Washing machine motor control solution with XMC™, IGBT, CoolSET™
January 2017
Learning objectives

› To demonstrate sensorless FOC for washing machine PMSM motor control

› Key software functions, a step-by-step implementation, and linking up with µC/Probe™ XMC™

› To use of µC/Probe™ XMC™ to visualise data and fine-tune FOC

› After the learning of this PPT, users will be able to fine-tune XMC1302 FOC example SW for own washing machine motor control
| 1 | Overview                |
| 2 | Key features            |
| 3 | Specification           |
| 4 | System block diagram    |
| 5 | Hardware overview       |
| 6 | Software overview       |
| 7 | Highlight MCU features  |
| 8 | Get started             |
Agenda (2/2)

9 Resource listing
The purpose of the training slides is to elaborate a low-cost and high-performance washing machine motor control solution, using:

- XMC™ 750 watt motor control application kit
- XMC1300 drive card
- DAVE™ 4 example project - PMSM_FOC_SL_XMC13

The HOT examples cover the key features and controls of the washing machine motor control application.
Washing machine motor control - the solution focuses on mainly 2 areas

- Infineon focus areas for washing machine motor control

Motor control
Power management

Focus of this value proposition
Infineon can provide all the critical components for washing machine motor control

### Motor control

**Functionality**
- FOC controller (3-phase PWM generation, motor phase current sensing, bus voltage sensing, over-current & over-voltage protection)

**IFX components**
- **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 (CCUB), general purpose timer (CCU4), serial communication (USIC)

### Power management

**Functionality**
- Power inverter
- Auxiliary power supply

**IFX components**
- **IKD10N60R**: discrete IGBT with anti-parallel diode, 600 V
- **6EDL04106NT**: EiceDRIVER™ gate driver IC
- **3F/2QR CoolSET™ flyback controller family** e.g.: ICE3RBR4765JG
- **IFX1763XEJ3V33**: wide input range low noise LDO
<table>
<thead>
<tr>
<th>Benefits</th>
<th>Addressed customer needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small code size and fast execution</td>
<td>Allows ample CPU time for more tasks</td>
</tr>
<tr>
<td>time</td>
<td>Small code size &lt; 16 kB, and super-fast code execution &lt; 20 μs (for optimized code)</td>
</tr>
<tr>
<td>Robust start-up</td>
<td>Direct-sensorless-FOC startup is robust, smooth and energy efficient at various load</td>
</tr>
<tr>
<td>conditions of washing machine</td>
<td></td>
</tr>
<tr>
<td>Less dependencies more robust</td>
<td>Only need one motor parameter to estimate rotor angle and speed for sensorless FOC</td>
</tr>
<tr>
<td>Ultra-low speed sensorless control</td>
<td>Robust / quieter operation with sensorless FOC drive even at ultra-low speed (e.g.:</td>
</tr>
<tr>
<td></td>
<td>0.8% of max speed)</td>
</tr>
<tr>
<td>BOM savings</td>
<td>€ 0.49-0.9 reduction of system BOM using XMC™ on-chip ADC gain. Complete sensorless</td>
</tr>
<tr>
<td></td>
<td>motor control eliminating Hall sensors / tachometer</td>
</tr>
<tr>
<td>ARM® Cortex®-M0 with MATH coprocessor</td>
<td>Replace costly MCUs (e.g. ARM® Cortex®-M3)</td>
</tr>
<tr>
<td>Embedded security solutions</td>
<td>Protect customer solution from being copied by customer’s competitors</td>
</tr>
<tr>
<td>Product portfolio</td>
<td>Infineon a “one-stop-shop” for motor control applications with complete power</td>
</tr>
<tr>
<td></td>
<td>semiconductor portfolio</td>
</tr>
<tr>
<td>Knowledge of vendor</td>
<td>Dedicate motor control expert team support with multiple connection of expertise for</td>
</tr>
<tr>
<td></td>
<td>local support</td>
</tr>
</tbody>
</table>

Why Infineon?  
Washing machine motor control solution
Washing machine motor control - 
Key features

Target application
› Washing machine motor control

Key features
› **Sensorless FOC control even at ultra-low speed**
› **Robust direct-sensorless-FOC startup**
› **Smooth bi-directional control at low-speed**
› **Flux Weakening (FW) at high speed for spin dry**
› **XMC™ on-chip ADC gain to reduce system BOM cost**
Specifications

› AC input voltage: 230 V\textsubscript{AC}

› Motor mechanical speed
  – Minimum 100 rpm
  – Maximum speed 16,000 rpm at Flux Weakening (FW) for spin dry
  – Motor speed at washing: 600 rpm

› Drum speed: 10 rpm to 1,600 rpm

› Bi-directional control at low-speed (e.g.: 100 rpm)

› No failure at least 500 times for motor startup bi-directionally at various load conditions
Washing machine motor control - System block diagram
Washing machine motor control - Hardware overview

› Kit information

<table>
<thead>
<tr>
<th>No.</th>
<th>Kit name</th>
<th>Kit description</th>
<th>Order number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>KIT_XMC1300_DC_V1</td>
<td>XMC1300 drive card</td>
<td>KIT_XMC1300_DC_V1</td>
</tr>
<tr>
<td>2</td>
<td>KIT_XMC750WATT_MC_AK_V1</td>
<td>XMC™ 750 watt motor control application kit</td>
<td>KIT_XMC750WATT_MC_AK_V1</td>
</tr>
</tbody>
</table>

› Key Infineon components utilized on kit:

<table>
<thead>
<tr>
<th>No.</th>
<th>Infineon components</th>
<th>Order number</th>
<th>Quantity per kit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>XMC™ microcontroller</td>
<td>XMC1302-T038X0200</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>3F/2QR CoolSET™ flyback controller family</td>
<td>e.g.: ICE3RBR4765JG</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>EiceDRIVER™ gate driver IC</td>
<td>6EDL04I06NT</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Discrete IGBT with anti-parallel diode, 600 V</td>
<td>IKD10N60R</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>LDO, wide input range, low noise</td>
<td>IFX1763XEJV33</td>
<td>1</td>
</tr>
</tbody>
</table>
Infineon offers both Quasi Resonant (QR) CoolSET™ and Fixed Frequency CoolSET™ in various packages, below design is an example.
Washing machine motor control - Microcontroller schematics

Schematic: washing machine motor control - microcontroller
Washing machine motor control - High-voltage gate driver schematics

Schematic: washing machine motor control - high-voltage gate driver
Washing machine motor control - 3-phase power inverter schematics

Schematic: washing machine motor control - 3-phase power inverter
Flow chart: washing machine motor control - software overview
Washing machine 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 $\mu$s
  - 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
Washing machine motor control - Get started - HW connections

› Connect washing machine PMSM motor U, V and W phases to Infineon **XMC™ 750 watt motor control application kit**

› Power board 110 V - 230 V / 750 W

› To motor phases U, V and W

› Washing machine PMSM motor

› XMC1300 drive card

› Op-Amp gain changed to x6 (R205, R206, R207, R212, R214, R216 reworked to 2 kΩ)

› 230 V\(_\text{AC}\) / 8 A
Washing machine motor control - Get started - DAVE™ 4

› Download the latest DAVE™ 4 installer package from
  
  DAVE™ (Version 4) - Development Platform for XMC™ Microcontrollers

› Installation requirements

2. RAM - 4 GB or more
3. Remember to install SEGGER J-Link when installing DAVE™ 4 (if not done so)
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
Washing machine 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”
Washing machine 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
Click “Rebuild Active Project”

“text” in red box indicates the code size, e.g.: about 13 kB
Washing machine motor control - Get started - download SW in DAVE™ 4

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

![Debug Configuration](image)

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

![Resume](image)
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.
#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
Washing machine motor control -
Get started - SW configuration (3/3)
XMC™ can use fixed points numbers / integers to represent floating-point quantities of the physical value (e.g. in SI unit).

User can define different levels of configurations (beginner level, intermediate level, advanced level).
Washing machine motor control - Get started - pmsm_foc_user_mcu_hwconfig.h

› MCU hardware resource management (VADC, CCU8)

› NVIC interrupts service routine resource management

› Debugging IO (DAC functionality)
Washing machine 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™
Washing machine motor control -
Get started - start motor using µC/Probe™

› The motor can be started by keying in a number in rpm (e.g.: 600) in the “Set Speed” box
Motor run time / motor stop time in each wash cycle can be modified on-the-fly at µC/Probe™

Default timing configured at `pmsm_foc_user_parameter.h`

```c
#define USER_MOTOR_RUN_TIME_S (5U) /* Motor run time in second*/
#define USER_MOTOR_STOP_TIME_S (3U) /* Stop time in second*/
#define USER_ENABLE_WASHING_CYCLE (1U) /* 1U: Enable washing (wash/stop/wash), 0U: disable*/
```

Total wash cycles undergone successfully is counted by XMC™, and displayed by µC/Probe™

Tick to enable wash cycle. Untick to disable

(To test Flux Weakening, must untick here)

Motor run time in each wash cycle, user can config

Motor stop time in each wash cycle, user can config

Microcontroller timer for run/stop timing, for display only

Total wash cycles have been finished, for display only
Washing machine 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

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

<table>
<thead>
<tr>
<th></th>
<th>P setting</th>
<th>I setting</th>
<th>SCALEKPKI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed Control</td>
<td>65535</td>
<td>256</td>
<td>12</td>
</tr>
<tr>
<td>Torque Control</td>
<td>22934</td>
<td>256</td>
<td>13</td>
</tr>
<tr>
<td>Flux Control</td>
<td>22934</td>
<td>256</td>
<td>13</td>
</tr>
<tr>
<td>PLL Control</td>
<td>6962</td>
<td>32</td>
<td>14</td>
</tr>
</tbody>
</table>

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

↑ this value by 1 will ↓ gain of PLL estimator controller by half
Washing machine 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`
Washing machine motor control -
Key features

1. **Key feature - sensorless FOC control even at ultra-low speed**
2. **Key feature - robust direct-sensorless-FOC startup**
3. **Key feature - smooth bi-directional control at low-speed**
4. **Key feature - Flux Weakening (FW) at high speed for spin dry**
5. **Key feature - XMC™ on-chip ADC gain to reduce system BOM cost**
1. Key feature - sensorless FOC control even at ultra-low speed
Washing machine - sensorless FOC - Block diagram

**No Inv. Park Transform**
Fast code execution

**Complete sensorless**
no Hall/tacho, BOM save

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**XMC™ HW CORDIC**
Fast calculation with XMC1300 MATH coprocessor

**PLL Observer**
Unique in industry. Only 1 motor parameter required for sensorless control

Block diagram: washing machine motor control - sensorless FOC
Sensorless FOC control at ultra-low speed - Waveforms

- Ultra-low speed: 100 rpm
- 200 rpm

- CH4 (Pink) - phase current Iu, from current probe (2 A/div)

Motor parameter:
L (per phase): 14 mH
R (per phase): 2.5 Ω
Pole-pair No.: 4
2. Key feature - robust direct-sensorless-FOC startup
Startup with load @ quilt + 37 kg water - Waveforms

- Competitor solution
- XMC™ sensorless FOC

- CH4 (Pink) - phase current Iu, from current probe (2 A/div)

Motor parameter:
- $L$ (per phase): 14 $mH$
- $R$ (per phase): 2.5 $\Omega$
- Pole-pair No.: 4
Washing machine - sensorless FOC - Robustness of direct-sensorless-FOC startup

› No failure in more than 500 wash cycles for motor startup bidirectionally at various load conditions

<table>
<thead>
<tr>
<th>Run Time</th>
<th>3 sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop Time</td>
<td>2 sec</td>
</tr>
<tr>
<td>Timer</td>
<td>77,940</td>
</tr>
<tr>
<td>Total Cycles</td>
<td>719</td>
</tr>
</tbody>
</table>

No failure for at least 500 cycles

› During the test, one wash cycle is: ... ➔ motor start clockwise ➔ washing ➔ motor stop ➔ motor start anticlockwise ➔ washing ➔ motor stop ➔ ...

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3. Key feature - smooth bi-directional control
Wash cycle @ 600 rpm, quilt + 38 kg water - Waveforms

- Wash cycles
  - Direct-FOC-startup each time
  
  - CH4 (Pink) - phase current Iu, from current probe (2 A/div)

  ![Waveform Image](image-url)

Motor parameter:
- L (per phase): 14 mH
- R (per phase): 2.5 Ω
- Pole-pair No.: 4
Washing @ 600 rpm, quilt + 38 kg water - Waveforms

› 600 rpm (quilt + 38 kg water)  

› CH4 (Pink) - phase current Iu, from current probe (2 A/div)

Motor parameter:
L (per phase): 14 mH  
R (per phase): 2.5 Ω  
Pole-pair No.: 4

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4. Key feature - Flux Weakening (FW)
Safety precautions

› **ATTENTION:** Washing machine motor phase-to-phase BEMF is kilovolts (kV) at high speed (e.g.: \(1.6 \text{kV}_{\text{p-p}} \) @ 12,000 rpm motor mechanical speed)

› Any loss of control at Flux Weakening (FW) range can result in equipment / board / component damage

› Only personnel familiar with the advanced motor control / FW should implement and test FW
Washing machine - Flux Weakening (FW) - Waveforms

- Competitor solution 11,280 rpm
- XMC™ FOC 11,000 rpm

- CH4 (Pink) - phase current Iu, from current probe (2 A/div)

Motor parameter:
- $L$ (per phase): 14 mH
- $R$ (per phase): 2.5 Ω
- Pole-pair No.: 4
5. Key feature - XMC™ on-chip ADC gain
Washing machine motor control - Current sensing schematics

2- and 3-shunts

Single shunt

Schematic: washing machine motor control - current sensing
Washing machine 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 $G=6$, $R_{dc}=0.05 \, \Omega$, $R_1=1 \, k\Omega$, $R_2=11 \, k\Omega$, $C_1=47 \, pF$

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

\[ \text{Gain: } 5.5 \]
\[ \text{Offset: } 2.5 \, V \]
Resource listing

› Washing machine motor control
  - Documentation
  - XMC™ 750 watt motor control application kit
  - DAVE™ project
### Support material:

#### Collaterals and Brochures
- Product Briefs
- Selection Guides
- Application Brochures
- Presentations
- Press Releases, Ads

#### Technical Material
- Application Notes
- Technical Articles
- Simulation Models
- Datasheets, MCDS Files
- PCB Design Data

#### Videos
- Technical Videos
- Product Information Videos

#### Contact
- Forums
- Product Support

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

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