

AN14099

使用MCX A153实现的PMSM无传感器FOC

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应用笔记

文档信息

信息	内容
关键词	AN14099、电机控制、磁场定向控制、PWM、ADC
摘要	本应用笔记介绍了如何在基于恩智浦MCX A153 MCU的FRDM-MCXA153板上实现三相永磁同步电机（PMSM）的无传感器磁场定向控制（FOC）。



1 简介

本应用笔记介绍了如何在FRDM-MCXA153板上实现三相永磁同步电机（PMSM）的无传感器磁场定向控制（FOC）。该板基于恩智浦MCXA153 MCU。

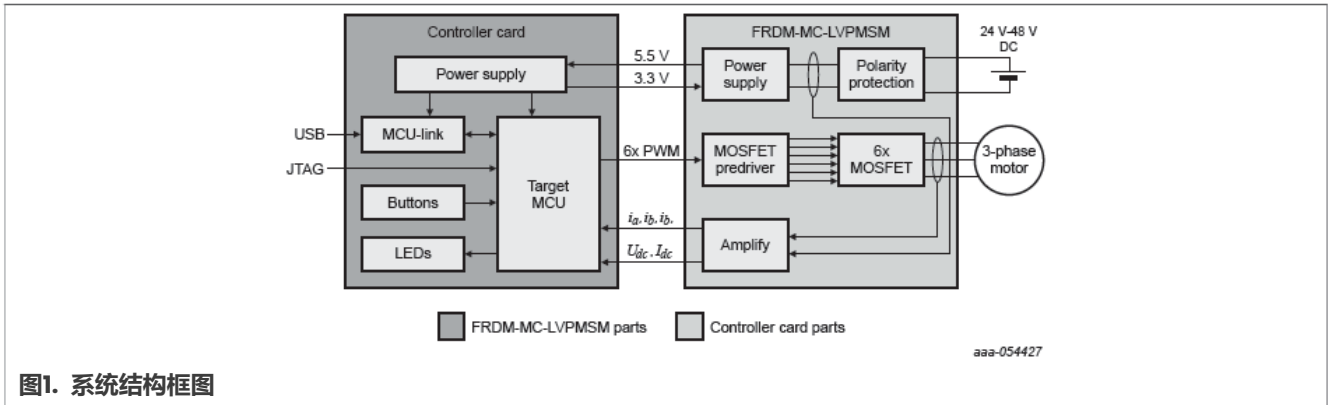
MCXA系列MCU扩展了MCX Arm Cortex-M33产品系列，提供了多个高速连接，运行频率高达96MHz；并提供高性能的PWM发生器，具有高达192MHz的时钟源、串行外设、定时器、4Msps的12位SAR ADC以及其他模拟外设和低功耗。

恩智浦Freedom板FRDM-MC-LVPMSM用作PMSM控制参考解决方案的硬件平台。此外，本文还解决了电机控制软件的硬件相关部分，包括详细的外设设置和驱动程序描述。本文还介绍了电机参数识别的理论和算法。

本文最后一部分介绍了用户界面，即基于FreeMASTER运行时调试工具的电机控制应用优化（MCAT）页面。这些工具为电机参数识别、算法调优、软件控制、调试和诊断提供了简单易用的方法。

2 开发平台

本节介绍了演示的开发硬件套件的具体情况。图1显示了该PMSM控制演示的系统结构和连接图。



FRDM-MC-LVPMSM低压三相PMSM Freedom开发板平台为设计应用添加了电机控制功能。FRDM-MC-LVPMSM开发平台的电源输入电压为24VDC至48VDC，具有反极性保护电路。为FRDM MCU板提供5.5VDC的辅助电源。输出电流高达5A RMS。该逆变器由三相MOSFET桥和三相MOSFET栅极驱动器组成。模拟量（如三相电机电流、直流母线电压和直流母线电流）在这个板上采样。还有一个速度和位置传感器（编码器、霍尔传感器）接口。

3 MCU的功能和外设设置

本节列出了以下MCU的功能和外设设置：

- MCX A142/143/152/153系列MCU是MCX Arm Cortex-M33产品系列的新成员，提供多种高速连接，运行频率高达96MHz（MCX A143运行频率高达48MHz）、串行外设、定时器、模拟和低功耗。

- MCX A153提供3个32位标准通用异步定时器/计数器。一个eFlexPWM包含三个子模块；每个子模块支持一对互补输出或两个独立输出，以及一个正交解码器实体。
- MCX A153有一个LPI2C、三个LPUART和两个LPSPI。
- MCX A153有一个I3C通信接口和一个USB FS设备，配备16个使用共享RAM的单向端点。
- MCX A153有一个可在12位模式下工作的ADC，采样速率为4Msps，有两个模拟比较器。

3.1 FRDM-MCXA153板

恩智浦设计的FRDM-MCXA153板包含MCX A153 MCU和外设接口。eFlexPWM、ADC和CMP是片上外设，分别用于电机控制、模拟采集和保护。

MCX A153上运行的应用软件包括：

- 基于PMSM BEMF观测器的FOC算法
- 实时控制嵌入式软件电机控制和功率转换库（RTCESL、CM33NODSP 4.7.1 for MCUXpresso）
- SDK 2.14.0

3.2 硬件时序和同步

采样时序对电机控制应用至关重要。因此，电机控制专用外设负责硬件层的时序和同步。此外，我们还可以将PWM频率设置为计算FOC算法的ADC中断（ADC ISR）频率的倍数。在本应用中，PWM频率等于FOC频率。

时序图如图2所示：

- 最上面的信号显示了eFlexPWM计数器（SM0计数器）。死区时间插入到PWM顶部和底部的上升沿。SM0子模块在每个PWM周期生成主循环的重新加载。
- SM0在PWM周期开始和中期通过比较值匹配事件生成触发信号。它还触发ADC通过INPUTMUX分别采样相电流（TRIG0）和直流母线电流/电压（TRIG1）。
- 相电流转换完成后，进入ADC ISR（ADC中断）。FOC计算在此中断中完成。

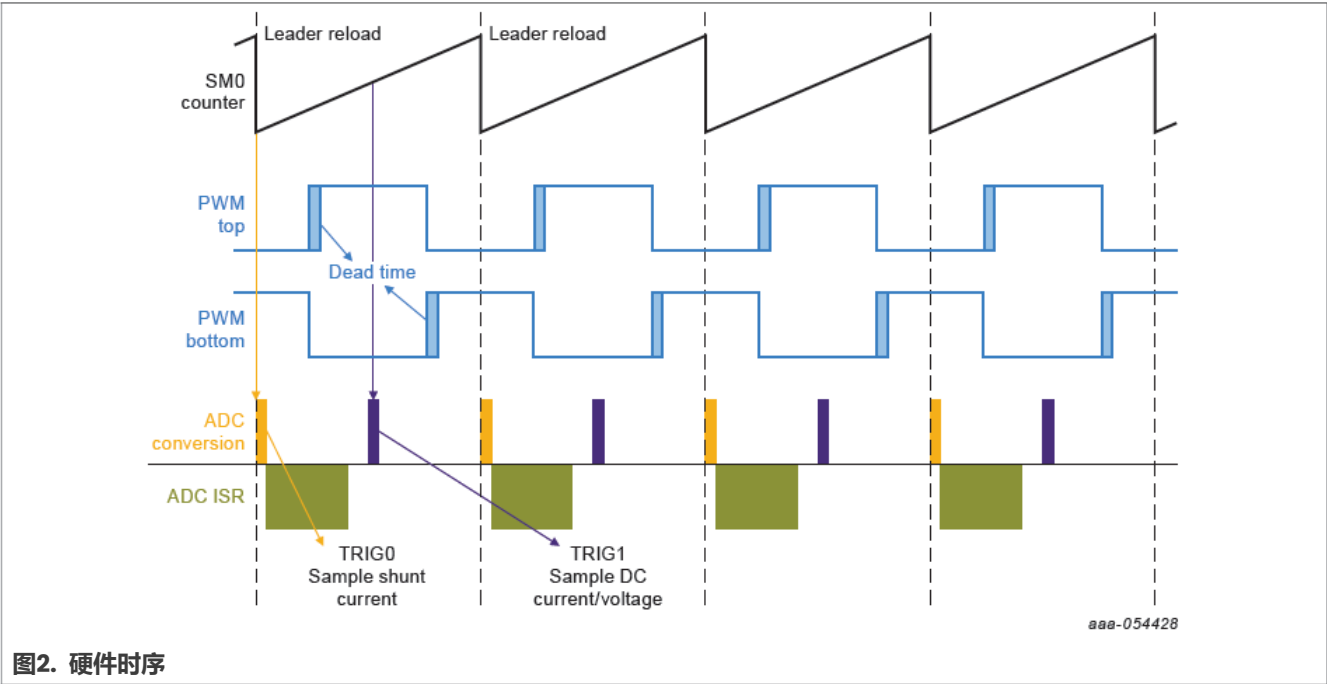


图2. 硬件时序

3.3 外设配置

本节介绍MCX A153上用于电机控制的外设。增强型eFlexPWM有三个子模块用于生成6通道PWM，一个12位ADC用于测量相电流和直流母线电压。eFlexPWM和ADC通过eFlexPWM的子模块0进行同步。

3.3.1 系统时钟生成器

系统时钟生成器（SCG）生成并控制本设计中各个模块的时钟。此模块使用可用的时钟源来生成时钟根。

电机控制应用中使用的时钟源是快速内部基准时钟（FIRC），其启动频率最高可达192MHz。Arm内核的最高时钟速度为96MHz，而eFlexPWM工作时钟频率最高可达192MHz。因此，首先必须将FIRC提升到相对较低的频率。然后，在设置了能让Arm内核正常工作的合适的分频因子后，再将其提升到192MHz，如图3所示。还要设置其他外设时钟源的分频因子。

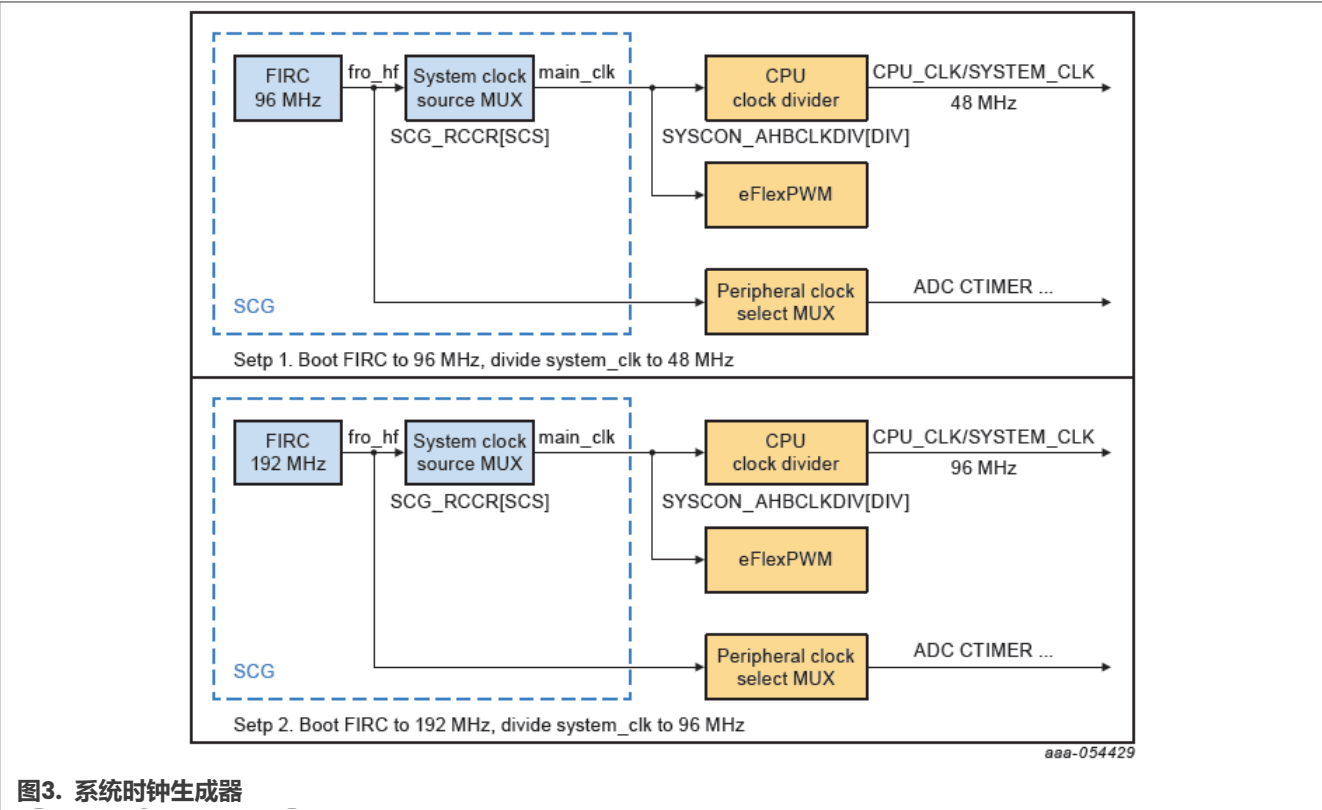


表1列出了电机控制所用的外设的时钟源。

表1. MCXA153电机控制外设时钟源

MCU上的模块	时钟源	分频
Arm核	FIRC	96 MHz
eFlexPWM	FIRC	192 MHz
ADC	FIRC	48 MHz
CTIMER	FIRC	96 MHz
LPUART	SIRC	12 MHz

3.3.2 PWM生成——eFlexPWM0

eFlexPWM由192MHz系统时钟提供时钟。三个子模块的六个通道用于生成三相PWM。

- 子模块0在每个PWM周期中生成主循环的重载。
- 子模块1和2从子模块0获取时钟。
- 子模块1和2的计数器与子模块0的主循环重载信号同步。
- 子模块0用于在PWM周期的开始和中间触发ADC：
 - 当计数器计数到VAL4时，子模块在PWM重新加载后生成TRIGO输出。
 - 当计数器计数到VAL5时，子模块在一个PWM周期的中间生成TRIGI输出。
- 子模块0、1和2的通道A和B启用故障模式，并自动清除故障。故障输入归零后，在第一次重新加载PWM时重新启用PWM输出。

- PWM周期（频率）取决于计数器从INIT计数到VALI所需的时间。默认情况下， $INIT = -MODULO/2 = -9600$ 和 $VALI = MODULO/2 - 1 = 9599$ 。eFlexPWM时钟为192MHz，因此所需时间为0.0001秒（10kHz）。
- 启用死区时间插入功能。死区时间长度由用户在MI_PWM_DEADTIME宏中定义。

3.3.3 外设触发控制——INPUTMUX

INPUTMUX用于将PWM触发器互连到ADC触发器输入。

INPUTMUX的结构框图如图4所示：

- PWM0_SMO_OUT_TRIG0输出触发器连接到ADC_TRIG0。
- PWM0_SMO_OUT_TRIG1输出触发器连接到ADC_TRIG1。

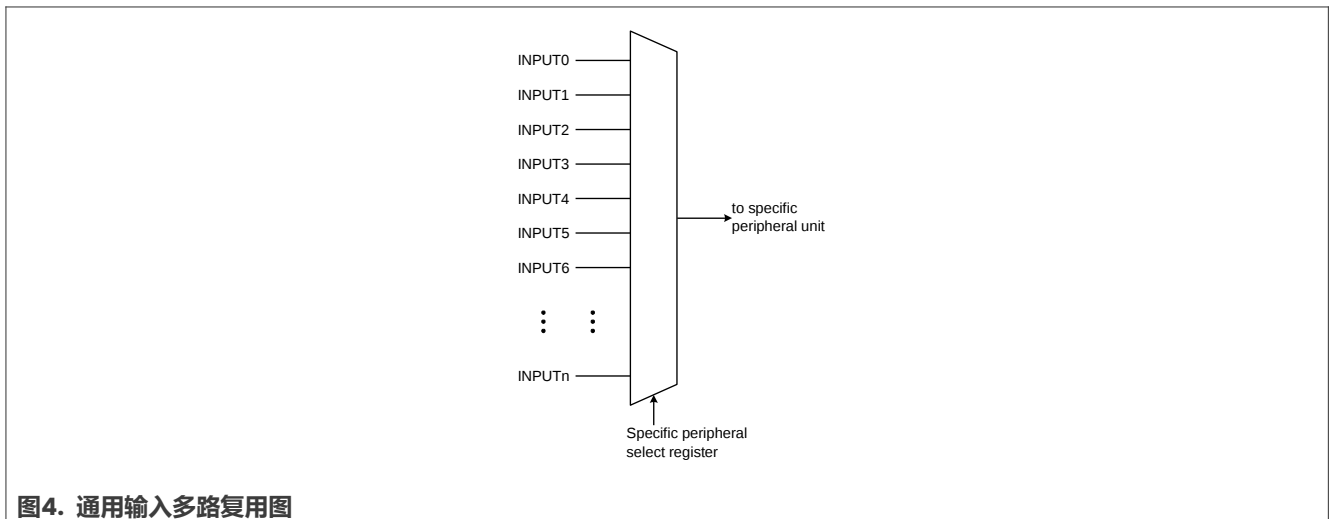


图4. 通用输入多路复用图

3.3.4 模拟感测——ADC0

ADC0用于电机控制模拟感测，包括相电流和直流母线电压的感测：

- ADC0的时钟频率为48MHz。它来自系统时钟并除以4。
- ADC采用单端转换和硬件触发，以12位模式运行。INPUTMUX通过eFlexPWM生成的触发信号触发ADC。
- 开启相电流转换完成中断，并为FOC快速环路算法提供服务程序。

3.3.5 慢环中断的生成——CTIMER0

CTIMER0用于生成慢环中断：

- CTIMER0的时钟由系统时钟除以2提供，因此CTIMER0的时钟频率为96MHz。
- 慢环通常比快环慢十倍。速度环路频率在MI_SPEED_LOOP_FREQ宏中设置，等于1000Hz。
- 将匹配值寄存器设置为96000。当计数器的值等于匹配3时，计数器初始化为0并生成中断请求。

3.3.6 FreeMASTER通信——LPUART0

LPUART0（低功耗通用异步接收器和发送器）用于MCU板和PC之间的FreeMASTER通信。

- 波特率设置为115,200bit/s。
- 接收器和发射器均已启用。
- 其他设置为默认值。

4 演示操作

本节演示电机控制演示的操作。

4.1 电机参数

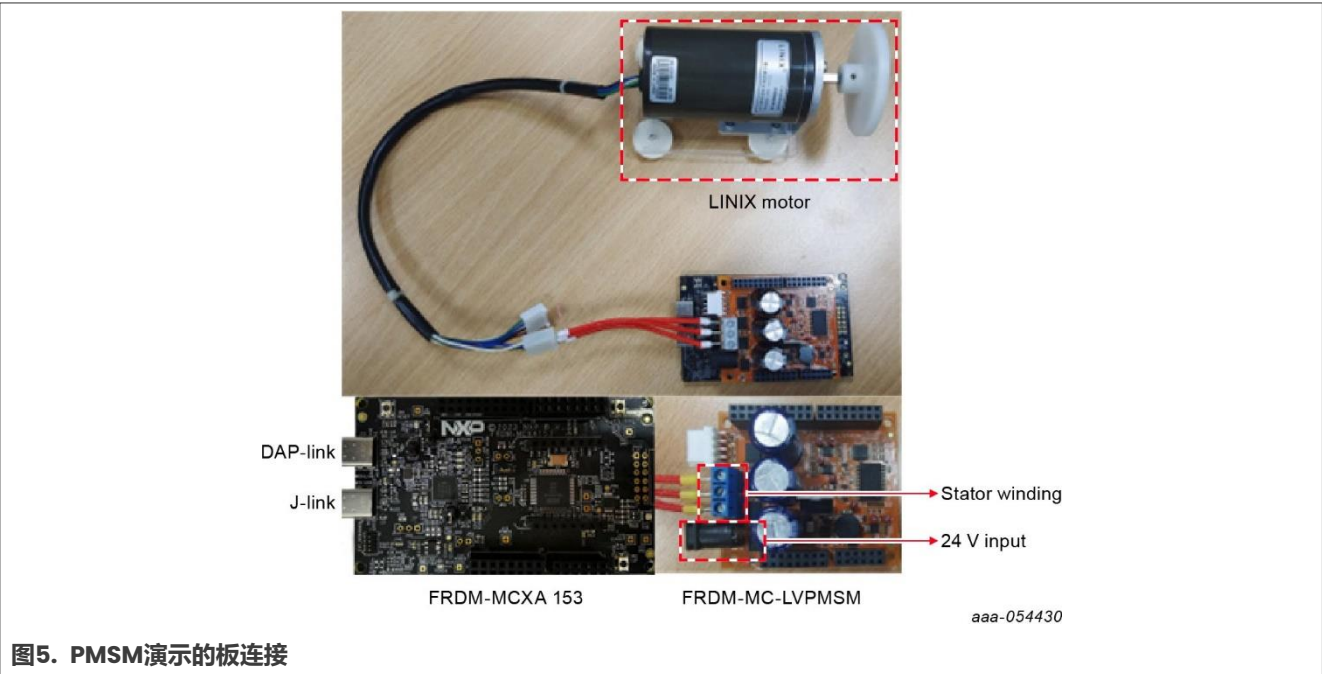
工程中的源文件(*.c)和头文件(*.h)的总数较多。因此，仅表2中重点提供了电机参数。

表2. PMSM参数

参数	数量	参数	数量
制造商	LINIX	定子电阻/ Ω	1.08
型号	45ZWN24-40	定子绕组电感d轴/ μH	426
额定转速/rpm	4000	定子绕组电感q轴/ μH	460
额定线电压/V	24	磁极对	2
额定功率/W	40	反电动势常数/ V.s.rad^{-1}	0.01456

4.2 电路板连接

图5显示了本演示的电路板连接。



硬件要求如下：

- FRDM-MCXA153板
- FRDM-MC-LVPMSM板

- LINUX电机
- USB-Type C电缆

要设置演示，请执行以下步骤：

1. 通过Arduino接口将FRDM-MCXA153和FRDM-MC-LVPMSM板连接在一起，并连接电机线，如图5所示。
2. 使用24V适配器（大于50W）为FRDM-MC-LVPMSM板供电。
3. 通过MCU-Link接口连接FRDM-MCXA153和PC，并采用USB-Type C电缆供电。
4. 打开版本不低于11.8的MCUXpresso集成开发环境，选择**File > Import**（Git代码库：<https://github.com/nxp-appcodehub/an-pmsm-foc-mcxa153>），如图6所示。

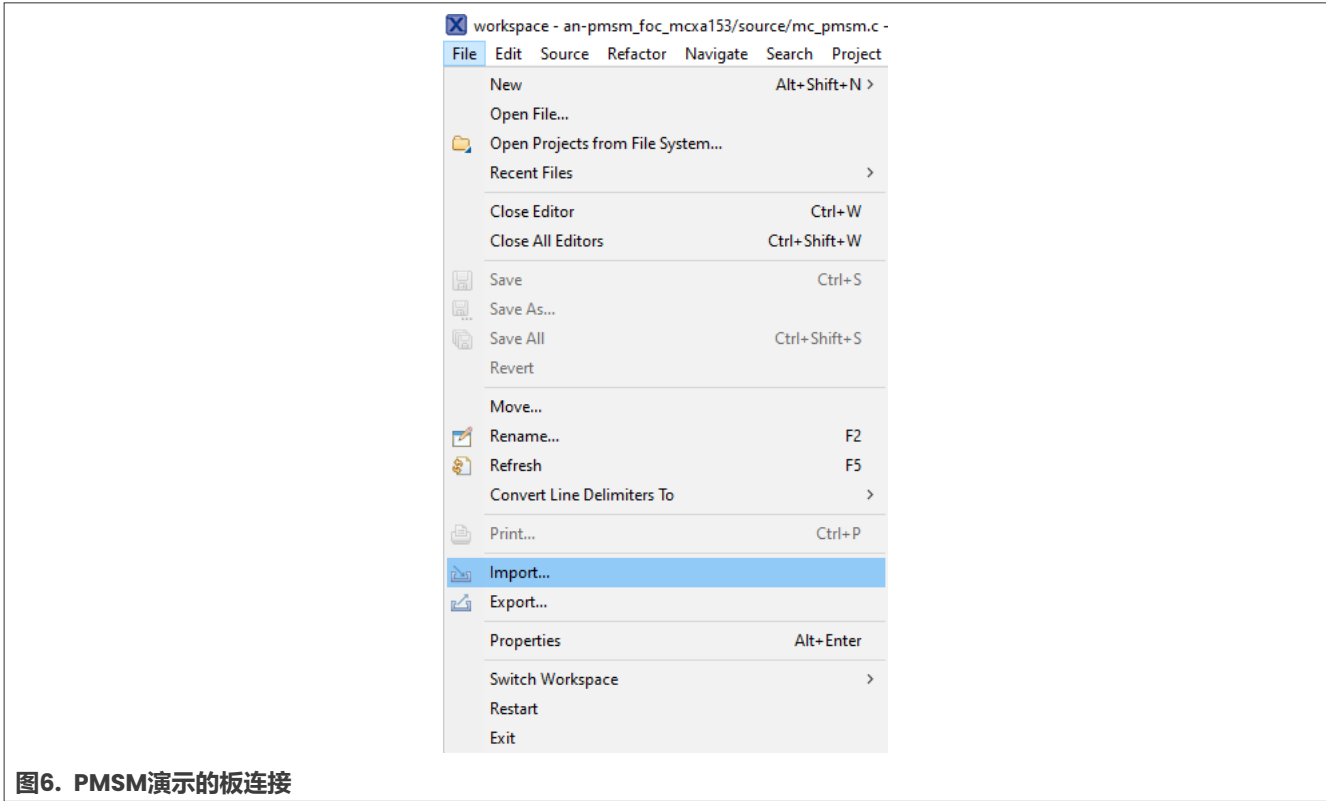


图6. PMSM演示的板连接

5. 选择**General > Existing Projects into Workspace**，如图7所示。

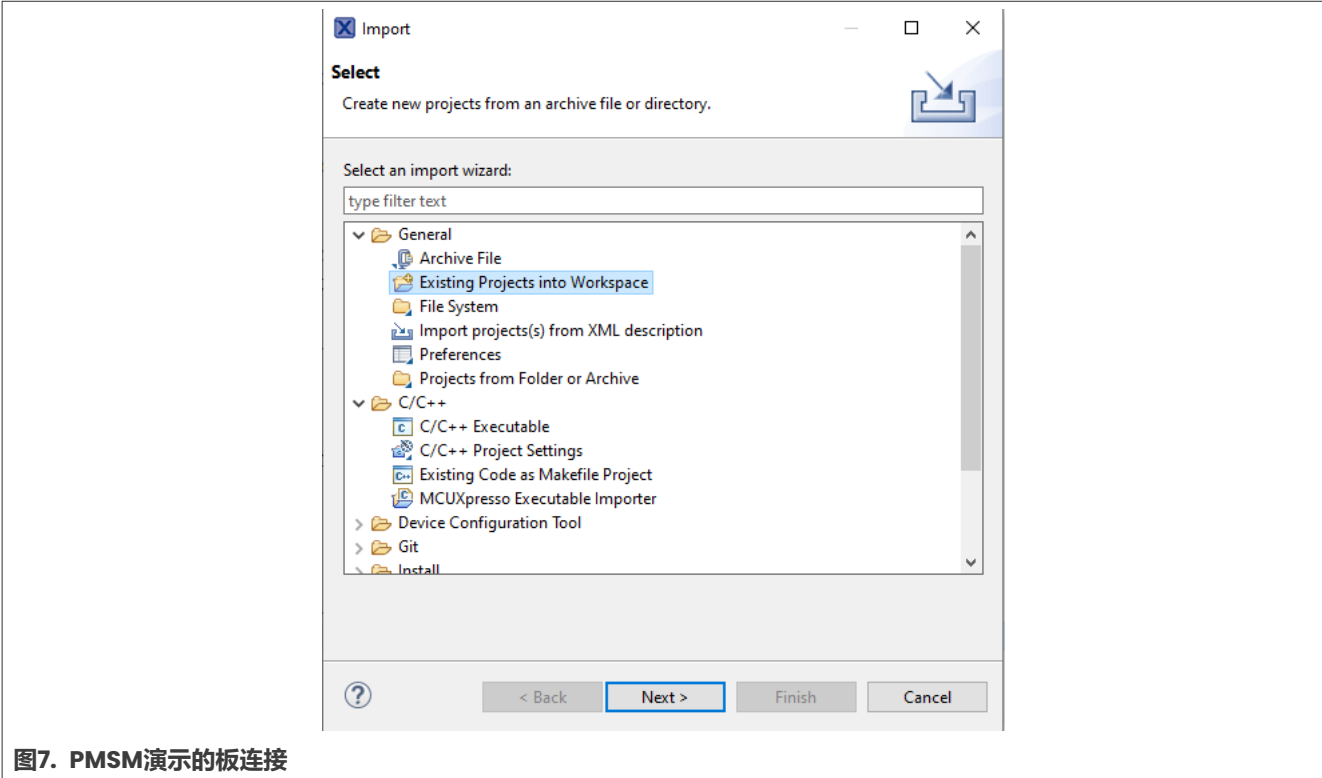


图7. PMSM演示的板连接

6. 单击**Browse**，选择已下载软件压缩包的本地路径，如图8所示。

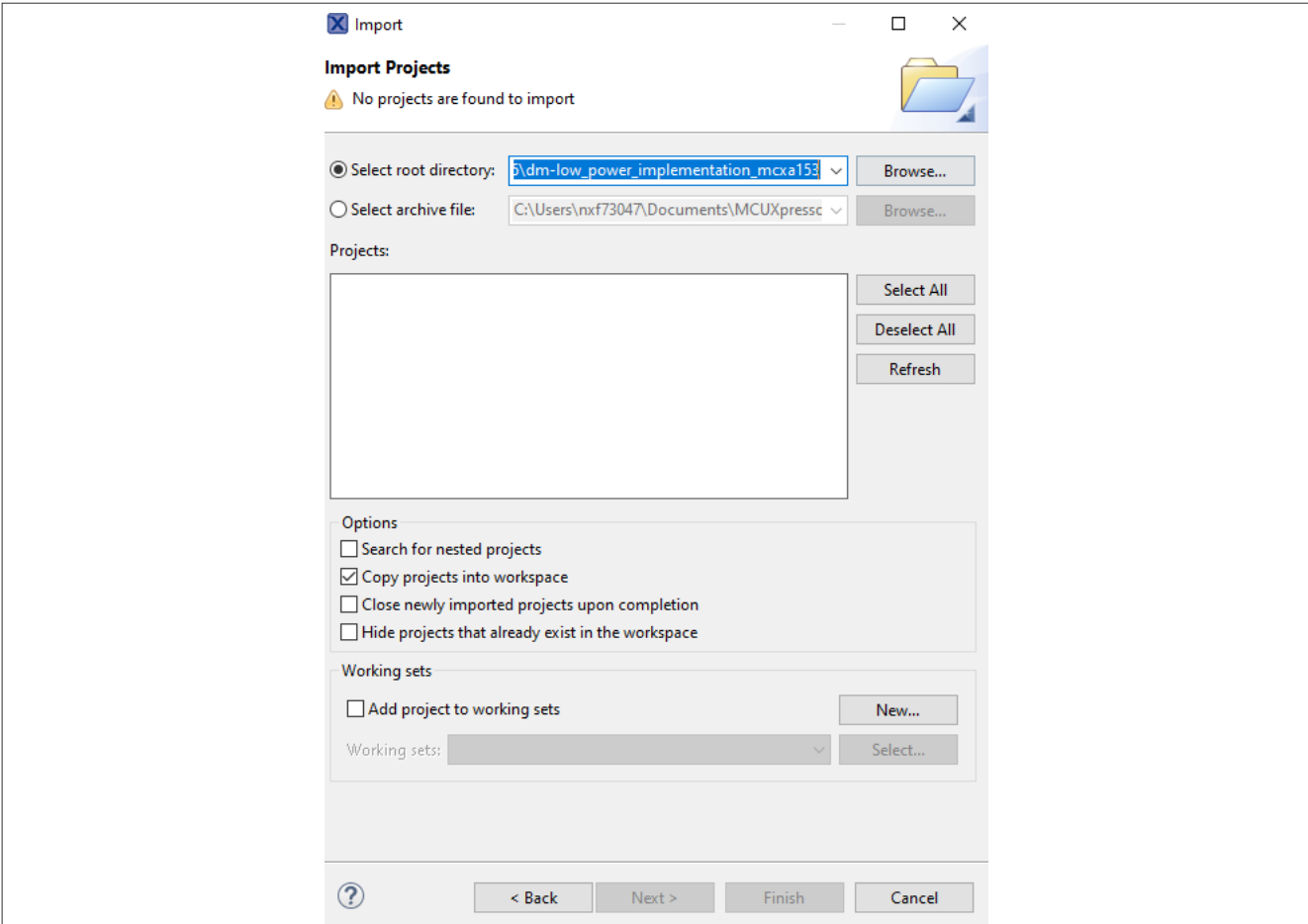


图8. PMSM演示的板连接

- 7. 编译工程，并将程序下载到MCU。
- 8. 要控制电机运行或停止，请按FRDM板上的SW3或使用代码包中的FreeMASTER工程pmsm_frac.pmpx。
- 9. 更改转子速度并观察速度或其他值。

4.3 FreeMASTER操作

为了完全控制和轻松调整无传感器FOC应用，可以使用FreeMASTER。本节将更详细地介绍FreeMASTER中演示的不同控制模式的操作。

4.3.1 标量控制

标量控制图如图9所示。这是最简单的电机控制技术。定子电压幅值和频率之间的比率必须保持在额定比率。因此，这种控制方法有时被称为每赫兹电压或V/Hz。即使不直接使用估计的位置信息，位置估计BEMF观测器和跟踪观测器算法也会在后台运行。

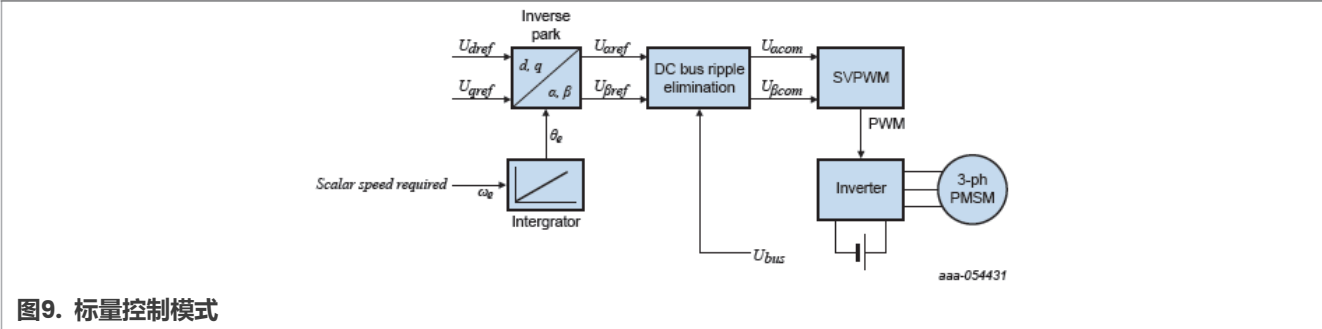


图9. 标量控制模式

选择FreeMASTER工程的**Scalar Control**子块，并在Variable Watch窗口中选择 “SCALAR_CONTROL[0]” 模式。

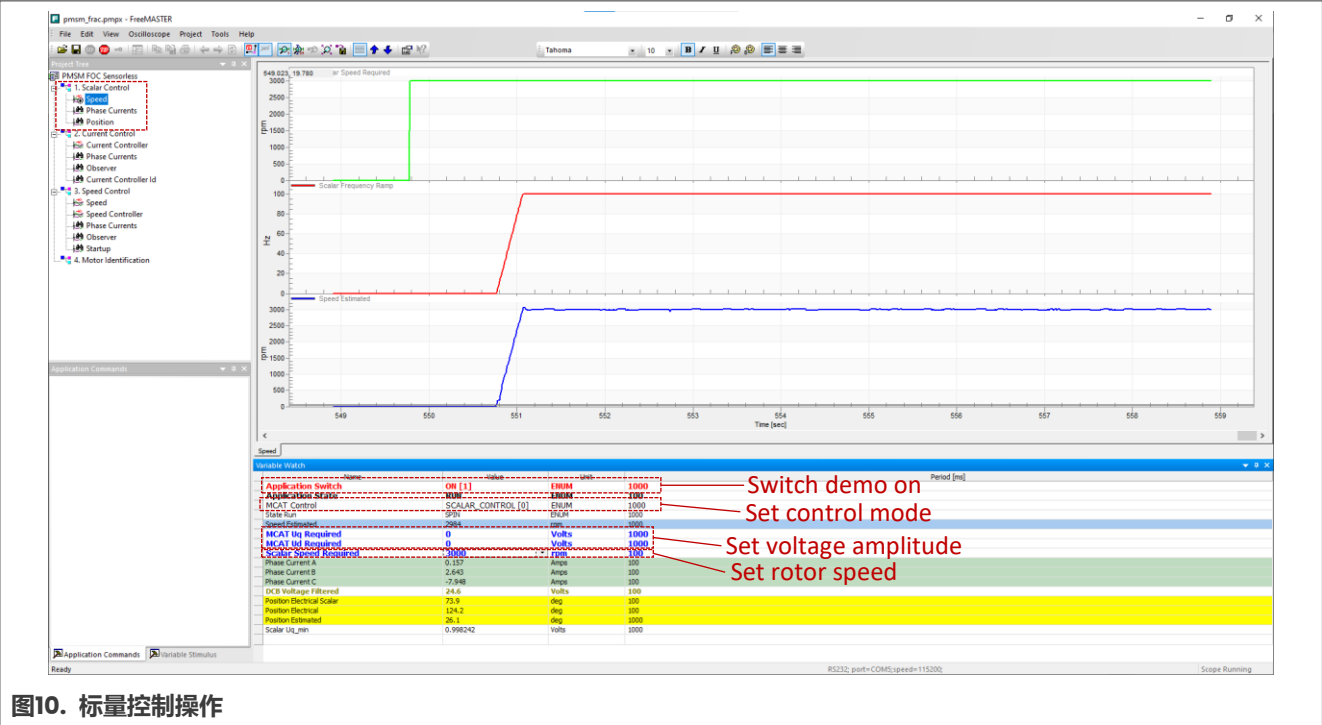


图10. 标量控制操作

4.3.2 电流控制

FOC电流控制需要转子位置反馈并将电流转换到d-q坐标系。电机控制有两个参考变量 i_{d_req} 和 i_{q_req} ，如图11所示。 i_{d_req} 负责转子磁场控制。电流的q轴分量 i_{q_req} 产生扭矩，通过施加扭矩，电机开始运行。通过改变电流 i_{q_req} 的极性，电机改变旋转方向。假设反电动势观测器调整正确，则可以使用FOC电流控制结构来调整PI电流控制器。

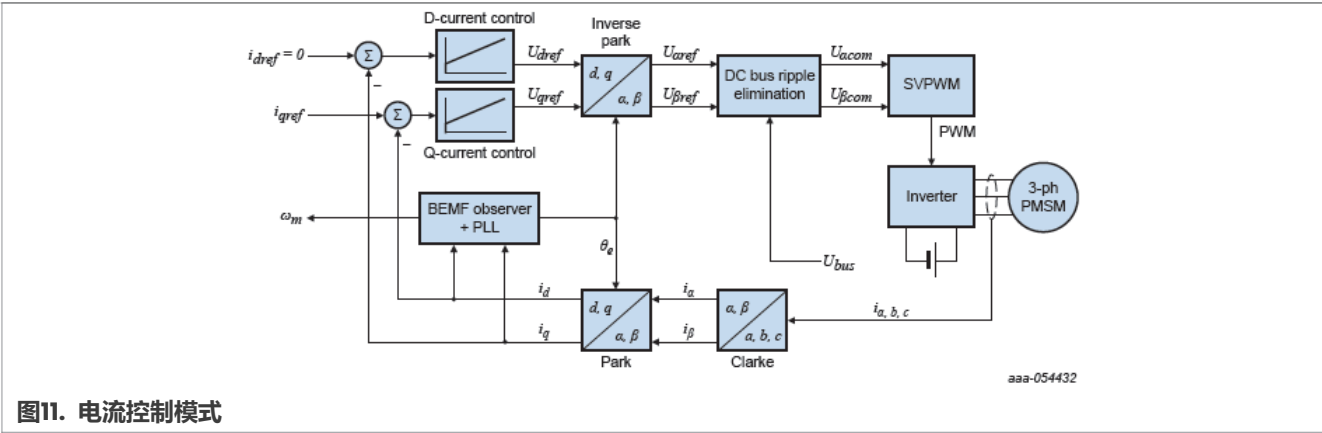


图11. 电流控制模式



图12. 电流控制操作

4.3.3 速度控制

通过启用FOC速度控制结构来激活速度PMSM传感器/无传感器FOC。在“speed_req”字段中输入所需的速度。在整个FOC操作期间，d轴基准电流保持为0。

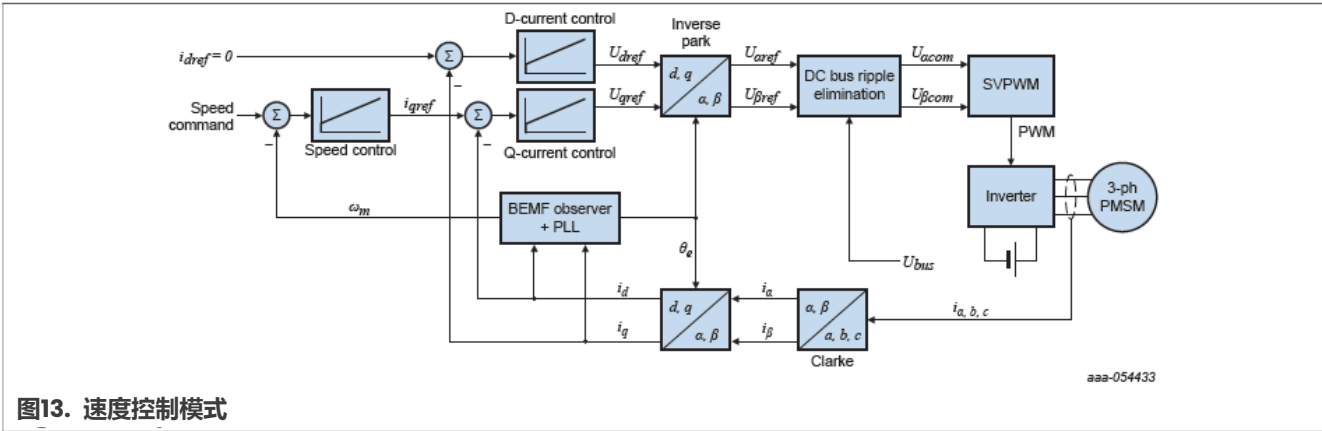


图13. 速度控制模式



图14. 速度控制操作

4.4 CPU负载和内存使用情况

以下信息适用于使用MCUXpresso IDE 11.8构建的演示应用，优化级别设置为“Optimize most (-O3)”。表3和表4显示了内存使用和CPU负载情况。使用SysTick定时器测量CPU负载。

表3. 系统内存

内存区域	使用大小	区域大小	所用的百分比
板卡FLASH	47,632字节	128kb	36.34%
板卡SARM	6772字节	24kb	27.56%

表4. CPU负载

CPU负载	系统节拍	总数	负载率
快速环路	3585	9600	37.3%
慢速环路	598	96000	0.62%

5 参考资料

以下参考资料可作为本文档的补充：

- MCX A153参考手册（文档[MCXAP64M96FS3RM](#)）

6 修订历史

[表5](#)总结了本文档的修订情况。

表5. 修订历史

文档ID	发布日期	说明
AN14099 v.1.0	2024年2月1日	初版发布

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