80W water pump evaluation board design for 12V application

OptiMOS-5™ 40 V S3O8 MOSFET, TLE9879QXA40 Embedded Power IC

Design Overview

This Reference Design Guide describes a detailed implementation of an automotive water pump application. The system is controlled by a system on chip microcontroller with integrated MOSFET driver in combination with OptiMOS™-5 leadless MOSFETs.

The design is capable to drive loads up to 80W at a battery voltage of 12 V.

This design guide contains a description of the design, schematics and measurement reports.

Thermal performance information is given and discussed.

Highlighted Components

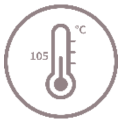
- TLE9879QXA40
- IPZ40N04S5-8R4, IPZ40N04S5-5R4

Target Application

- Water Pump
- 80W BLDC Motor for 12 V application

Highlighted Design Aspects

80W functional



Thermally tested

Evaluation Board Design and Assembly Example

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1 System Description

The reference design describes a solution for a water pump with a power capability. This solution can be used for similar applications with smaller or equal power consumption. The circuit contains an integrated 3-phase motor control solution. The SoC microcontroller is a member of the Embedded Power IC family. It combines an Arm® Cortex®-M3 microcontroller with application specific modules like an integrated 3-phase MOSFET driver, power supply and LIN-transceiver. In combination with the OptiMOS™-5 PG-TSDSON-8 (S3O8) MOSFETs the system is optimized for a minimum of PCB size for this power class. The focus of the reference design is to use standard PCB materials and processes.

1.1 Design Specifications

The design specifications are related to the used components and design considerations. They shouldn't differ from the product datasheet values. In case of misalignment, the datasheet values of the products are valid.

Table 1 Design Specifications

Parameter	Symbol	Values			Unit	Comment
		Min.	Typ.	Max.		
System Parameters						
Input voltage	V_{IN}	-0.3	12	40	V	P_1.1.1 (TLE9879QXA40)
Functional input voltage	V_{IN}	8.5	12	15	V	Specified for Design
Output current peak	I_{OUT}	-	-	8.5	A	Peak current (<10 s), air cooling attached
Output current continous	I_{OUT}	-	4	7	A	Specified for Design
LIN interface	V_{LIN}	-28	12	40	V	P_1.1.7 (TLE9879QXA40)
Phase 1,2,3	V_{SH}	-8.0	12	48	V	P_1.1.11 (TLE9879QXA40)
Thermal						
Operating temperature	T_A	-40	25	105	°C	Specified for Design
Mechanical Specification						
Dimensions	58 mm x 58 mm x 12 mm (W x D x H)					
PCB	1.6mm 4-layer 2 oz Standard FR4 Ø58 mm					

1.2 Overview

Figure 1 shows the 3D CAD view of the system. The board has seven TSDSON-8 MOSFETs, one 3-phase gate driver, and a shunt resistor. All active components, including the seven MOSFETs and one driver IC, are carefully located on the board to distribute the heat over the whole area of the PCB. As passive components, the shunt resistor is an additional heat source. The board is designed to dissipate the heat of the MOSFETs, driver IC and shunt effectively through thermal pad and also through the mounting bolts. As most of the PCB bottom-side does not have any components mounted, it is possible to attach a simple flat heatsink at the bottom of the board. Only the lead of the 5-pin connectors for LIN and debugger has to avoid the contact to the heatsink.

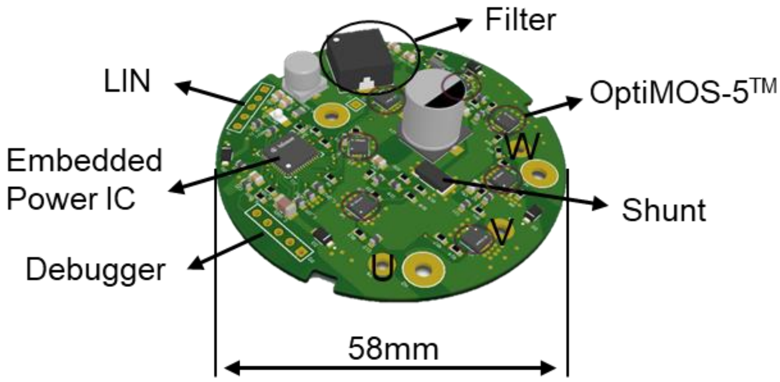


Figure 1 External view of the evaluation board

1.3 Highlighted Products

1.3.1 OptiMOS-5TM 40 V Shrinked-Super-SO8 (TSDSON-8) MOSFET

The S3O8 package offers compact 9mm² footprint size with $R_{DS(on)}$ ranging from 2.8 ~8.4 [mΩ]. Its current rating is the double of Dual-SSO8 and quite similar to that of SSO8-HB package. Even though SSO8-HB package can offer even more compact system design mainly due to the integrated half-bridge structure, S3O8 can still offer higher degree of freedom in designing the board layout, enabling heat spread over wide area. In combination with Infineon's OptiMOS-5™ 40 V power MOS technology, TSDSON package offers a compact solution for automotive 3-phase motor drive up to 150W at Infineon's well known quality level for robust automotive packages.

Table 2 Automotive S3O8 MOSFET with 40 V OptiMOS-5TM

Package	Silicon Technology	Product	Max $R_{DS(on)}$ [mΩ]
S3O8 (TSDSON-8)	OptiMOSTM-5	IPZ40N04S5-2R8	2.8
		IPZ40N04S5-3R1	3.1
		IPZ40N04S5L-4R8	4.8
		IPZ40N04S5-5R4	5.4
		IPZ40N04S5L-7R4	7.4
		IPZ40N04S5-8R4	8.4

1.3.2 3-Phase Bridge Driver IC with Integrated Arm® Cortex®-M3

The TLE987x family addresses a wide range of smart 3-phase brushless DC motor control applications such as auxiliary pumps and fans. It provides an unmatched level of integration and system cost to optimize the target application segments. In addition, it offers scalability in terms of flash memory sizes and MCU system clock frequency supporting a wide range of motor control algorithms, either sensor-based or sensor-less. For more information about the product, please visit Infineon web-page linked below.

- www.infineon.com/tle987x

Table 3 Product Family of 3-Phase Bridge Driver IC with Integrated Arm® Cortex®-M3

Grade	Product	Flash	RAM	Frequency	Interface	Tjmax
Grade-0	TLE9873QXW40	48 kByte	3 kByte	40 MHz	PWM + LIN	175 °C
	TLE9877QXW40	64 kByte	6 kByte	40 MHz	PWM + LIN	175 °C
	TLE9879QXW40	128 kByte	6 kByte	40 MHz	PWM + LIN	175 °C
Grade-1	TLE9871QXA20	36 kByte	3 kByte	24 MHz	PWM	150 °C
	TLE9877QXA20	64 kByte	6 kByte	24 MHz	PWM + LIN	150 °C
	TLE9877QXA40	64 kByte	6 kByte	40 MHz	PWM + LIN	150 °C
	TLE9879-2QXA40	128 kByte	6 kByte	40 MHz	PWM + LIN	150 °C
	TLE9879QXA40	128 kByte	6 kByte	40 MHz	PWM + LIN	150 °C

2 Getting Started

2.1 Toolchain Installation

In order to get the board ready and running, the software shown in Table 4 shall be installed.

The µVision software is a development tool provided by Arm® Keil®. With code length limitation, the shareware version of the µVision is still able to edit, compile and debug. The Infineon Config Wizard is a tool for configuring peripherals of the Embedded Power IC. The tool can be called from the pull-down menu of the µVision and helps users changing parameters from its user interface and then generates the software code accordingly. Infineon provides standard motor drive software codes for the Embedded Power IC. It can be downloaded from the Pack Installer within the µVision.

Table 4 Software Toolchain Installation Guide

Steps	Company	Description
STEP1 Download and Install **Keil® µVision5**	Arm® Keil®	• Arm® Keil® µVision is an integrated development environment which consists of code editor, compiler and debugger. • To learn how to use Arm® Keil® µVision 5, check out our video "**Get your motor spinning**".
STEP2 Download Config Wizard	Infineon Technologies	• Infineon provides the Config Wizard free of charge, which is designed for configuration of chip modules. Config Wizard supports easy configuring of Embedded Power IC peripherals. • Config Wizard can be installed via the Infineon Toolbox. If you don´t have the Infineon Toolbox yet, please go to **Infineon Toolbox** and enjoy the release management for updates.
STEP3 Download and Install **Segger J-Link Driver**	SEGGER	• SEGGER J-Link is a widely used driver for "on-board" or "stand-alone" debugger.
STEP4 Download the SDK via µVision5 Pack Installer	Infineon Technologies	• The Embedded Power Software Development Kit (SDK) is a low level driver library which can be downloaded within Keil® µVision via the "Pack Installer"

For the toolchain installation and free motor drive software, please check below link.
www.infineon.com/embedded-power
For more information about the tool chain installation steps, watch our video.
Toolchain Installation for Embedded Power ICs / TLE98xx

2.1.1 Configuration

Open a motor drive code project in µVision5 and go to "Tools" and open "Config Wizard". From there, setup the parameters of motor, speed/current controller and the peripherals of TLE987x. As the Embedded Power IC has a current-source gate driving scheme, the switching speed is not controlled by gate resistors, but by the "Gate Charge/Discharge" parameters in the BDRV tap of the peripherals. For more details about the configuration, please visit the Infineon website of Embedded Power ICs.

3 System Design

The evaluation board design is an automotive 3-phase motor controller for 12 V automotive applications. Target application is a water pump within the engine compartment with a power of up to 80W with the housing exposed to the air flow. The functional blocks of the system are shown in Figure 2. The two main active components are:

- *3-Phase Bridge Driver IC with Integrated Arm® Cortex® -M3 (TLE9879QXA40)*
- OptiMOS-5™ MOSFET in S3O8 package (*IPZ40N04S5-8R4, IPZ40N04S5-5R4*)

OptiMOS-5™ is one of the generation of Infineon's low voltage MOSFET silicon technology. Combined with the compact Shrinked-Super-SO8 (S3O8) package, the product is a good fit for motor drive under 150W within the engine compartment, with small form factor and quality for automotive applications. The TLE987x is an Embedded Power IC, combining a 3-phase bridge driver with a 32-bit Arm® Cortex® M3 core and peripherals such as timer modules, ADCs, double stage charge pump, voltage regulators, external sensor supply, RAM, flash memory and LIN communication module. This Embedded Power IC is equipped with many popular functions, requiring just a few passive components nearby, with the capability to perform advanced motor control, such as sensorless FOC with current-controlled gate driving.

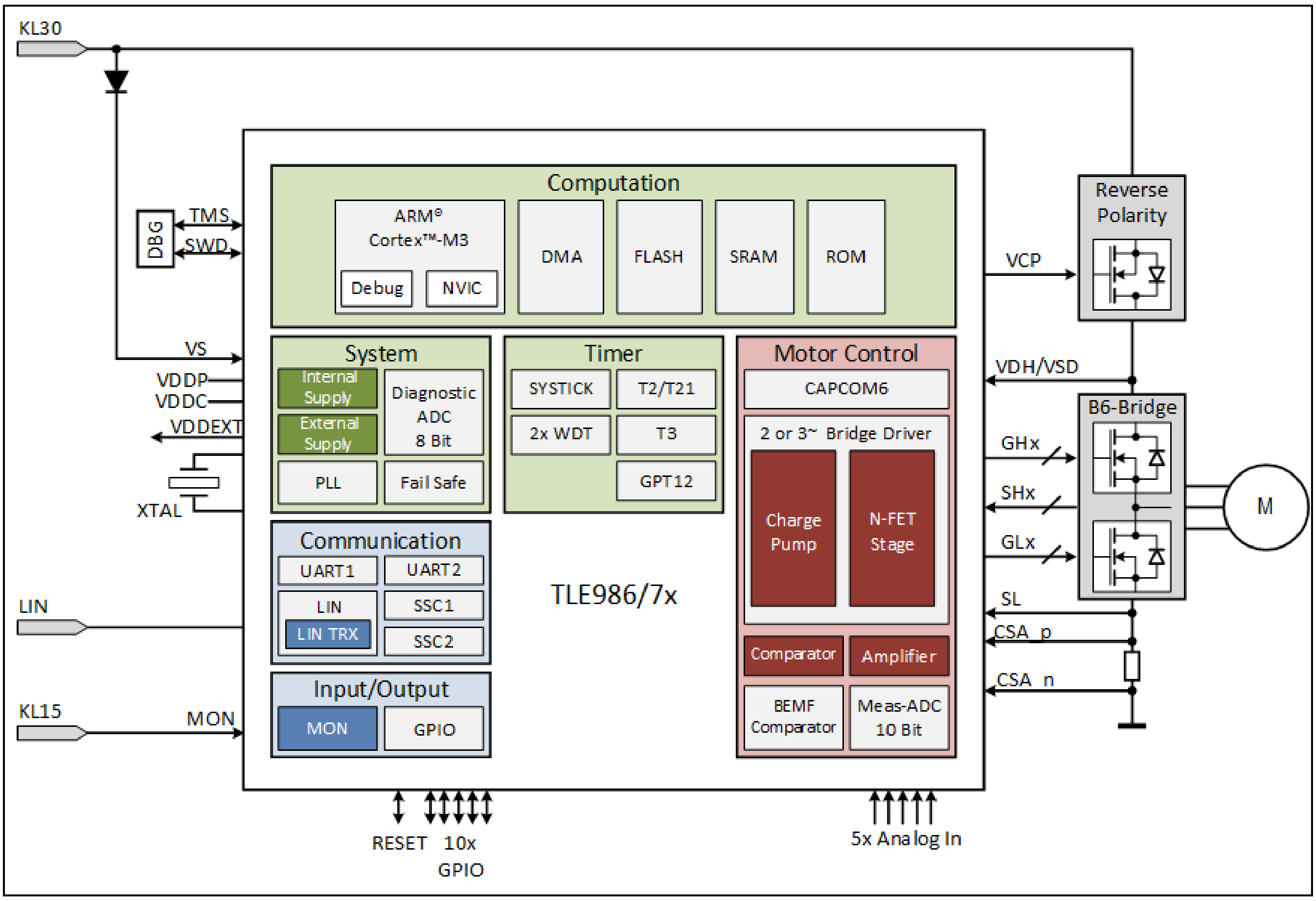


Figure 2 **System block diagram**

3.1 Electrical Design and Components

3.1.1 DC-link Electrolytic Capacitor

Document [4] shows a simple analytical expression for the current stress on the DC-link capacitor. For the case where the inverter controls a permanent-magnet AC machine (with near unity power factor), the worst-case current-stress estimation, used as a basis for the capacitor dimensioning, is given by $I_{C,rms} \approx {}^{1}/_{\sqrt{2}} \cdot I_{Out,rms}$.

Targeting the voltage ripple of the capacitor within 1 V, at 8.5 A rms output current, a total capacitance of 300 µF is required. In this design, a 330 µF electrolytic capacitor is used.

3.1.2 Shunt Resistor

The resistance, temperature coefficient, wattage, derating, form-factor, stray-inductance and environmental robustness are the main features to consider when choosing a shunt resistor. As shown in the Table 5, the maximum value of the differential input voltage of the operational amplifier is given by the expression 1.5 / G, where G is the selected gain of the currente sense amplifier. Therefore, the value of the shunt resistor can be determined considering the targeted maximum shunt current. In this evaluation design, the differential gain is set to 20, resulting in the maximum differential input voltage of 75 mV. With a 3 W, 5 mΩ shunt resistor, the maximum shunt current is equal to: I_shunt_max = (75 mV/5 mΩ) = 15 A. And the maximum power rating of the shunt is 0.9 W at 150 °C, considering the specified 70% derating.

Table 5 Differential Input Voltage Range of the Operational Amplifier of TLE9879QXW40

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Differental gain (uncalibrated)	G	9.5 19 38 57	10 20 30 40	10.5 21 42 63		Gain settings GAIN<1:0> 00 01 10 11
Differential input operating voltage range OP2 - OP1	VIX	-1.5 / G	-	1.5 / G	V	G is the gain specified

According to the resistor specification, the resistance is expected to be 5.015 mΩ at 150°C. Thus, the power dissipation at 8.5 A rms current is: $(8.5\ A)^2$ x 5.015 mΩ ≈ 0.36 W. The total area of the shunt resistor is 6.3 mm x 3.2 mm = 20.16 mm^2.

3.1.3 Snubber

The value of the RC snubber is based on Cornell Dubilier application guide [5], chosen by double pulse switching test. The 1 Ω, 15 nF RC snubber is combined with 35 V, 10 µF DC-link ceramic capacitor. And the single 330 µF electrolytic capacitor works as a DC-link filter for the bridge. The power dissipation of the snubber has been calculated and verified at 18 V / 20 kHz switching frequency.

4 System Performance

This chapter shows the performance and characteristics of the evaluation design, driving a water pump motor in the lab.

4.1 Motoring Test Setup

The setup is designed for 80W water pump supplied by 8.5 V ~ 15 V power source. Its startup duty-cycle is 12% and maximum speed is 4500 rpm.

Table 6 Parameters of Pump Motor

Parameter	Value	Unit
Phase Resistance	0.11	Ω
Phase Inductance	270	µH
Pole Pairs	2	
Maximum Speed	4500	rpm

4.1.1 Motor Parameter Setup

The parameters of the pump-motor are entered into the Config Wizard, as shown in Figure 3. Then the Config Wizard configures the relevant software code, which will be compiled into an execution file by µVision. This is an essential step to read the back-EMF properly, as the feedback of the control.

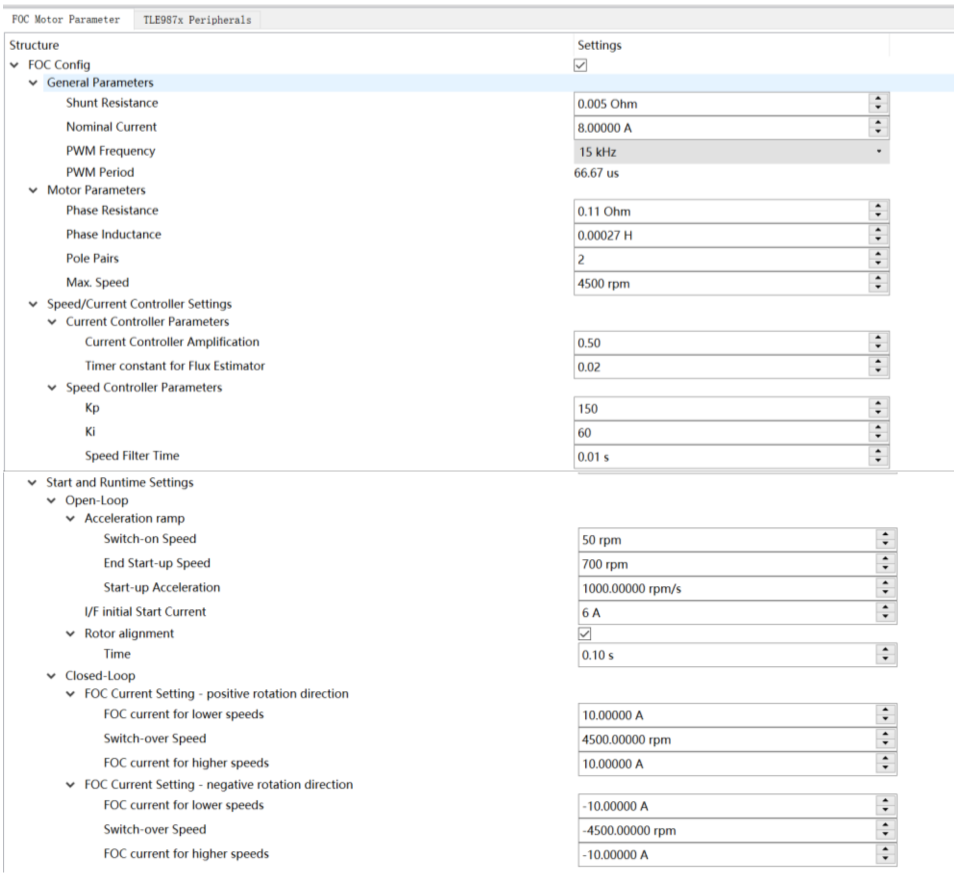


Figure 3 Motor parameter setting of Config Wizard

4.1.2 Gate-drive Setup

The gate driver stage of TLE987x has sophisticated function sets and protection schemes. It has an overcurrent detection and a shutdown feature, adjustable cross conduction protection, supply voltage (VSD) monitoring including adjustable over- and undervoltage shutdown, VDS comparators for short circuit detection in on- and off-state and open-load detection feature in MOSFET off-state, to name a few. Taking a look at the bridge driver parameters setup, the Config Wizard has a 'TLE987x Peripherals' tap, where the user can configure the setting of each function module. Under this, In the BDRV tap, bridge driver parameters such as charge pump, diagnosis and gate charge/discharge can be configured. The MOSFET switching speed is determined by the parameters under 'Gate Charge/Discharge'. Here the user can select the charge/discharge current range. The pull-down menu offers two different ranges, 0 ~ 150 mA or 0 ~ 300 mA. This range is broken down to 31 steps, by which the effective charge/discharge current is determined. By changing these parameters, the gate driving current capacity can be tuned in order to have desired switching speed. Furthermore, the 'Charge Sequencer' and the 'Discharge Sequencer' enables fine tuning of the driving current level over four consecutive time periods, DRV_ON_I_1 ~ DRV_ON_I_4 or DRV_OFF_I_1 ~ DRV_OFF_I_4. In this way, the dynamic characteristics of the MOSFET switching can be fine tuned to fit the application use. For more details, please refer to Chapter 5 of 'TLE986x_TLE987x Bridge Driver Application Note'. The example of the bridge driver setup in the Config Wizard is shown in Figure 4.

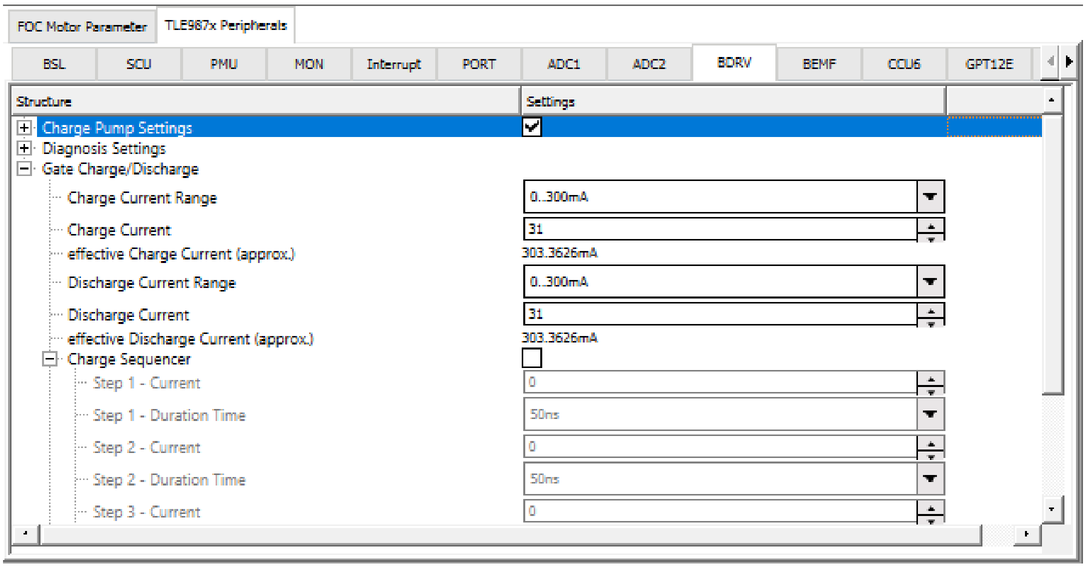
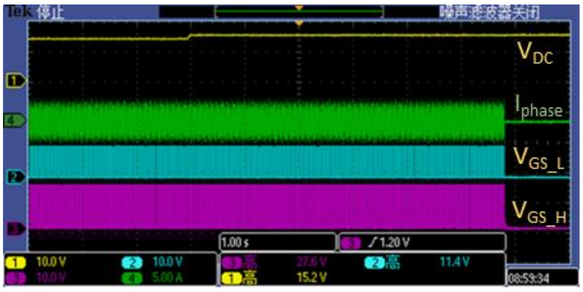


Figure 4 Bridge driver setting of Config Wizard

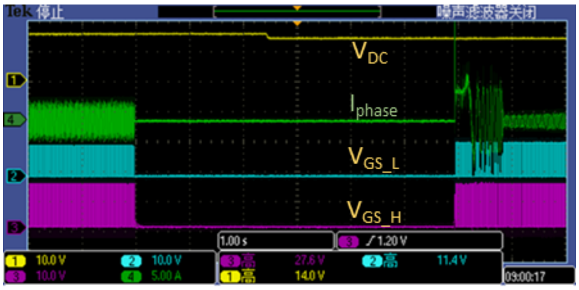
4.2 Electrical Test Result

4.2.1 Supply Protection

Figure 5 and Figure 6 show the system supply protection. Over voltage protection is activated in 5 seconds when the supply voltage is over 15V. Then the system stays stopped until the supply voltage drops down below 14.5V. Under voltage protection works opposite way. The system stops operation when the supply voltage drops below 8.5V for more than 5 seconds. The system restarts when the supply voltage comes back up to 9V.

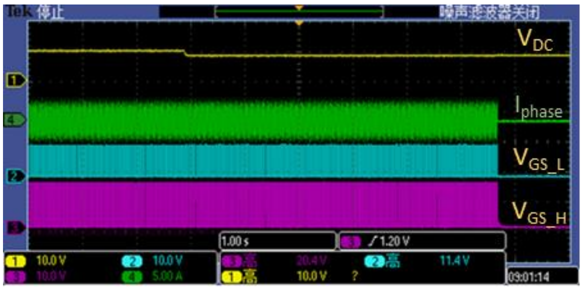


(a) Shutdown; Over 15V for more than 5s

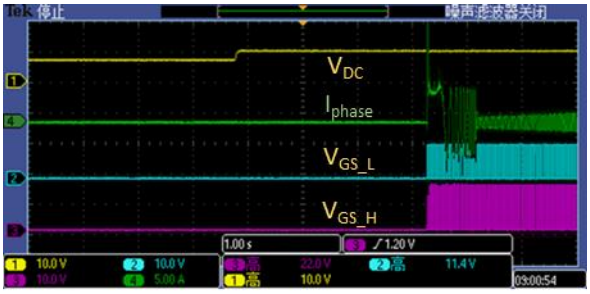


(b) Restart; below 14.5V after OV

Figure 5 System over-voltage protection



(a) Shutdown; Under 8.5V for more than 5s



(b) Restart; over 9V after UV

Figure 6 System under-voltage protection

4.2.2 Motoring Characteristics

During the motor start-up, the current and the angle is plotted in Figure 7. The motor starts with V/F open-loop control mode for about 750ms. And then the FOC sensorless algorithm takes over the control afterward. It also shows electrical angle and phase current during the motor start-up.

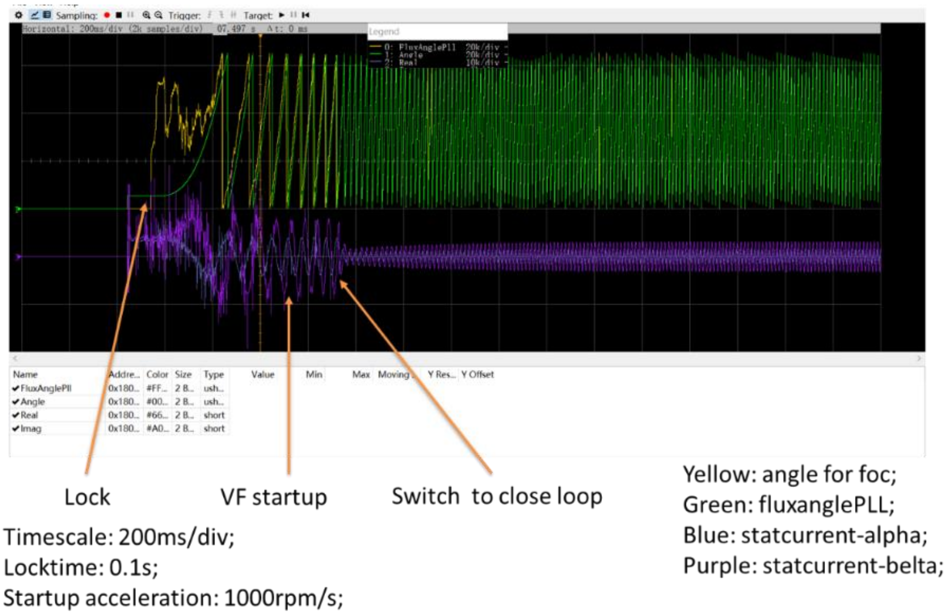


Figure 7 Motor start-up; angle and phase current waveform

Figure 8 shows the D/Q rotating axis current during the start-up sequence. As soon as the FOC takes over the control, the current of D axis become zero, showing the speed control loop is working properly.

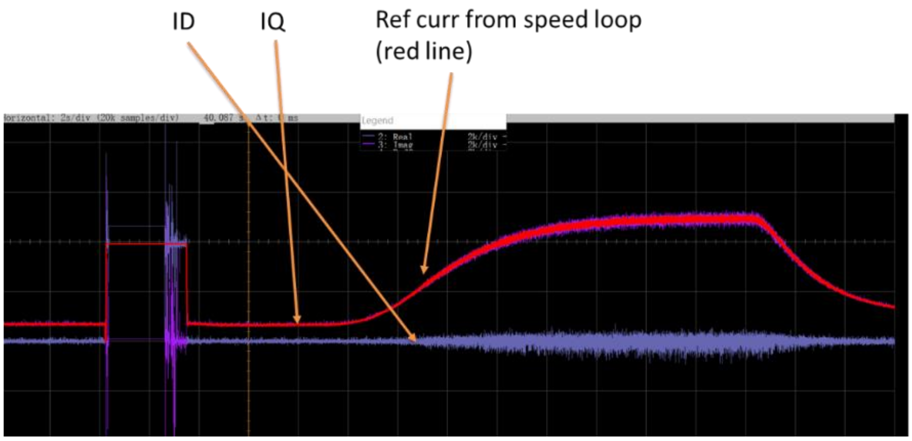


Figure 8 Motor start-up; D-Q current waveform

Figure 9 and Figure 10 shows the switching waveform of a MOSFET. Measured dV/dt of the Vds is 489 V/µs for turn-on and 916 V/µs for turn-off. The switching speed can be easily adjusted at the software setting without changing physical gate resistance. Please find more details of the gate drive parameter setting of TLE9879QXA at “TLE987x_TLE987x Bridge Driver Application Note”. [2]

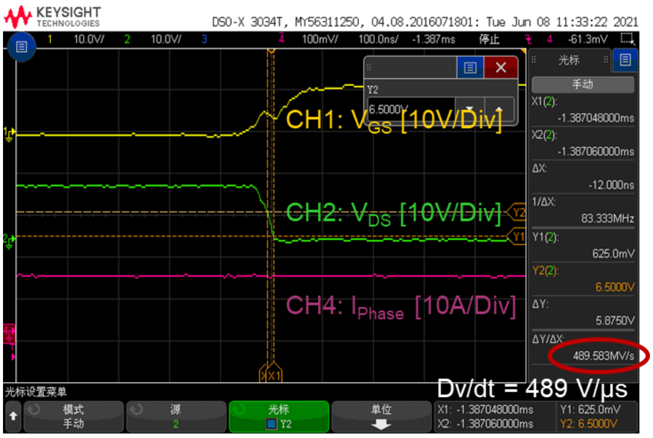


Figure 9 Low-side MOSFET turn-on dv/dt

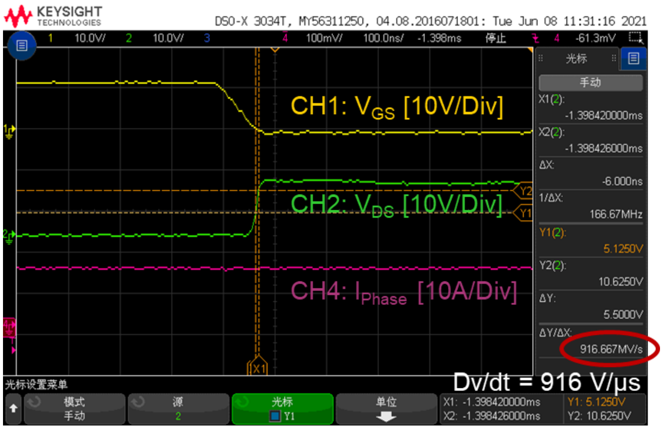


Figure 10 Low-side MOSFET turn-off dv/dt

Figure 11 shows the phase current waveform at 3000 RPM motor speed in closed-loop control. Channel 1 is the speed feedback signal from the observer sensor. And channel 2 is the speed command coming from LIN communication port. It shows all of three waveforms of the speed command, phase current and speed sensing are well aligned. The max speed of the test setup can reach up to 4700 RPM with 90W DC power, with FOC closed-loop control, out of the shunt reading.

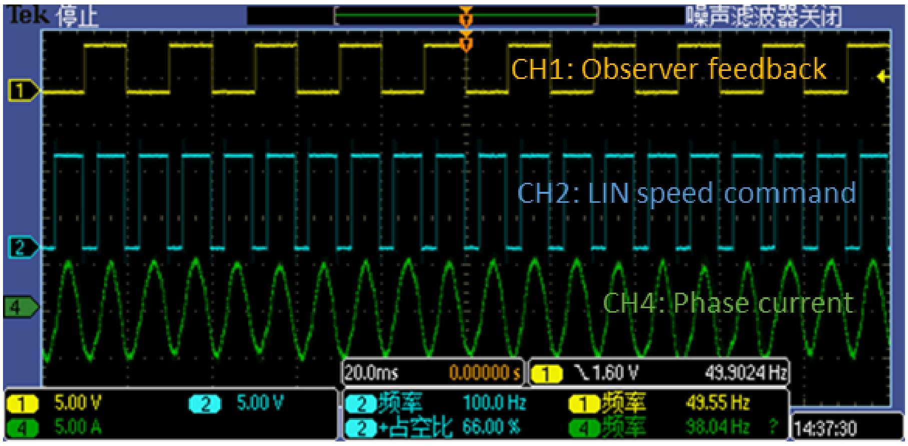


Figure 11 Phase current waveform from 3000 RPM motor run

4.3 Thermal Behavior

4.3.1 Housing Assembly for Thermal Test

The housing of an after-market water pump is assembled in order to perform thermal test. Thermal pad and the PCB are mounted on the housing as shown in Figure 12. The setup was placed at room temperature. Thermal pad with 1mm thickness and 3.6 W/mK thermal conductivity is used in this test. The PCB board is mounted on the heatsink with three of M3 screws to provide close contact between PCB, thermal pad and housing. As the bottom side of the board does not have any component, it does not need complex surface contour in terms of housing design.

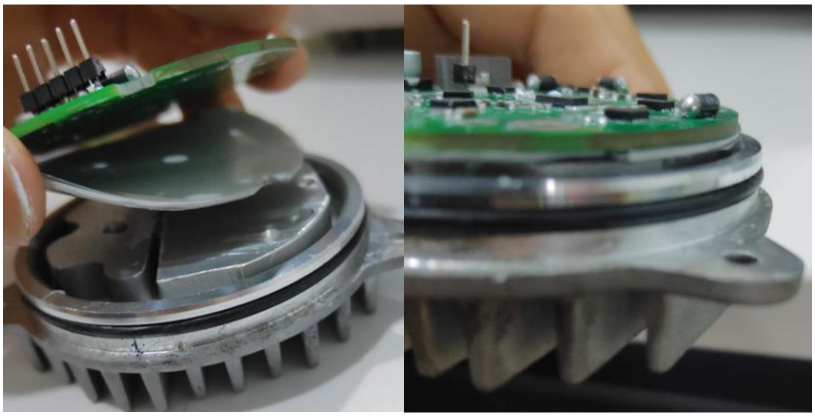
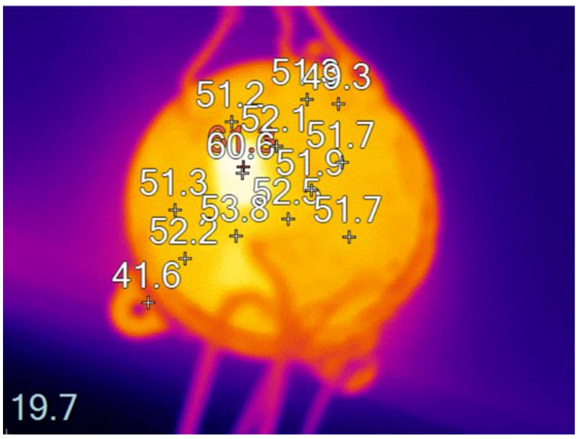


Figure 12 Housing assembly

4.3.2 Thermal Image

Figure 13 is an example of a thermal image from the pump test setup. The image was taken from the test run of the pump at 12.05 V, 7.2 Adc test condition. The system was in the still air of room-temperature. MOSFETs, TLE9879 and the shunt resistor are the major components that dissipate power and increase system temperature. The temperature of those components are within the same range at this operating condition. The reverse protection MOSFET, T_RP1, has slightly higher temperature as the current of all three legs are flowing through this MOSFET. Having lower Rds(on) on this MOSFET, compared to bridge MOSFETs is generally recommended. The image was captured after 30 minutes of constant current operation at this condition.



Device	Temp(°C)
TLE9879	51.7
U1	52.2
U2	51.2
U3	51.9
U4	51.3
U5	51.3
U6	51.7
T_RP1	53.8
Shunt	52.1
Mounting bolt	49.3
Housing	41.6

Figure 13 Thermal image showing the temperature reading point

4.3.3 Temperature Profile

Figure 14 is the temperature profile of the components during the pump operation at room temperature. The temperature of the bridge MOSFETs shows 65~70°C at 8.3A input current. This translated to 150~155°C mold temperature at 110°C ambient. And the system still can run at its max overload conditions (8.5Adc) during short period of times. The reverse battery protection switch shows the highest temperature between MOSFETs. But it can still handle the max overload condition under the 110°C ambient. The temperature of TLE9879 gate driver is similar to that of MOSFETs. Even in higher current condition, the gate driver temperature does not increase as much as MOSFETs, because the direct self heating of the driver is mainly from its internal power regulators and charge pumps, which is much less than indirect heating from the MOSFETs nearby.

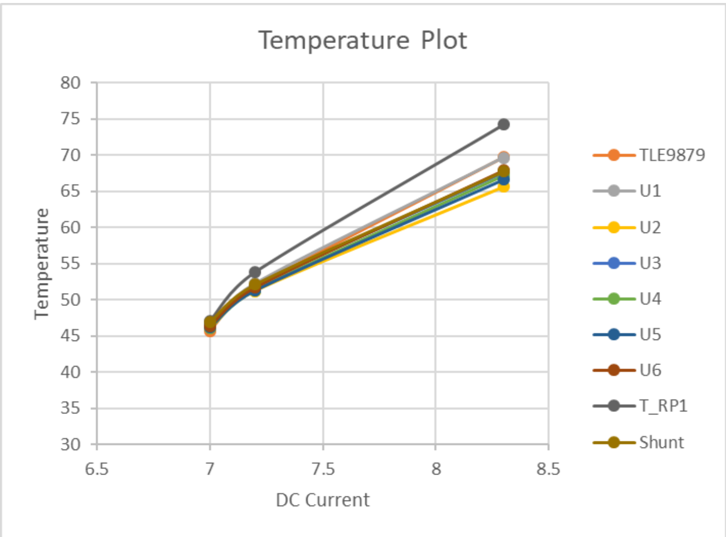
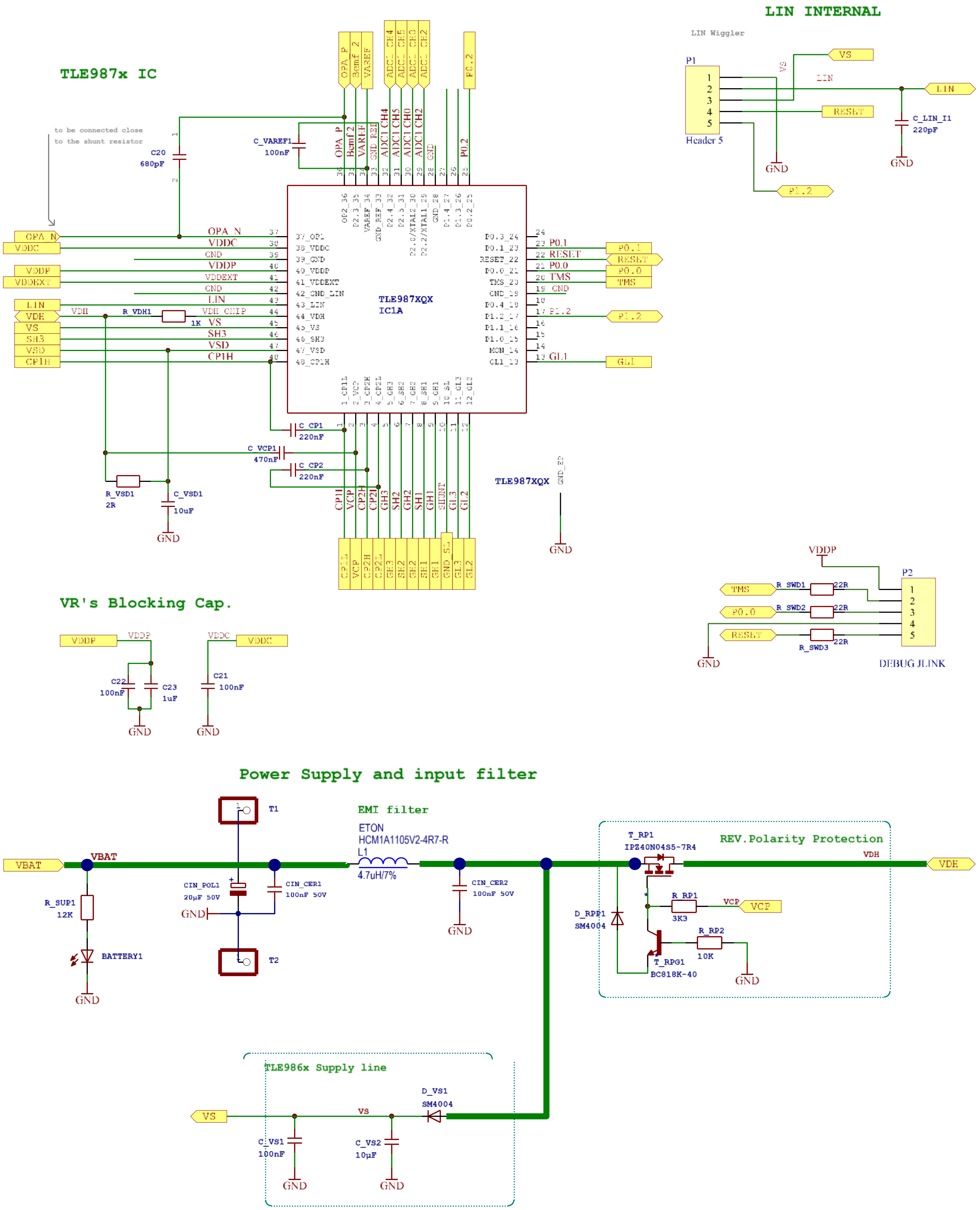


Figure 14 Measured Temperature versus Input Current.

5 Project Collaterals

5.1 Schematics



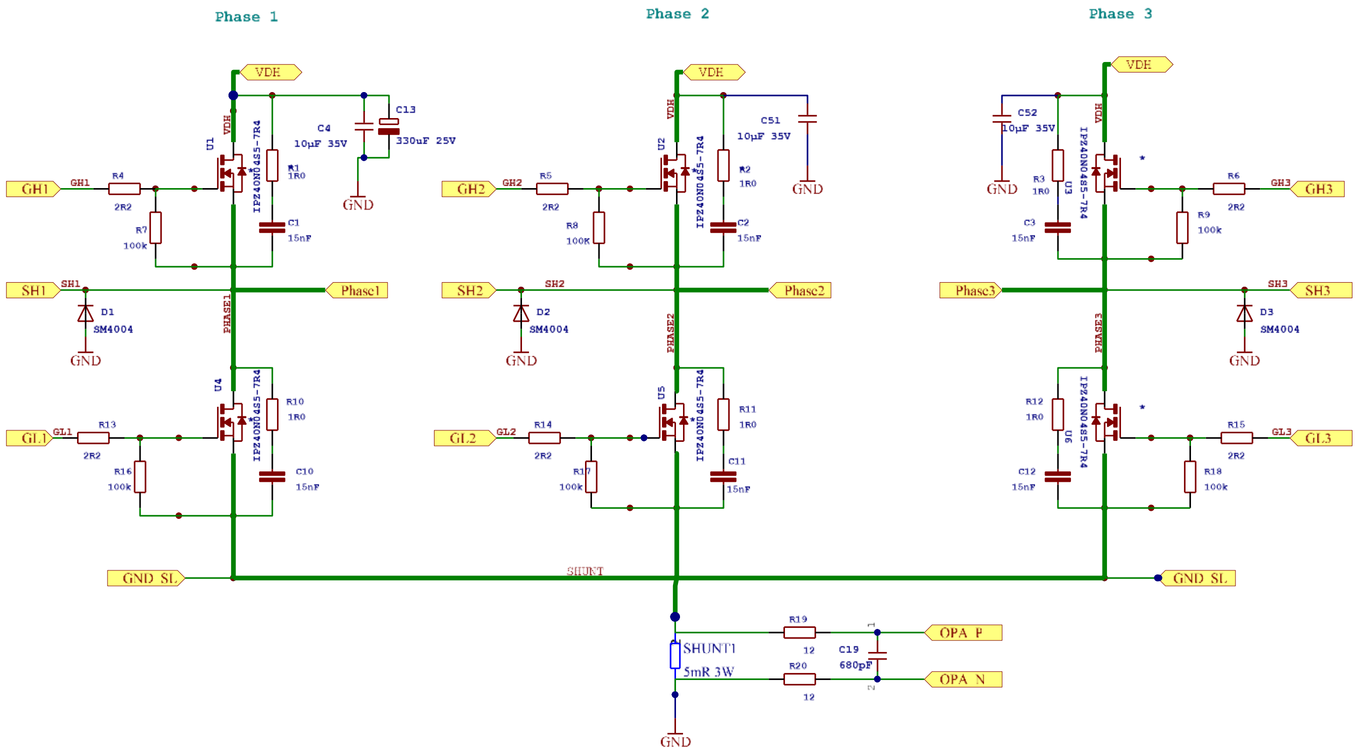


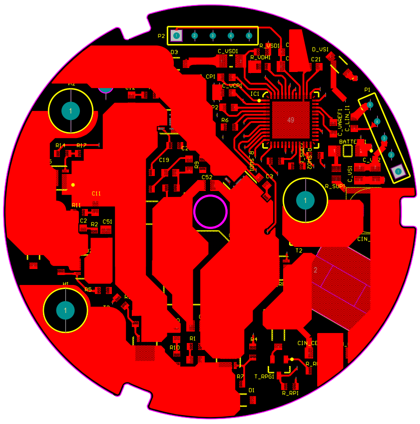
Figure 15 **Circuit Schematics**

5.2 Bill of Material

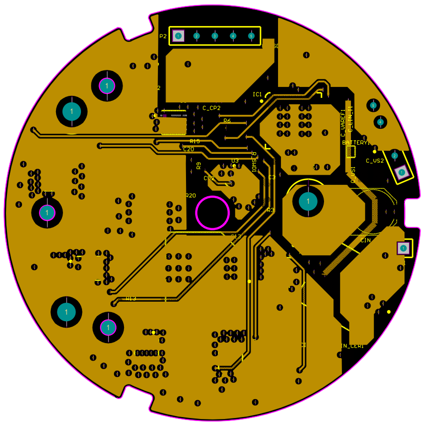
Table 7 Bill of material

	Designator	Value	Description	Quantity
1	BATTERY1	F32LEDSMT1206	LED OSRAM - CHIPLED	1
2	C1, C2, C3, C10, C11, C12	15nF	MLCC 0805	6
3	C4, C51, C52	10µF 35V	MLCC 0805	3
4	C13	330uF 25V	Panasonic， EETG1E331UP	1
5	C19, C20	680pF	MLCC 0805	2
6	C21, C22, C_VAREF1	100nF	MLCC 0805	3
7	C23	1uF	MLCC 0805	1
8	C_CP1, C_CP2	220nF	MLCC 0805	2
9	C_LIN_I1	220pF	MLCC 0805	1
10	C_VCP1	470nF	MLCC 0805	1
11	C_VS1	100nF	MLCC 0805	1
12	C_VS2	10µF	MLCC 0805	1
13	C_VSD1	10uF	MLCC 1206	1
14	CIN_CER1, CIN_CER2	100nF 50V	MLCC 0805	2
15	CIN_POL1	47µF 35V	Panasonic, EEETPV470XAP, ϕ6.3	1
16	D1, D2, D3, D_RPP1, D_VS1	SM4004	Shottky Diode SMD	5
17	H1, H2	Screw hole	Washer hole	2
18	IC1	TLE9879QXA40	QFN50P700X700X90	1
19	L1	HCM1A1105V2-4R7-R	EATON SMD Inductor	1
20	P1	Header 5	Header, HDR1X5	1
21	P2	DEBUG JLINK	Header, HDR1X5	1
22	R1, R2, R3, R10, R11, R12	1R0	RES SMD 1206	6
23	R4, R5, R6, R13, R14, R15	2R2	RES SMD 0805	6
24	R7, R8, R9, R16, R17, R18	100k	RES SMD 0805	6
25	R19, R20	12	RES SMD 0805	2
26	R_RP1	3K3	RES SMD 0805	1
27	R_RP2	10K	RES SMD 0805	1
28	R_SUP1	12K	RES SMD 0805	1
29	R_SWD1, R_SWD2, R_SWD3	22R	RES SMD 0805	3
30	R_VDH1	1K	RES SMD 0805	1
31	R_VSD1	2R	RES SMD 0805	1
32	SHUNT1	5mR 3W	RES SMD ERJMS4HF5M0U	1
33	T1, T2		HDR1X1	2
34	T3, T4, T5		PHASE Conn PAD	3
35	U1, U2,U3, U4, U5,U6	IPZ40N04S5-8R4	SFET5 40V S3O8	6
36	T_RPG1	BC818K-40	NPN Transistor, SOT95	1
37	T_RP1	IPZ40N04S5-5R4	SFET5 40V S3O8	1

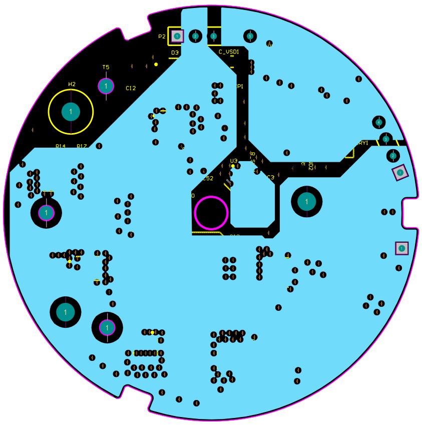
5.3 Layout Printing



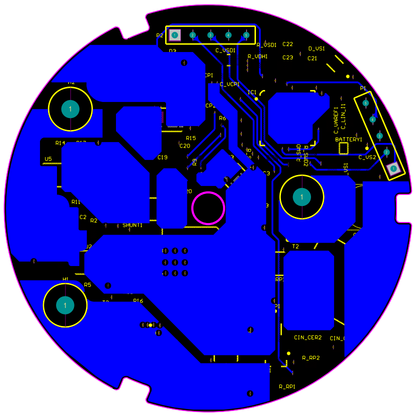
TOP



POWER



GROUND



BOTTOM

Figure 16 PCB layout printing of 6 Copper layers

6 Abbreviations and definitions

Table 8 Abbreviations

Abbreviation	Definition
LIN	Local Interconnect Network
FOC	Field Oriented Control
MI	Modulation Index
RBP	Reverse Battery Protection
ECU	Electrical Control Unit
PWM	Pulse Width Modulation
PCB	Printed Circuit Board
EMC	Electromagnetic Compatibility
IC	Integrated Circuit
DC	Direct Current
ESR	Equivalent Series Resistance
DUT	Device under test
BDRV	Bridge Driver Module of Embedded Power IC

7 Reference documents

This document should be read in conjunction with the following documents:

[1] TLE9879QXA40 datasheet, Infineon Technologies AG, https://www.infineon.com/dgdl/Infineon-TLE9879QXA40-DS-v01_00-EN.pdf?fileId=5546d4625a888733015a89d10a283f20

[2] TLE987x_TLE987x Bridge Driver Application Note, 2018-12, Infineon Technologies AG, Rev 1.02 https://www.infineon.com/dgdl/Infineon-TLE987x_TLE986x-BDRV-ApplicationNotes-v01_02-EN.pdf?fileId=5546d46267c74c9a0167cbe1686a191d

[3] TLE987x User Manual, 2020-10, Infineon Technologies AG, Rev 1.5.3 https://www.infineon.com/dgdl/Infineon-TLE9879QXA40-UserManual-v15_03-EN.pdf?fileId=5546d4624e24005f014e52ca1628452c

[4] IPZ40N04S5-8R4 datasheet, Infineon Technologies AG, https://www.infineon.com/dgdl/Infineon-IPZ40N04S5-8R4-DS-v01_00-EN.pdf?fileId=5546d462584d1d4a0158d8a817e4652a

[5] IPZ40N04S5-5R4 datasheet, Infineon Technologies AG, https://www.infineon.com/dgdl/Infineon-IPZ40N04S5-5R4-DS-v01_01-EN.pdf?fileId=5546d4624cb7f111014d660122db4898

[6] Analytical calculation of the RMS current stress on the DC-link capacitor of voltage-PWM converter systems, 2006-07, IEE Proc.-Electr. Power Appl., Vol. 153, No.4.

Revision history

Major changes since the last revision

Date	Version	Description
28-Jun-2021	V0.6	Initial version
09-Sep-2021	V1.0	Final document

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