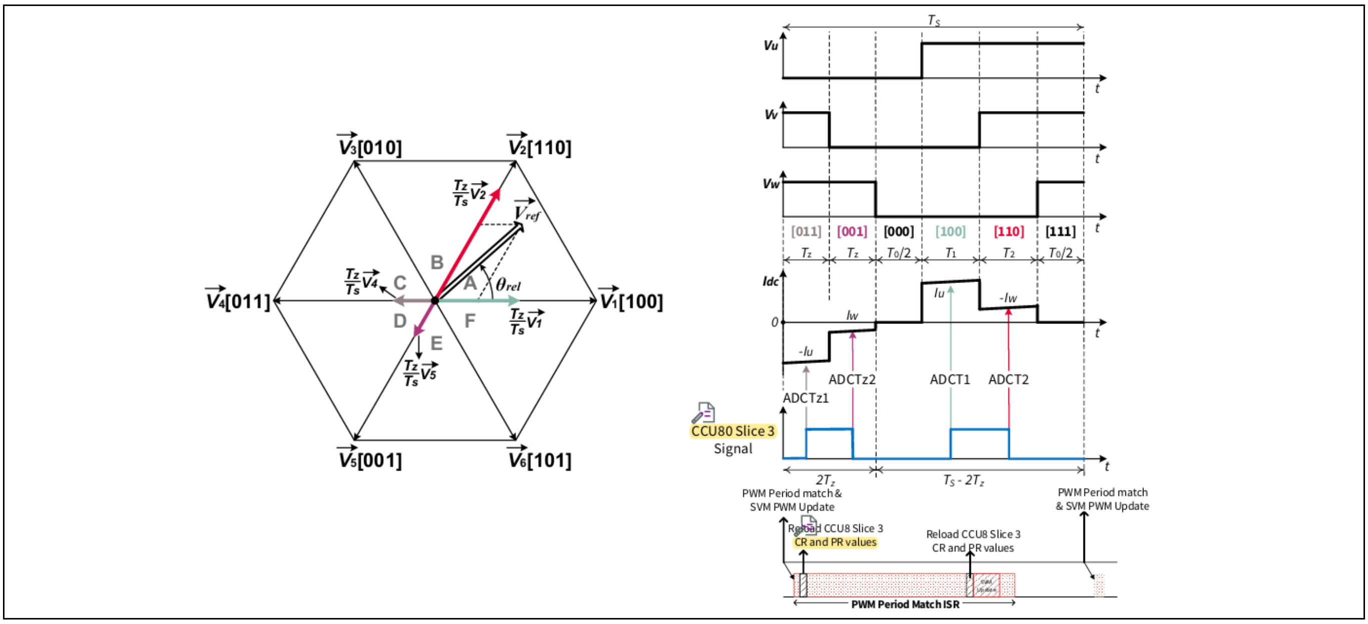


Figure 10 Single-shunt three-phase current sensing in sector A

Four-segment SVM

This SVM pattern is also used in the single-shunt current sensing technique. PZV is useful in certain conditions, at sector crossovers or when the length of the vector is low. However, if PZV is used throughout, the motor might not be able to spin up to its maximum target speed due to the limitation in the voltage amplitude. The higher the TZ value, the lower the motor speed it can reach. To resolve this condition, a four-segment SVM is used.

In the PMSM_FOC software, a transition between PZV and four-segment SVM PWM generation is implemented to resolve this issue. When T1 and T2 are greater than T_{min} and the motor speed is more than 75 percent of the maximum motor speed, a four-segment SVM is used. In this way, the maximum target speed can be achieved.

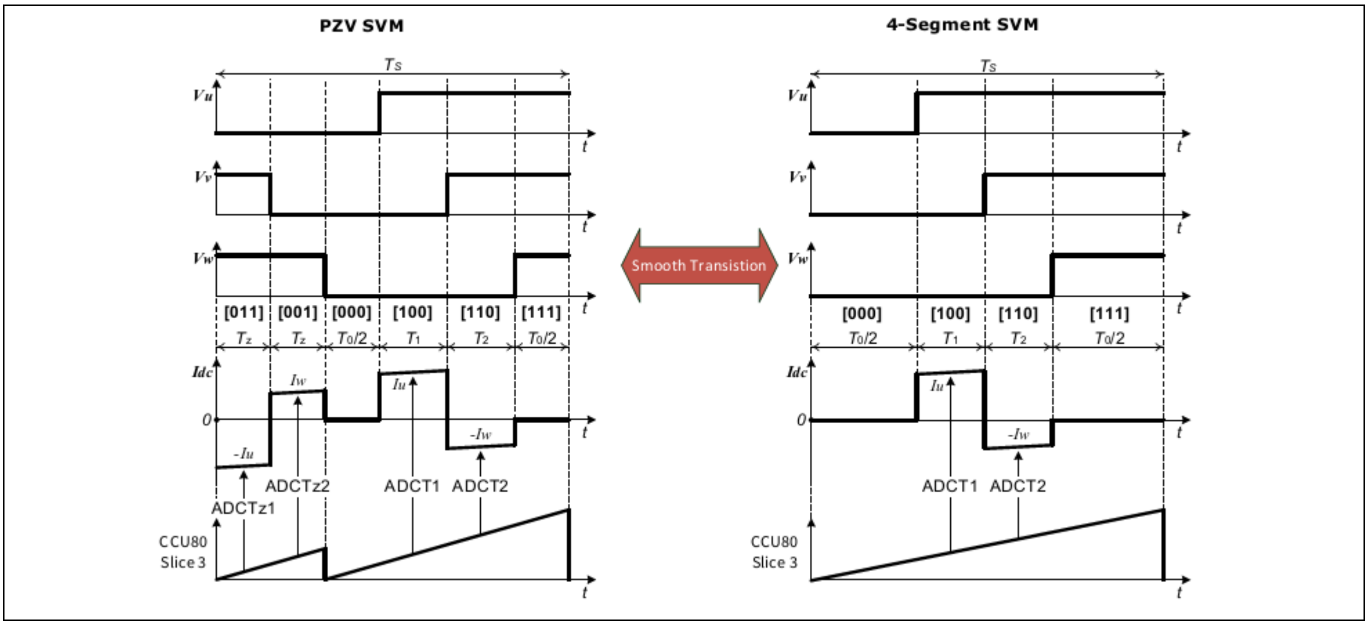


Figure 11 **Smooth transition from PZV to four-segment SVM in sector A**

2.4.3 Motor overcurrent protection

There are two OCPs in place:

- Software OCP
- Hardware OCP

2.4.3.1 Software overcurrent protection

This compares the absolute value current of motor phases U, V, and W to the overcurrent preset limit value. Once the absolute value of any of the phase currents exceeds the preset limit value, protection occurs and disables the inverter function by setting the inverter pin to tristate, stopping the motor immediately.

The i_OCP_limit value can be adjusted through the software.

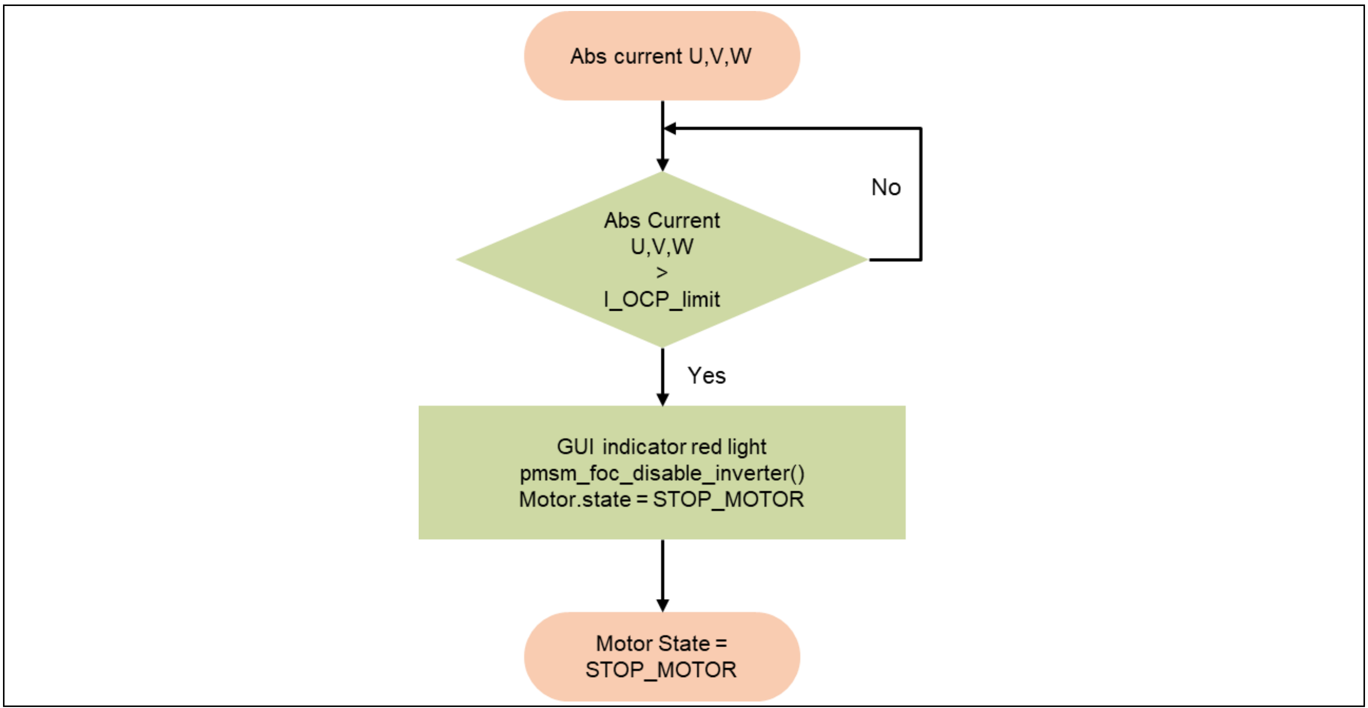


Figure 12 Software OCP flowchart

2.4.3.2 Hardware overcurrent protection

This hardware OCP feature uses the XMC™ internal analog comparator (ACMP) to compare the overcurrent threshold (OC_{th}) reference voltage and the shunt current input voltage. When the shunt current voltage exceeds the OC_{th}, overcurrent occurs, making the ACMP output high.

The hardware OC_{th} level is set at around 4.6 A by the circuit, as shown in Figure 13. For this design, the OC_{th} is at 0.875 V, and once I_{BUS} senses a voltage greater than this threshold, hardware OCP will be triggered by the system. Hardware OCP serves as extra protection in case the software OCP is not triggered when there is an overcurrent event.

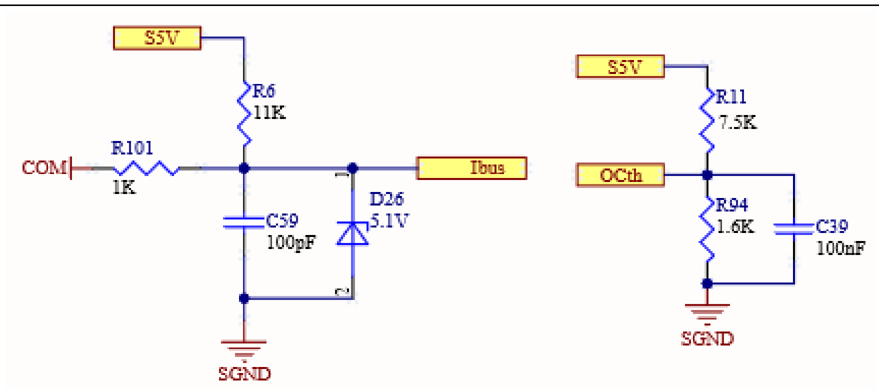


Figure 13 Hardware OCP circuit

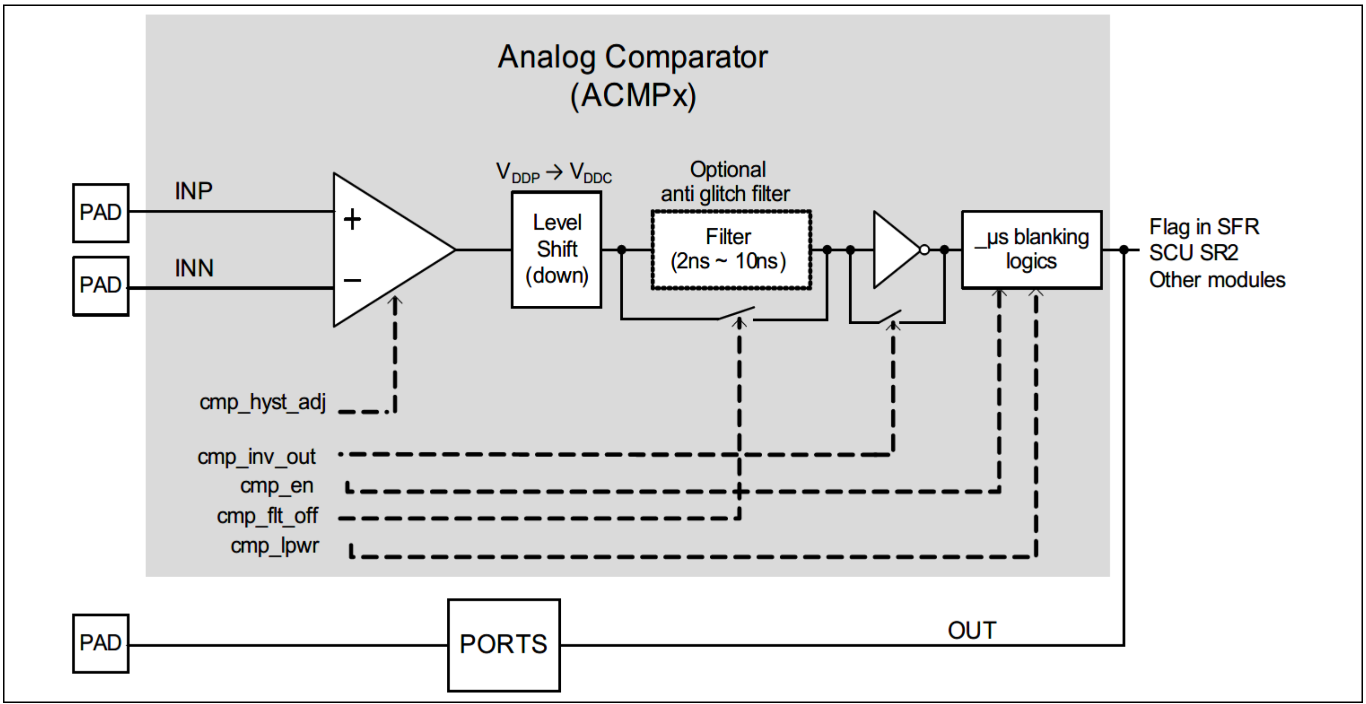
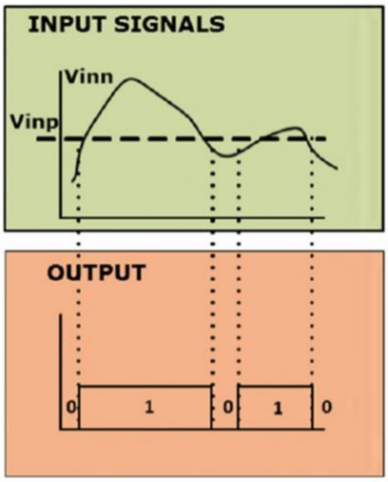


Figure 14 **Block diagram of the analog comparator**



ACMP output (Invert on)		
v+(ref)	v-(input)	output
low	high	high
high	low	low

Figure 15 **ACMP input output logic**

Cmp_hyst_adj: Define the hysteresis voltage value to reduce noise sensitivity, having the following voltage values: off, 10 mV, 15 mV, and 20 mV

Cmp_inv_out: Enable or disable the inversion of the comparator output

Cmp_en: Enable or disable the comparator

Cmp_flt_off: Enable or disable absorbing generated spikes

Cmp_lpwr: Enable or disable low-power state

ACMP ERU C-trap

C-trap is a way of stopping the motor by using the CCU8 trap function. When ACMP output is high, the event request unit (ERU) detects the rising edge and thus triggers the output signal. This output from the ERU is mapped as an input signal for the CCU8 trap and then triggers the CCU8 trap interrupt, executing the C-trap function. This C-trap function sets the CCU8 outputs to a passive level. In the interrupt service routine (ISR), the motor state is set to TRAP_PROTECTION. This ISR is set to the highest priority level of 0.

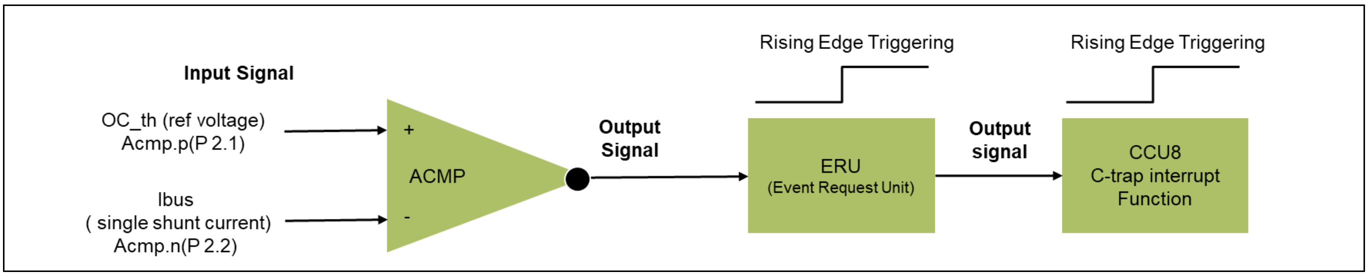


Figure 16 OCP signals

The time taken from the ACMP output until the C-trap function to disable all of the three-phase outputs is around 139 ns.

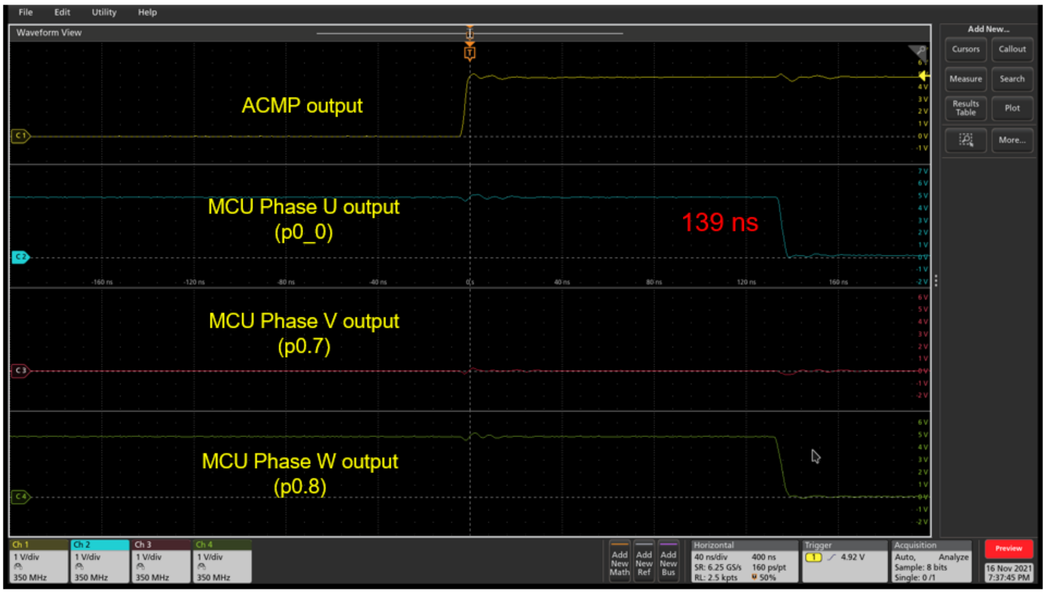


Figure 17 ACMP output to ERU to C-trap: 139 ns

The time taken from ACMP input to ACMP output: 37.5 ns
Total time taken from ACMP input to C-trap disabled: 139 ns + 37.5 ns = 176.5 ns

2.4.4 Overvoltage/undervoltage protection

This compares the ADC value of the DC-link voltage (V DC) to the limit value set. Once the V DC value exceeds the overlimit and the underlimit values set, the protection occurs and executes the “disable inverter” function, which disables the inverter pin by setting it to tristate, thus stopping the motor immediately.

The over_limit and the min_limit values can be adjusted through the software.

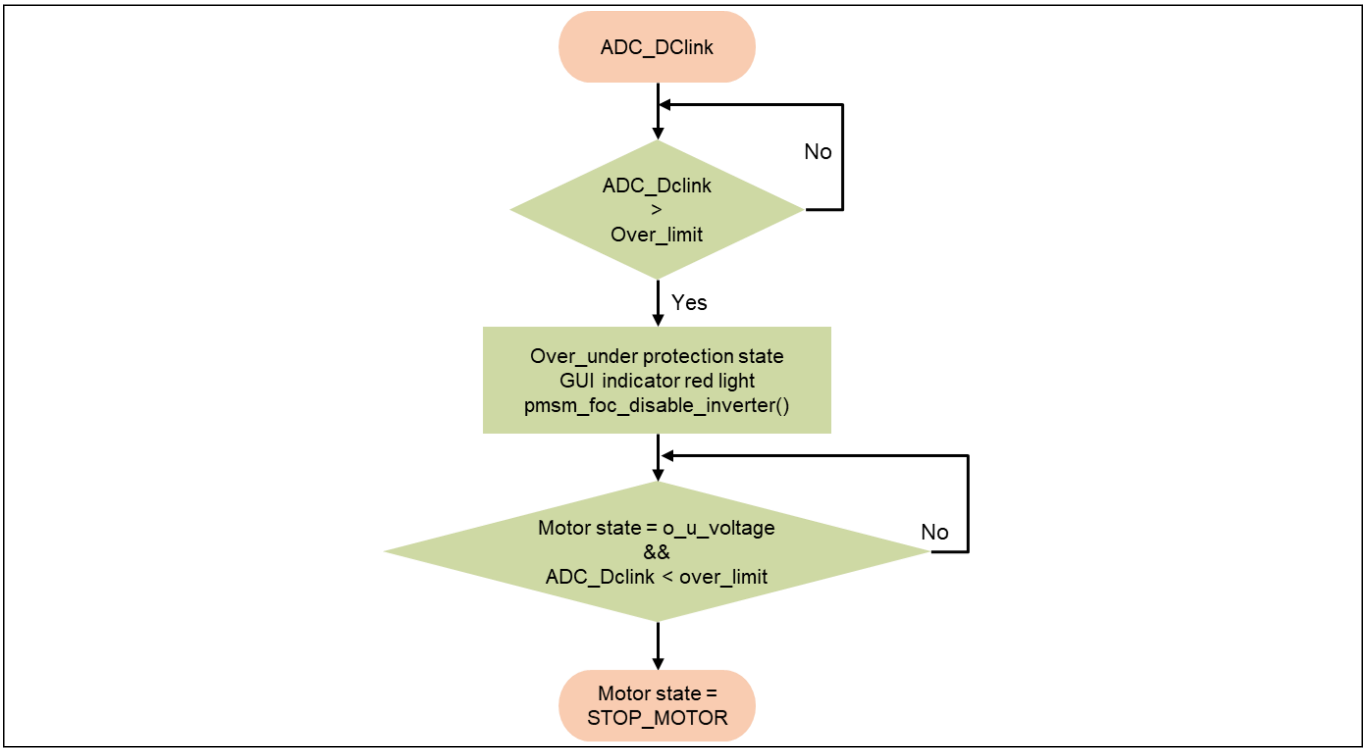


Figure 18 OVP flowchart

2.4.5 Remote control description

2.4.5.1 Radio frequency remote control

The RF remote control used in this project has four buttons in sync with the remote module. Each button on the remote control is remotely connected to a data output (DO) in the remote module. The DO will be connected to an assigned MCU port pin.

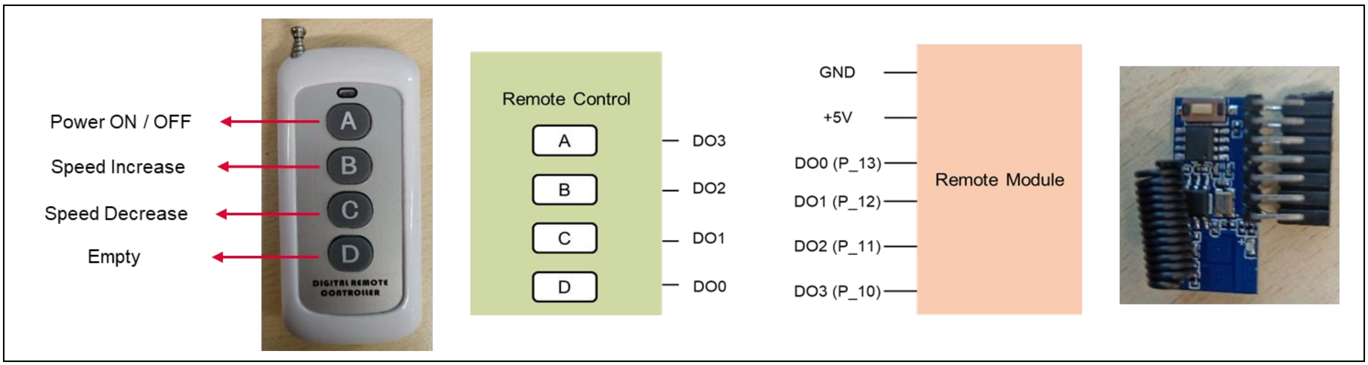


Figure 19 RF remote control block diagram

Overview of button functionality

Button A (power on/off):

- In the initial power on, fan is auto-started at speed level 1.
- Subsequent button is turned on, it is set to the last speed level when the button is turned off.

Button B (increase speed level): At initial power on, speed level is 1; this button scales the speed level up, up to the maximum speed level of 5.

Button C (decrease speed level): Similar to button B, but it decreases the speed level to the minimum speed level (1).

Button D: Empty function

Button hold detection: This button detects if you are holding the button. It always counts as being pressed once (1x).

2.4.5.2 Remote Module & Controller

See the following links to learn more about the remote module used in this ceiling fan application:

- CF_Remote_Module
- CF_Remote_Module_&_Controller

2.4.5.3 Infrared remote control

The IR remote control uses the NEC protocol. It sends the modulated signal to the IR receiver module. The IR receiver module processes and outputs the demodulated signal to a receiver pin in the XMC™ MCU.

The signal from the receiver pin is decoded to get the hex value. Each button on the IR remote controller has a different hex value used to determine which button was pressed on the IR remote controller.

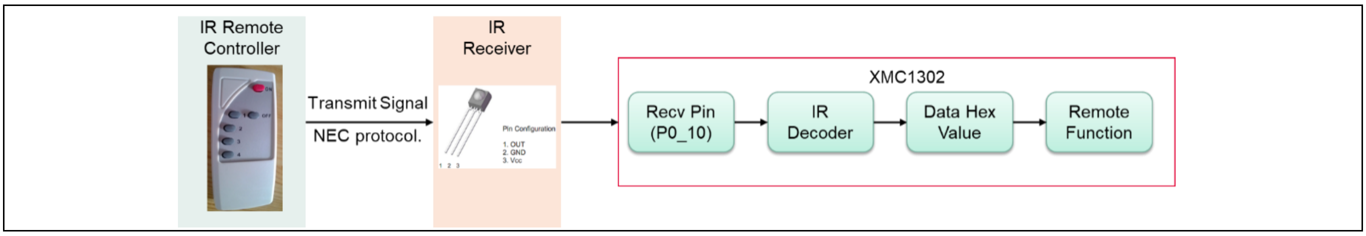


Figure 20 IR remote control block diagram

Overview of button functionality

The currently used IR remote controller has six buttons but only three buttons are used. Each button has the same functionality as the above RF remote control.

Button on (power on/off):

- At initial power on, the fan auto-starts at speed level 1.
- When the subsequent button is turned on, it is set to the last speed level when the button was turned off.

Button B (increase speed level): At initial power on, speed level is 1; it scales the speed level up, up to the maximum speed level of 5.

Button C (decrease speed level): Similar to button B, but it decreases the speed level up to the minimum speed level (1).

2.4.6 Sleep mode

The main purpose of the Deep Sleep mode function is to save power consumption while the motor is in the Stop state. Both normal sleep mode and Deep Sleep mode are used in this ceiling fan project.

Going into Deep Sleep mode

When powering off the ceiling fan, the fan comes to a stop and goes to Motor State: Stop. 16 s into the Motor State Stop, the MCU enters Deep Sleep mode.

The timing can be adjusted through the software.

Waking up from sleep mode

Pressing the RF remote control power on button wakes the MCU up and the fan resumes the last speed level. When pressing the power on button, it sends a high signal to the ERU pin, thus triggering the ERU interrupt that wakes up the MCU.

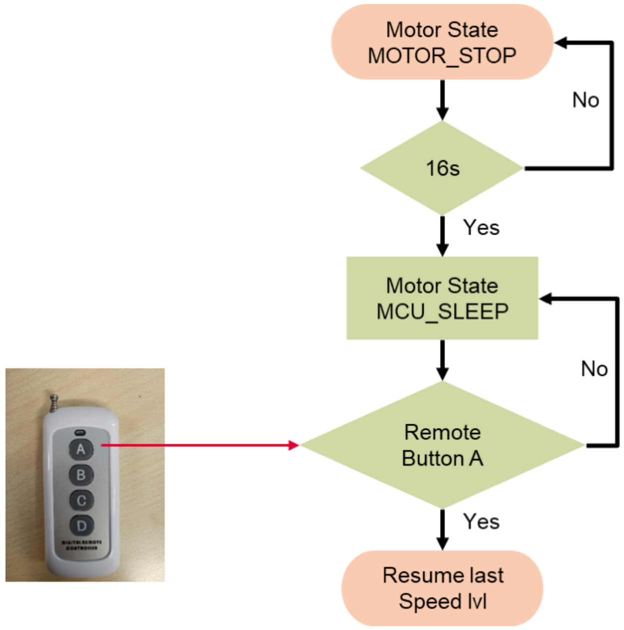


Figure 21 Deep Sleep mode function flowchart

2.4.6.1 Sleep mode vs. Deep Sleep mode

Sleep mode

1. Clock to CPU is stopped.
2. Clocks of peripherals that are not needed during sleep mode can be gated before entering the sleep state.
3. Flash can be put into shutdown using register PWRSVCR.

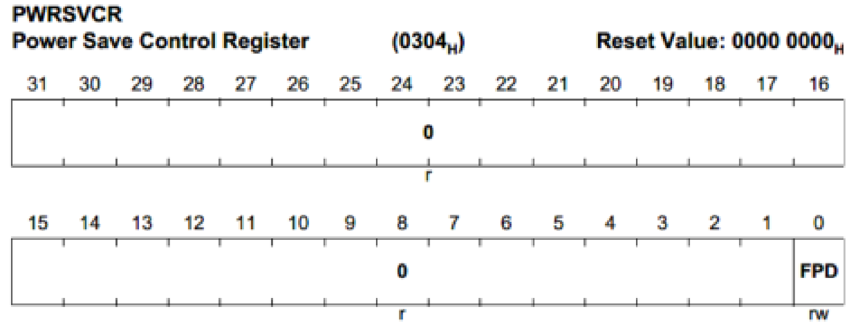


Figure 22 Setting the flash power down value

Table 2 Setting the Flash Power Down value

Field	Bits	Type	Description
FPD	0	rw	**Flash Power Down** 0_B no effect 1_B Flash power down when entering power save mode. Upon wake-up, CPU is able to fetch code from flash.
0	[31:1]	r	**Reserved** Read as 0

4. Shut down operation after the wait for interrupt (WFI) instruction.
5. On wakeup, the flash is operable again before the CPU can continue fetch and execute code. A certain wake-up time is needed for the Flash to reach the Active state.

Deep sleep mode

1. The same as sleep mode.
2. PCLK (peripheral) and MCLK (main) switch to slow the standby clock (DC02 – 32.678 kHz).
3. DC01 (64 MHz) is put into power-down mode.
4. Peripherals runs under the slow standby clock.

2.4.6.2 Sleep mode power consumption

At 230 V AC input, the power consumption during sleep mode is as shown in Table 3.

Table 3 Sleep mode power consumption

Motor state	Standby power (W)
MOTOR_STOP	0.83
MCU_SLEEP (sleep mode)	0.77
MCU_SLEEP (Deep Sleep mode)	0.70

2.4.7 Stall detection

During motor stalling, there is a certain motor stall phase current that is still ongoing. This stall detection function detects the stall condition and executes the disable inverter function, which disables the inverter pin by setting it to tristate, stopping the motor immediately.

2.4.8 Retry function

When any of the following faults occur, the motor comes to a complete stop. Once the fault is cleared, it goes to the STOP_MOTOR motor state. During the STOP_MOTOR state, after a set duration, the auto-retry function is executed. This auto-retry function allows the motor to resume its last speed level.

There can be a certain number of retry attempts. Once the attempt limit is reached, it does not auto-retry and goes into the STOP_MOTOR state. Resume the fan by pressing the “Power on” button again.

The number of retry attempts and the the timing before the auto-retry function is executed is adjustable through the software.

The following faults have the auto-retry function after being cleared:

1. Stall detection
2. Software OCP
3. Hardware OCP (ACMP)
4. OVP/UVP

Figure 23 Auto-retry when stall detection occurs: Attempt count 3

2.4.9 Catch-free run

There are situations where a fan is running due to external forces such as wind or pressure. During power on, if the fan is running above a minimun speed threshold, instead of starting from zero, the motor starts from a set speed with the help of the CFR algorithm.

The CFR function also detects the free-running motor direction and, in the case of reverse direction, it brakes the motor for a certain time.

This function enables a better dynamic response and smooth startup of the ceiling fan.

2.4.10 Rotor initial position detection (IPD)

The inductive sense method is used to determine the initial motor position when the IPD feature is enabled. This approach is particularly useful in applications where motor reverse rotation is not tolerated, and higher startup torque is required. Additionally, it enhances motor startup time, ensuring faster and more reliable operation.

2.4.11 Power Limiting

The power limiting function is to limit the speed if the output power exceeds the user-defined maximun power limit value. This is done by calculating and getting the normalized power limit torque current threshold value. In the speed control, if the normalized magnitude of current space vector has exceeded the threshold value, it then ramps down the speed reference value until the normalized magnitude current space vector is below the threshold.

3 System design

3.1 Schematics

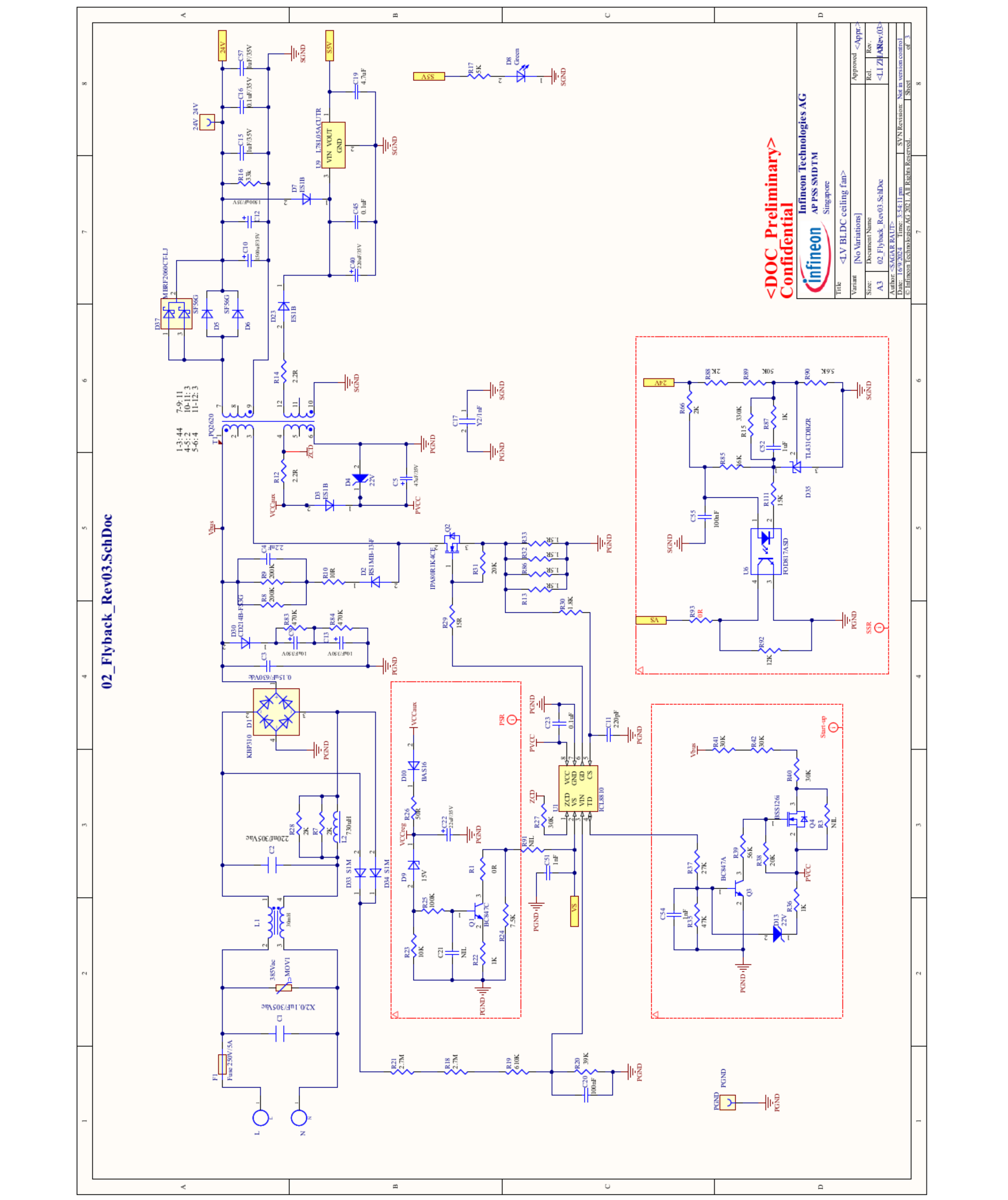


Figure 24 Flyback schematic

Figure 24 shows the RF remote control module (left) and the IR remote (right). RF control has dedicated pins for each button on the controller. IR control only requires one signal pin for all buttons. See Section 2.4.5 for more details.

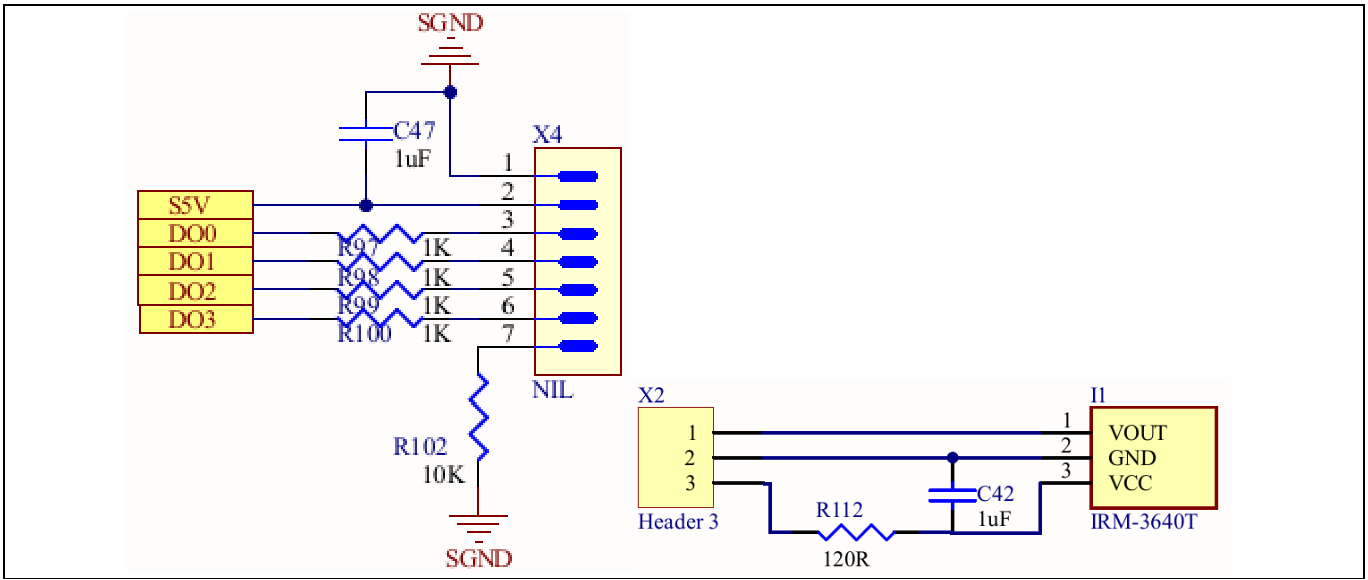


Figure 25 Remote control schematic

The 6-channel integrated gate driver 6ED2742S01Q incorporates three drivers into a single chip to reduce cost and component count as well as save space on PCB layout. The gate drivers used have external bootstrap resistors and diodes to ensure undervoltage does not happen during switching.

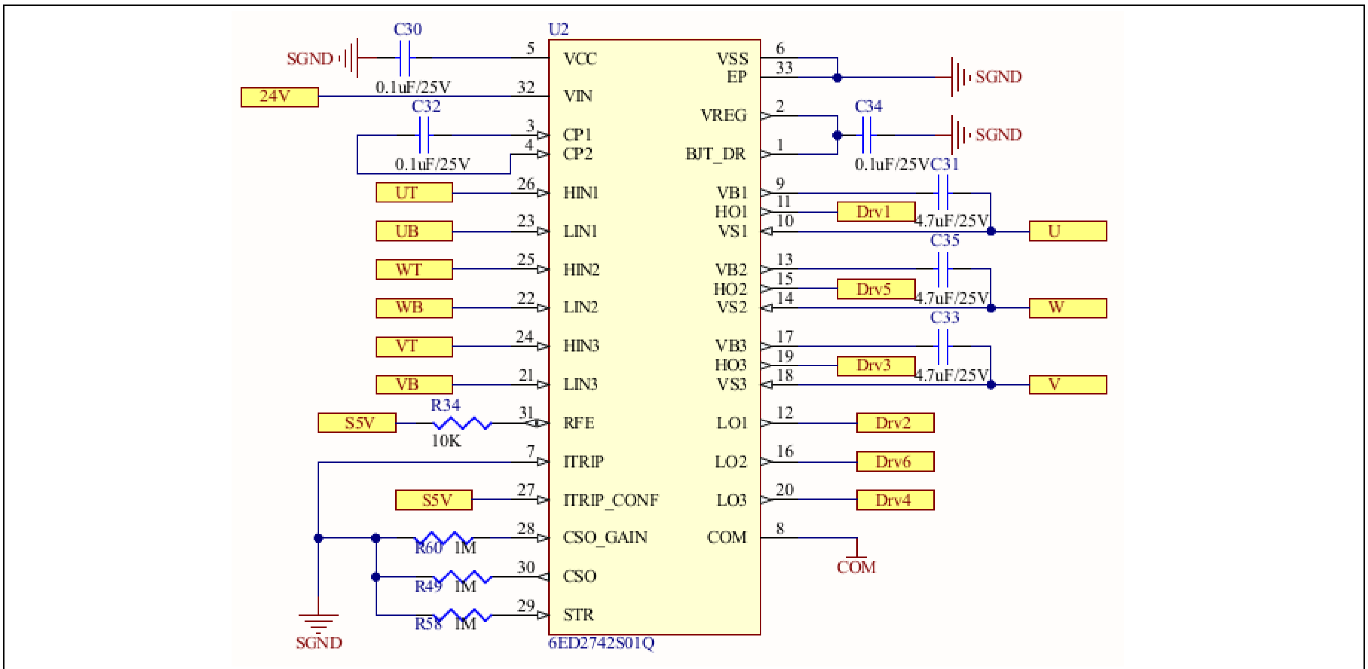


Figure 26 Motor gate driver schematic

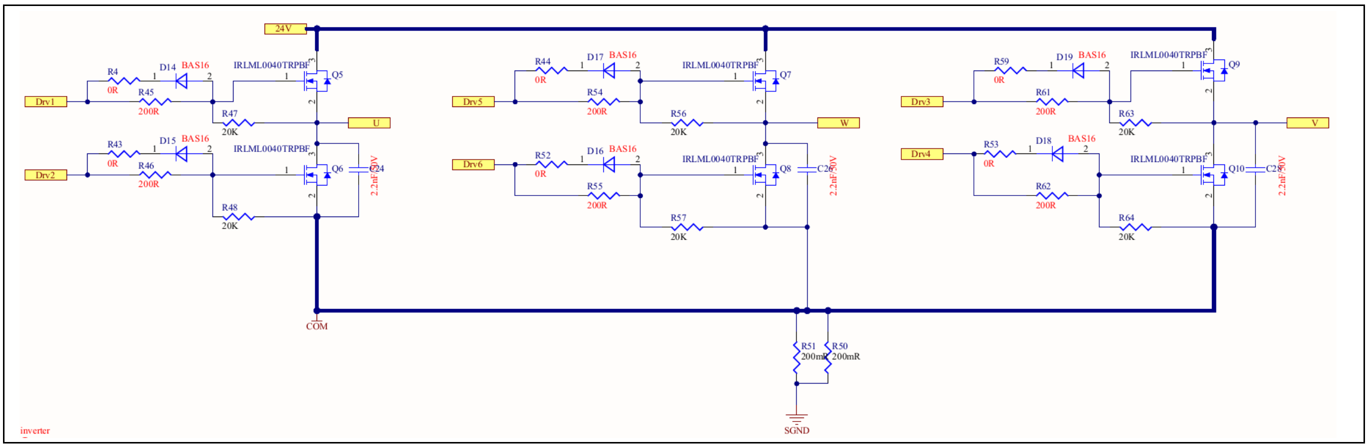


Figure 27 Motor inverter schematic

Other schematics can be found earlier in this section.

3.2 Layout

3.2.1 Main board layout

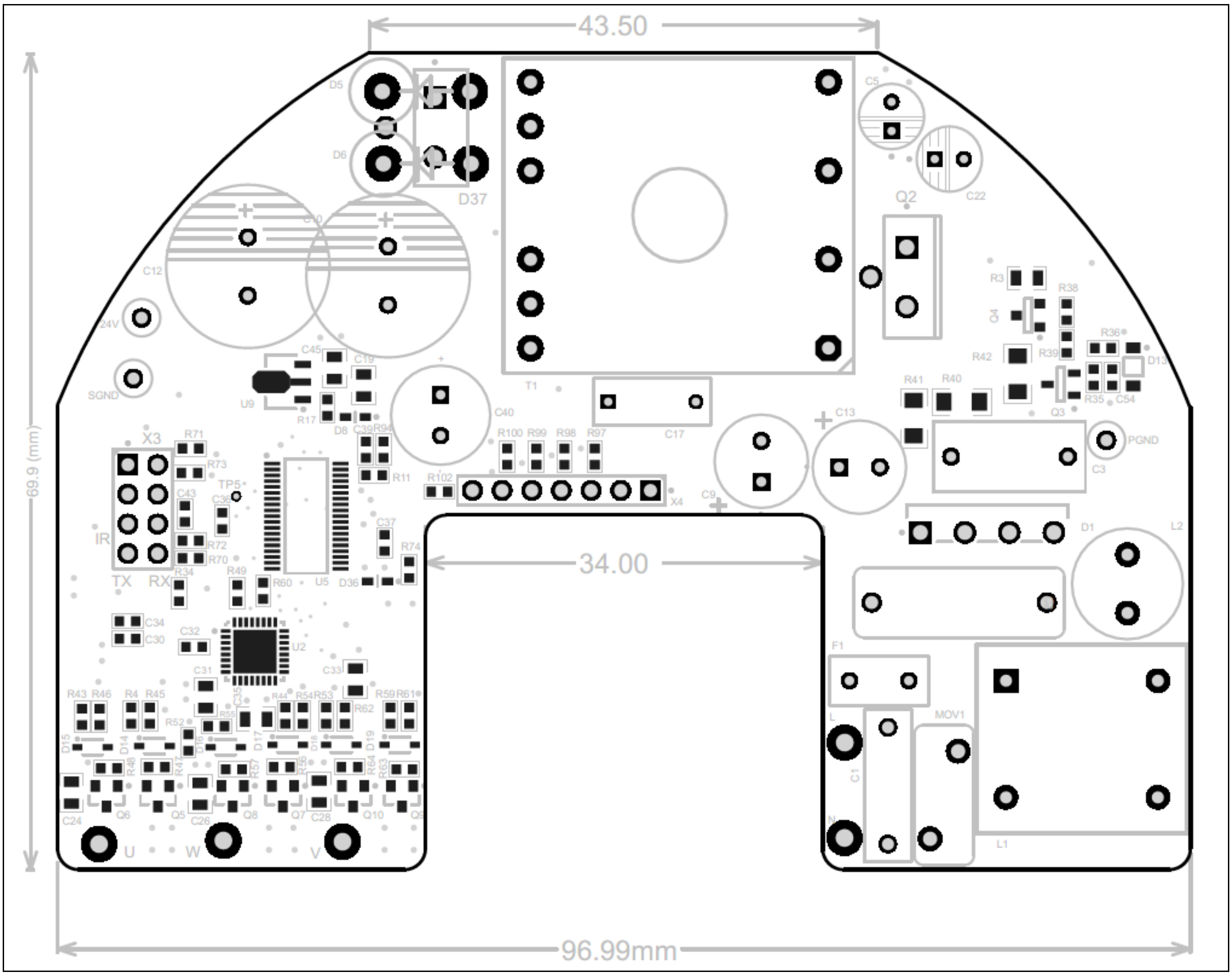


Figure 28 Main board top side

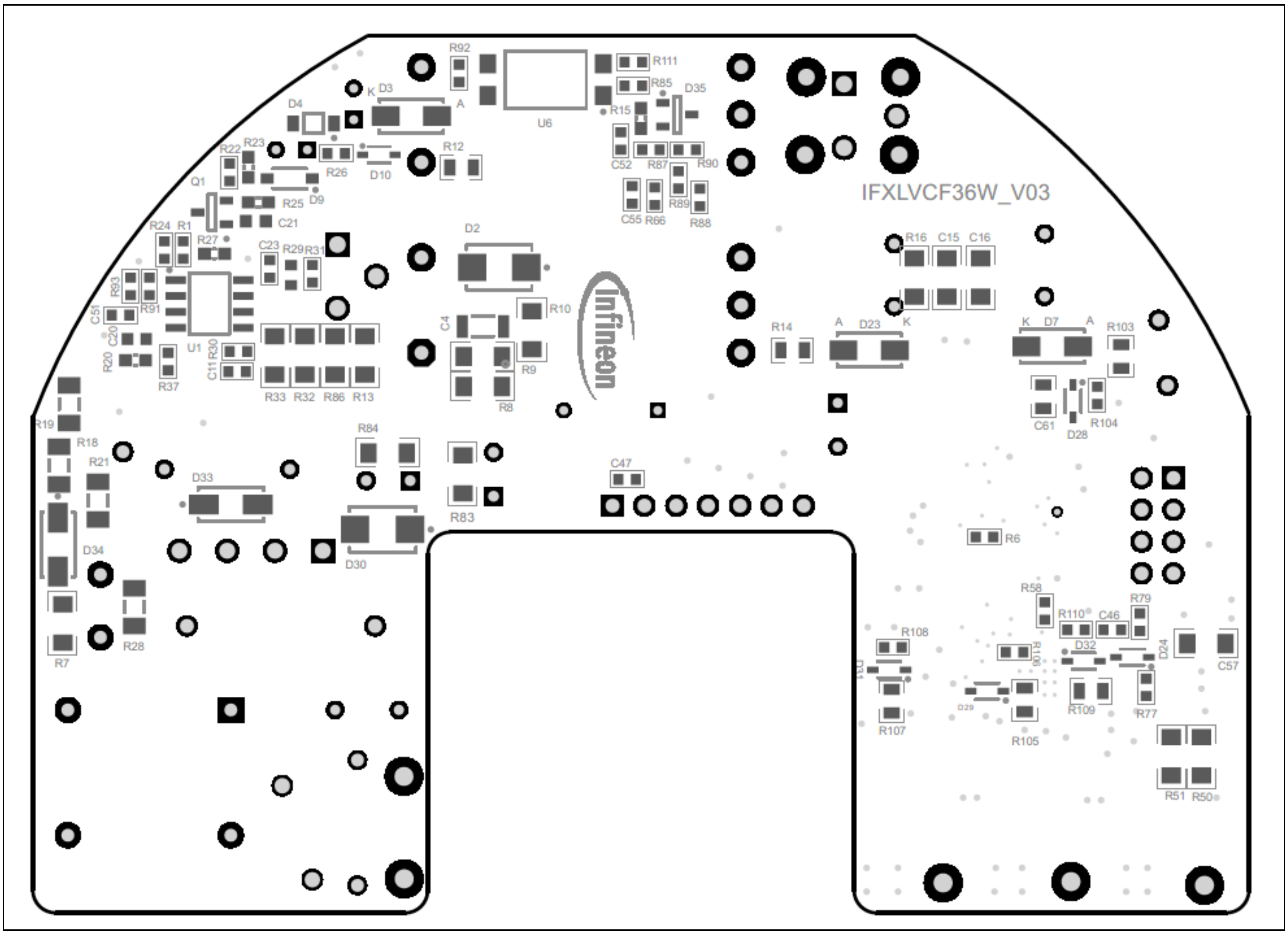


Figure 29 Main board bottom side

3.2.2 Daughter board layout

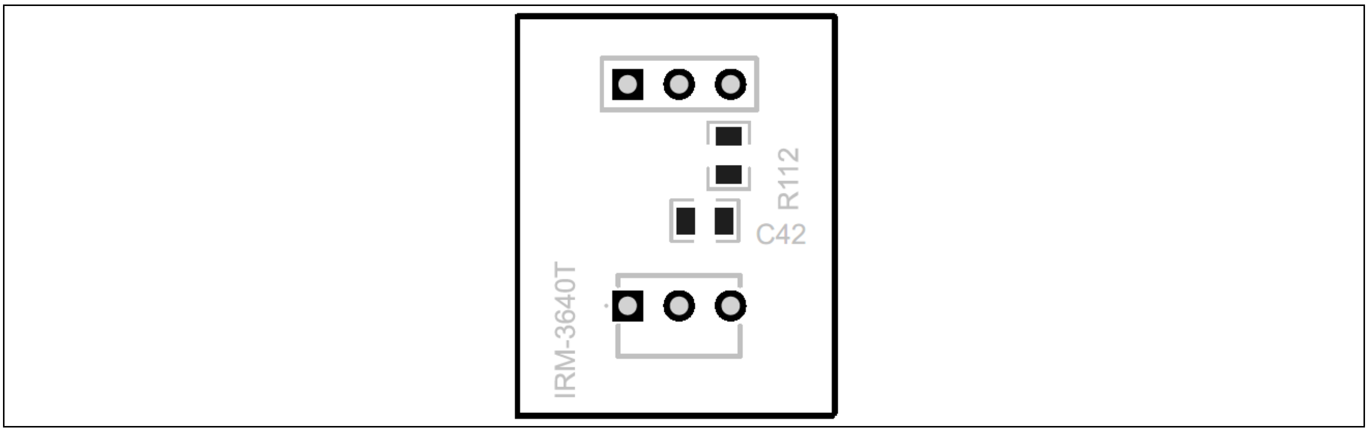


Figure 30 IR daughter board

3.3 Transformer design

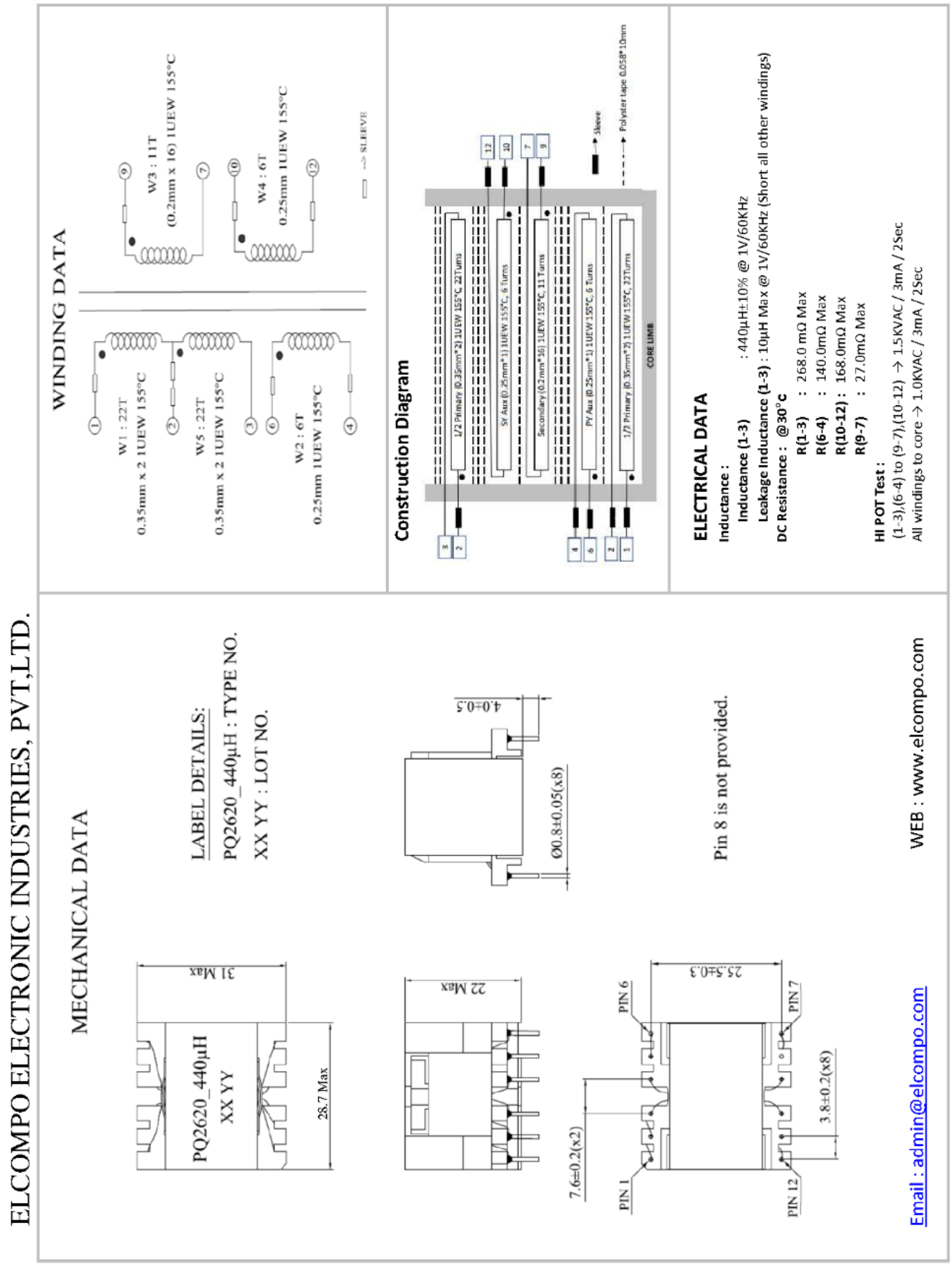


Figure 31 Transformer winding design

3.4 Bill of materials

Primary-side regulation (PSR) components are indicated as NIL.

Table 4 Design specifications

S/N	Designator	Comments	Description	Manufacturer
1	C1	X2/0.1 µF/305 V AC	Radial ceramic capacitor, mil-spec size CK05	Epcos
2	C2	220 nF/305 V AC	Radial ceramic capacitor, mil-spec size CK05	Epcos
3	C3	0.15 µF/630 V DC	Film capacitor/150 nF/630 V/20%/-/-40°C to 110°C/10.00 mm C x 0.60 mm W x 13.00 mm L x 6.00 mm T x 12.00 mm H	-
4	C4	2.2 nF	Ceramic capacitor/2.2 nF/ 1 kV/10%/X7R (EIA)/-55°C to 125°C/1206(3216)/SMD	-
5	C5	47 µF/35 V	Polarized capacitor (radial)/47 µF/35 V, 5 x 9 mm. pitch 2.5 mm	Würth Electronik
6	C7, C45, C61	0.1 µF	SMD general capacitor	-
7	C8	22 µF/35 V	Polarized capacitor (radial)/22 µF/35 V, 5 x 9 mm. pitch 2.5 mm	Würth Electronik
8	C22	NIL	-	-
8	C9, C13	10 µF/350 V	Polarized capacitor (radial)/10 µF/350 V	
10	C10, C12	1500 µF/35 V	Polarized capacitor (radial)/1500 µF/35 V, 12.5 x 20 mm pitch 5 mm	Würth Electronik
11	C11	220 pF	SMD general capacitor	-
12	C14	0.33 µF	SMD general capacitor	-
13	C15, C57	1 µF/35 V	SMD general capacitor	-
14	C16	0.1 µF/35 V	SMD general capacitor	-
15	C17	Y2/1 nF	Film capacitor (radial)/ 1000 pF/20%/1 kV DC	-
16	C19	4.7 µF	SMD general capacitor	-
17	C20	100 nF	SMD general capacitor	-
18	C21	NIL		-
19	C23, C37, C37, C43, C48	0.1 µF	SMD general capacitor	-
20	C24, C26, C28	2.2 nF/50 V	SMD general capacitor	-

S/N	Designator	Comments	Description	Manufacturer
21	C25, C27, C29	0.1 µF/50 V	SMD general capacitor	-
22	C30, C32, C34	0.1 µF/25 V	SMD general capacitor	-
23	C31, C33, C35	4.7 µF/25 V	SMD general capacitor	-
24	C38, C51, C54	1 nF	SMD general capacitor	-
25	C39, C55	100 nF	SMD general capacitor	-
26	C40	47 µF/35 V	Polarized capacitor (radial)/ 47 µF/35 V/5 x 9 mm pitch 2.5 mm	-
27	C46, C59	100 pF	SMD general capacitor	-
28	C47, C52	1 µF	SMD general capacitor	-
29	D1	KBP310	HV bridge rectifier/temp. range (-55°C to 150°C)	-
30	D2	RS1MB-13-F	Fast recovery rectifier/1 A	-
31	D3, D23	ES1B	Surface-mount ultrafast plastic rectifie/ temp. range (-55°C to 150°C)	-
32	D4, D13	22 V	Zener voltage regulator/22 V/ 500 mW/2-pin SOD-123/Pb-free/tape and reel	-
33	D5, D6	NIL		-
34	D8	Green	EXCELED series chip LED/green/560 nm	-
35	D9, D10	NIL	Zener diode/22 V/5%/500 mW	-
37	D12, D14, D15, D16, D17, D18, D19, D20, D21, D22	BAS16	Silicon switching diode	-
37	D24, D26, D28, D29, D31, D32	5.1 V	Small-signal Zener diode	-
38	D30		Fast-response rectifier chip diode	-
39	D33, D34	US1M-E3/61T	Fast diode/1000 V/1 A/75 ns recovery/surface mount	Vishay
40	D35	TL431CDBZR	Precision programmable reference	-
41	D37	Red	EXCELED series chip LED/red/ 620 nm	-

S/N	Designator	Comments	Description	Manufacturer
42	D37	MBRF20200CT	200 V/20 A/Schottky barrier rectifier	Littelfuse
43	F1	250 V/5 A	Radial lead fuse rectangular/time lag/5 A/250 V	-
44	L1	PE_30 mH	Common-mode power line choke/type UU10/30 mH	Elcompo Electronic Industries Ltd.
45	L2	700 µH	Inductor/700 µH, 1.6 A_{RMS}	Elcompo Electronic Industries Ltd.
46	MOV1	385 V AC	MOV voltage dependent resistor (VDR)/385 V AC/0.6 W	-
47	Q1		NPN silicon AF transistor	-
48	Q2	IPA80R1K4CE	800 V CoolMOS™ CE power transistor	Infineon Technologies
49	Q3	BC847A	NPN silicon AF transistor	-
50	Q4	BSS126i	SIPMOS small-signal transistor/ V_{DS}/600 V/I_{DSS_min} 0.007 A	Infineon Technologies
51	Q5, Q6, Q7, Q8, Q9, Q10	IRLML0040TRPBF	HEXFET® power MOSFET/40 V/ -55°C to 150°C/three-pin SOT-23/RoHS/tape and reel	Infineon Technologies
52	R4 R43, R44, R52, R53, R59, R70, R71, R72, R73, R93	-	SMD general resistor	-
53	R2, R5	-	SMD general resistor	-
54	R3	-	SMD general resistor	-
55	R6, R79	-	SMD general resistor	-
56	R7, R28	-	SMD general resistor	-
57	R8, R9, R83, R84	-	SMD general resistor	-
58	R10	-	SMD general resistor	-
59	R11	-	SMD general resistor	-
60	R12, R14	-	SMD general resistor	-
61	R13, R32, R33, R86	-	SMD general resistor	-
62	R15	-	SMD general resistor	-
63	R16	-	SMD general resistor	-
64	R17, R74, R111	-	SMD general resistor	-
65	R18, R21	-	SMD general resistor	-
66	R19	-	SMD general resistor	-
67	R20, R27	-	SMD general resistor	-

S/N	Designator	Comments	Description	Manufacturer
68	R37, R69, R77, R87, R97, R98, R99, R100	-	SMD general resistor	-
69	T1	440 µH	PQ2620	Elcompo Electronic Industries Ltd.
70	U1	ICL8810	ICL8800_SOIC127P600X175-8N-22	Infineon Technologies
71	U2	6ED2742S01Q	160V pre-regulated three phase SOI gate driver with integrated charge pump, current sense amplifier, over-current protection, and bootstrap diodes	Infineon Technologies
72	U5	XMC1302-T038X0200AB	XMC1000 family of microcontrollers based on the Arm® Cortex®-M0 processor core address the real-time control	Infineon Technologies
73	U6	FOD817ASD	Phototransistor optocoupler/4 µs rise/3 µs fall/5000 V_{RMS}/-55°C to 110°C/four-pin MDIP/RoHS/tape and reel	-
74	U9	L78L05ACUTR	Positive voltage regulator/5 V/four-pin SOT-89/tape and reel	-

Table 5 BOM of remote-control modules

S/N	Designator	Comments	Discription	Manufacturer
1	X4	RX480E	Four-channel 433 MHz wireless RF remote 1527 encoding module	Qiachip
2	I1	IRM-3740T	Infrared 940 nm wireless receiver module	Everlight

4 System performance

The performance results and waveforms are tested based on a trapezoidal four-pole pair ceiling fan with a maximum electrical speed of 350 RPM. The system runs with RF remote control.

4.1 Efficiency, PF and iTHD

Table 6 Efficiency, PF and iTHD

Input voltage (V AC)	Speed level	Fan speed (RPM)	System input power (W)	Inverter output power (W)	Efficiency (%)	PF	iTHD (%)
90	0		0.92				
	1	149	5.10	3.38	66.27	0.950	6.1
	2	199	9.04	6.95	76.88	0.980	6.5
	3	248	15.82	13.02	82.30	0.986	7.4
	4	301	25.37	21.24	83.72	0.987	8.5
	5	330	34.06	28.27	83.00	0.943	33.0
140	0		0.96				
	1	151	5.11	3.42	66.93	0.835	8.2
	2	198	9.17	7.16	78.08	0.927	7.3
	3	251	15.61	12.81	82.06	0.965	7.4
	4	298	25.10	21.32	84.93	0.973	10.5
	5	345	36.22	30.95	85.45	0.973	13.1
230	0		0.98				
	1	151	5.26	3.42	64.94	0.500	12.9
	2	200	9.26	7.10	76.64	0.700	9.6
	3	249	15.74	12.95	82.27	0.834	9.8
	4	298	24.61	21.15	85.94	0.895	10.2
	5	343	36.33	31.27	86.07	0.922	13.8
300	0		1.07				
	1	150	5.38	3.40	63.20	0.330	14.7
	2	198	9.35	7.00	74.86	0.574	12.2
	3	249	15.83	12.86	81.24	0.743	10.6
	4	298	25.30	21.29	84.15	0.831	13.6
	5	344	36.37	31.14	85.62	0.859	18.0

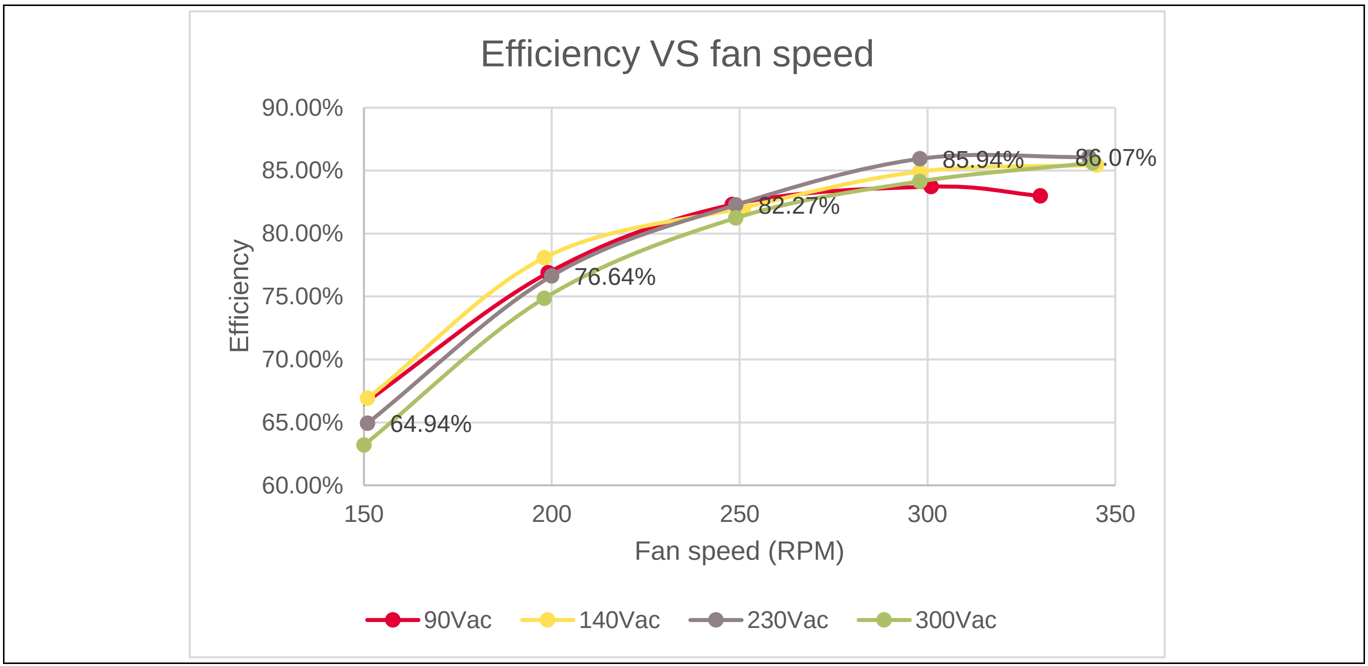


Figure 32 **Efficiency vs. fan speed**

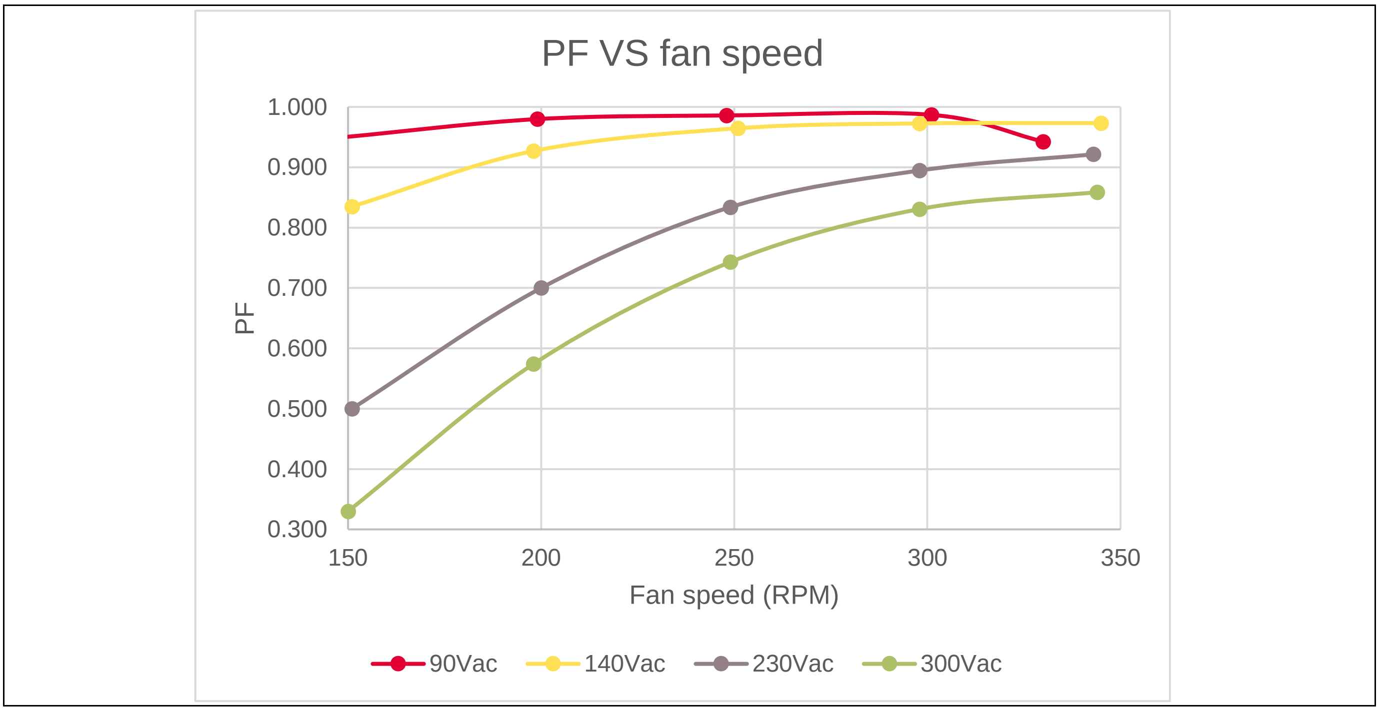


Figure 33 **PF vs. fan speed**

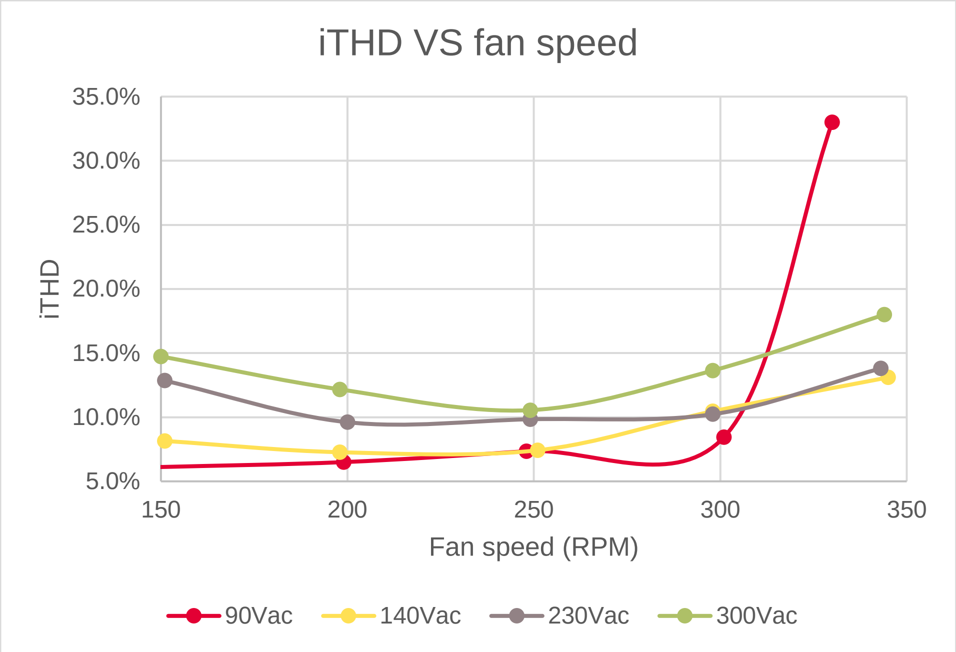


Figure 34 **iTHD vs. fan speed**

4.2 PFC performance

4.2.1 Startup

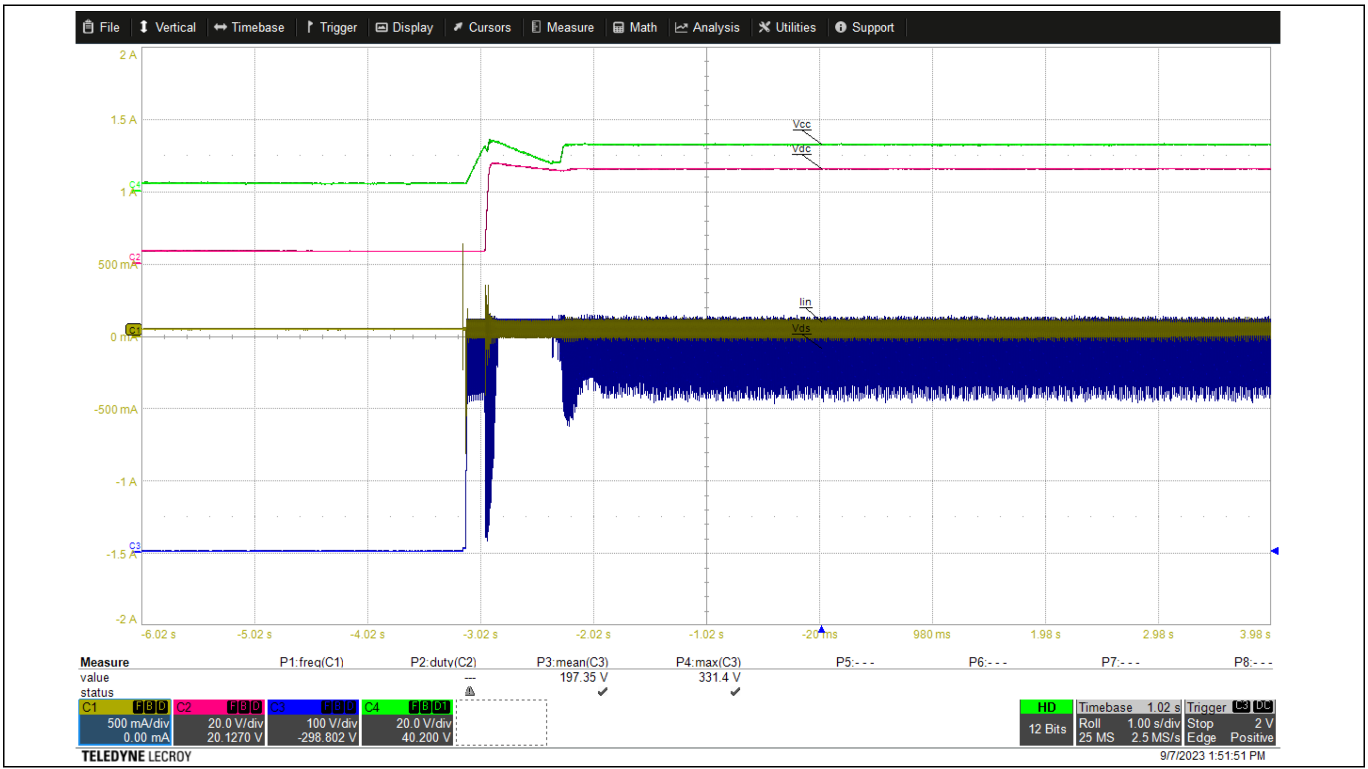


Figure 35 Startup input waveforms at 230 V AC input

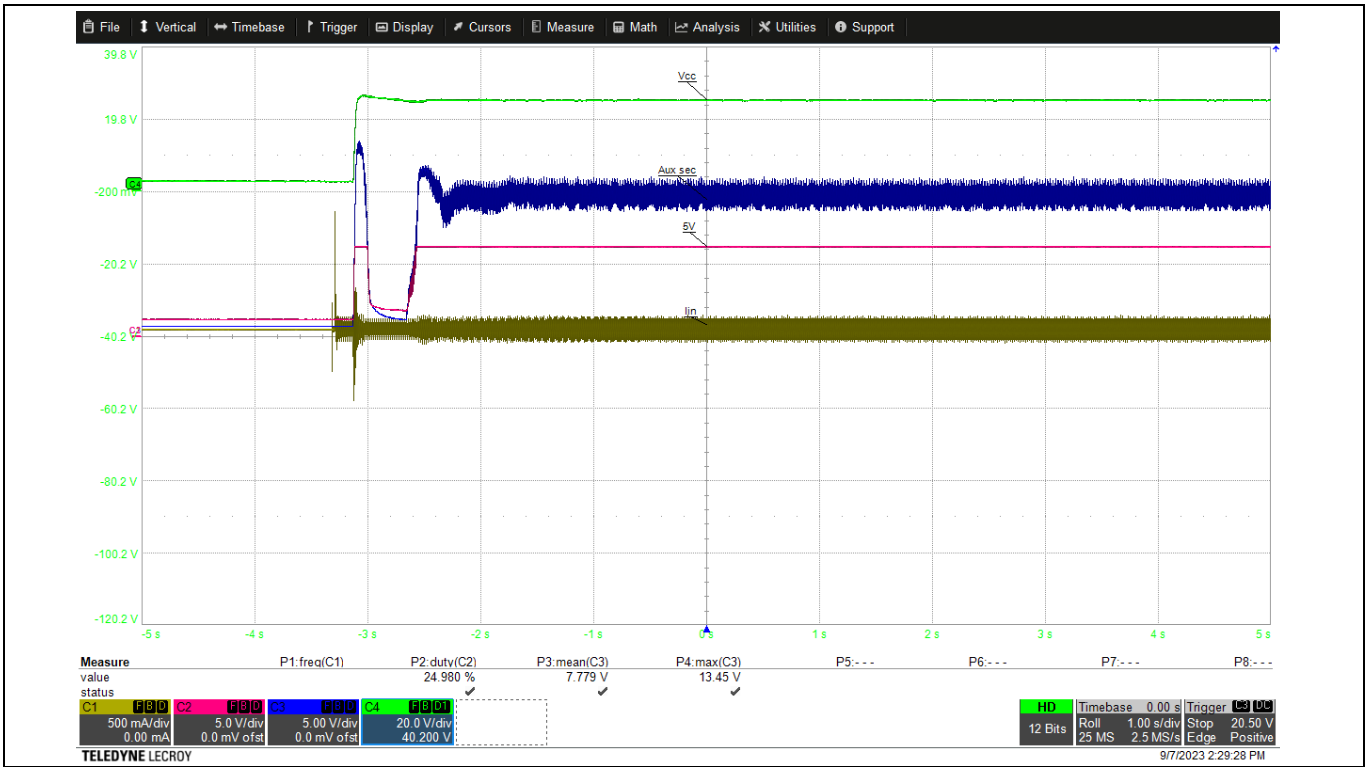


Figure 36 Startup output waveforms at 230 V AC input

4.2.2 Input current waveforms

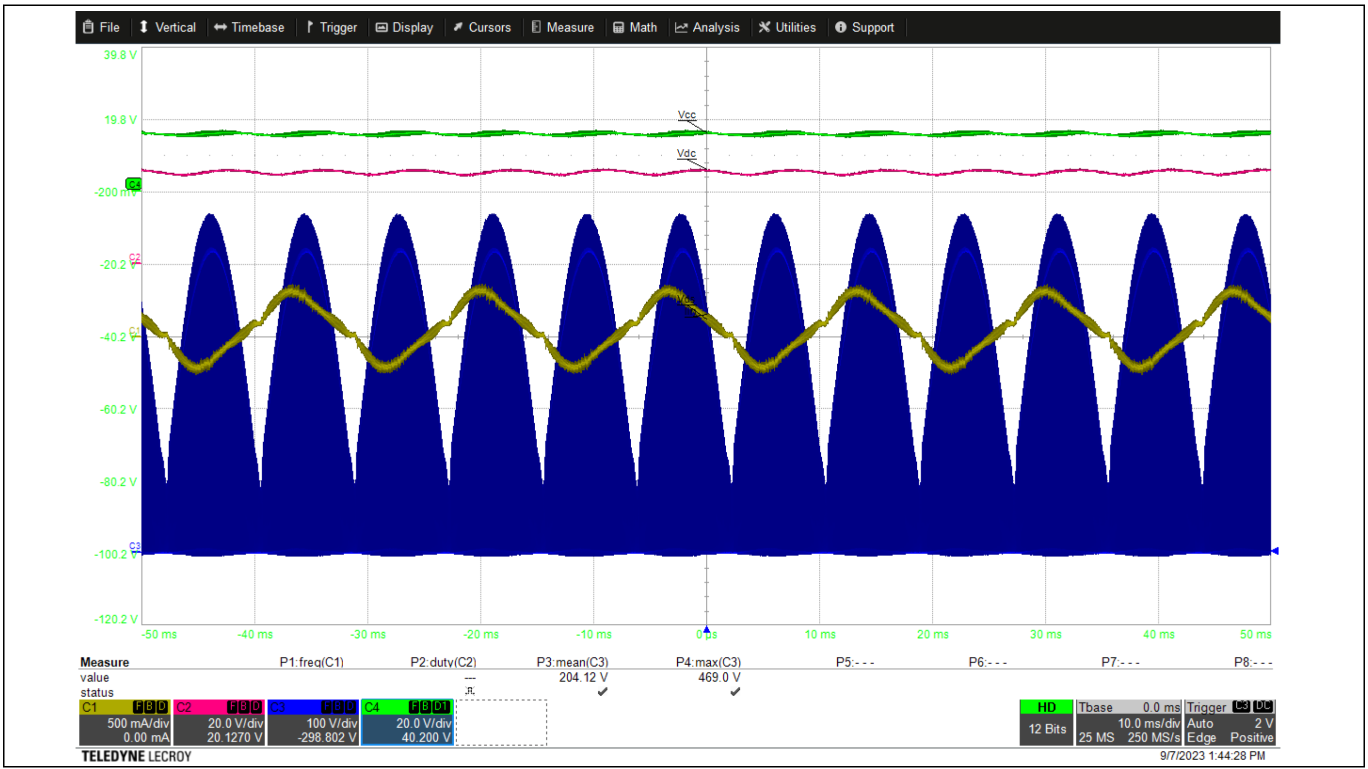


Figure 37 Input current at 230 V AC input

4.2.3 Output ripple

Output ripple is ~1.4 V at 230 V AC at full load.

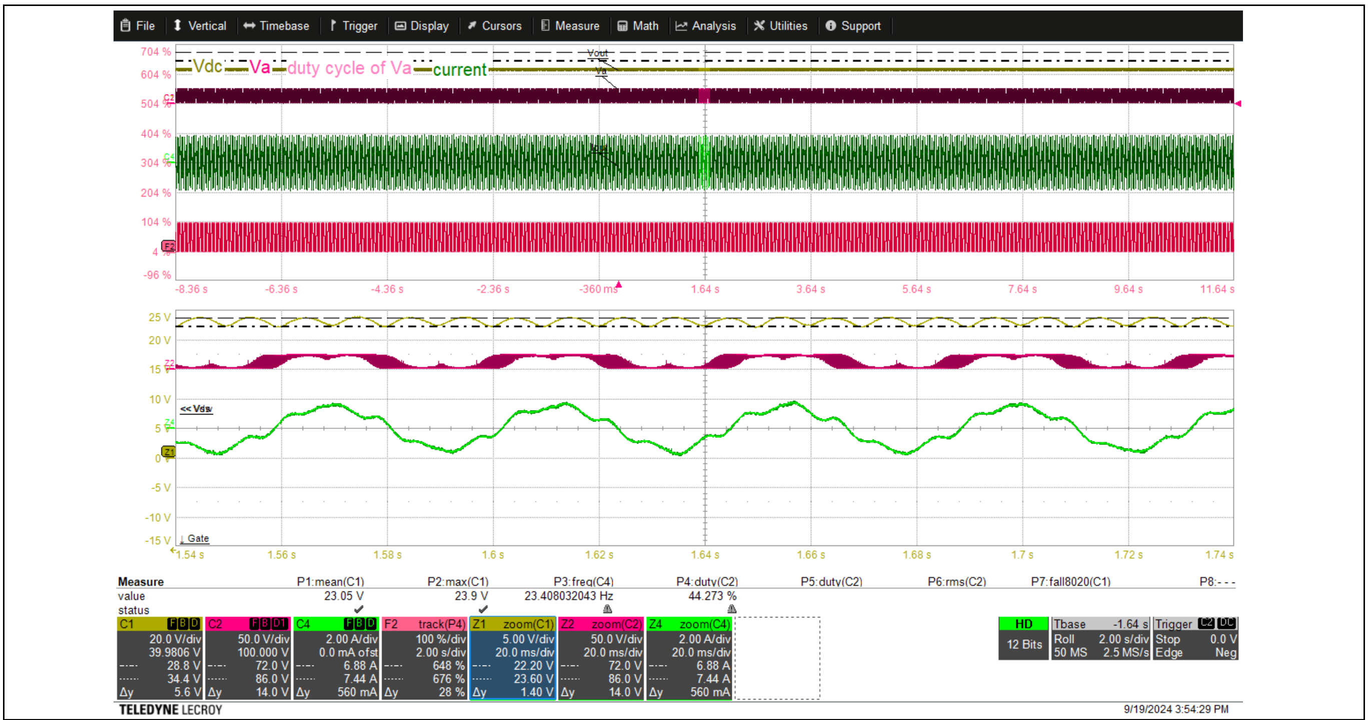


Figure 38 Output ripple at 230 V AC input

4.2.4 PFC MOSFET

At 230 V AC, the MOSFET switches on at the second valley with a frequency of 66.4 kHz.

Figure 39 Drain-to-source voltage at 230 V AC input

The drain-to-source voltage dv/dt is ~12.66 V/ns at a full speed of 350 RPM.

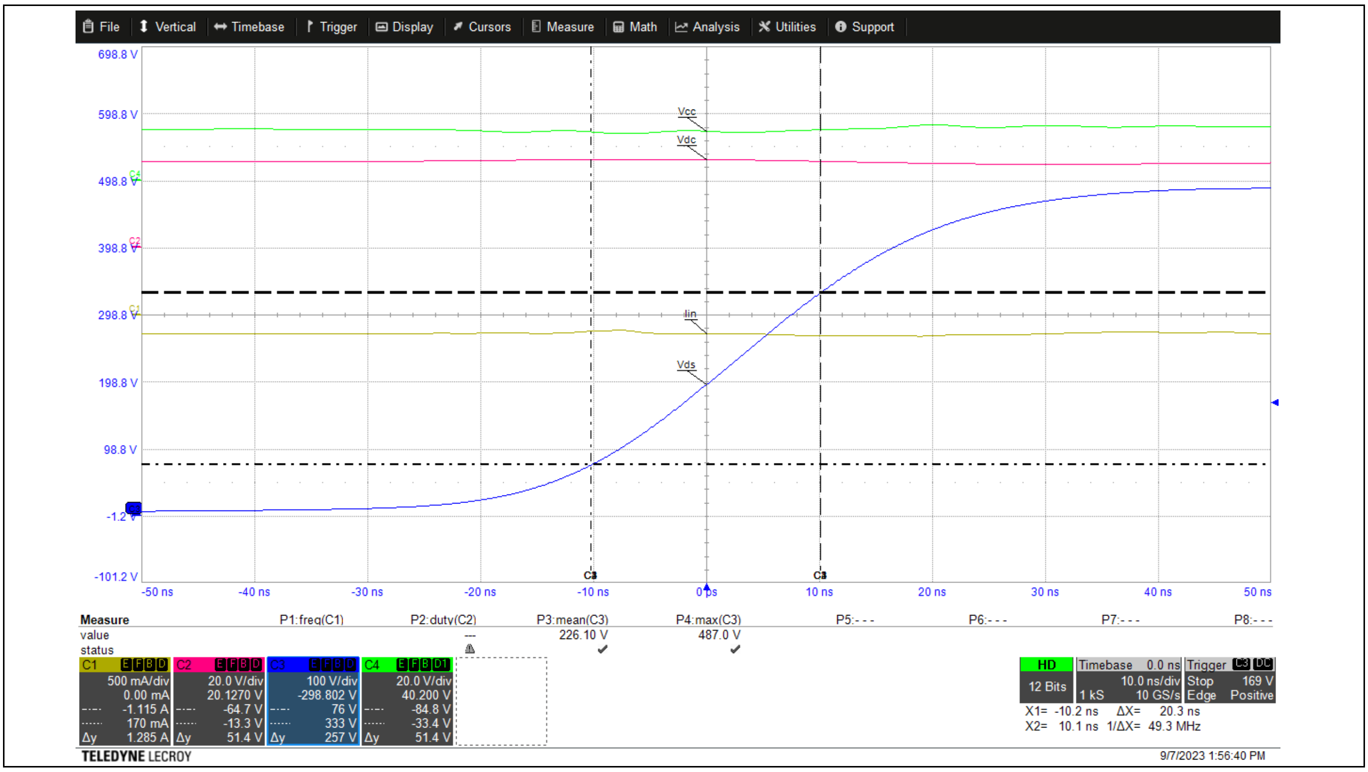


Figure 40 MOSFET V_{DS} dv/dt at 230 V AC input

4.2.5 Burst mode

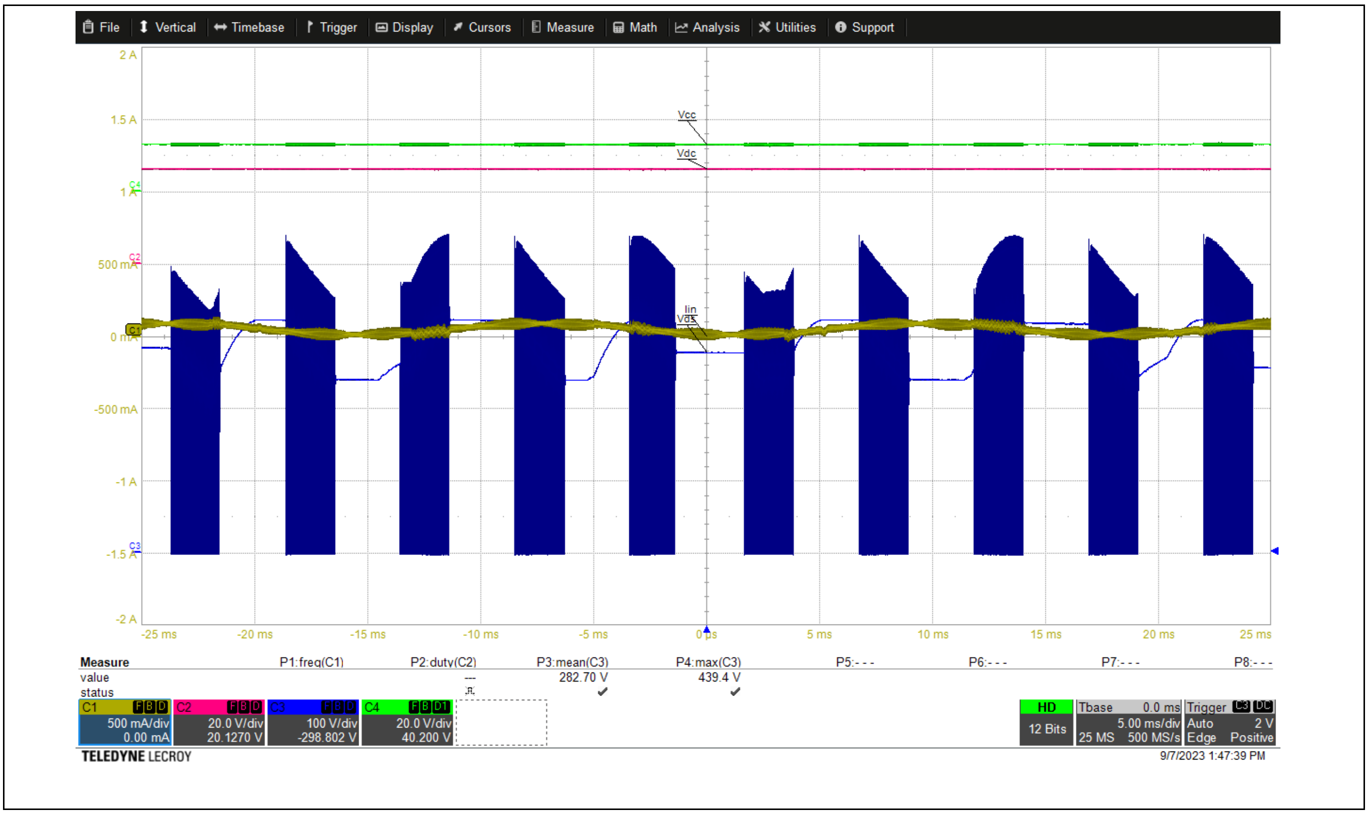


Figure 41 Burst mode at 230 V AC

4.3 Motor drive

4.3.1 Dynamic performance

4.3.1.1 Motor startup

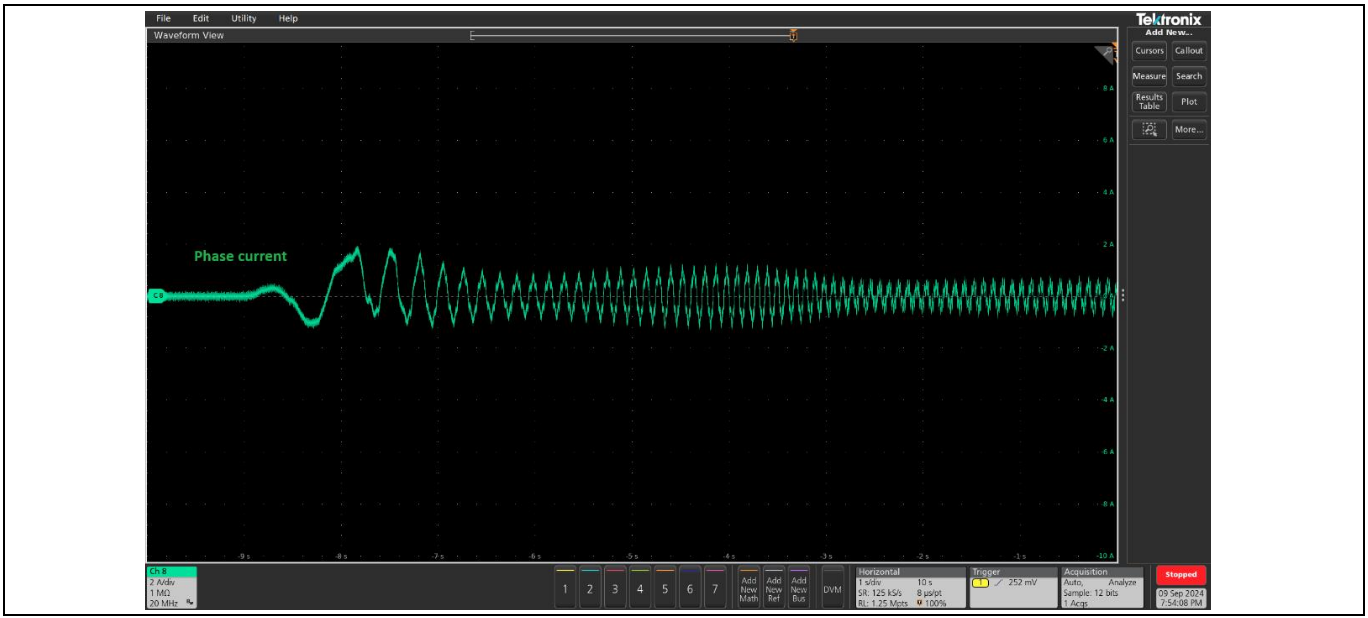


Figure 42 Minimum speed startup at 230 V AC

The system takes ~10 s to reach its full speed of 350 RPM from stop.

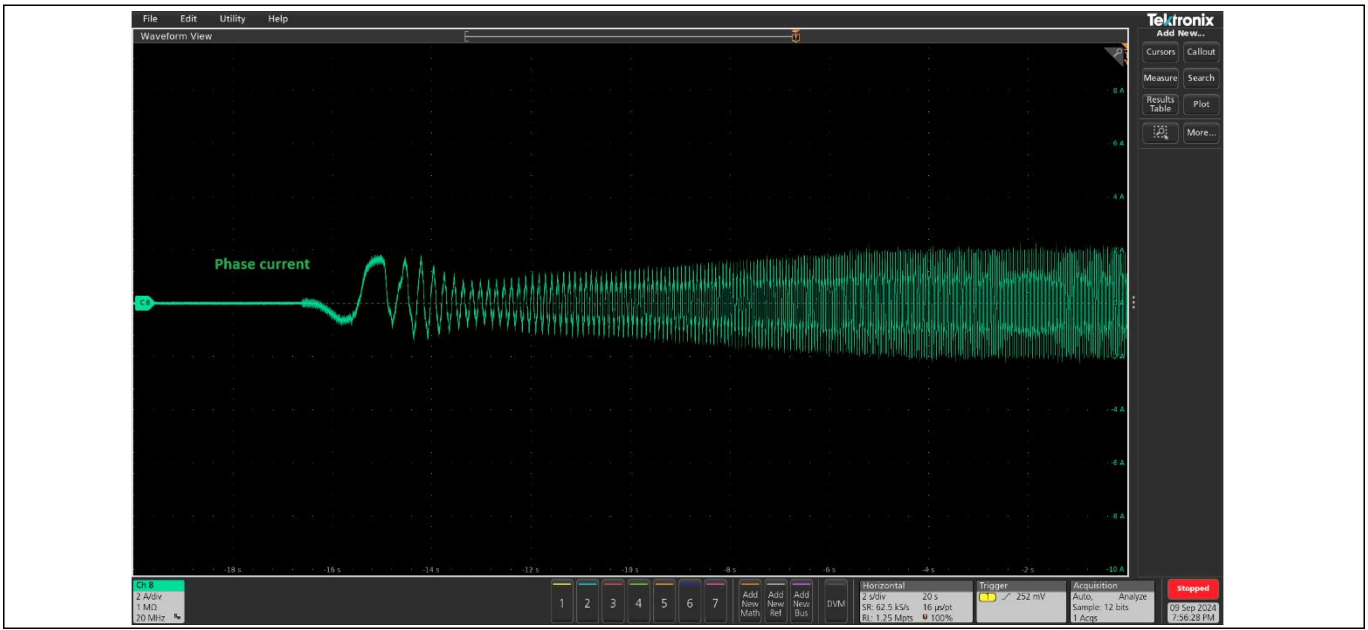


Figure 43 **Maxmimum speed startup at 230 V AC**

4.3.1.2 Motor speed change

There is a smooth transient response between minimum and maximum speed.

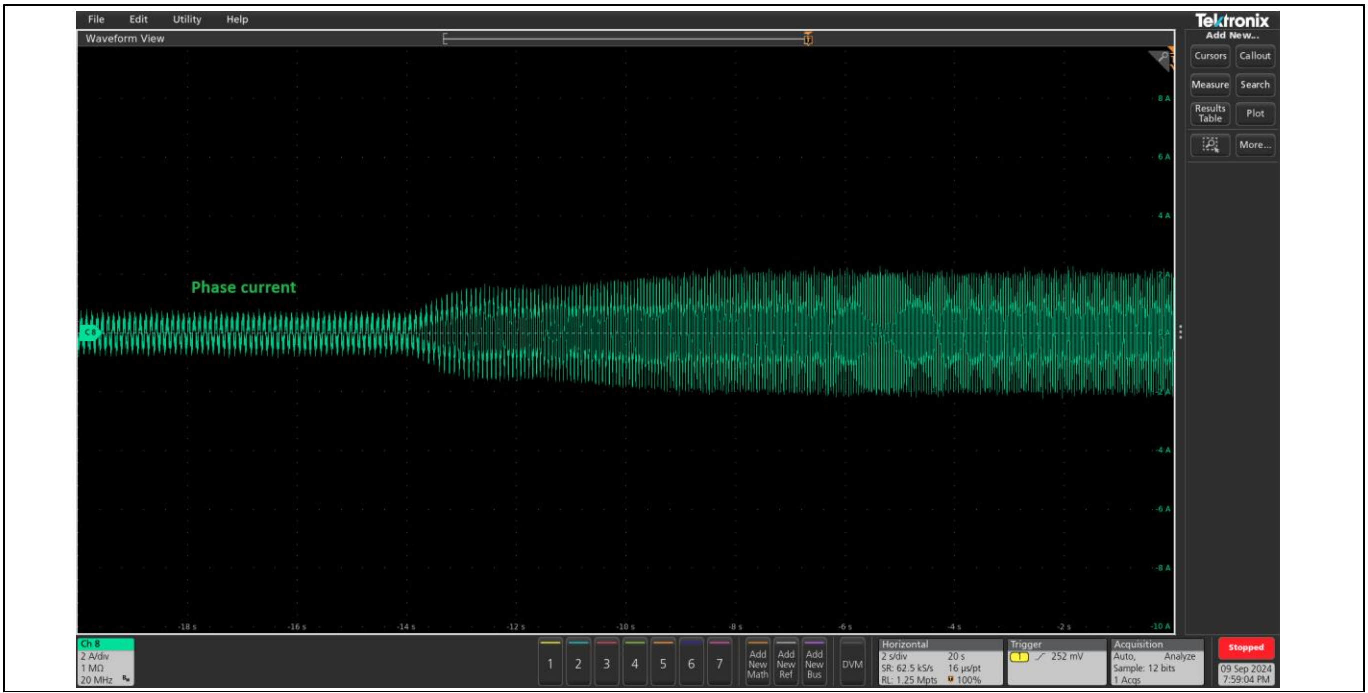


Figure 44 **Minimum to maximum speed dynamic**

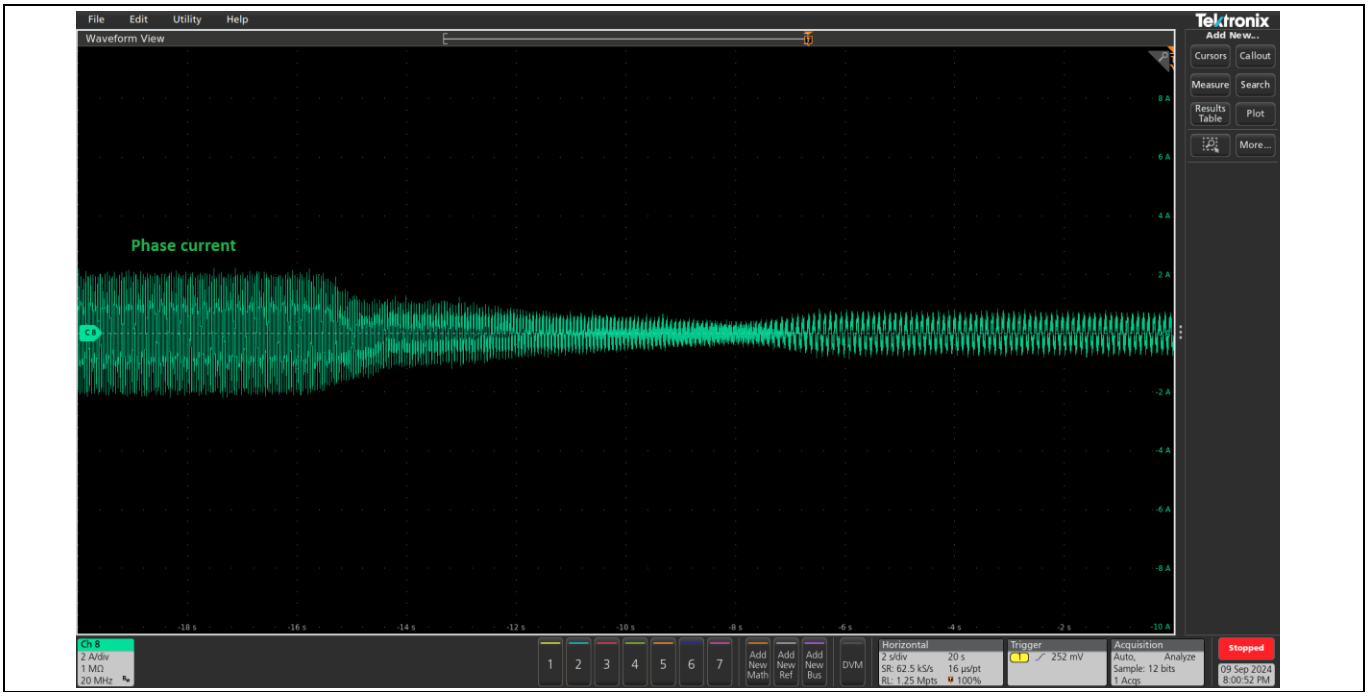


Figure 45 Maximum to minimum speed dynamic

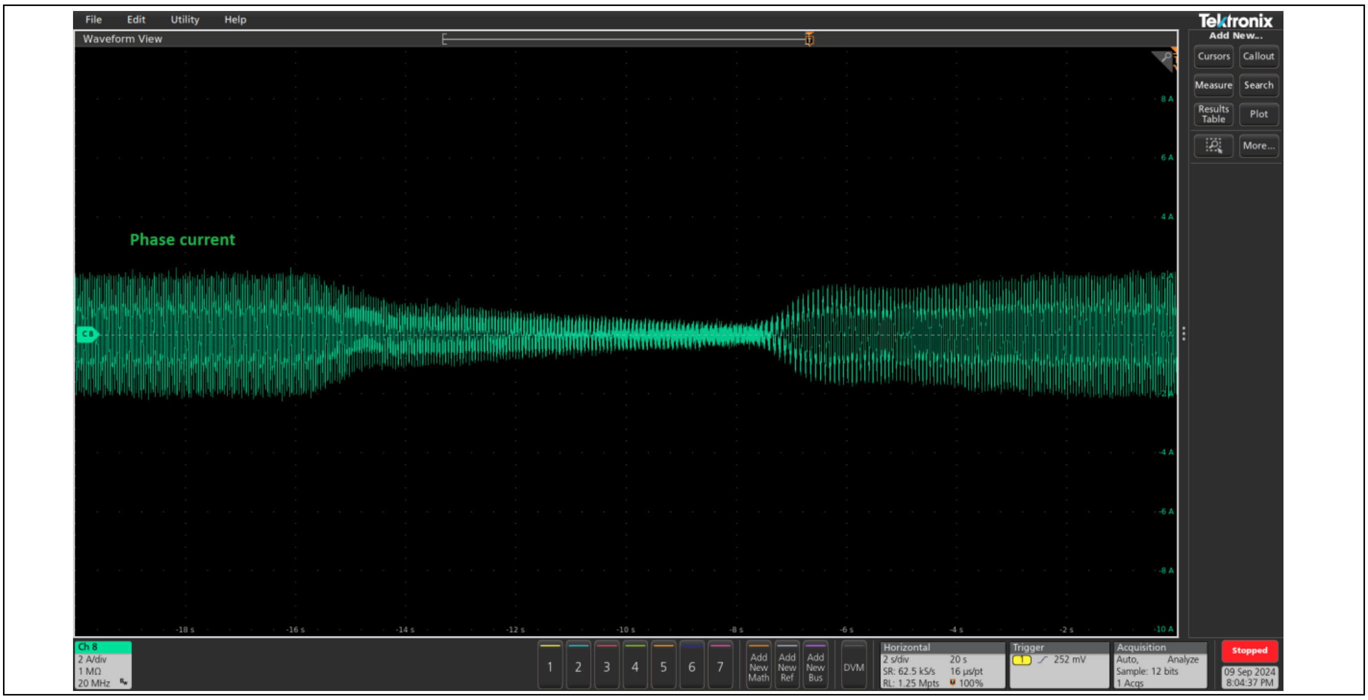


Figure 46 Motor restart at low speed

4.3.1.3 Motor stop

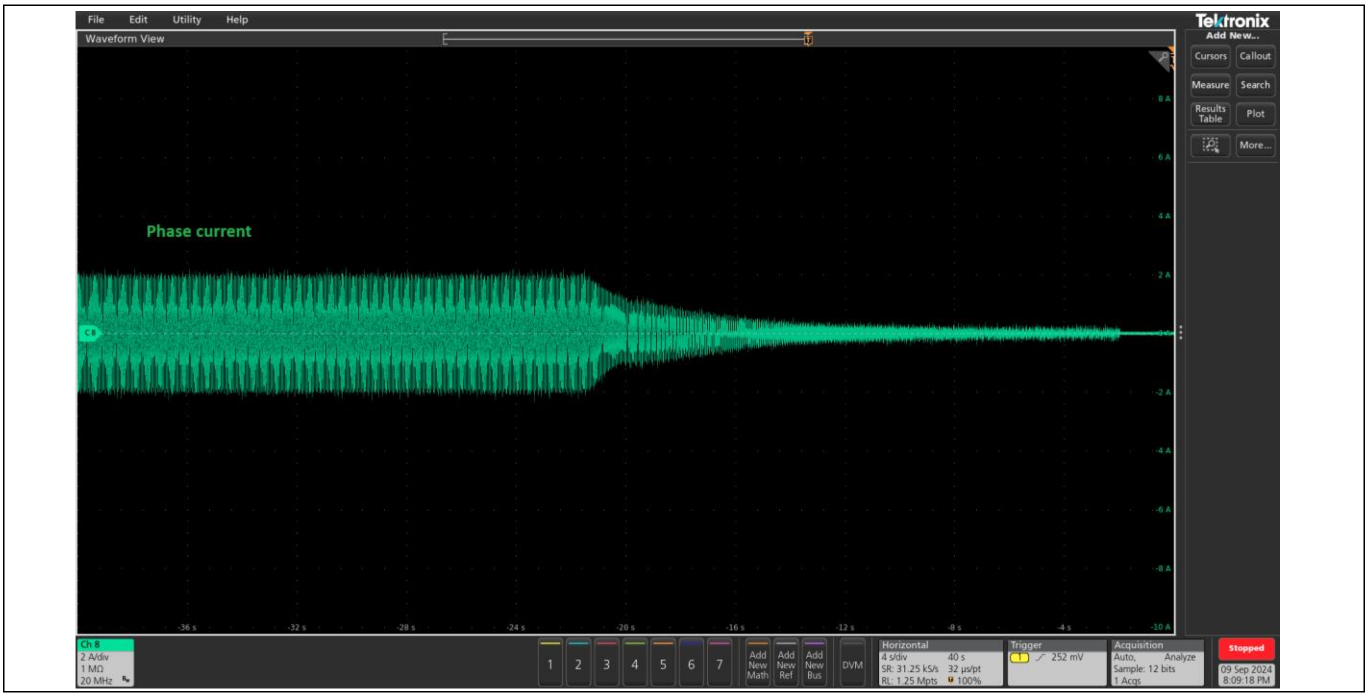


Figure 47 Maximum speed motor stop at 230 V AC

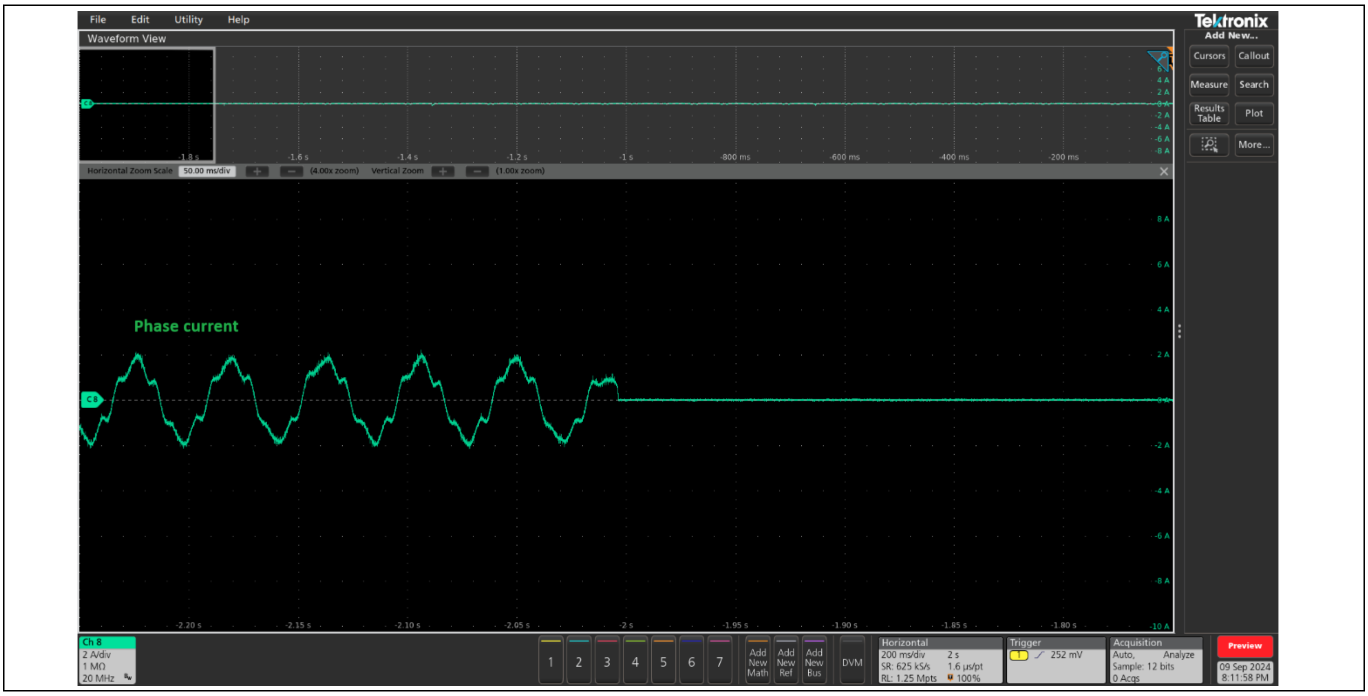


Figure 48 Power cut-off at 230 V AC

4.3.2 Motor current waveforms

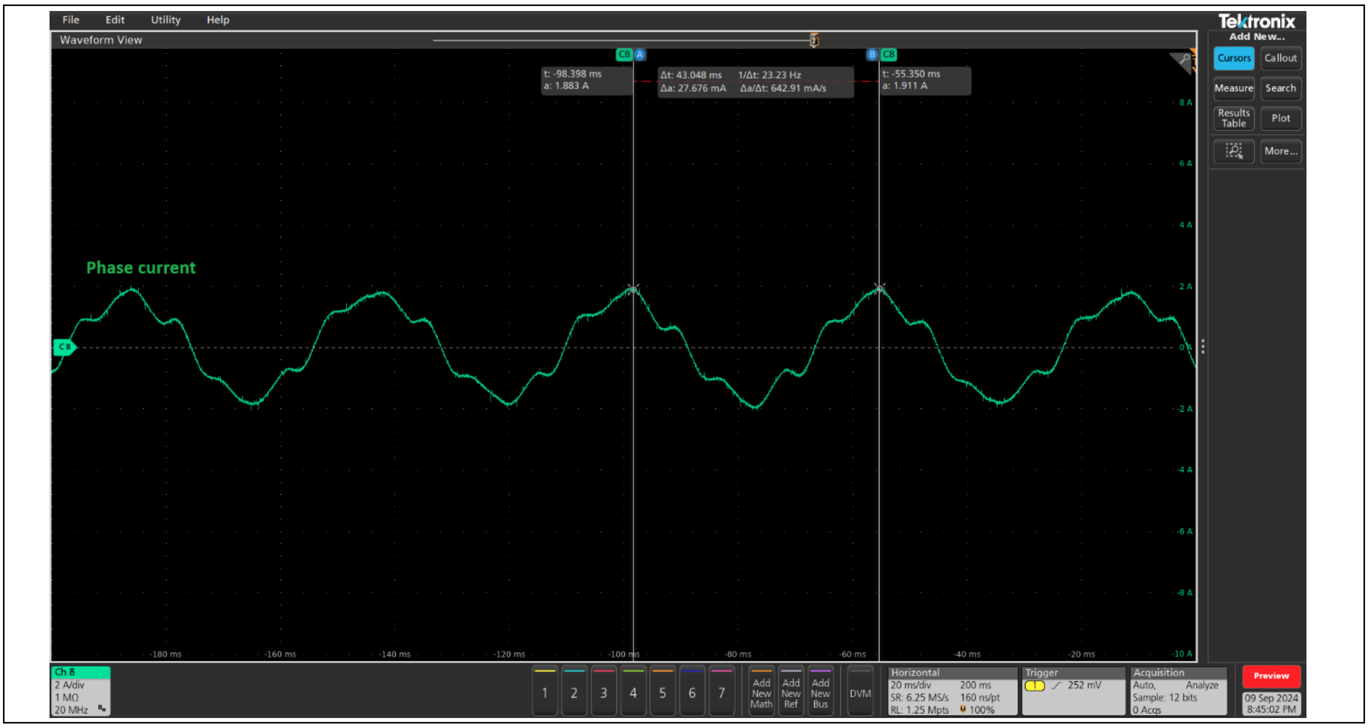


Figure 49 Full speed (350 RPM) motor current at 230 V AC

4.3.3 Inverter waveforms

4.3.3.1 Inverter dv/dt performance

High-side drain-to-source dv/dt is 0.32 V/ns during turn-on, and 0.26 V/ns dv/dt during turn-off.

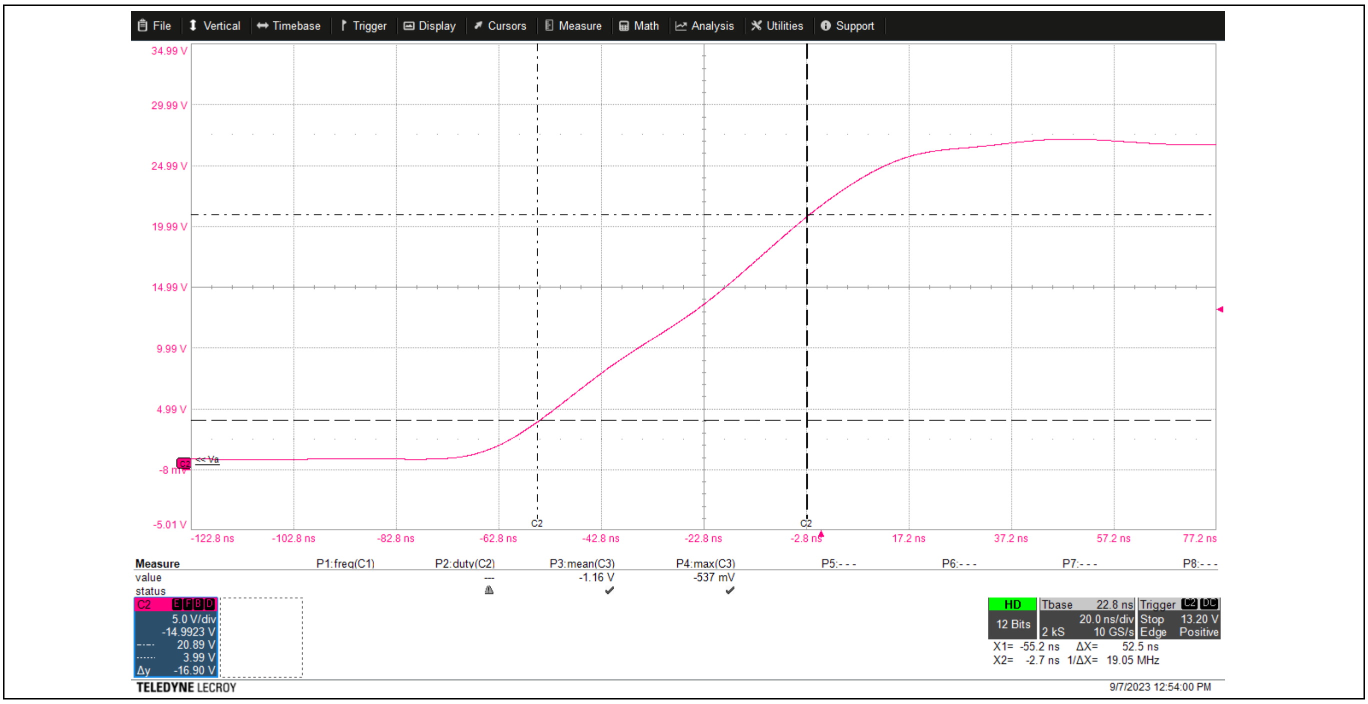


Figure 50 Inverter high-side turn-on

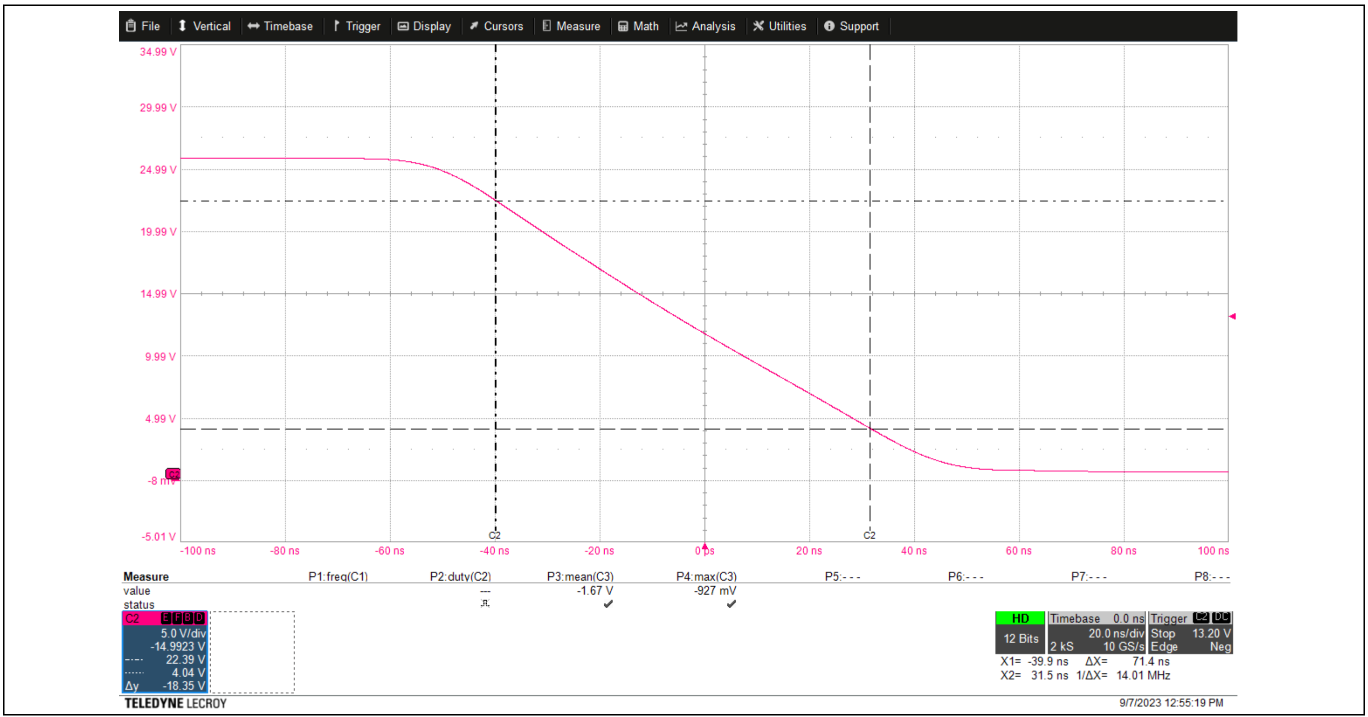


Figure 51 Inverter high-side turn-off

4.3.3.2 Inverter dead time

The dead time measured is around 282 ns, where the firmware setting is 300 ns.

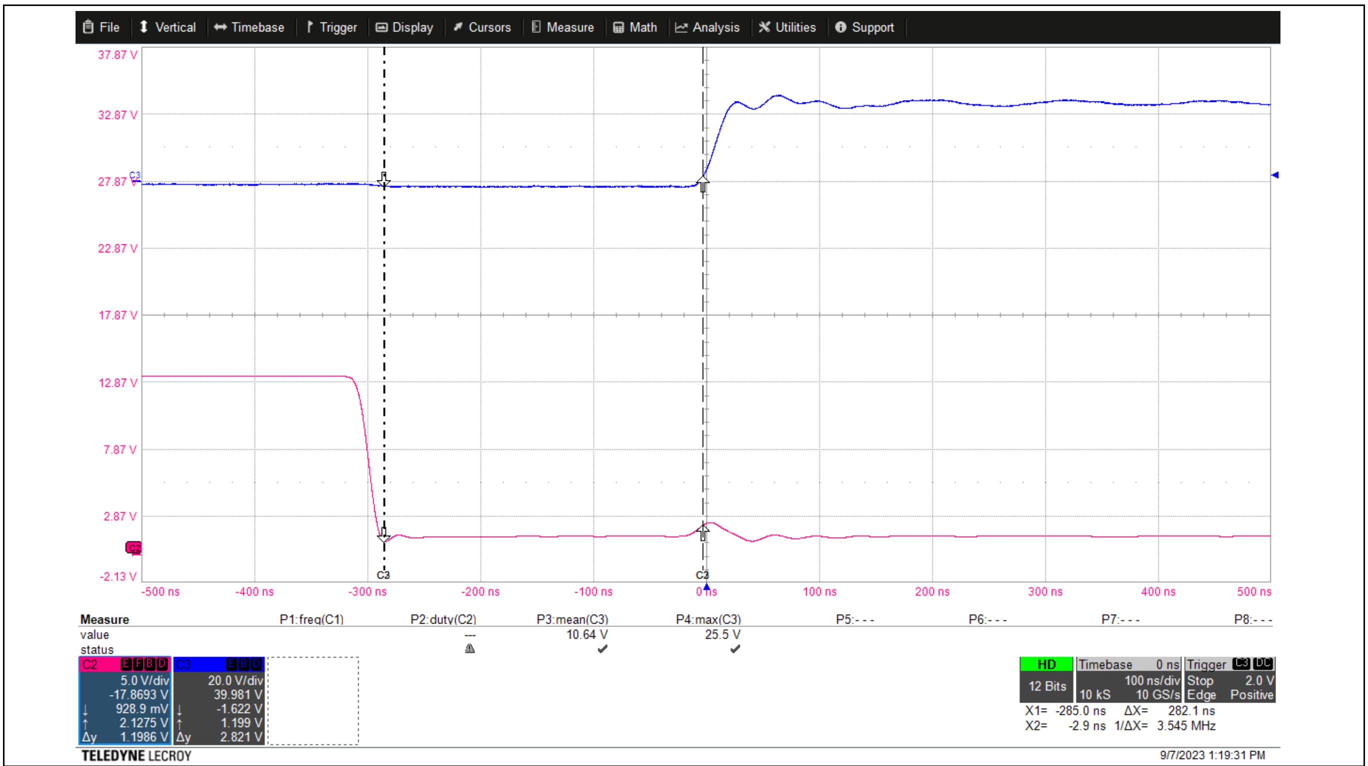


Figure 52 Inverter dead time

4.3.4 Stall detection and retry function

Figure 53 shows how the system monitors the fault and tries to auto-restart three times based on the firmware design. It stops retrying if the fault is still present after three retry attempts.

Figure 53 Stall detection and retry function

4.3.5 Catch-free run

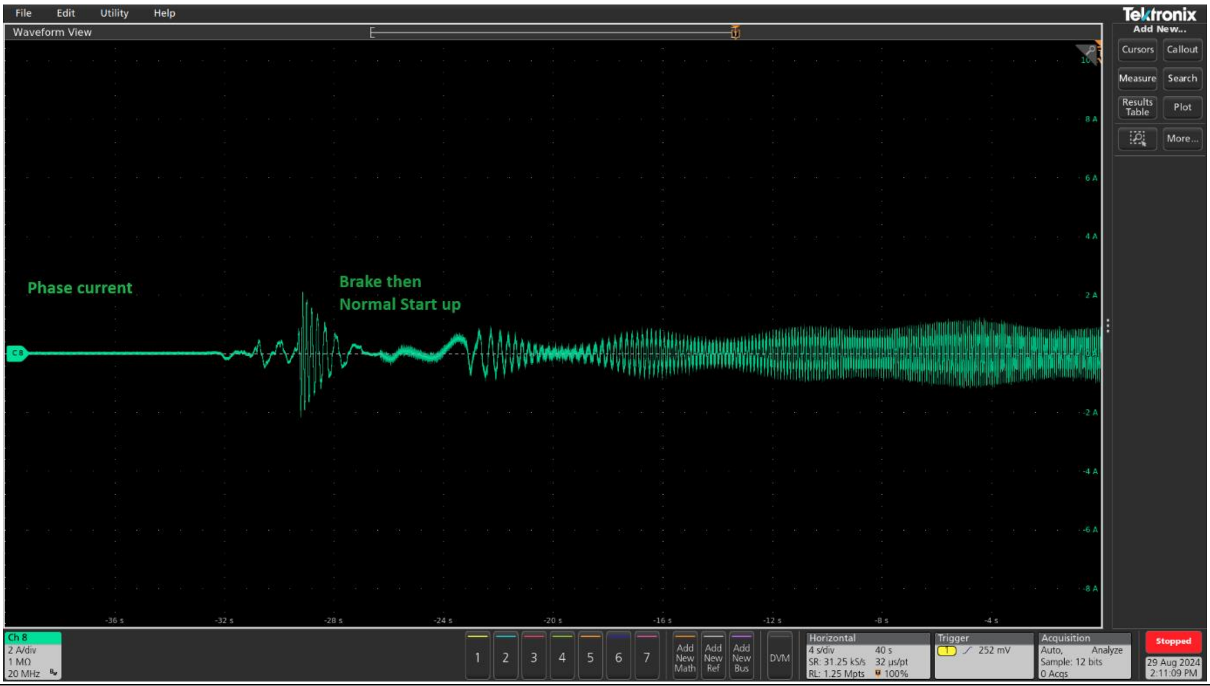


Figure 54 Reverse direction scenario observed a normal startup

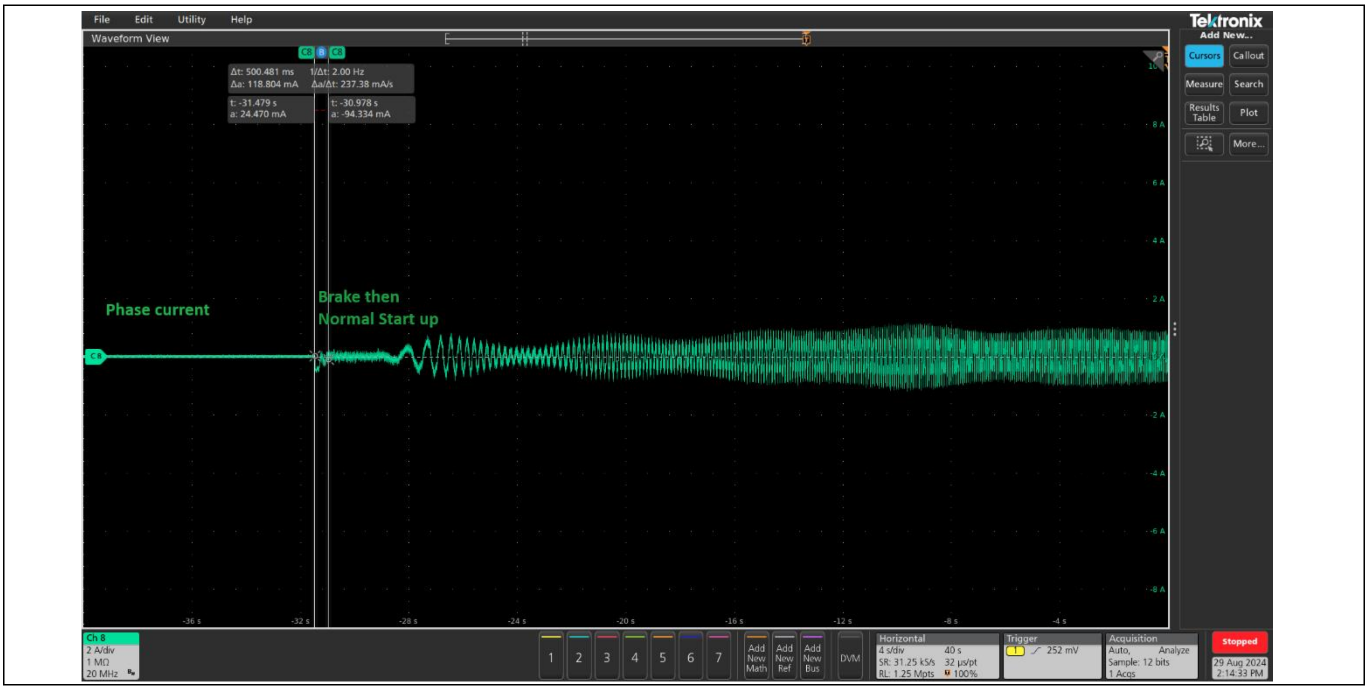


Figure 55 Forward direction scenario lower than CFR threshold observed a normal startup

Figure 56 Forward direction scenario higher than CFR threshold observed a CFR startup

4.4 Thermal performance

Table 7 PFC thermal performance

Input (V AC)	Input power (W)	Component with max. temperature	Max. thermal (℃)	ΔT (℃)
90	35			
140	37			
230	36	Output diode	66.3	41.3
300	37			
Condition	Room temperature: 25°C Open condition, board is not inside any cases or containers Motor setup 16 kHz PWM, three-phase single-shunt FOC, motor speed: 350 RPM (330 RPM at 90 V AC) 20 minutes of motor running			

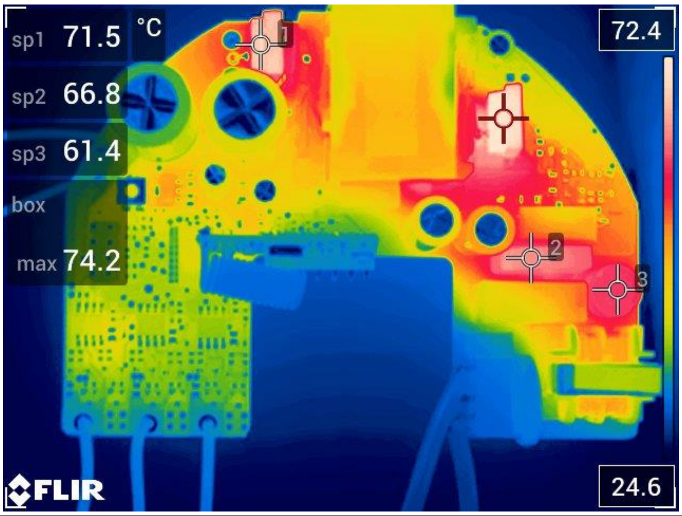
Location	Component	Temperature (°C)	Thermal image
Sp1	Output diode	71.5	
Sp2	Rectifier bridge	66.8	
Sp3	Differential-mode choke	61.4	
max	PFC MOSFET	74.2	

Figure 57 Input voltage 90 V – top side

Location	Component	Temperature (°C)	Thermal image
Sp1	PFC MOSFET	67.9	
Sp2	Differential-mode choke	61.2	
Sp3	Output diode	59.6	
max	Snubber circuit	70.8	

Figure 58 Input voltage 90 V – bottom side

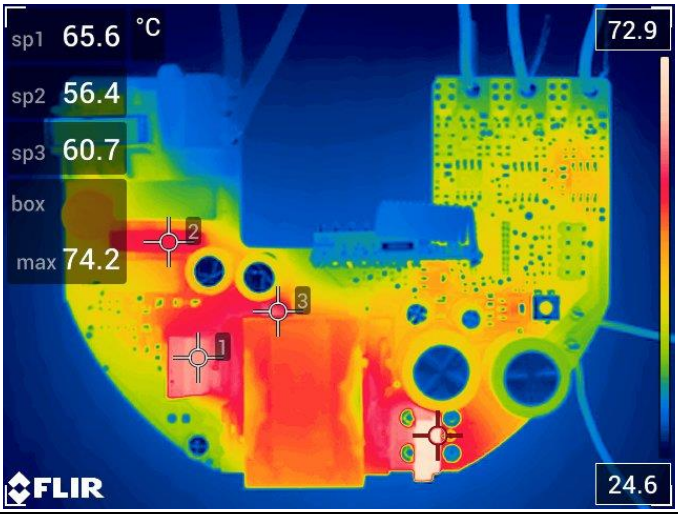
Location	Component	Temperature (°C)	Thermal image
Sp1	PFC MOSFET	65.6	
Sp2	Rectifier bridge	56.4	
Sp3	Underneath transformer	60.7	
max	Output diode	74.2	

Figure 59 Input voltage 140 V – top side

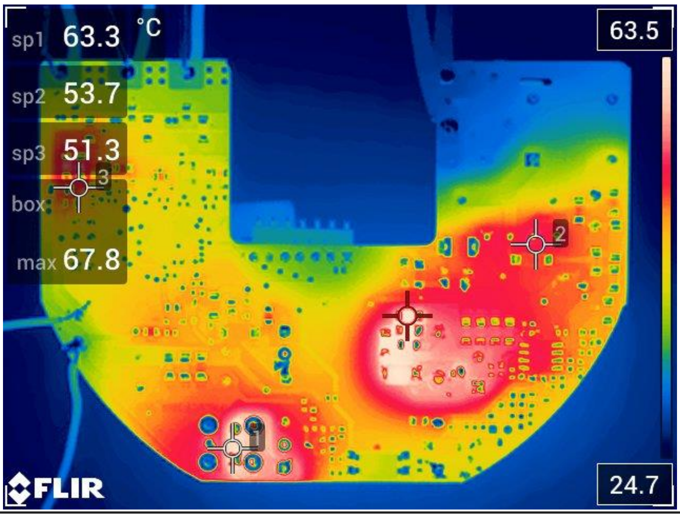
Location	Component	Temperature (°C)	Thermal image
Sp1	Output diode	63.3	
Sp2	Rectifier bridge	53.7	
Sp3	Motor shunt resistors	51.3	
max	Snubber circuit	67.8	

Figure 60 Input voltage 140 V – bottom side

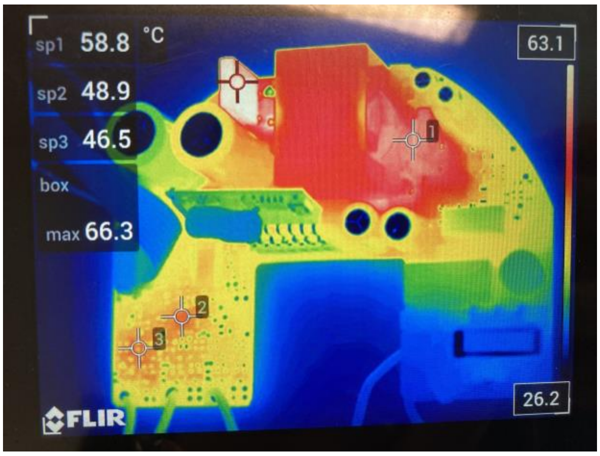
Location	Component	Temperature (°C)	Thermal image
Sp1	PFC MOSFET	58.8	
Sp2	Gate driver	48.9	
Sp3	Back of shunt sensing	46.5	
max	Output diode	66.3	

Figure 61 Input voltage 230 V – top side

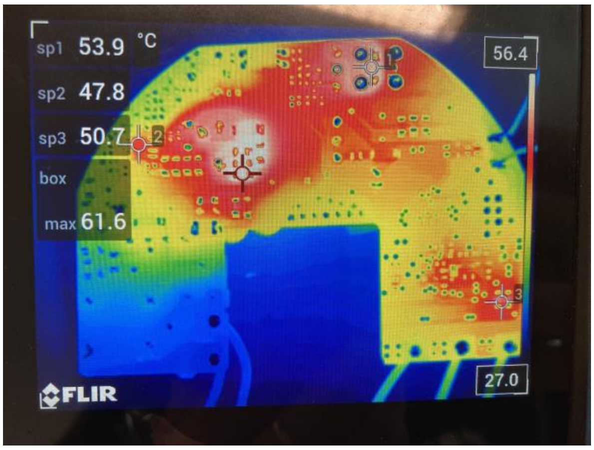
Location	Component	Temperature (°C)	Thermal image
Sp1	Output diode	53.9	
Sp2	PFC IC ICL8810	47.8	
Sp3	Motor single-shunt	50.7	
max	Snubber circuit	61.6	

Figure 62 Input voltage 230 V – bottom side

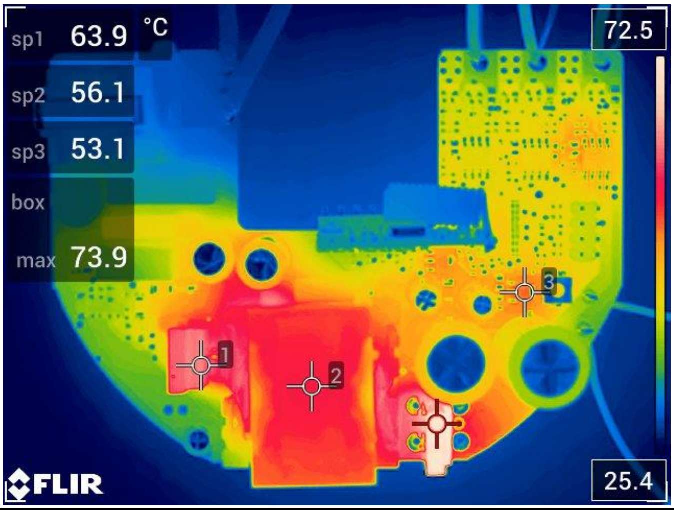
Location	Component	Temperature (°C)	Thermal image
Sp1	PFC MOSFET	63.9	
Sp2	Transformer	56.1	
Sp3	5 V LDO	53.1	
max	Output diode	73.9	

Figure 63 Input voltage 300 V – top side

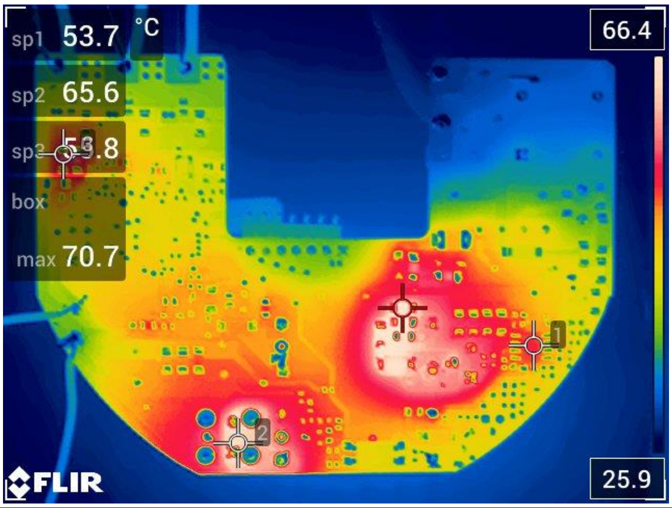
Location	Component	Temperature (°C)	Thermal image
Sp1	PFC IC ICL8810	53.7	
Sp2	Output diode	65.5	
Sp3	Motor single-shunt	59.8	
max	Snubber circuit	70.7	

Figure 64 Input voltage 300 V – bottom side

4.5 Lightning surge immunity test

The test is compliant with IEC standards: IEC61000-4-5; L to N at 4 kV.

Surge pulses are added from 0.5 kV to 4 kV with 0.5 kV interval on L-N. PFC runs normally without any disturbance or protections triggered; V DC is maintained at 24.7 V throughout the immunity test. The board did not connect to an actual fan; instead, a 20 Ω resistor load was connected to simulate a full-load condition.

Table 8 Lightning surge pulse condition

Pulse voltage	Basic voltage	Connection	SYNC angle (degrees)	Interval time
± 0.5~4 kV	230 V AC	L-N	0, 90, 180, 270	20 s

5 Appendix A – Angle and speed scaling

In the PMSM_FOC SW the PLL estimator estimates the rotor angle in Q31 format to represent angles of -Π to Π.

Following is the angle scaling:

$$Rotor\ Angle_{rad} = \frac{\Pi}{2^{31}} \cdot Rotor\ Angle_{integer}$$

Equation 7

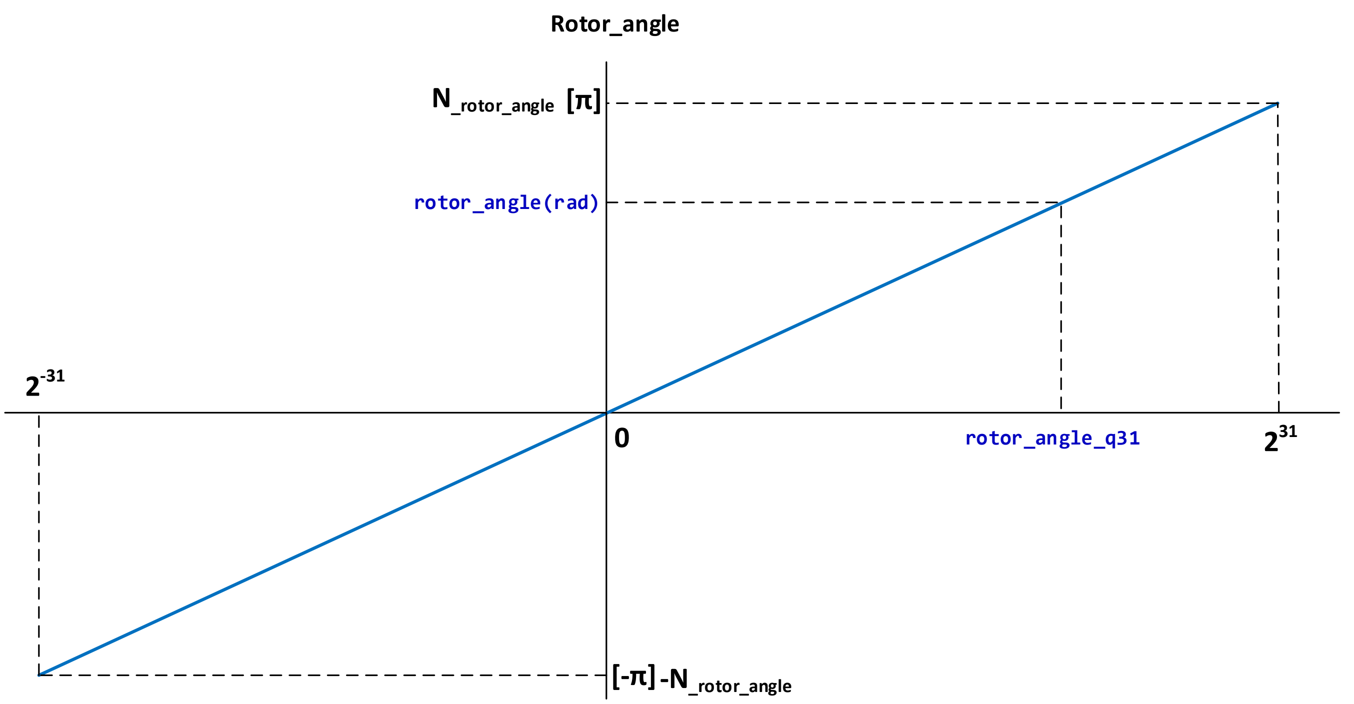


Figure 65 Angle scaling

In the PMSM_FOC SW, the electric motor speed is represented in radians per PWM period.

Speed scaling:

$$\omega\_(rad/pwm\_period) = N\_(max\_speed)/2\verb|^|15 \ \cdot \omega\_integer$$

Equation 8

Where $\omega_{integer}$ is the speed in radians per PWM period estimated by PLL observer every PWM cycle.

The target value for speed is:

$$N_{max\_speed} = \frac{USER\_SPEED\_HIGH\_LIMIT\_RPM * USER\_MOTOR\_POLE\_PAIR}{60 * f_{CCU8\_PWM}} * 2\Pi\ radians/pwm\_period$$

Equation 9

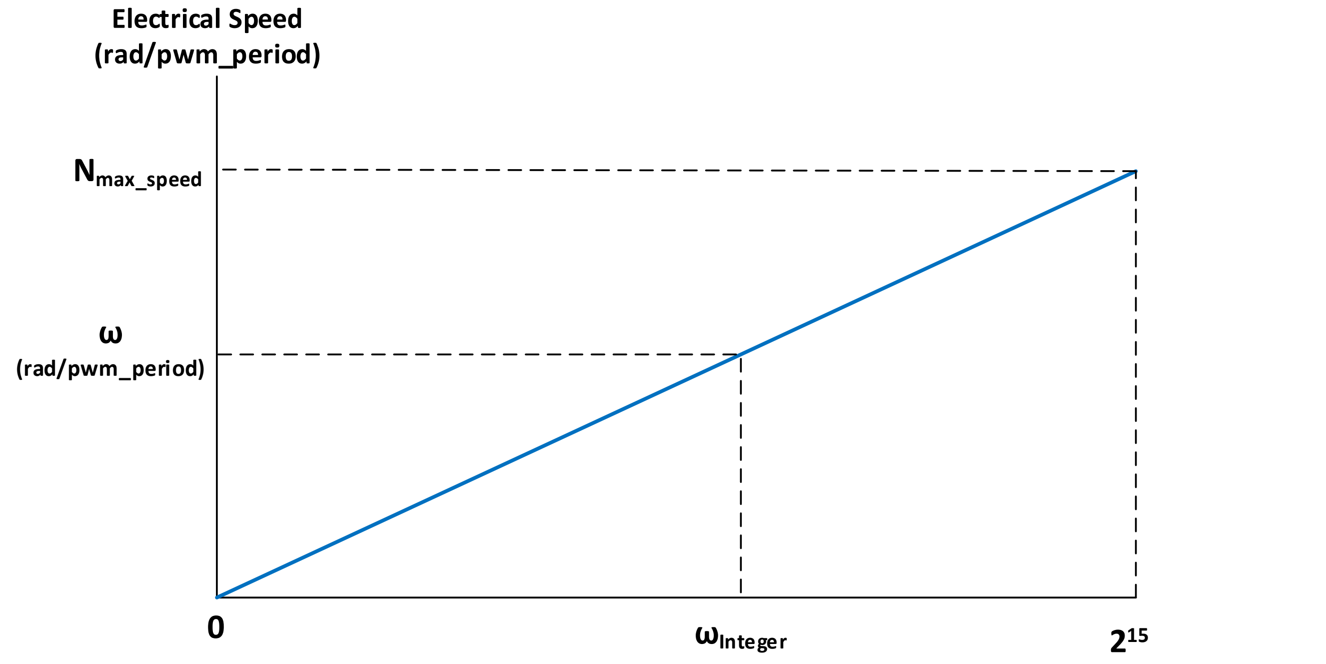


Figure 66 Speed scaling

Example:

- Motor maximum speed, USER_SPEED_HIGH_LIMIT_RPM = 50,000 rpm
- Motor pole pairs, USER_MOTOR_POLE_PAIR = 2
- CCU8 PWM frequency = 20 kHz

⇨ $N_{max\_speed} = \frac{(50000\ rpm*2)*2\Pi}{60*20{,}000} = 0.524\ radian\ /\ pwm\_period$ (electrical speed)

⇨ $max\_speed\_integer = 32767$

To represent a speed of 500 rpm, the SW integer, $\omega_{integer}$= 327

6 References

[1] Infineon Technologies AG: *Datasheet - ICL88XX*; Available online

[2] Infineon Technologies AG: *Datasheet - XMC1300 AB-Step*; Available online

[3] Infineon Technologies AG*: Datasheet - 800 V CoolMOS™ P7 Power Transistor (IPA80R750P7)*; Available online

[4] Infineon Technologies AG: *Datasheet - 6ED2742S01Q – 160V pre-regulated three phase SOI gate driver with integrated charge pump, current sense amplifier, over-current protection, and bootstrap diodes*; Available online

[5] Infineon Technologies AG: *Datasheet - IRLML0040TRPBF inverter*; Available online

Revision history

Document revision	Date	Description of changes
V 1.0	2023-09-26	Initial release
V 2.0	2024-12-13	Angle-speed scaling changed

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