Drone
Electronic Speed Controller(ESC) with XMC™, Gate Driver, OptiMOS™

October 2016

Learning objectives

- To demonstrate the implementation of sensorless FOC as Electronic Speed Controller (ESC) in quadcopter application
- Key software functions, a step-by-step implementation, and linking up with µC/Probe™ XMC™
- To use of µC/Probe™ to visualise data and fine-tune ESC
- After the learning of this PPT, users will be able to fine-tune FOC example software which is easy scalability for quadcopter ESC applications

Agenda (1/2)

Agenda (2/2)

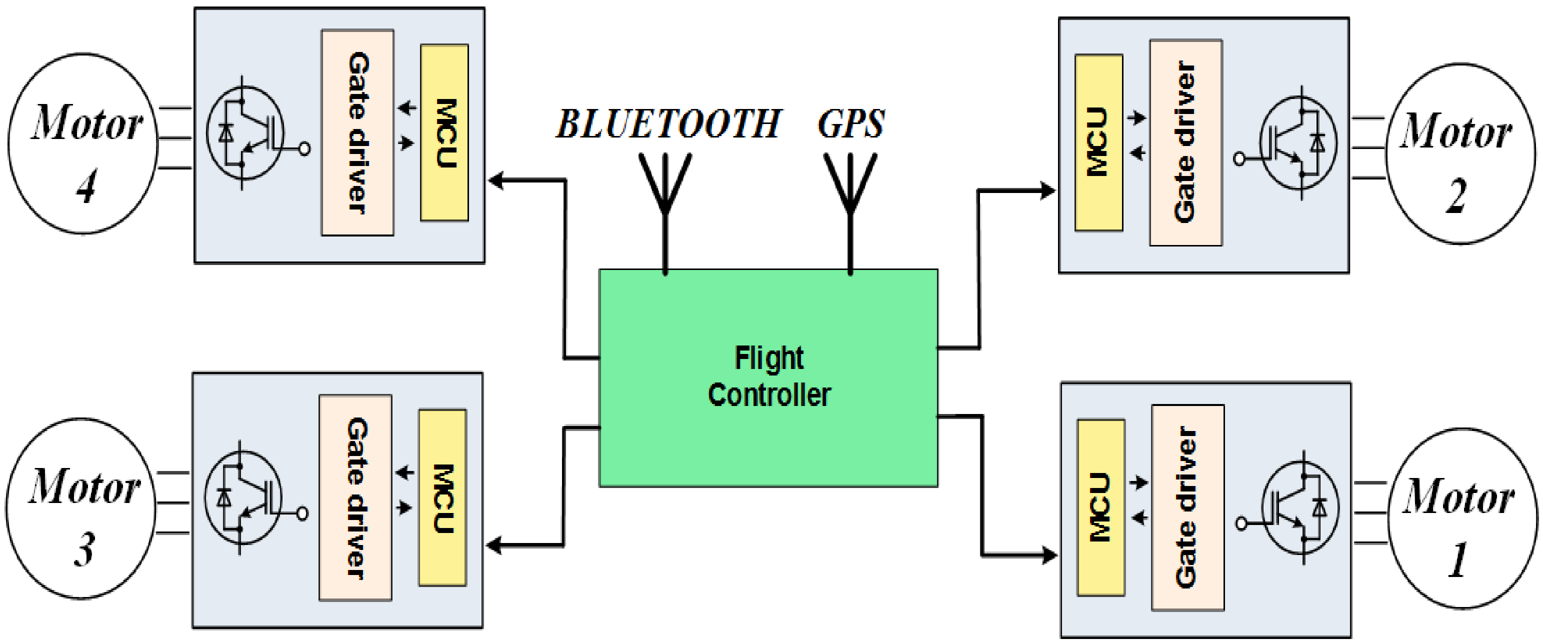
9 Resource listing

Electronic Speed Controller Reference Design-Overview

- The purpose of the training slides is to elaborate a low-cost and high-performance quadcopter ESC solution, using
  - XMC™ PINUS Inverter
  - 12V 2300KV 3 phase brushless motor
  - DAVE™ 4 ESC example project - PMSM_FOC_SL_XMC13
- The HOT examples cover the key features and controls of the 3 phase brushless drone motor

Quadcopter System Block

› Consists of a flight controller and four ESCs, one for each motor.



› Each ESC contains a three phase inverter driven by MCU with a specialized FOC motor control software

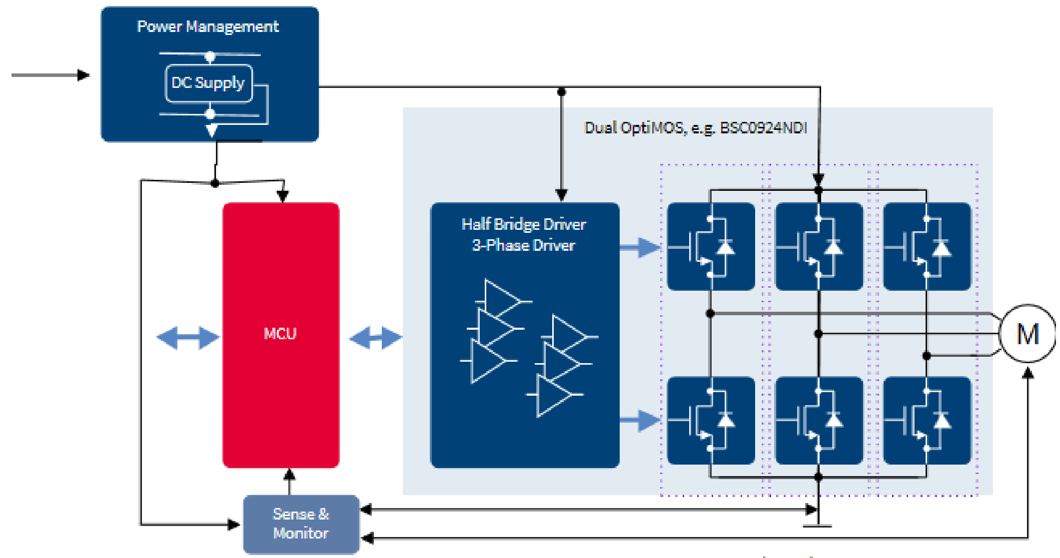
Infineon can provide all the critical components for quadcopter ESC Reference Design

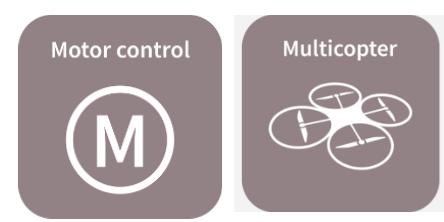
Motor control

Functionality	IFX components
› FOC controller (3-phase PWM generation, motor phase current sensing, bus voltage sensing, over-current & over-voltage protection)	› **XMC1302**: ARM® Cortex®-M0 32-bit processor @ 32 MHz, up to 200 kB flash,16 kB SRAM,MATH coprocessor, 12-bit ADC with 2 sample & hold stages, motor control PWM timer (CCU8), general purpose timer (CCU4), serial communication (USIC)

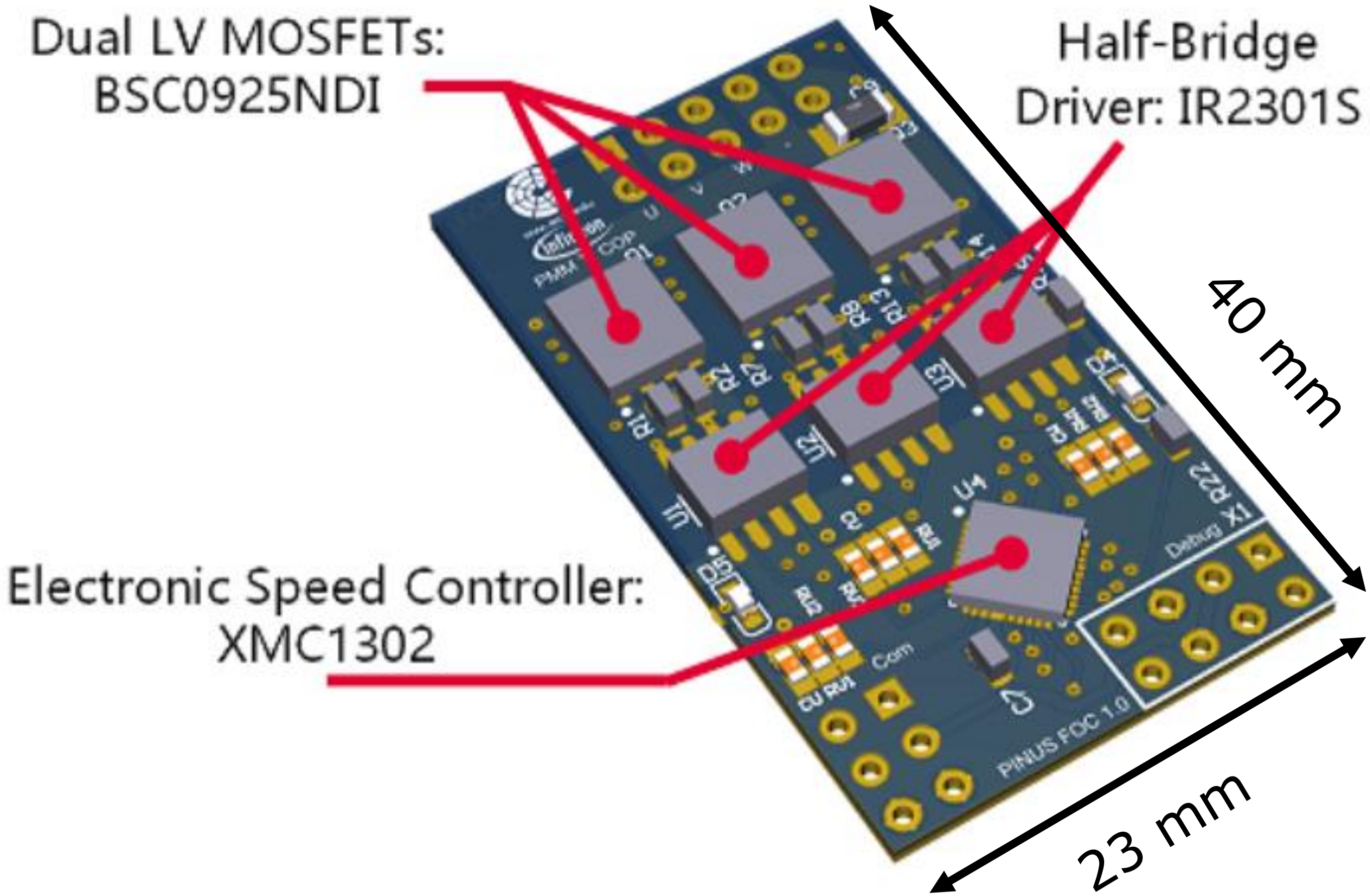
Power stage

Functionality	IFX components
› Power inverter	› **BSC0925ND**: OptiMos Power-MOSFET Dual N-channel › **IR2301S:** High and Low Side gate driver
› Auxiliary power supply	› **IFX91041V50**: 5 V LDO (Coming from Flight Controller)





ESC Reference Design 3D PCB view



Value arguments of ESC Reference Design

	Benefits	Addressed customer needs
Strong arguments	Small code size and fast execution time	Allows ample CPU time for more tasks Small code size < 16 kB, and super-fast code execution < 20 μs (for optimized code)
	Robust start-up	Direct-sensorless-FOC startup is robust, smooth and energy efficient at various load conditions of ESC
	Less dependencies more robust	Only need one motor parameter to estimate rotor angle and speed for sensorless FOC
	Ultra-low speed sensorless control	Robust / quieter operation with sensorless FOC drive even at ultra-low speed (e.g.: 0.8% of max speed)
	BOM savings	€ 0.49-0.9 reduction of system BOM using XMC™ on-chip ADC gain. Complete sensorless motor control eliminating Hall sensors / tachometer
Medium arguments	ARM® Cortex®-M0 with MATH coprocessor	Replace costly MCUs (e.g. ARM® Cortex®-M3) from competitors
	Embedded security solutions	Protect customer solution from being copied by competitors
Soft arguments	Product portfolio	Infineon a “one-stop-shop” for motor control applications with complete power semiconductor portfolio
	Knowledge of vendor	Dedicate motor control expert team support with multiple connection of expertise for local support

ESC Reference Design - Key features

Target application

- Quadcopter application

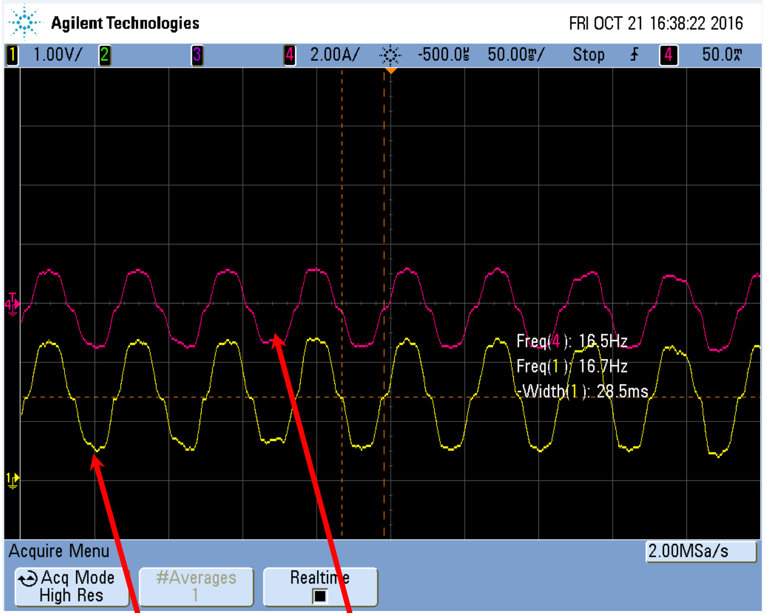
Key features

- Sensorless FOC control even at ultra-low speed
- Robust direct-sensorless-FOC startup
- Fast execution FOC with XMC™ Cortex M0
- XMC™ on-chip ADC gain to reduce system BOM cost

ESC Reference Design - Specification

Specifications

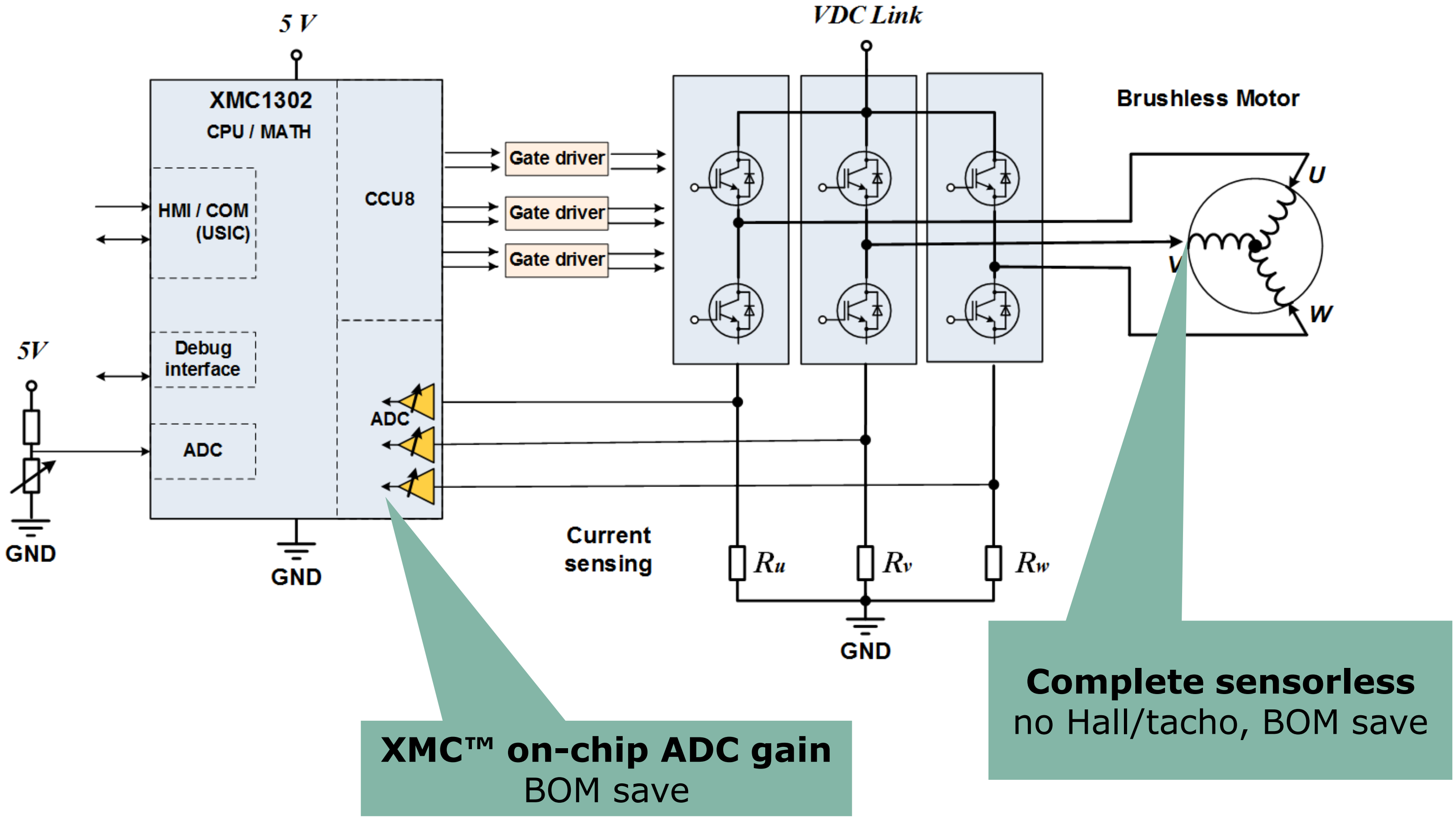
- DC input voltage: 12Vdc and 5Vdc (Coming from Flight Controller)
- Motor mechanical speed
  - Maximum speed 15,000 rpm
  - Motor Pole Pair: 6
  - KV = 2300
  - Max Continuous current (A) = 5.7A
  - Max Continuous Power (W) = 63.3W
- Speed adjustable via Potentiometer / uC Probe GUI / UART Communication



- Motor BEMF

- DAC Signal from MCU (Reconstructed Phase U Current)

ESC Reference Design - block diagram



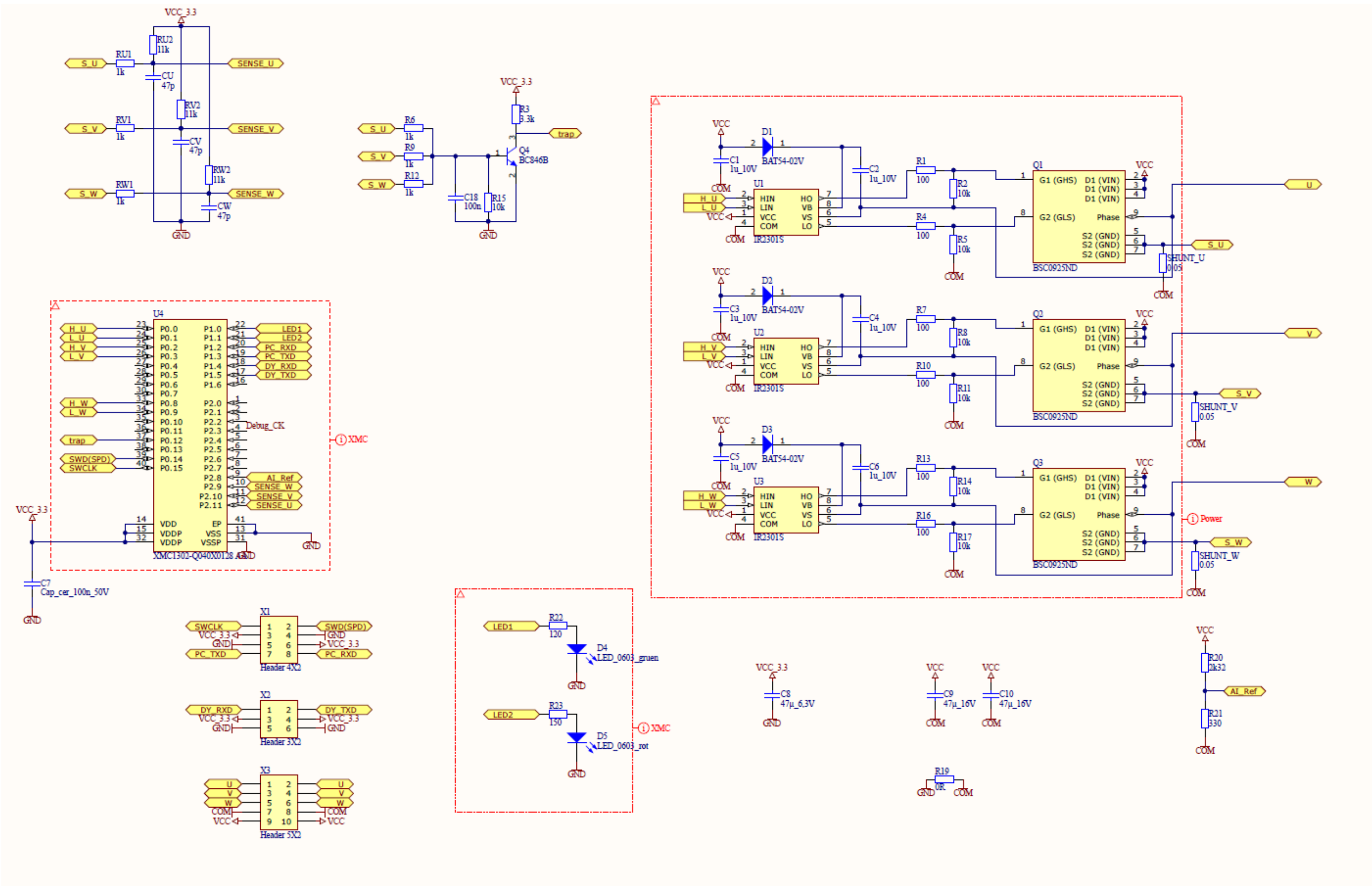
ESC block diagram: ESC motor control

ESC motor control - Hardware overview

› Key Infineon components utilized on PINUS Inverter:

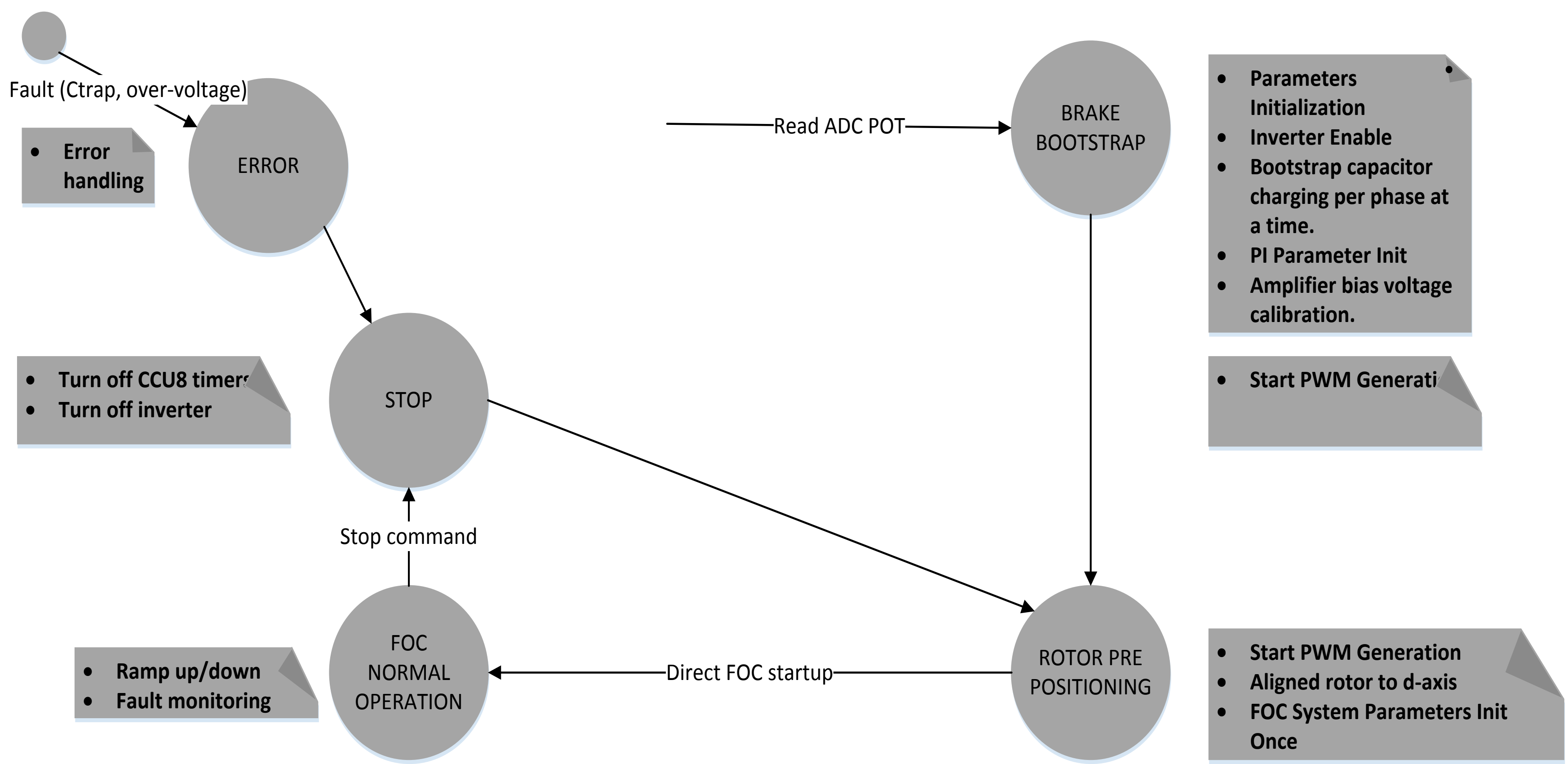
No.	Infineon components	Order number
1	XMC™ microcontroller	XMC1302-Q040X0128
2	Gate Driver IC	IR2301S
3	OptiMOS™ Power MOSFET, 30V, Dual N Channel	BSC0925ND

ESC motor control - 3-phase PINUS inverter schematics



Schematic: ESC motor control - 3-phase inverter

ESC motor control - Software overview (Torque Control Mode)



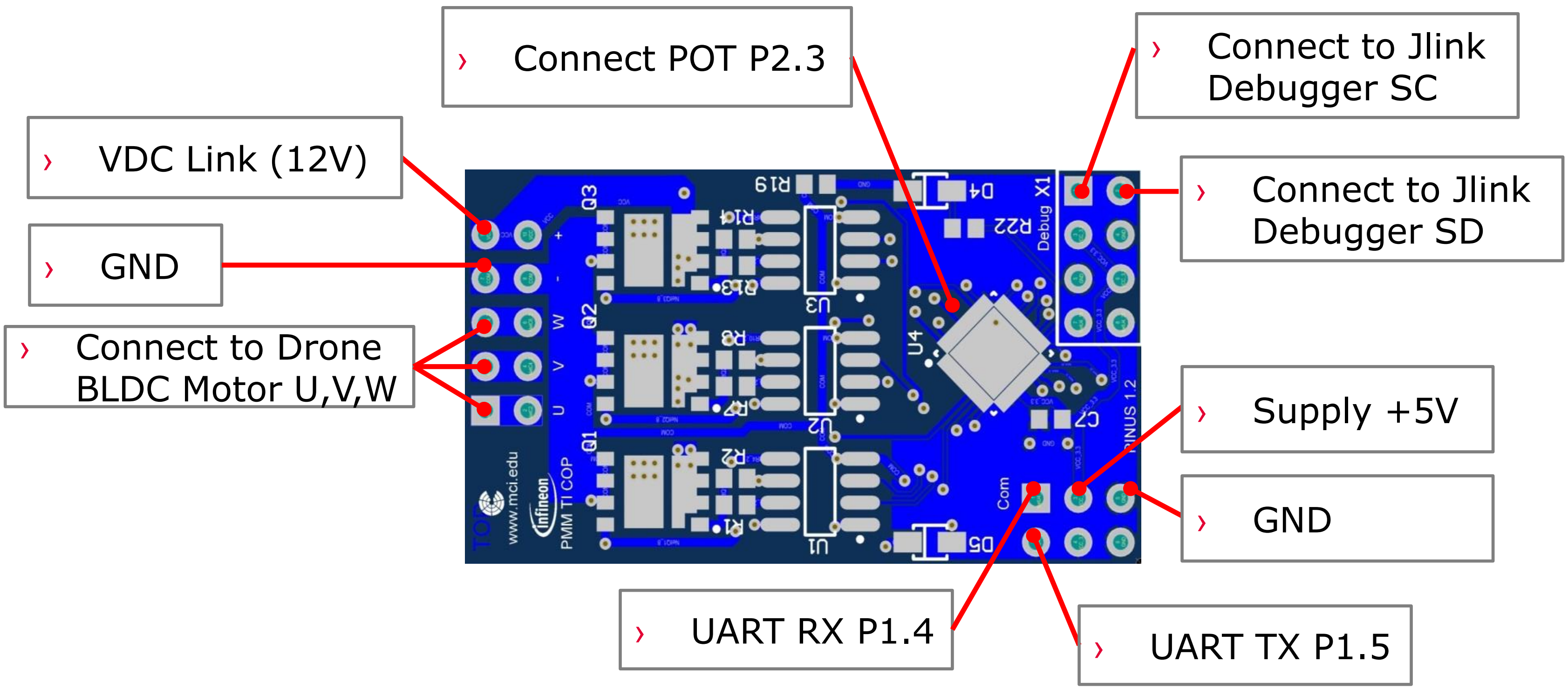
Flow chart: ESC motor control - software overview

ESC motor control - Highlight MCU features

- MATH coprocessor
  - 38x faster sine, cosine and arctangent calculations
  - High-resolution Park/Inverse Park Transforms at 24-bit in less than 1 μs
  - 7x faster division compared to other ARM® Cortex®-M0 devices
- CCU8 PWM
  - Generate PWM patterns for all kind of motors
  - Interact with ADC for ADC triggering at sensorless control of motors
  - Operate always in a safe state - even in an error condition
  - Dead time control to minimum hardware effort
  - 16-bit resolution for high precision space vector PWM generation
- ADC
  - On-chip ADC gain (x1, x3, x6, or x12) to eliminate external Op-Amp
  - Simultaneously sample of multiple analog channels
  - Fast ADC reduces torque ripple due to minimized blind angle in sensorless FOC
  - Used to sense motor three phase current as feedback to the system

ESC motor control - Get started - HW connections

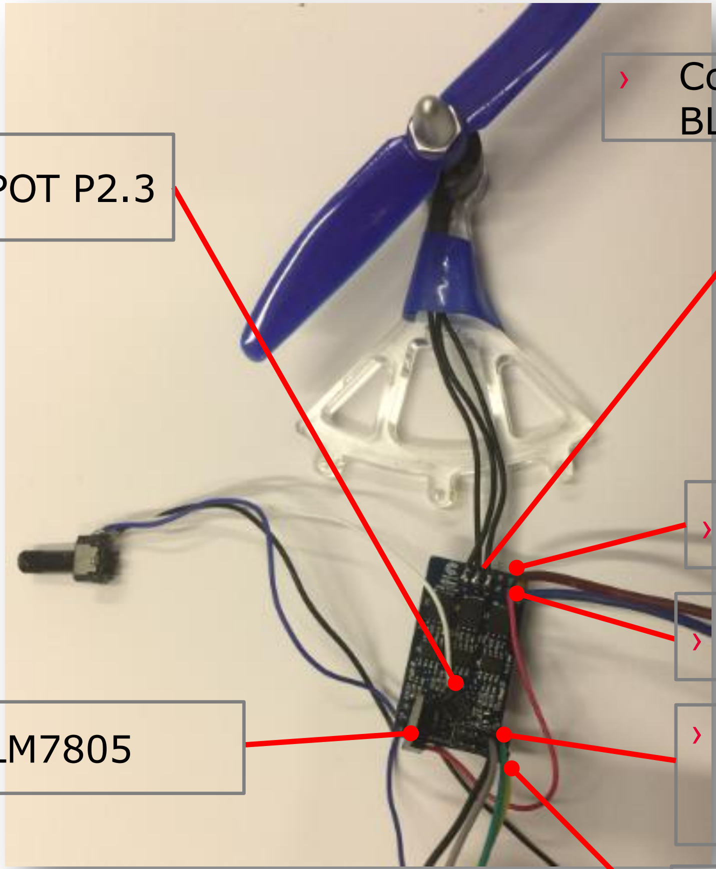
› Connect BLDC motor U, V and W phases to PINUS Inverter

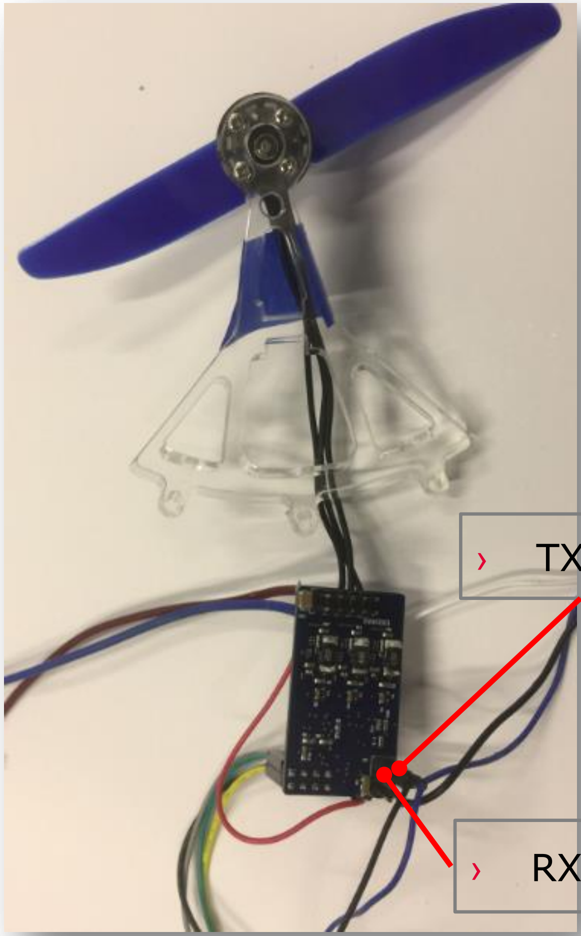


ESC motor control -
Get started – Real HW connections

- UART RX P1.4

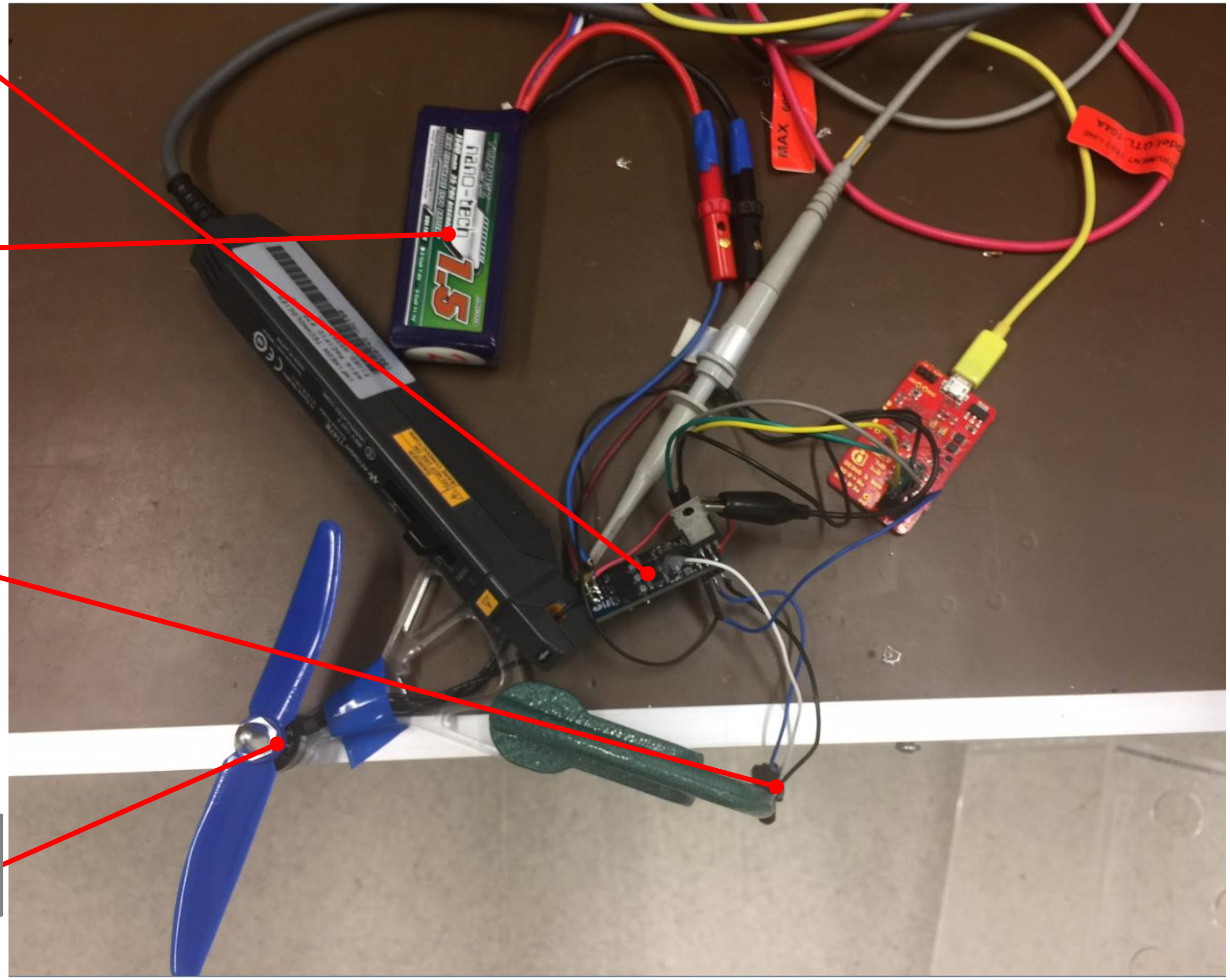
- Connect BLDC motor U, V and W phases to PINUS Inverter





ESC motor control – Test Setup

- PINUS ESC
- 3S LiPo Battery pack
- Potentiometer
- BLDC 3 Phase Motors



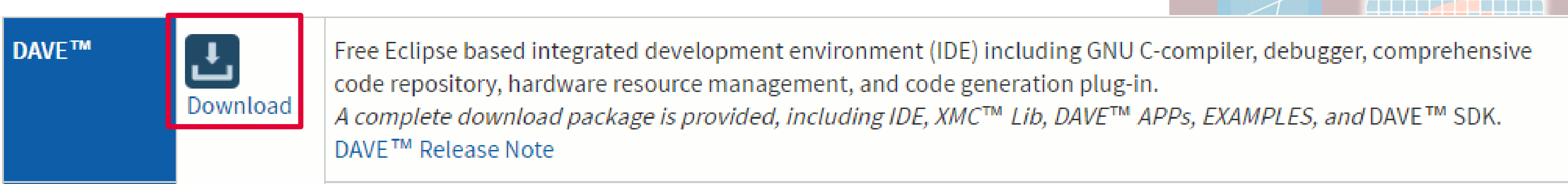
ESC motor control - Get started - DAVE™ 4

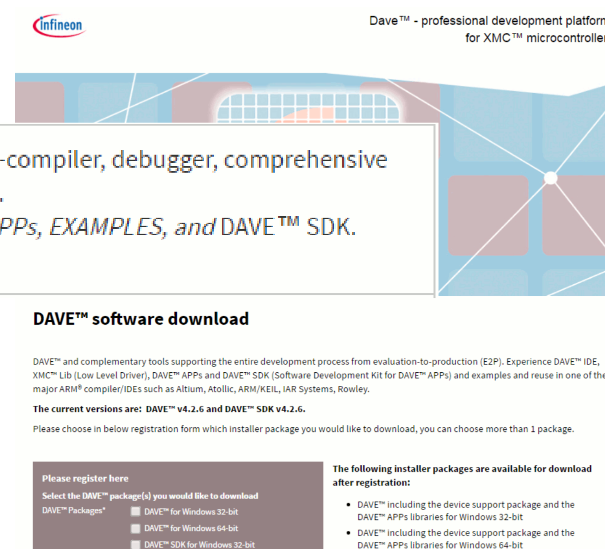
- Download the latest DAVE™ 4 installer package from

  [DAVE™ (Version 4) - Development Platform for XMC™ Microcontrollers]

- Installation requirements

  1. PC with Windows 7, Windows 8.1, Windows 10, Windows Vista - 32bit & 64bit
  2. RAM - 4 GB or more
  3. Remember to install SEGGER J-Link when installing DAVE™ 4 (if not done so)





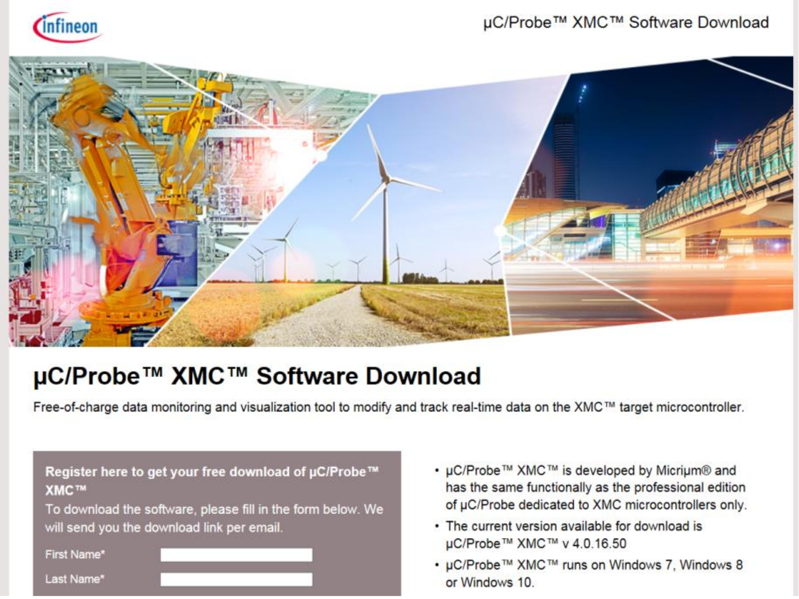
ESC motor control - Get started - µC/Probe™ XMC™

- Download the latest µC/Probe™ XMC™ installer package from

  https://infineoncommunity.com/uC-Probe-XMC-software-download_ID712

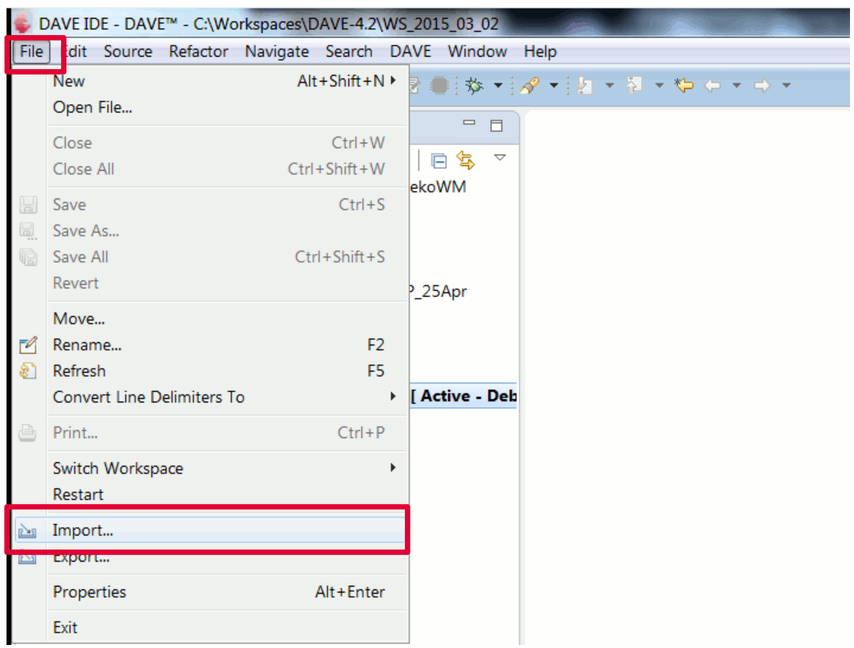
- Installation requirements

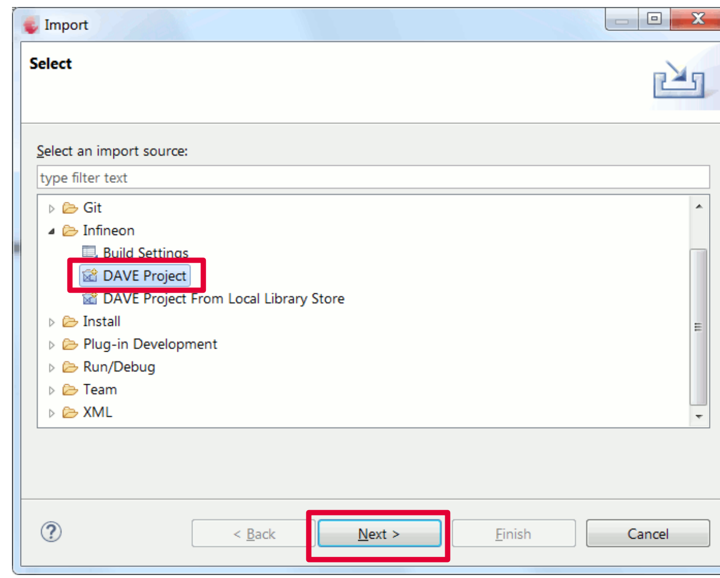
  1. PC with Windows Vista, Windows 7, Windows 8, Windows 10 - 32bit & 64bit
  2. RAM - 3 GB or more



ESC motor control - Get started - import SW to DAVE™ 4 (1/2)

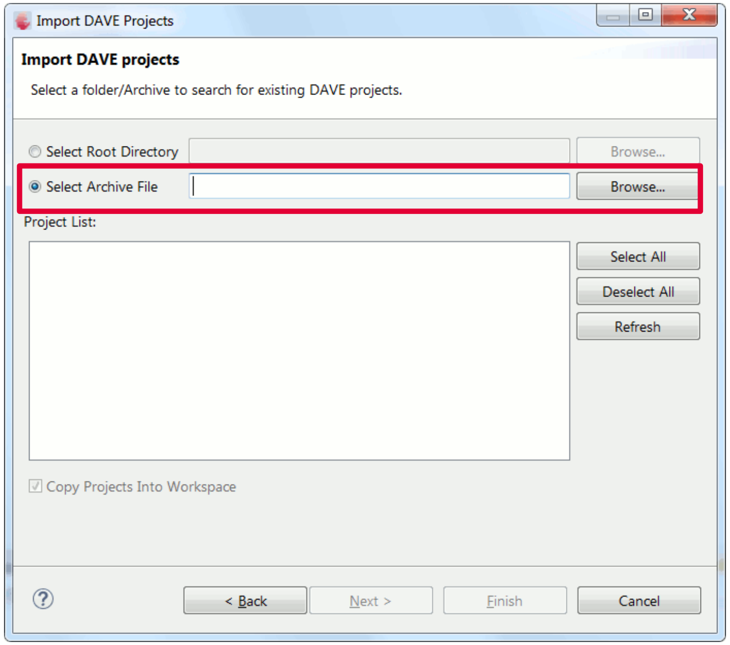
- Open DAVE™ 4
- Click on **File > Import** to import sample code
- Select **Infineon > DAVE project** and click "**Next**"

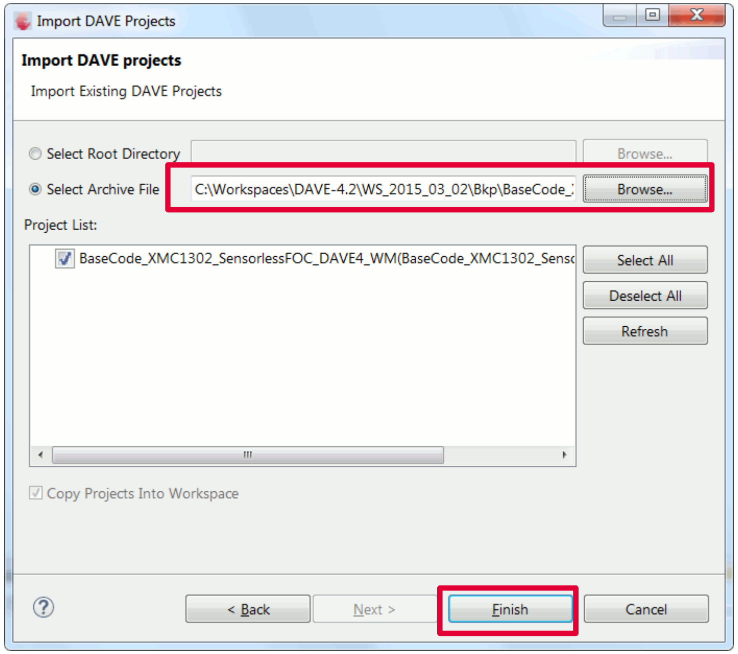




ESC motor control - Get started - import SW to DAVE™ 4 (2/2)

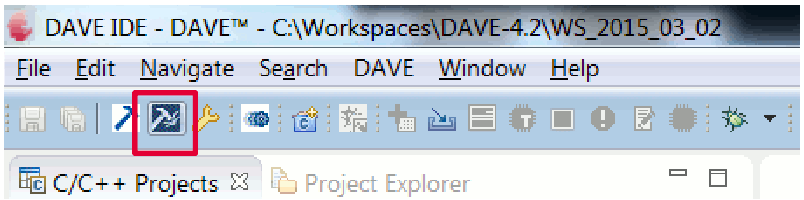
- Next click on **Select Archive File > Browse**
- Select the folder containing the sample code and click "**OK**"
- Click on "**Finish**" to import the code into DAVE™ 4



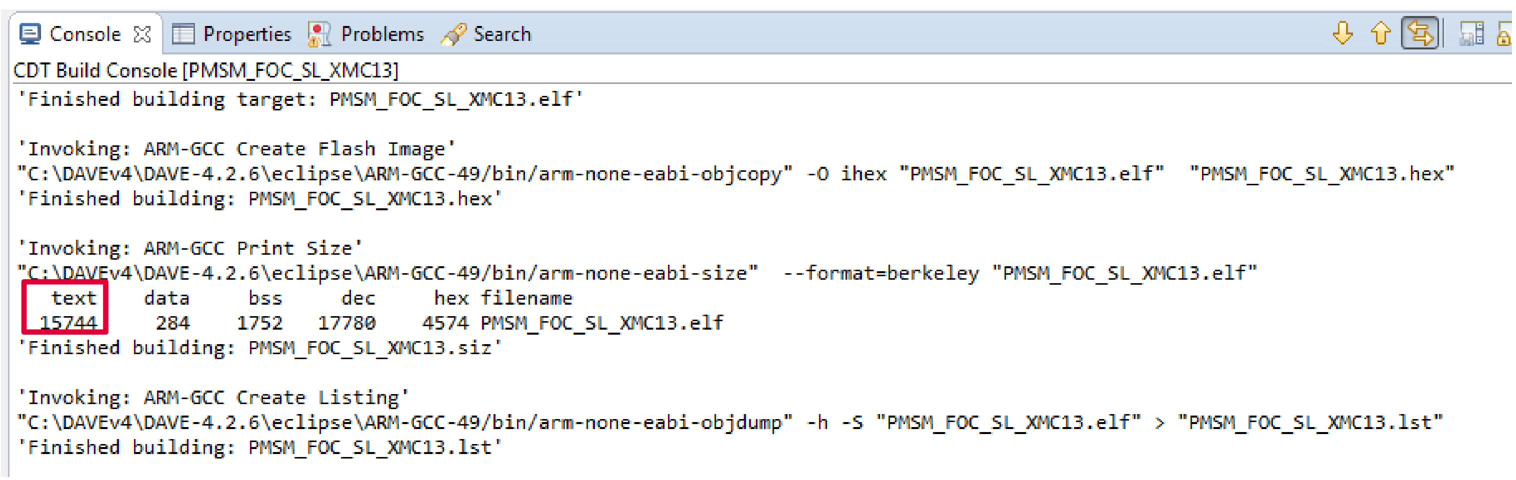


ESC motor control - Get started - build SW in DAVE™ 4

› Click "**Rebuild Active Project**"

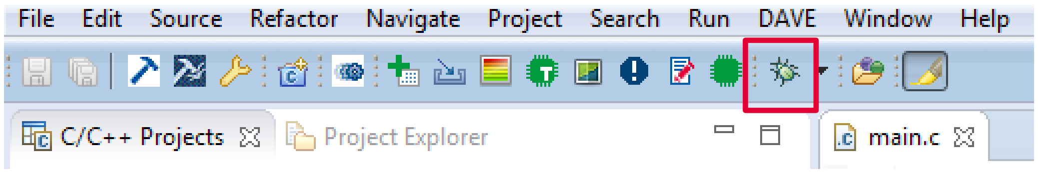


› "**text**" in red box indicates the code size, e.g.: about 15.7 kB

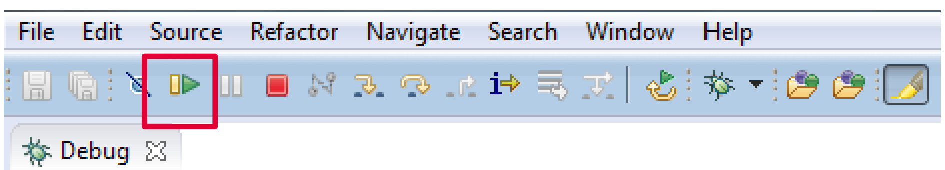


ESC motor control - Get started - download SW in DAVE™ 4

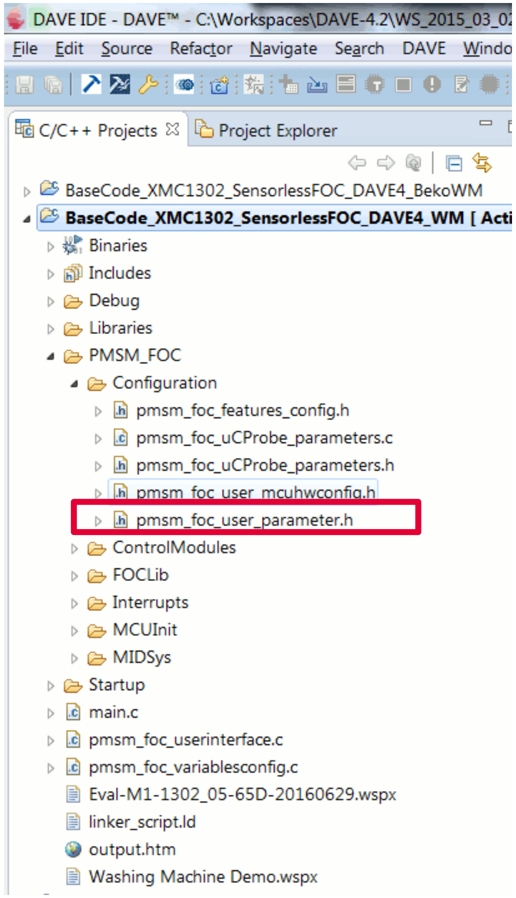
› Click “**Debug Configuration**” to download the code



› Click “**Resume**” to start the motor control application SW



ESC motor control - Get started - SW configuration (1/3)



› The FOC example SW enables the user to change certain parameters in order to fine tune motors

› To access the code within DAVE™ 4:

- Under "**C/C++ Projects**" section, you will find your project (with Active - Debug on it)
- Select **"Project Title" > PMSM_FOC > Configuration > pmsm_foc_user_parameter.h**
- Double click to open the file

› **Note:** Files with **"user"** in it indicates that there are **parameters** that can be changed as per hardware and user requirements

ESC motor control - Get started - SW configuration (2/3)

```c
/*****************************************************************************************************
 * MACROS
 *****************************************************************************************************/
#define  PMSM_FOC_HARDWARE_BOARD                  IFX_XMC_PINUS_V2              /*1. KIT_XMC1X_AK_MOTOR_001
                                                                                  2. KIT_XMC750WATT_MC_AK_V1
                                                                                  3. IFX_XMC_LVPB_R2
                                                                                  4. IFI_EVAL_24V_250W
                                                                                  5. IFX_XMC_LVPB_R3
                                                                                  6. IFX_XMC_PINUS_V2*/
/*       ---------------------------------------------------- Motor Type Selection ---------------------------------------- */
#define  MOTOR_TYPE                               MCI_DRONE_MOTOR                   /*1. MCI_DRONE_MOTOR
                                                                                  2. DJI_DRONE_MOTOR
                                                                                  3. VORNADO_FAN_MOTOR
                                                                                  4. NANOTEC_MOTOR
                                                                                  5. MAXON_MOTOR
                                                                                  6. BEKO_WM_MOTOR
                                                                                  7.EBM_PAPST_VENTI_FAN_MOTOR              */
/*       ---------------------------------------------------- Current feedback Sensing Mechanism ---------------------------------------- */
#define  CURRENT_SENSING                          USER_THREE_SHUNT_SYNC_CONV         /*1. USER_SINGLE_SHUNT_CONV
                                                                                   2. USER_THREE_SHUNT_ASSYNC_CONV
                                                                                   3. USER_THREE_SHUNT_SYNC_CONV*/
/*       ---------------------------------------------------- FOC Control and Startup Scheme (Only select 1 scheme at one time) ------------------------------- */
#define MY_FOC_CONTROL_SCHEME                     CONSTANT_TORQUE_DIRECT_FOC      /*1. CONSTANT_SPEED_VF_ONLY,
                                                                                  2. CONSTANT_SPEED_VF_MET_FOC
                                                                                  3. CONSTANT_SPEED_DIRECT_FOC
                                                                                  4. CONSTANT_TORQUE_DIRECT_FOC
                                                                                  5. CONSTANT_VQ_DIRECT_FOC */
/*       ---------------------------------------------------- FOC Control Safety Protection ---------------------------------------- */
#define VDC_UNDER_OVERVOLTAGE_PROTECTION          ENABLED                      /*1. ENABLED       2. DISABLED*/
#define OVERCURRENT_PROTECTION                    ENABLED                      /*1. ENABLED       2. DISABLED*/

#if(MOTOR_TYPE == MCI_DRONE_MOTOR)
/*       ---------------------------------------------------- Motor Parameters ---------------------------------------- */
#define  USER_MOTOR_R_PER_PHASE_OHM               (0.1f)          /* Motor Resistance per phase in Ohm*/
#define  USER_MOTOR_L_PER_PHASE_uH                (60.0f)         /* Motor Inductance per phase in uH */
#define  USER_MOTOR_POLE_PAIR                     (6.0f)          /* Motor Pole Pairs (change to integer) */
/*       ---------------------------------------------------- Constant Speed Control Mode (Used when Constant Speed Control is enabled) ---------------------------------------- */
/*       ---------------------------------------------------- POT ADC, or PWM to Adjust Speed ---------------------------------------- */
#define USER_SPEED_HIGH_LIMIT_RPM                 (16000U)          /* Max Speed of User Motor*/
#define USER_SPEED_LOW_LIMIT_RPM                  (uint32_t) (USER_SPEED_HIGH_LIMIT_RPM / 30U)
#define USER_SPEED_RAMPUP_RPM_PER_S               (3000U)
#define USER_SPEED_RAMPDOWN_RPM_PER_S             (3000U)
/*       ---------------------------------------------------- V/F Start Up Parameters ---------------------------------------- */
#define USER_STARTUP_SPEED_RPM                    (0U)
#define USER_STARTUP_SPEED_THRESHOLD_RPM          (100U)            /* threshold Speed to transit from Open loop to closed loop
                                                                     * threshold Speed to transit from Open loop to
                                                                     * closed loop
```

#1

#2

#3

- #1: The motor type can be changed according to the motor being used
- #2: The control scheme can also be modified according to user requirements
- #3: The speed of the motor and its ramping can be modified as per the user's requirements

ESC motor control - Get started - SW configuration (3/3)

```
#endif

/*      --------------------------------------------------- Hardware Inverter Parameters ---------------------------------------- */
#if(PMSM_FOC_HARDWARE_BOARD == IFX_XMC_PINUS_V2)
#define INTERNAL_OP_GAIN                        ENABLED             /*1. ENABLED      2. DISABLED (Please configure OP-Gain manually) */   #4
#define USER_VDC_LINK_V                         (12.0f)               /* Hardware Inverter VDC link voltage in V  */
#define USER_DEAD_TIME_US                       (0.75f)               /* deadtime, rise(left) and fall values in us  */
#define USER_CCU8_PWM_FREQ_HZ                   (30000U)            /* CCU8 PWM Switching Frequency in Hz*/
#define USER_BOOTSTRAP_PRECHARGE_TIME_MS        (20U)               /* Initial Bootstrap precharging time in ms */   #5
#define USER_DC_LINK_DIVIDER_RATIO              (float)(0.33f/(0.33f+2.32f))          /* R1/(R2+R1) ratio for DC link MCU ADC */
#define USER_VBEMF_RATIO                        (float)(0.33f/(0.33f+2.32f))          /* R1/(R2+R1) ratio for BEMF Voltage sensing circuit ratio */
#define USER_CURRENT_TRIP_THRESHOLD_A           (1.2f)              /* threshold current for trip detection in Ampere*/
#define USER_TRIP_THRESHOLD_TIME_MS             (100U)              /* threshold time for trip detection in ms */
#define USER_MAX_RETRY_MOTORSTARTUP_TRIP        (3U)               /* Max retry of motor startup if trip  */
/*      --------------------------------------------------- Motor Phase Current Measurement ---------------------------------------- */
#define USER_R_SHUNT_OHM                        (0.05f)             /* Phase shunt resistor in ohm */
#define USER_DC_SHUNT_OHM                       (0.030f)             /* DC link shunt current resistor in ohm */   #6
#define USER_RIN_PHASECURRENT_KOHM              (5.1f)               /* R_IN (of equivalent amplifier) kohm */
#define USER_R_PHASECURRENT_FEEDBACK_KOHM       (39.0f)                /* R_FEEDBACK (of equivalent amplifier) kohm */
#define USER_RIN_DCCURRENT_KOHM                 (10.0f)                /* Rf for dc current sensing */
#define USER_R_DCCURRENT_FEEDBACK_KOHM          (75.0f)                 /* Rin for dc current sensing */
#define USER_MAX_ADC_VDD_V                      (5.0f)                  /* VDD5, maximum voltage at ADC */
#define G_OPAMP_PER_PHASECURRENT                (USER_R_PHASECURRENT_FEEDBACK_KOHM / USER_RIN_PHASECURRENT_KOHM)
#define I_MAX_A                                 ((VAREF_V/(USER_R_SHUNT_OHM * OP_GAIN_FACTOR)) / 2U)          /* For IFX_XMC_LVPB_R3, I_MAX_A = 13.16A */

#if(INTERNAL_OP_GAIN == ENABLED)
#define OP_GAIN_FACTOR                          (6U)                  /* Different HW Board has different OP Gain factor, XMC13 built-in Gain Factor available 1, 3, 6 and 12 only*/
#elif(INTERNAL_OP_GAIN == DISABLED)
#define OP_GAIN_FACTOR                          G_OPAMP_PER_PHASECURRENT
#endif
```

- #4: PINUS inverter is designed to make use of XMC1302 internal OP-Amp Gain for phase current ADC sensing
- #6: CCU8 PWM Peripherals configuration
- #5: Macros to configure based on Inverter HW specs

ESC motor control - Get started - pmsm_foc_user_parameters.h

- XMC™ can use fixed points numbers / integers to represent floating-point quantities of the physical value (e.g. : in SI unit)

- User can defined different level of configurations based on Inverter hardware specs

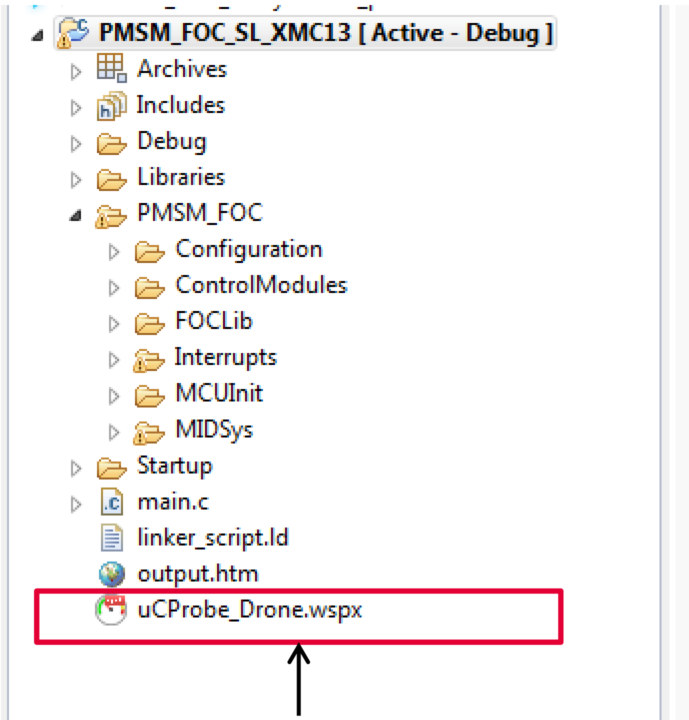
ESC motor control - Get started - pmsm_foc_user_mcuhwconfig.h

- MCU hardware resource management (VADC, CCU8)
- NVIC interrupts service routine resource management
- Debugging IO (DAC functionality)

ESC motor control - Get started - starting µC/Probe™ XMC™

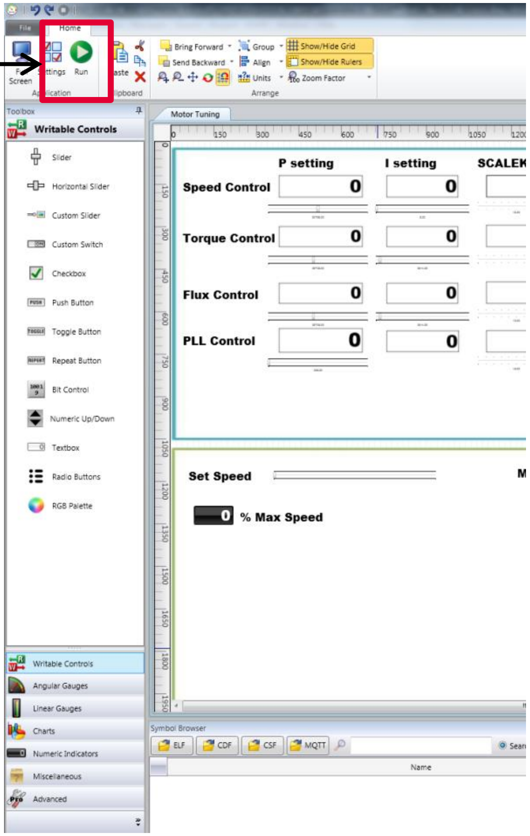
› Double-click "***.wspx**" file in the DAVE™ 4 IDE to start µC/Probe™

› Click "**Run**" to control the speed of the motor using µC/Probe™

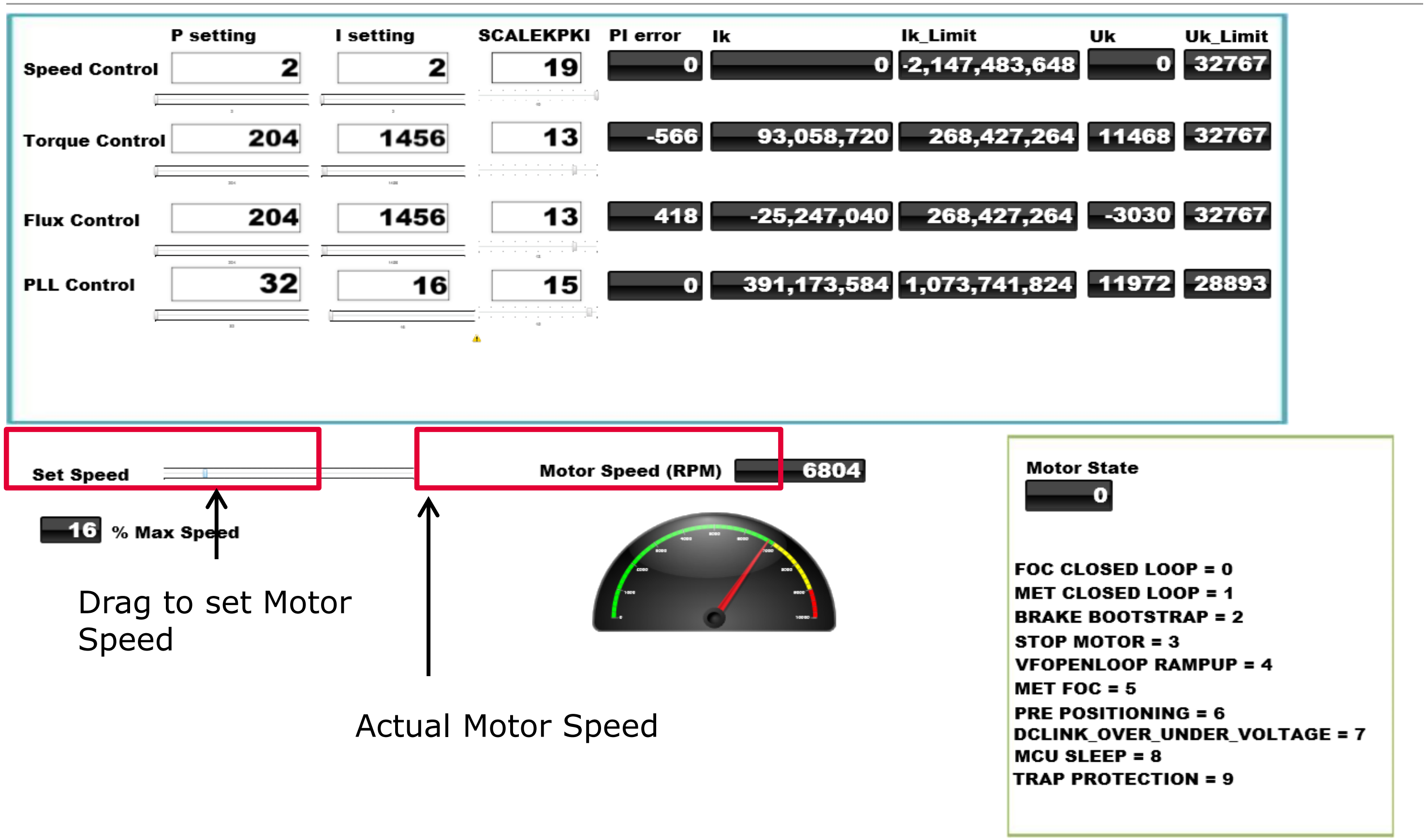


.wspx file

Run



- The motor can be started by adjusting the slider in the “**Set Speed**” box



ESC motor control - Get started - fine-tune Kp/Ki using µC/Probe™

- If the motor does not spin in FOC close loop, ↑ the SCALEKPKI of PLL Control and check the motor behavior. If motor start to move slowly, ↑ the SCALEKPKI further, else, ↓ the SCALEKPKI
- Apply similar tactic for the tuning of Speed Control

$$\text{PI gains: } K_p = \frac{P\ setting}{2^{SCALEKPKI}},\ K_i = \frac{I\ setting}{2^{SCALEKPKI}}$$

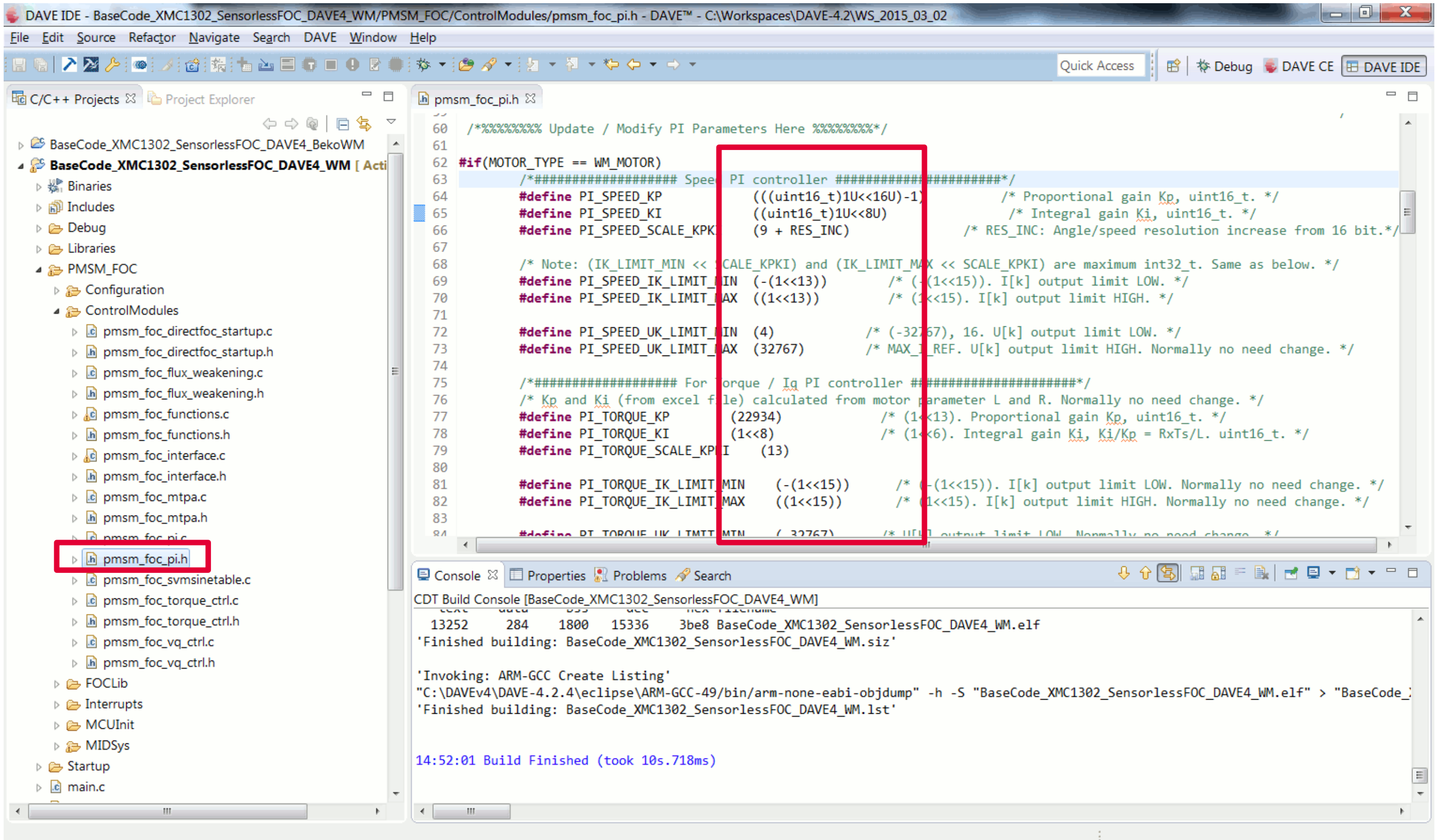
		P setting	I setting	SCALEKPKI
2	Speed Control	65535	256	12
	Torque Control	22934	256	13
	Flux Control	22934	256	13
1	PLL Control	6962	32	14

↑ this value by 1 will ↓ gain of Speed controller by half

↑ this value by 1 will ↓ gain of PLL estimator controller by half

ESC motor control - Get started - pmsm_foc_pi.h

› In DAVE™ 4, user needs to input /save the final optimal PI parameters to **pmsm_foc_pi.h**

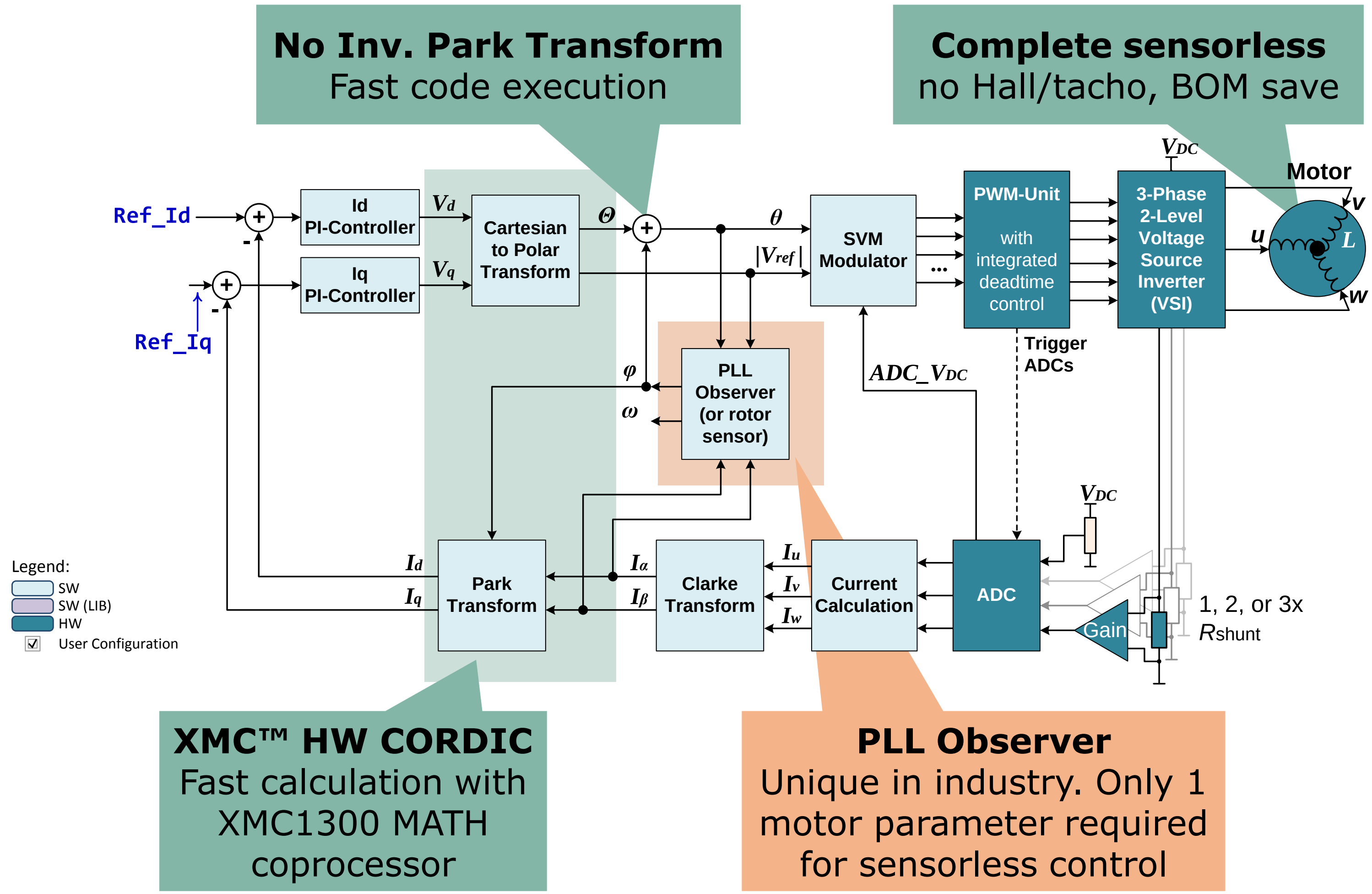


ESC motor control - Key features

1. Sensorless FOC control even at ultra-low speed
2. Robust direct-sensorless-FOC startup
3. Fast execution FOC with XMC™ Cortex M0
4. XMC™ on-chip ADC gain to reduce system BOM cost

1. Key feature - sensorless FOC control even at ultra-low speed

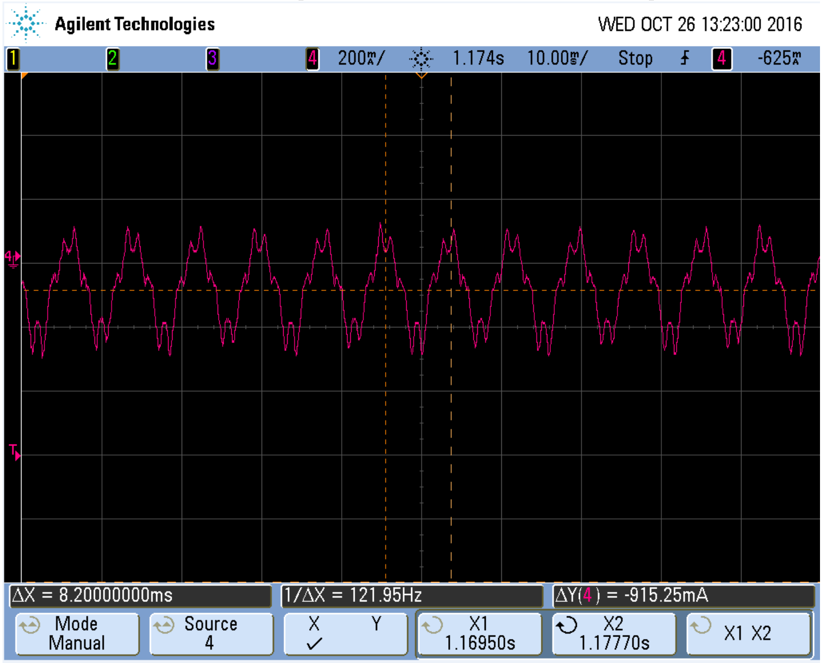
ESC - sensorless FOC - Block diagram

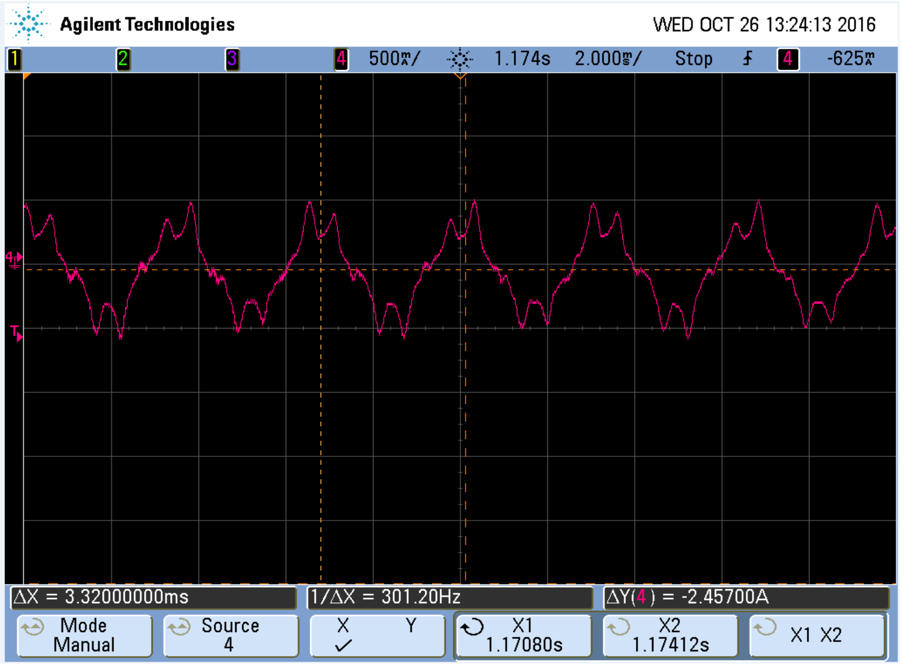


Block diagram: ESC motor control - sensorless FOC

Sensorless FOC control at ultra-low speed - Waveforms

- Ultra-low speed: 1000 rpm   2000 rpm





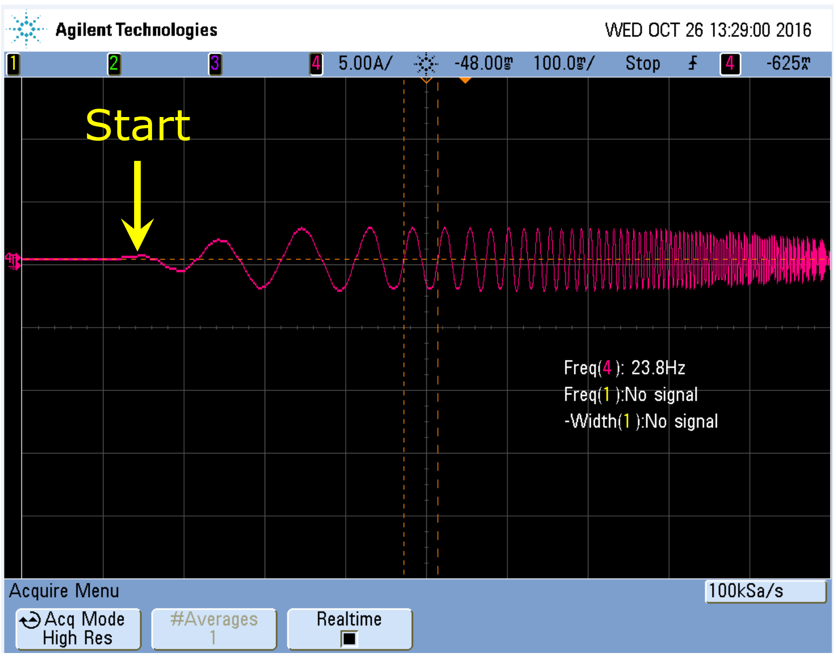
- CH4 (Pink) - phase current Iu, from current probe – with High Resolution Mode enabled

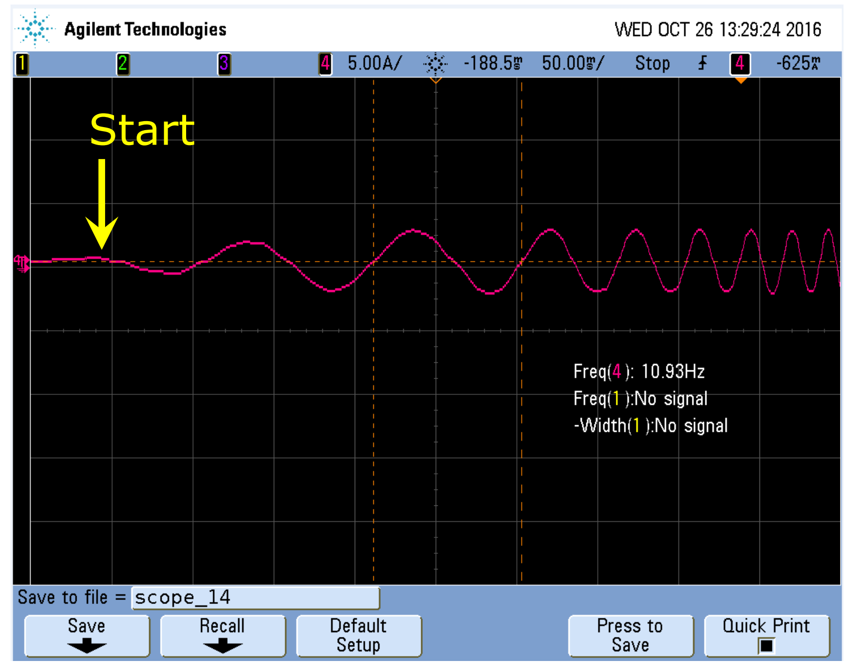
Motor parameter:
L (per phase): 60 *u*H
R (per phase): 0.1 *Ω*
Pole-pair No.: 6

2. Key feature - robust direct-sensorless-FOC startup

Startup with load Waveforms

› From 0 rpm to 10,000 rpm XMC™ sensorless FOC Direct Startup

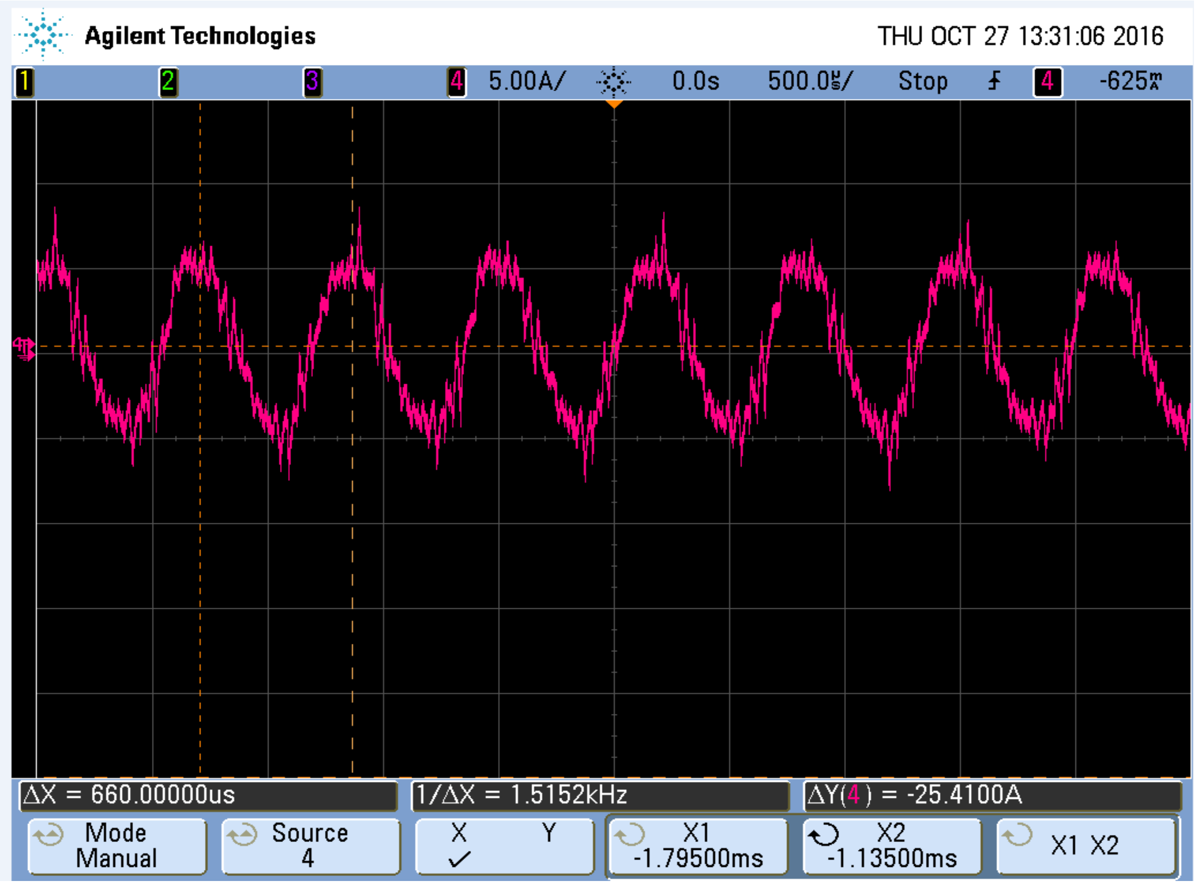




› CH4 (Pink) - phase current Iu, from current probe – with High Resolution Mode enabled

<u>Motor parameter:</u>
L (per phase): 60 *u*H
R (per phase): 0.1 *Ω*
Pole-pair No.: 6

XMC™ sensorless FOC with load
Waveform @ 15000 rpm VDC = 12V, 5A



➤ **Channel 4 (pink): Current of fan motor Phase U (measured by current probe, 0.1V/A)**

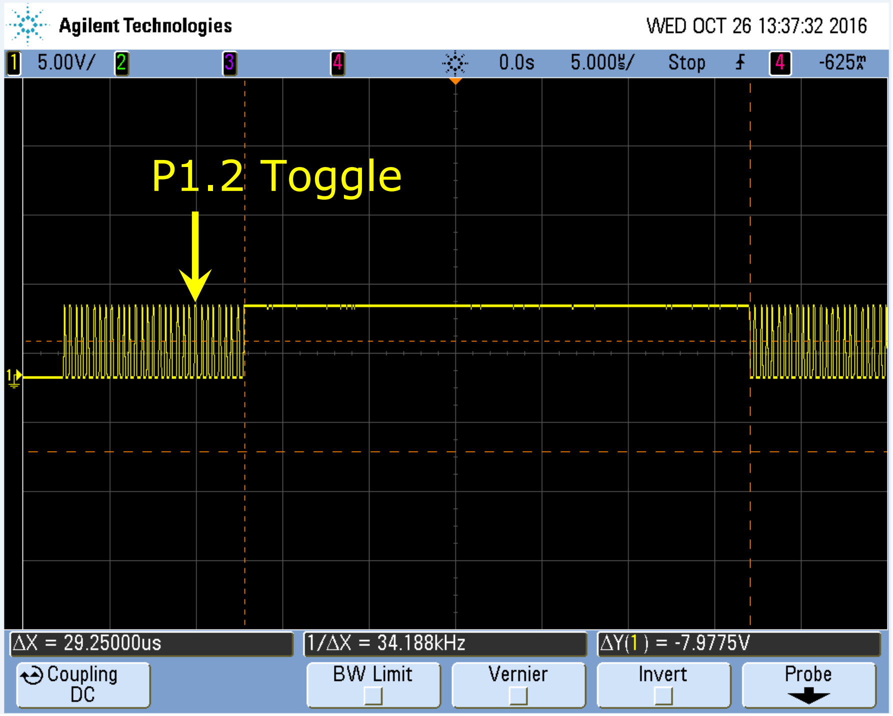
Waveforms: Drone

3. Key feature – Fast Execution FOC with XMC™ Cortex M0

ESC FOC Execution with XMC™ 1302

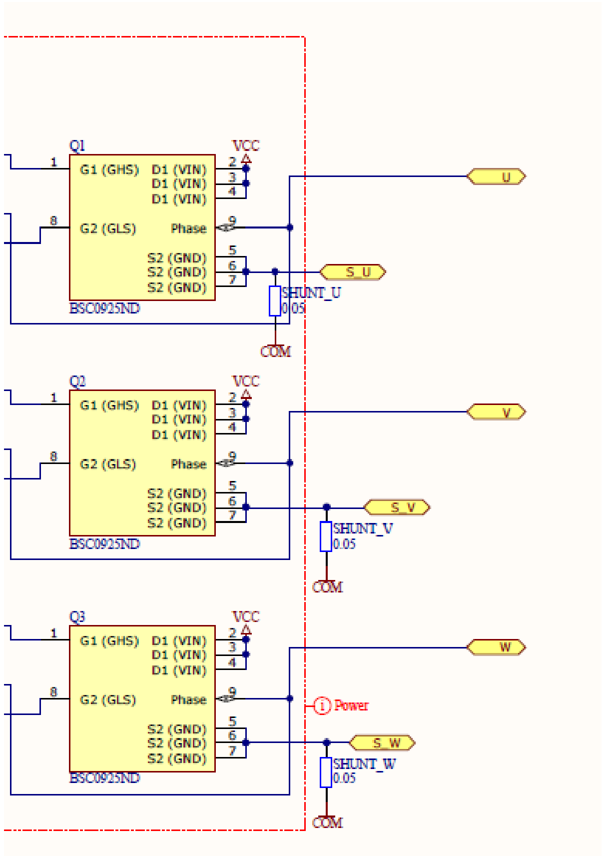
S/N	FOC SW Description	Sensorless FOC Execution Time and CPU Load (CCU8 PWM 25kHz / 40μs) – Code Executed from RAM: Execution Time	Free Time per PWM	CPU Load
1	Latest PMSM_FOC Base Code	29.25 μs	10.75 μs	**75%**

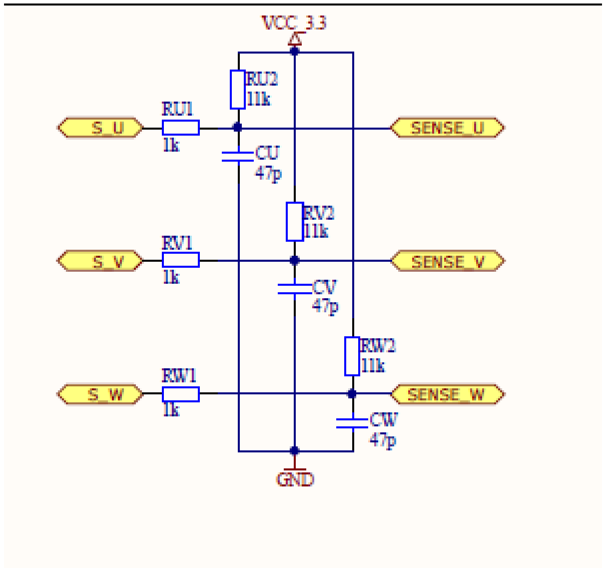
- **The execution time is measured by toggling P1.2 at while loop in main.c**



5. Key feature - XMC™ on-chip ADC gain

ESC motor control - Current sensing schematics



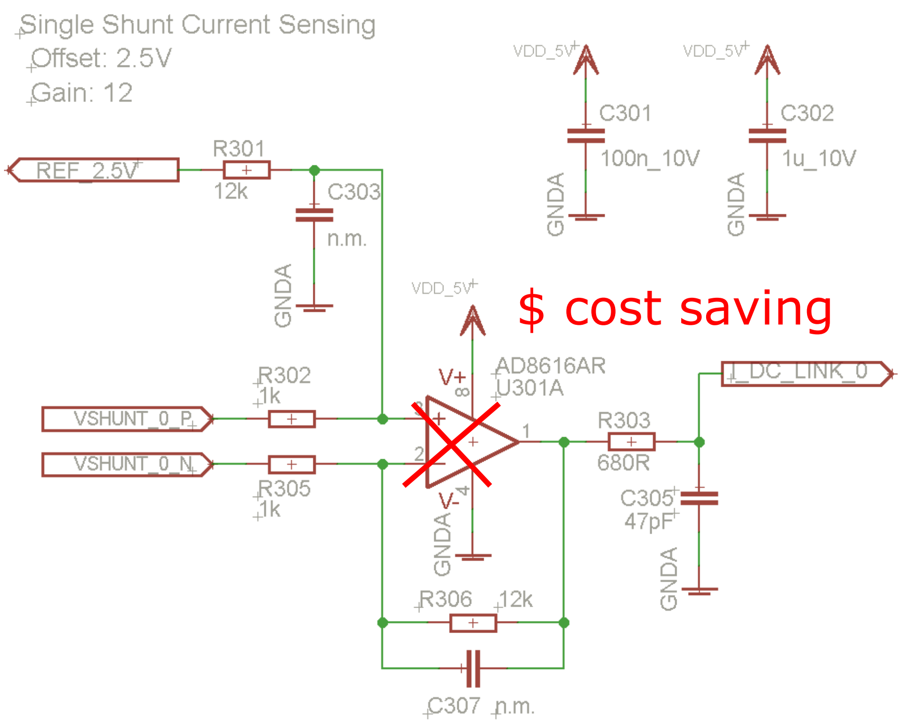


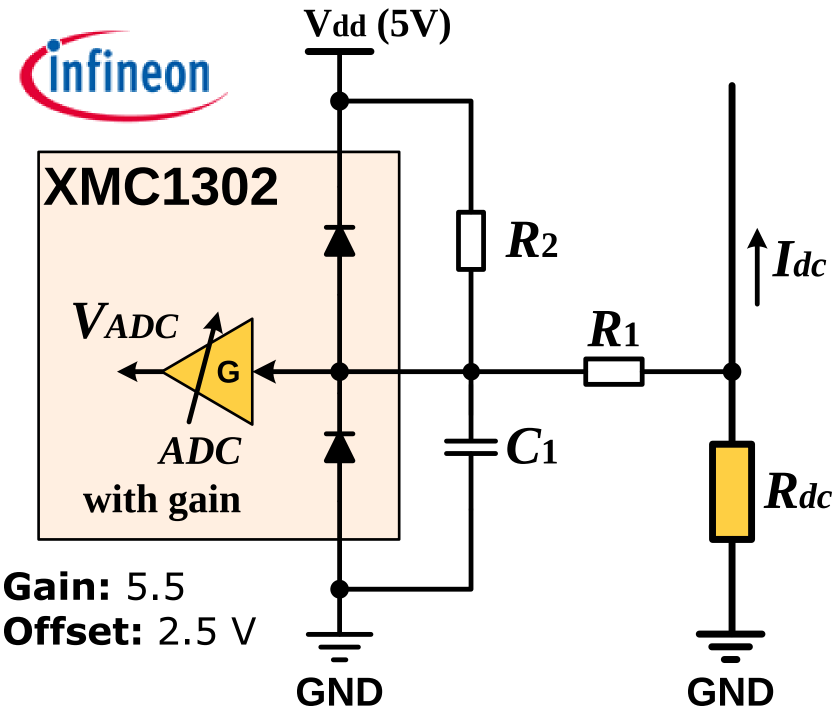
Schematic: ESC motor control - current sensing

ESC motor control - XMC™ on-chip ADC gain for current sensing

- R_1 limits current flow in / out of XMC1302 ADC pin. R_2 offset ADC input
- e.g.: for an application G=6, R_{dc}=0.05 Ω, R_1=1 kΩ, R_2=11 kΩ, C_1=47 pF

$$\boxed{V_{ADC} \approx \frac{GR_1}{R_1+R_2}V_{dd} + \frac{R_2}{R_1+R_2}G \cdot R_{dc} \cdot I_{dc}}$$





Gain: 5.5
Offset: 2.5 V

Resource listing

- ESC motor control
  - Documentation
  - Infineon multicopter solution landing page
  - DAVE™ project

Support material:

Collaterals and Brochures (Document, Info)	– Product Briefs – Selection Guides – Application Brochures – Presentations – Press Releases, Ads	– www.infineon.com/XMC
Technical Material (Tools, Evaluation Board)	– Application Notes – Technical Articles – Simulation Models – Datasheets, MCDS Files – PCB Design Data	– www.infineon.com/XMC – Kits and Boards – DAVE™ – Software and Tool Ecosystem
Videos (Play)	– Technical Videos – Product Information Videos	– Infineon Media Center – XMC Mediathek
Contact (Support)	– Forums – Product Support	– Infineon Forums – Technical Assistance Center (TAC)

Glossary abbreviations (1/2)

AC	Alternating Current
ADC	Analog-to-Digital Converter
BEMF	Back ElectroMotive Force
BOM	Bill Of Material
CPU	Central Processing Unit
DAC	Digital-to-Analog Converter
DAVE™	Digital Application Virtual Engineer
DC	Direct Current
FOC	Field-Oriented Control
GUI	Graphical User Interface
HMI	Human-Machine Interface
HW	Hardware

Glossary abbreviations (2/2)

IDE	Integrated Development Environment
IGBT	Insulated-Gate Bipolar Transistor
MCU	MicroController Unit
PLL	Phase-Locked Loop
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse Width Modulation
RAM	Random-Access Memory
SW	Software
SWD	Serial Wire Debug
UART	Universal Asynchronous Receiver / Transmitter
USIC	Universal Serial Interface Channel
XMC™	Cross-Market Microcontrollers

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