

# **Sensorless Field Oriented Control of 3-Phase Induction Motors Using Control Law Accelerator (CLA)**

Manish Bhardwaj

## **ABSTRACT**

This application report presents a solution to control an AC induction motor using the Control Law Accelerator (CLA) which is a small foot print coprocessor present on some of the microcontrollers from the C2000™ family of MCU. TMS320F2803x devices are part of the family of C2000 microcontrollers which enable cost-effective design of intelligent controllers for three phase motors by reducing the system components and increase efficiency. With these devices it is possible to realize far more precise digital vector control algorithms like the Field Orientated Control (FOC). This algorithm's implementation is discussed in this document. The FOC algorithm maintains efficiency in a wide range of speeds and takes into consideration torque changes with transient phases by processing a dynamic model of the motor. Among the solutions proposed are ways to eliminate the phase current sensors and use an observer for speed sensorless control.

This application report covers the following:

- A theoretical background on field oriented motor control principle.
- Incremental build levels based on modular software blocks
- Experimental results

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## 1 Introduction

The motor control industry is a strong, aggressive sector. To remain competitive new products must address several design constraints including cost reduction, power consumption reduction, power factor correction, and reduced EMI radiation. In order to meet these challenges advanced control algorithms are necessary. Embedded control technology allows both a high level of performance and system cost reduction to be achieved. According to market analysis, the majority of industrial motor applications use AC induction motors. The reasons for this are higher robustness, higher reliability, lower prices and higher efficiency (up to 80%) on comparison with other motor types. However, the use of induction motors is challenging because of its complex mathematical model, its non linear behavior during saturation and the electrical parameter oscillation which depends on the physical influence of temperature. These factors make the control of induction motor complex and call for use of a high performance control algorithms such as “vector control” and a powerful microcontroller to execute this algorithm.

During the last few decades the field of controlled electrical drives has undergone rapid expansion due mainly to the benefits of microcontrollers. These technological improvements have enabled the development of very effective AC drive control with lower power dissipation hardware and more accurate control structures. The electrical drive controls become more accurate in the sense that not only are the DC quantities controlled but also the three phase AC currents and voltages are managed by so-called vector controls. This document briefly describes the implementation of the most efficient form of a vector control scheme: the Field Orientated Control method. It is based on three major points:

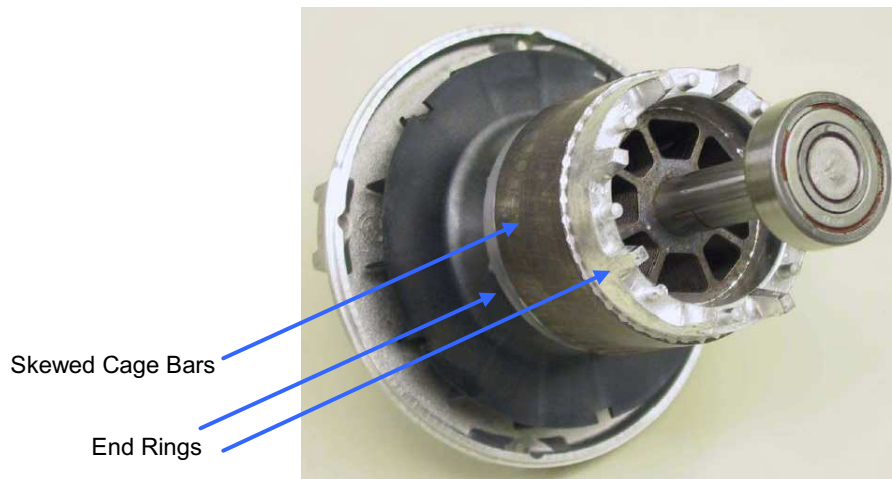
- Machine current and voltage space vectors
- The transformation of a three-phase speed- and time-dependent system into a two coordinate time invariant system
- Effective Space Vector Pulse Width Modulation pattern generation

These algorithms allow the control of an AC machine to acquire every advantage of DC machine control and free itself from mechanical commutation drawbacks. Furthermore, this control structure, by achieving a very accurate steady state and transient control, leads to high dynamic performance in terms of response times and power conversion.

## 2 Induction Motors

Induction motors derive their name from the way the rotor magnetic field is created. The rotating stator magnetic field induces currents in the short circuited rotor. These currents produce the rotor magnetic field, which interacts with the stator magnetic field, and produces torque, which is the useful mechanical output of the machine.

The three phase squirrel cage AC induction motor is the most widely used motor. The bars forming the conductors along the rotor axis are connected by a thick metal ring at the ends, resulting in a short circuit as shown in [Figure 1](#). The sinusoidal stator phase currents fed in the stator coils create a magnetic field rotating at the speed of the stator frequency ( $\omega_s$ ). The changing field induces a current in the cage conductors, which results in the creation of a second magnetic field around the rotor wires. As a consequence of the forces created by the interaction of these two fields, the rotor experiences a torque and starts rotating in the direction of the stator field.



**Figure 1. Induction Motor Rotor**

As the rotor begins to speed up and approach the synchronous speed of the stator magnetic field, the relative speed between the rotor and the stator flux decreases, decreasing the induced voltage in the rotor and reducing the energy converted to torque. This causes the torque production to drop off, and the motor will reach a steady state at a point where the load torque is matched with the motor torque. This point is an equilibrium reached depending on the instantaneous loading of the motor. In brief:

- Since the induction mechanism needs a relative difference between the motor speed and the stator flux speed, the induction motor rotates at a frequency near, but less than, that of the synchronous speed.
- This slip must be present, even when operating in a field-oriented control regime.
- The rotor in an induction motor is not externally excited. This means that there is no need for slip rings and brushes. This makes the induction motor robust, inexpensive and need less maintenance.
- Torque production is governed by the angle formed between the rotor and the stator magnetic fluxes.

In [Figure 2](#) the rotor speed is denoted by  $\Omega$ . Stator and rotor frequencies are linked by a parameter called the slip  $s$ , expressed in per unit as  $s = (\omega_s - \omega_r) / \omega_s$ .

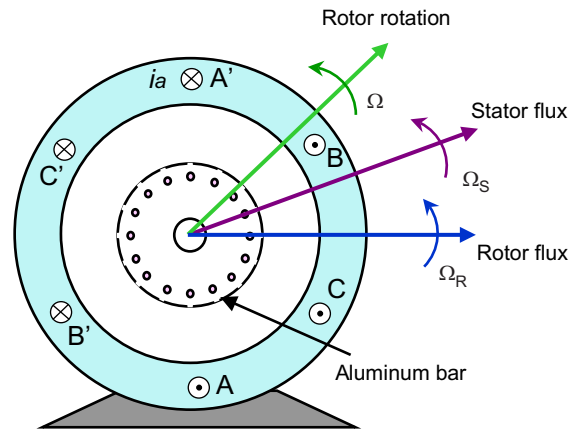


Figure 2. Squirrel Cage Rotor AC Induction Motor Cutaway View

- Stator rotating field speed ( $rad / s$ ):  $\Omega_s = \frac{\omega}{p} \cdot \left\{ \begin{array}{l} \omega : AC \text{ supply freq } (rad / s) \\ p : \text{stator poles pairs number} \end{array} \right\}$
- Rotor rotating speed ( $rad / s$ ):  $\Omega = (1 - s) \Omega_s = (1 - s) \frac{\omega}{p}$

where  $s$  is called the “slip”: it represents the difference between the synchronous frequency and the actual motor rotating speed.

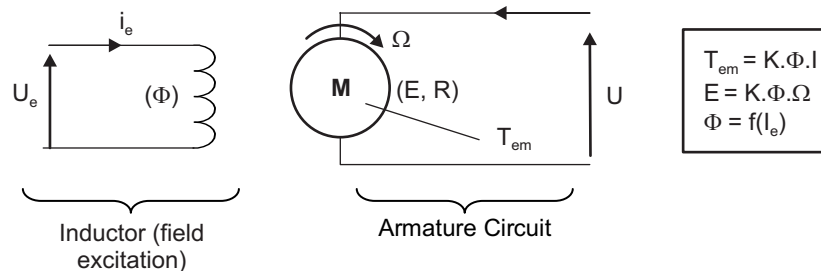
### 3 Field Oriented Control

#### 3.1 Introduction

A simple control such as the V/Hz strategy has limitations on the performance. To achieve better dynamic performance, a more complex control scheme needs to be applied, to control the induction motor. With the mathematical processing power offered by the microcontrollers, we can implement advanced control strategies, which use mathematical transformations in order to decouple the torque generation and the magnetization functions in an AC induction motor. Such decoupled torque and magnetization control is commonly called rotor flux oriented control, or simply Field Oriented Control (FOC).

#### 3.2 The Main Philosophy Behind the FOC

In order to understand the spirit of the Field Oriented Control technique, let us start with an overview of the separately excited direct current (DC) Motor. In this type of motor, the excitation for the stator and rotor is independently controlled. An electrical study of the DC motor shows that the produced torque and the flux can be independently tuned. The strength of the field excitation (the magnitude of the field excitation current) sets the value of the flux. The current through the rotor windings determines how much torque is produced. The commutator on the rotor plays an interesting part in the torque production. The commutator is in contact with the brushes, and the mechanical construction is designed to switch into the circuit the windings that are mechanically aligned to produce the maximum torque. This arrangement then means that the torque production of the machine is fairly near optimal all the time. The key point here is that the windings are managed to keep the flux produced by the rotor windings orthogonal to the stator field.



**Figure 3. Separated Excitation DC Motor Model**

Induction machines do not have the same key features as the DC motor. However, in both cases we have only one source that can be controlled which is the stator currents. On the synchronous machine, the rotor excitation is given by the permanent magnets mounted onto the shaft. On the synchronous motor, the only source of power and magnetic field is the stator phase voltage. Obviously, as opposed to the DC motor, flux and torque depend on each other.

The goal of the FOC (also called vector control) on synchronous and asynchronous machine is to be able to separately control the torque producing and magnetizing flux components. The control technique goal is to (in a sense) imitate the DC motor's operation.

#### 3.3 Why Field Oriented Control

Asynchronous machines have some natural limitations with a V/Hz control approach. FOC control bypasses these limitations by decoupling the effect of the torque and the magnetizing flux. With decoupled control of the magnetization, the torque-producing component of the stator flux can now be thought of as independent torque control. Now, decoupled control, at low speeds, the magnetization can be maintained at the proper level, and the torque can be controlled to regulate the speed.

To decouple the torque and flux, you must engage several mathematical transforms, wherein the microcontrollers add the most value. The processing capability provided by the microcontrollers enables these mathematical transformations to be carried out very quickly. This in turn implies that the entire algorithm controlling the motor can be executed at a fast rate, enabling higher dynamic performance. In addition to the decoupling, a dynamic model of the motor is now used for the computation of many quantities such as rotor flux angle and rotor speed. This means that their effect is accounted for, and the overall quality of control is better.

### 3.4 Technical Background

The Field Orientated Control consists of controlling the stator currents represented by a vector. This control is based on projections which transform a three phase time and speed dependent system into a two co-ordinate (d and q coordinates) time invariant system. These projections lead to a structure similar to that of a DC machine control. Field orientated controlled machines need two constants as input references: the torque component (aligned with the q co-ordinate) and the flux component (aligned with d co-ordinate). As Field Orientated Control is simply based on projections the control structure handles instantaneous electrical quantities. This makes the control accurate in every working operation (steady state and transient) and independent of the limited bandwidth mathematical model. The FOC thus solves the classic scheme problems, in the following ways:

- The ease of reaching constant reference (torque component and flux component of the stator current)
- The ease of applying direct torque control because in the (d,q) reference frame the expression of the torque is:

$$m \propto \Psi \frac{i}{R S q}$$

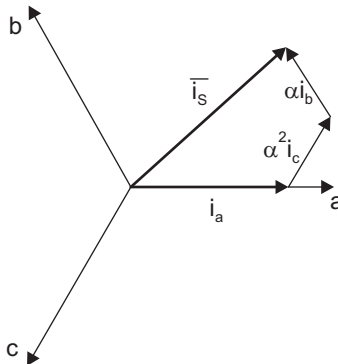
By maintaining the amplitude of the rotor flux ( $\phi_R$ ) at a fixed value we have a linear relationship between torque and torque component ( $i_{sq}$ ). We can then control the torque by controlling the torque component of stator current vector.

### 3.5 Space Vector Definition and Projection

The three-phase voltages, currents and fluxes of AC-motors can be analyzed in terms of complex space vectors. With regard to the currents, the space vector can be defined as follows. Assuming that  $i_a, i_b, i_c$  are the instantaneous currents in the stator phases, then the complex stator current vector  $\bar{i}_s$  is defined by:

$$\bar{i}_s = i_a + \alpha i_b + \alpha^2 i_c$$

where  $\alpha = e^{j\frac{2}{3}\Pi}$  and  $\alpha^2 = e^{j\frac{4}{3}\Pi}$ , represent the spatial operators. The following diagram shows the stator current complex space vector:



**Figure 4. Stator Current Space Vector and Its Component in (a,b,c)**

where (a,b,c) are the three phase system axes. This current space vector depicts the three phase sinusoidal system that you must transform into a two time invariant coordinate system. This transformation can be split into two steps:

- (a,b,c)  $\rightarrow$  ( $\alpha, \beta$ ) (the Clarke transformation), which outputs a two coordinate time variant system
- (a,  $\beta$ )  $\rightarrow$  (d,q) (the Park transformation), which outputs a two coordinate time invariant system

### 3.6 The (a,b,c) → (α, β) Projection (Clarke Transformation)

The space vector can be reported in another reference frame with only two orthogonal axis called (α, β). Assuming that the axis a and the axis α are in the same direction, you have the following vector diagram:

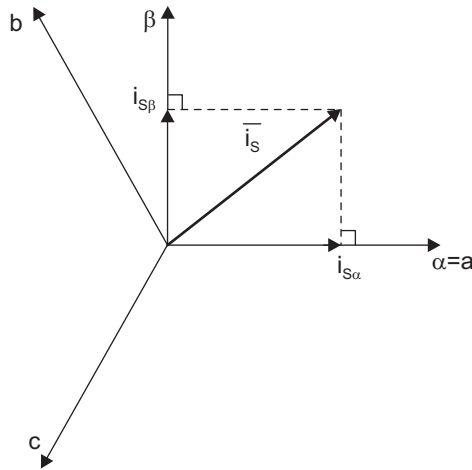


Figure 5. Stator Current Space Vector and Its Component in the Stationary Reference Frame

The projection that modifies the three phase system into the (α, β) two dimension orthogonal system is:

$$\begin{cases} i_{s\alpha} = i_a \\ i_{s\beta} = \frac{1}{\sqrt{3}}i_a + \frac{2}{\sqrt{3}}i_b \end{cases}$$

The two phase (α, β) currents still depend on time and speed.

### 3.7 The (α, β) → (d,q) Projection (Park Transformation)

This is the most important transformation in the FOC. In fact, this projection modifies a two phase orthogonal system (α, β) into the d,q rotating reference frame. If we consider the d axis aligned with the rotor flux, Figure 6 shows, for the current vector, the relationship from the two reference frame:

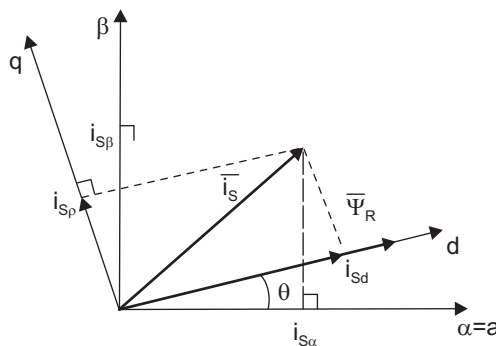


Figure 6. Stator Current Space Vector and Its Component in (α, β) and in the d,q Rotating Reference Frame

where θ is the rotor flux position. The flux and torque components of the current vector are determined by the following equations:

$$\begin{cases} i_{sd} = i_{s\alpha} \cos \theta + i_{s\beta} \sin \theta \\ i_{sq} = -i_{s\alpha} \sin \theta + i_{s\beta} \cos \theta \end{cases}$$



These components depend on the current vector ( $\alpha, \beta$ ) components and on the rotor flux position; if we know the right rotor flux position then, by this projection, the d,q component becomes a constant. Two phase currents now turn into dc quantity (time-invariant). At this point the torque control becomes easier where constant  $i_{sd}$  (flux component) and  $i_{sq}$  (torque component) current components controlled independently.

### 3.8 The Basic Scheme for the FOC

Figure 7 summarizes the basic scheme of torque control with FOC:

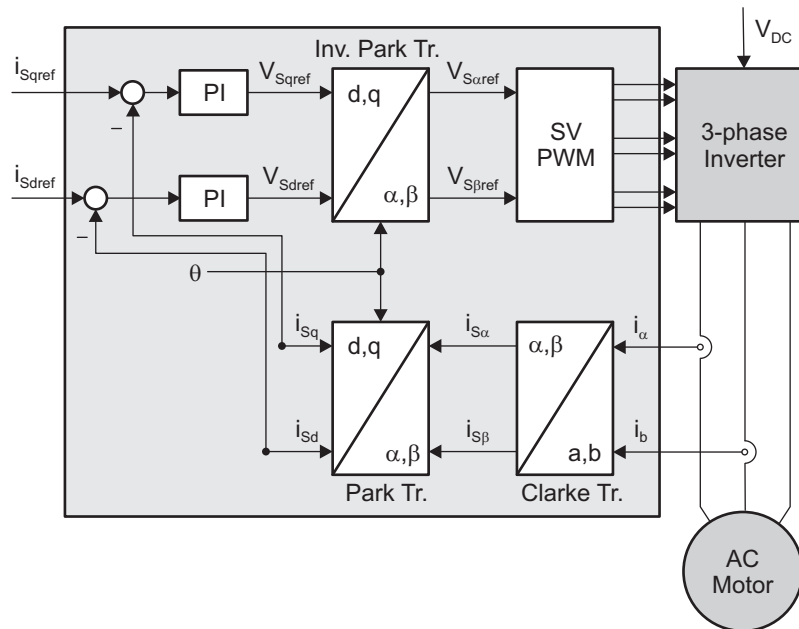


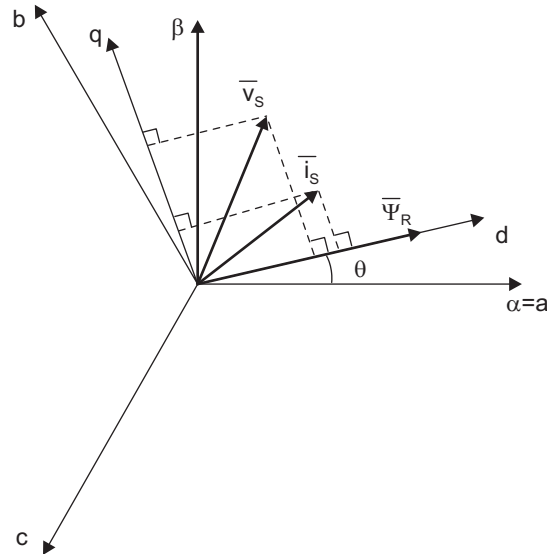
Figure 7. Basic Scheme of FOC for ACI Motor

Two motor phase currents are measured. These measurements feed the Clarke transformation module. The outputs of this projection are designated  $i_{s\alpha}$  and  $i_{s\beta}$ . These two components of the current are the inputs of the Park transformation that gives the current in the d,q rotating reference frame. The  $i_{sd}$  and  $i_{sq}$  components are compared to the references  $i_{sdref}$  (the flux reference) and  $i_{sqref}$  (the torque reference). At this point, this control structure shows an interesting advantage: you can control either synchronous or induction machines by simply changing the flux reference and obtaining rotor flux position. In a synchronous permanent magnet a motor, the rotor flux is fixed (determined by the magnets) and there is no need to create additional flux. Therefore, when controlling a PMSM,  $i_{sdref}$  should be set to zero. Since induction motors need a rotor flux creation in order to operate, the flux reference must not be zero. This conveniently solves one of the major drawbacks of the “classic” control structures: the portability from asynchronous to synchronous drives.

The torque command  $i_{sqref}$  could be the output of the speed regulator when we use a speed FOC. The outputs of the current regulators are  $V_{sdref}$  and  $V_{sqref}$ . They are applied to the inverse Park transformation. The outputs of this projection are  $V_{saref}$  and  $V_{sbetaf}$ , which are the components of the stator vector voltage in the ( $\alpha, \beta$ ) stationary orthogonal reference frame. These are the inputs of the space vector pulse width modulation (PWM). The outputs of this block are the signals that drive the inverter. Note that both Park and inverse Park transformations need the rotor flux position. Obtaining this rotor flux position depends on the AC machine type (synchronous or asynchronous machine). Rotor flux position considerations are made in Section 3.9.

### 3.9 Rotor Flux Position

Knowledge of the rotor flux position is the core of the FOC. In fact, if there is an error in this variable the rotor flux will not be aligned with d-axis, and  $i_{sd}$  and  $i_{sq}$ , flux and torque components of the stator current, will be incorrect. Figure 8 shows the (a,b,c), ( $\alpha$ ,  $\beta$ ) and (d,q) reference frames, and the correct position of the rotor flux, the stator current, and stator voltage space vector that rotates with d,q reference at synchronous speed.



**Figure 8. Current, Voltage and Rotor Flux Space Vectors in the d,q Rotating Reference Frame and Their Relationship With a,b,c and ( $\alpha$ ,  $\beta$ ) Stationary Reference Frame**

The measure of the rotor flux position is different if we consider synchronous or induction motor:

- In the synchronous machine the rotor speed is equal to the rotor flux speed. Then  $\theta$  (rotor flux position) is directly measured by position sensor or by integration of rotor speed.
- In the induction machine the rotor speed is not equal to the rotor flux speed (there is a slip speed), then it needs a particular method to calculate  $\theta$ . The basic method is to use the current model which needs two equations of the motor model in d,q reference frame.

Theoretically, the field oriented control for an induction motor drive can be mainly categorized into two types: indirect and direct schemes. The field to be oriented could be a rotor, stator, or airgap flux linkage. In the indirect field oriented control, the slip estimation with measured or estimated rotor speed is required in order to compute the synchronous speed. There is no flux estimation appearing in the system. For the direct scheme, the synchronous speed is computed basing on the flux angle which is available from flux estimator or flux sensors (Hall effects). In this implementing system, the direct (rotor) flux oriented control system with flux and open-loop speed estimators is described. The key module of this system is the flux estimator. The overall block diagram of this project is depicted in Figure 9.

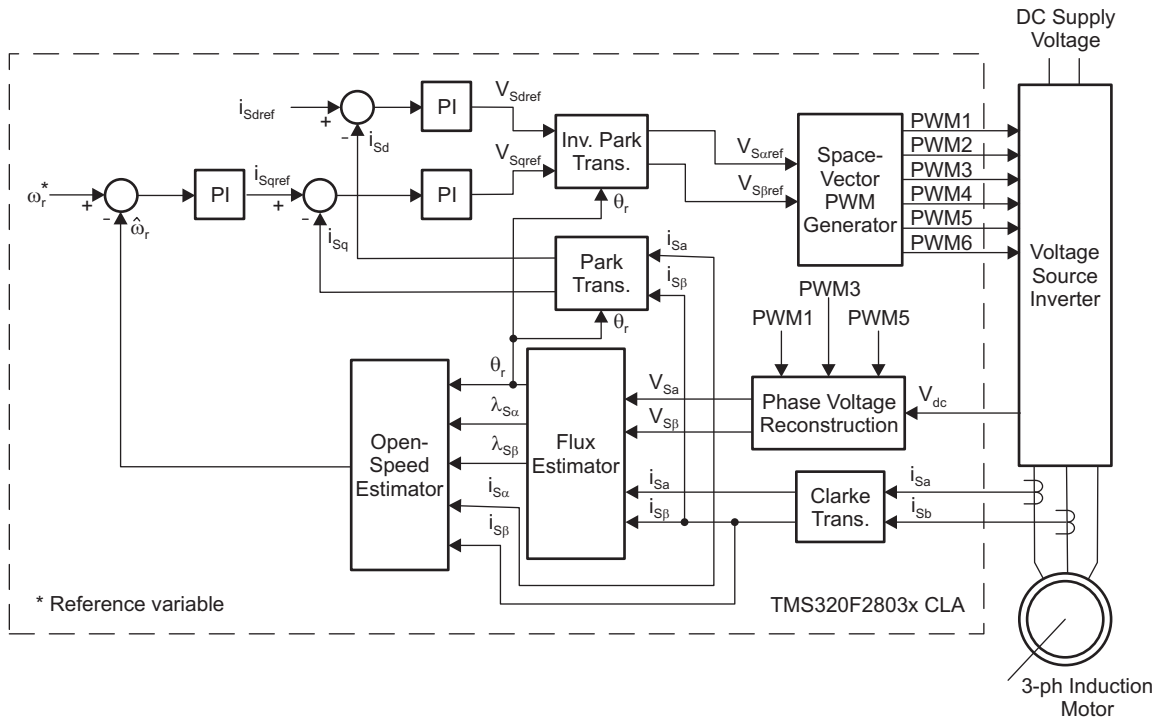


Figure 9. Overall Block Diagram of Direct Rotor Flux Oriented Control

#### 4 Benefits of 32-Bit C2000 Controllers for Digital Motor Control (DMC)

The C2000 family of devices possesses the desired computation power to execute complex control algorithms along with the right mix of peripherals to interface with the various components of the DMC hardware like the ADC, ePWM, QEP, eCAP, and so forth. These peripherals have all the necessary hooks for implementing systems which meet safety requirements, like the trip zones for PWMs and comparators. Along with this the C2000 ecosystem of software (libraries and application software) and hardware (application kits) help in reducing the time and effort needed to develop a Digital Motor Control solution. The DMC Library provides configurable blocks that can be reused to implement new control strategies.

Therefore, with the C2000 family of devices it is easy and quick to implement complex control algorithms (sensored and sensorless) for motor control. The use of C2000 devices and advanced control schemes provides the following system improvements:

- Favors system cost reduction by an efficient control in all speed range implying right dimensioning of power device circuits.
- Advanced control algorithms reduce torque ripple, thus resulting in lower vibration and longer life time of the motor.
- Advanced control algorithms reduce harmonics generated by the inverter thus reducing filter cost.
- Sensorless algorithms eliminate the need for speed or position sensor.
- Fewer look-up tables which reduces the amount of memory required.
- Real-time generation of smooth near-optimal reference profiles and move trajectories results in better performance.
- Generation of high-resolution PWMs is possible with the use of ePWM peripheral for controlling the power switching inverters.
- Single chip control system.

For advanced controls, C2000 controllers:

- Enable control of multi-variable and complex systems using modern intelligent methods such as neural networks and fuzzy logic
- Perform adaptive control. C2000 controllers have the speed capabilities to concurrently monitor and control the system. A dynamic control algorithm adapts itself in real time to variations in system behavior.
- Perform parameter identification for sensorless control algorithms, self commissioning, online parameter estimation update
- Perform advanced torque ripple and acoustic noise reduction.
- Provide diagnostic monitoring with spectrum analysis. By observing the frequency spectrum of mechanical vibrations, failure modes can be predicted in early stages.
- Produce sharp-cut-off notch filters that eliminate narrow-band mechanical resonance. Notch filters remove energy that would otherwise excite resonant modes and possibly make the system unstable.

## 5 Digital Motor Control on CLA

Control Law Accelerator (CLA) is a small footprint floating point co processor which is present on some microcontrollers from the C2000 family of MCU's by Texas Instruments. Most control algorithms can be split into three tasks: excite the system, sample the system and control the system. Exciting the system for motor control type application implies changing duty cycle of the PWM waveform. Sampling the system involves reading the ADC results values and controlling the system implies computing the control effort. The excite sample and control loop is run at the switching rate of the power stage. Given the complexity of the FOC algorithm, which is typically used for efficient motor control, the CPU is left with little bandwidth to do other tasks such as diagnostics, monitoring, and others.

CLA is designed to offload the control task burden from the CPU, thus freeing up bandwidth on the main CPU, C28x, core. The CLA has access to the control peripherals such as PWM and the ADCs which it shares with the main CPU. The CLA has it's own program and data bus as shown in figure below, and executes independently of the main core. The CLA interacts with the main core with use of message rams and has access to the control peripheral simultaneous to the main CPU.

The CLA however does not have hardware support to support a full standard C- compiler, for example the CLA does not have a stack. Also the instruction set of the CLA is reduced and cannot support all the functions of the standard C – compiler. Therefore a “CLA-C Compiler” which supports most but not all C compiler functions is available for programming the CLA. For example the CLA only supports one level nesting of function calls to avoid overhead in function calls. More details about how to set up the CLA C compiler on your machine visit the following wiki page which details the CCS environment setup and codegen tool necessary for the CLA C compiler.

[http://processors.wiki.ti.com/index.php/C2000\\_CLA\\_C\\_Compiler](http://processors.wiki.ti.com/index.php/C2000_CLA_C_Compiler)

The CLA-C compiler is integrated into the CCS IDE and files meant to be executed by the cla are identified with \*.cla extension. The DMC library for CLA follows the same format as the DMC library for the C28x.

The DMC CLA project is composed of three key files:

- **{ProjectName}-Main.c:** This file comprises all of the peripheral initialization and sets up the CLA by assigning the program RAM and dataRAM.
- **{ProjectName}-Shared.h:** This file consists of key variables that are shared between the CPU and the CLA. These variables must be declared in the message RAM.
- **{ProjectName}-tasks\_C.cla:** This is the run-time file of the CLA, that includes 8 task interrupts defined which can be used to execute the algorithm in this task the Task 8 is reserved for initialization of the variables that are in the CLA writable data space.

The DMC blocks are in form of macros that are similar to the DMC C28x library with changes made to the trigonometric functions. The macro approach matches well with the CLA C compiler as it only allows two levels of nesting. The CLA math library is used to realize the trigonometric functions.

All the DMC library variables are declared in the CLA data ram, as these need to be computed by the CLA. **Note:** These variables will not be visible on the C28x side, however if the JTAG is connected the variables can be observed on the watch window.

The variables such as SpeedRef and lsw(LoopSwitch) are declared in the CpuToCLAMsgRAM, whereas a variable such as calculated speed that needs to be monitored by the CPU is declared in the CLAtoCPUMsgRAM.

## 6 TI Literature and CLA DMC Library

The literature distinguishes two types of FOC control:

- Direct FOC control: In this case we try to directly estimate the rotor flux based upon the measurements of terminal voltages and currents.
- Indirect FOC control: in this case the goal is to estimate the slip based upon the motor model in FOC condition and to recalculate the rotor flux angle from the integration of estimated slip and measured rotor speeds. Again knowing the motor parameters, especially rotor time constant, is key in order to achieve the FOC control.

In this document the Direct FOC Control is discussed.

The CLA Digital Motor Control (DMC) library is composed of functions represented as blocks. These blocks are categorized as:

- Transforms and Estimators (Clarke, Park, Sliding Mode Observer, Phase Voltage Calculation, and Flux, and Speed Calculators and Estimators)
- Control (Signal Generation, PID, Space Vector Generation)
- Peripheral Drivers (PWM abstraction for multiple topologies and techniques, ADC drivers)

Each block is a modular software macro and separately documented with source code, use, and technical theory. For the source codes and explanation of macro blocks, install the controlSUITE software from <http://www.ti.com/controlsuite>. After installing the software, check the following folders for the source codes and explanations for macro blocks:

- C:\TI\controlSUITE\libs\app\_libs\motor\_control\math\_blocks\CLA\_v1.0

These modules allow users to quickly build, or customize, their own systems. The library supports the three motor types: ACI, PMSM and comprises both peripheral dependent (software drivers) and target dependent modules.

The DMC library components have been used by TI to provide system examples. At initialization all DMC Library variables are defined and inter-connected. At run-time the macro functions are called in order. Each system is built using an incremental build approach, which allows some sections of the code to be built at a time, so that the developer can verify each section of their application one step at a time. This is critical in real-time control applications where so many different variables can affect the system and many different motor parameters need to be tuned.

### 6.1 System Overview

This document describes the “C” real-time control framework used to demonstrate the sensorless field oriented control of induction motors. The “C” framework is designed to run on TMS320C2803x CLA-based controllers on Code Composer Studio™. The framework uses the following modules.

For details and the theoretical background of each macro, see the PDF documents in C:\TI\controlSUITE\libs\app\_libs\motor\_control.

| Macro Names     | Explanation  |
|-----------------|--|
| CLARKE          | Clarke Transformation  |
| PARK / IPARK    | Park and Inverse Park Transformation                                       |
| PI              | PI Regulators  |
| RC              | Ramp Controller (slew rate limiter)  |
| RG              | Ramp / Sawtooth Generator  |
| ACI_SE / ACI_FE | Flux and Speed Estimators for Sensorless Applications                      |
| SVGEN           | Space Vector PWM with Quadrature Control (includes IClarke Transformation) |
| PHASEVOLT       | Phase Voltage Calculator   |
| PWM / PWMDAC    | PWM and PWMDAC Drives  |

In this system, the sensorless Direct Field Oriented Control (DFOC) of Induction Motor will be experimented and the performance of the speed controller will be explored. The induction motor is driven by a conventional voltage-source inverter. The TMS320F2803x control card is used to generate three pulse width modulation (PWM) signals. The motor is driven by an integrated power module by means of space vector PWM technique. Two phase currents of induction motor ( $i_a$  and  $i_b$ ) are measured from the inverter and sent to the TMS320x2803x via two analog-to-digital converters (ADCs). In addition, the DCbus voltage in the inverter is measured and sent to the TMS320x2803x via an ADC. This DC-bus voltage is necessary to calculate the three phase voltages when the switching functions are known.

HVACI\_Sensorless\_CLA project has the following properties:

| <b>C Framework</b>   |   |                                    |
|----------------------|---|------------------------------------|
| <b>System Name</b>   | <b>CLA Program Memory Usage<br/>2803x</b> | <b>CLA Data Memory Usage 2803x</b> |
| HVACI_Sensorless_CLA | 3272 words                                | 1360 words                         |

| <b>CPU Utilization</b>   |                    |                     |
|--------------------------|--------------------|---------------------|
|                          | <b>With CLA</b>    | <b>Without CLA</b>  |
| Total Number of Cycles   | 873 <sup>(1)</sup> | 1133 <sup>(1)</sup> |
| CPU Utilization @ 60 MHz | 14.5%              | 18.8%               |
| CPU Utilization @ 40 MHz | 21.8%              | 28.3%               |

<sup>(1)</sup> At 10 kHz ISR frequency. Debug macros excluded (in other words, PWMDAC, Datalog).

| <b>System Features</b> |  |
|------------------------|--|
| Development/Emulation  | Code Composer Studio V4.0 (or above) with real-time debugging  |
| Target Controller      | TMS320F2803x CLA   |
| PWM Frequency          | 10 kHz PWM (Default), 60 kHz PWMDAC  |
| PWM Mode               | Symmetrical with a programmable dead band  |
| Interrupts             | ADC, end of conversion – Implements 10 kHz ISR execution rate  |
| Peripherals Used       | PWM 1 / 2 / 3 for motor control<br>PWM 6A, 6B, 7A and 7B for DAC outputs<br>ADC A7 for DC Bus voltage sensing, A1 and B1 for phase current sensing |

The overall system implementing a 3-ph induction motor control is depicted in [Figure 10](#). The induction motor is driven by the conventional voltage-source inverter. The TMS320F2803x is being used to generate the six pulse width modulation (PWM) signals using a space vector PWM technique, for six power switching devices in the inverter. Two input currents of the induction motor ( $i_a$  and  $i_b$ ) are measured from the inverter and they are sent to the TMS320F2803x via two analog-to-digital converters (ADCs). In addition, the DC-bus voltage in the inverter is measured and sent to the TMS320F2803x via an ADC as well. This DC-bus voltage is necessary in order to calculate three phase voltages of induction motor when the switching functions are known.

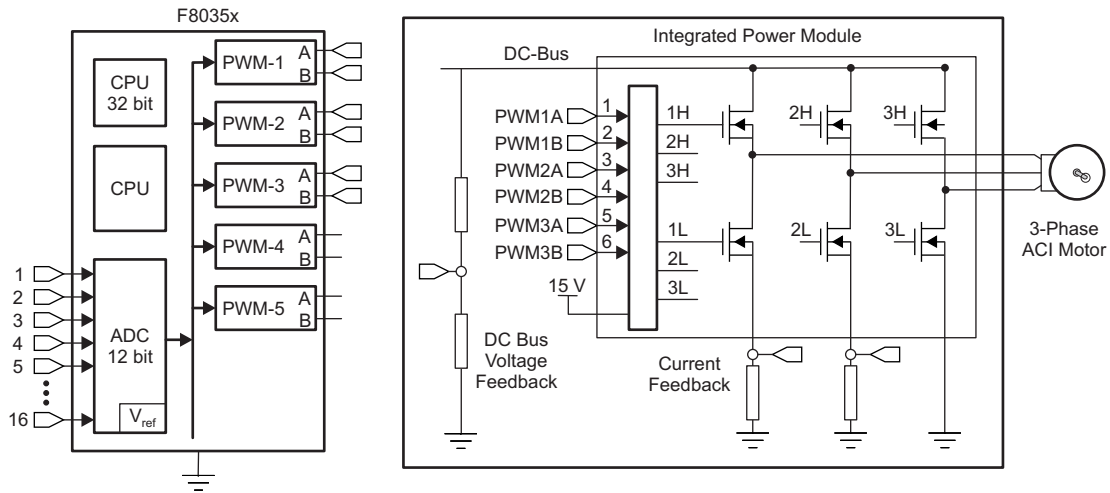


Figure 10. A 3-ph Induction Motor Drive Implementation



## 7 Hardware Configuration (HVDMC R1.1 Kit)

For an overview of the kit's hardware and steps on how to set up this kit, see the *HVMotorCtrl+PFC How to Run Guide* located at: [www.ti.com/controlsuite](http://www.ti.com/controlsuite) and choose the HVMotorKit installation.

The guide will be installed at: C:\TI\controlSUITE\development\_kits\HVMotorCtrl+PfcKit\_v2.0\~Docs.

Some of the hardware setup instructions are captured below for quick reference.

### 7.1 Hardware Setup Instructions

1. Open the Lid of the HV Kit
2. Install the Jumpers [Main]-J3, J4 and J5, J9 for 3.3V, 5V and 15V power rails and JTAG reset line.
3. Unpack the DIMM style controlCARD and place it in the connector slot of [Main]-J1. Push down vertically using even pressure from both ends of the card until the clips snap and lock. (to remove the card simply spread open the retaining clip with thumbs)
4. Connect a USB cable to connector [M3]-JP1.  
This step enables an isolated JTAG emulation to the C2000 device. [M3]-LD1 should turn on. Make sure [M3]-J5 is not populated. If the included Code Composer Studio is installed, the drivers for the onboard JTAG emulation will automatically be installed. If a Windows® installation window appears, try to automatically install drivers from those already on your computer. The emulation drivers are found at <http://www.ftdichip.com/Drivers/D2XX.htm>. The correct driver is the one listed to support the FT2232.
5. If a third party JTAG emulator is used, connect the JTAG header to [M3]-J2 and additionally [M3]-J5 needs to be populated to put the onboard JTAG chip in reset.
6. Ensure that [M6]-SW1 is in the "Off" position.
7. Connect 15-V DC power supply to [M6]-JP1.
8. Turn on [M6]-SW1. Now [M6]-LD1 should turn on. Notice the control card LED will light up as well indicating the control card is receiving power from the board.
9. Note that the motor should be connected to the [M5]-TB3 terminals after you finish with the first incremental build step.
10. Note the DC Bus power should only be applied during incremental build levels when instructed to do so. The two options to get DC Bus power are:
  - To use DC power supply, set the power supply output to zero and connect [Main]-BS5 and BS6 to DC power supply and ground respectively.
  - To use AC Main Power, Connect [Main]-BS1 and BS5 to each other using banana plug cord. Now connect one end of the AC power cord to [Main]-P1. The other end needs to be connected to output of a variac. Ensure that the variac output is set to zero and it is connected to the wall supply through an isolator.

Since the motor is rated at 220 V, the motor properly runs only at a certain speed and torque range without saturating the PID regulators in the control loop when the DC bus is fed from 110-V AC entry. As an option, the user can run the PFC on HV DMC drive platform as boost converter to increase the DC bus voltage level or directly connect a DC power supply.

For reference, the following figures show the jumper and connectors that need to be connected for this lab.

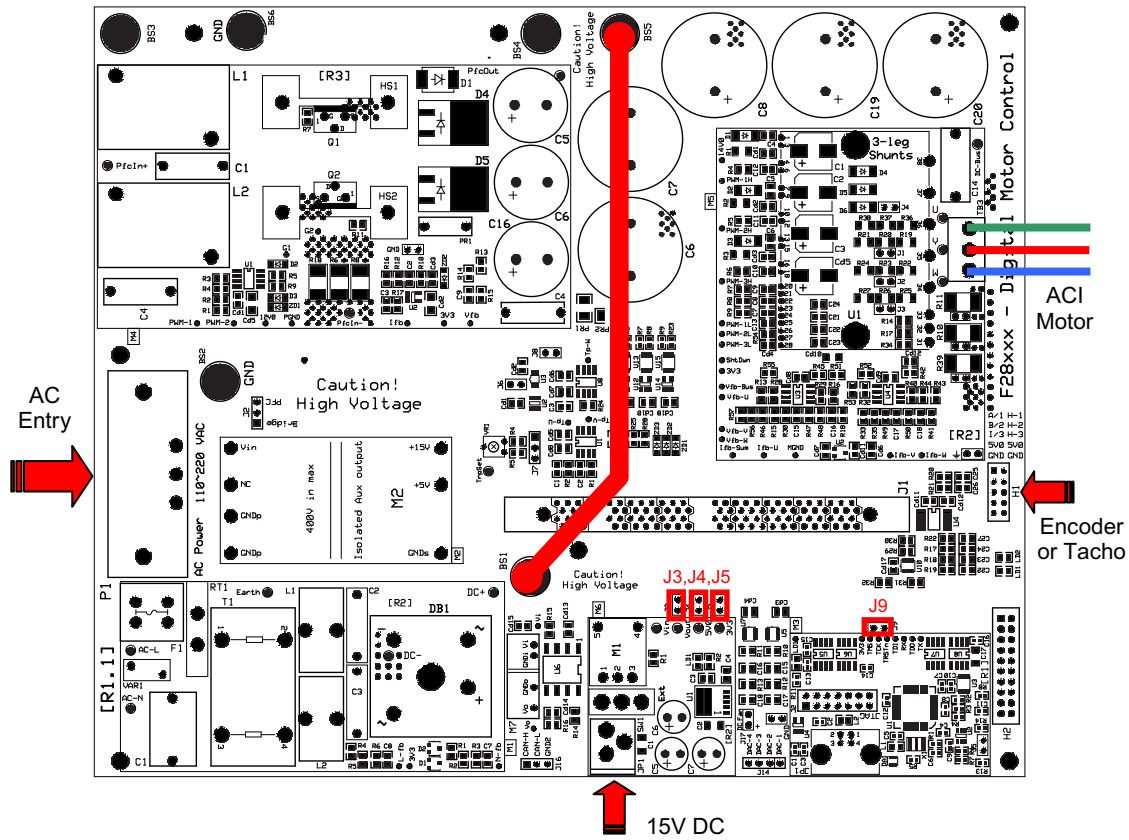


Figure 11. Using AC Power to Generate DC Bus Power

**CAUTION**

The inverter bus capacitors remain charged for a long time after the high power line supply is switched off or disconnected. Proceed with caution!

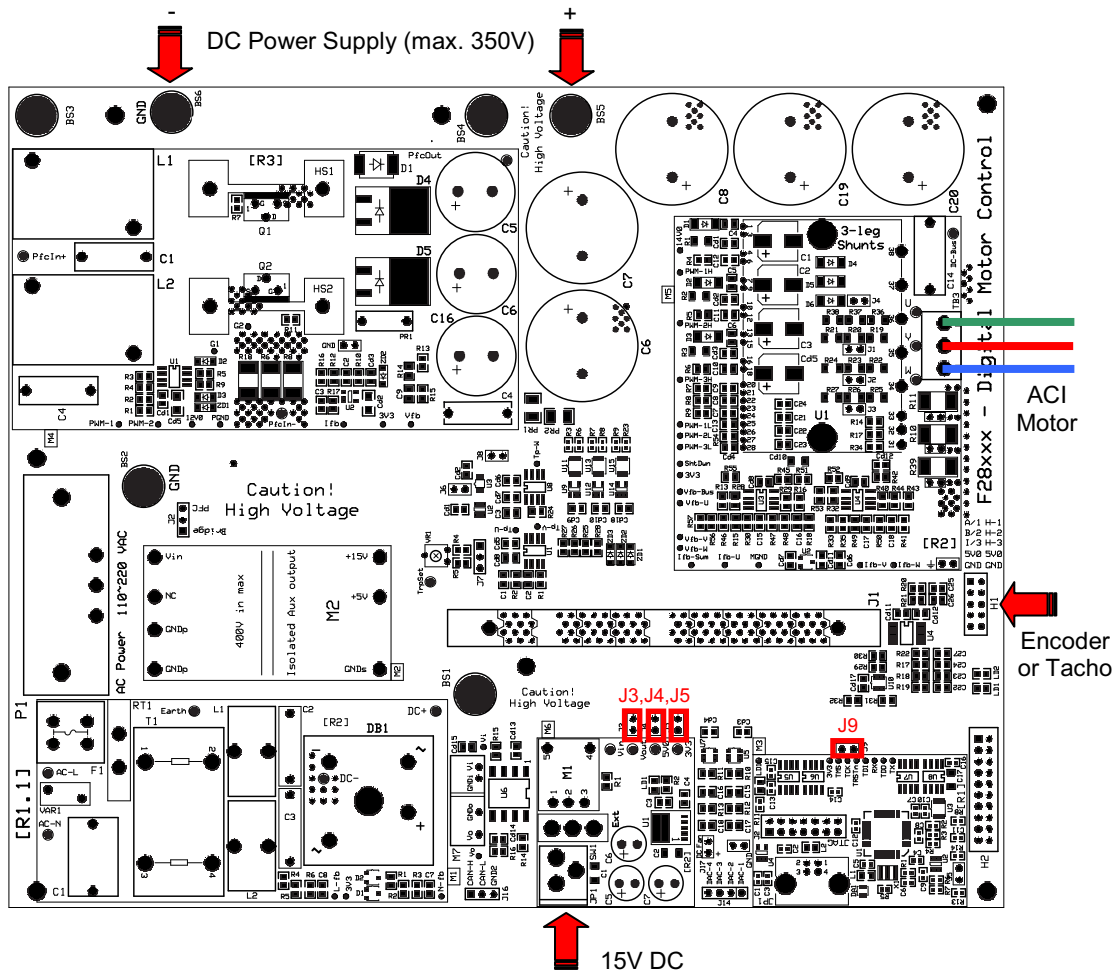


Figure 12. Using External DC Power Supply to Generate DC-Bus for the Inverter

**CAUTION**

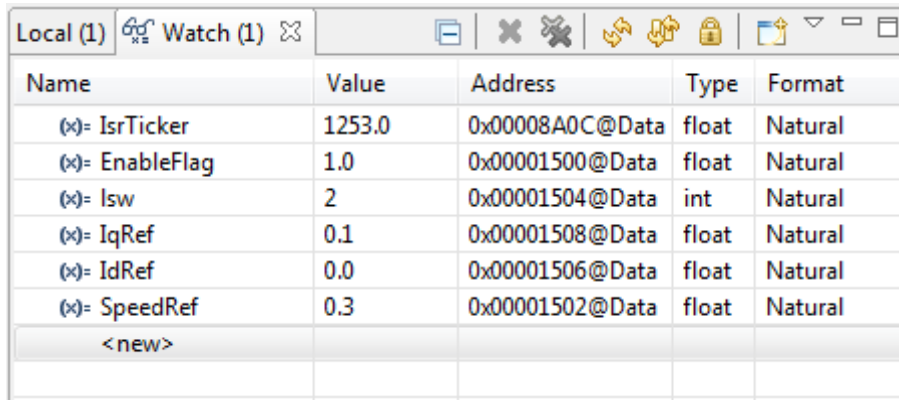
The inverter bus capacitors remain charged for a long time after the high power line supply is switched off or disconnected. Proceed with caution!

## 7.2 Software Setup Instructions to Run HVACI\_Sensorless\_CLA Project

For more information, see the *Software Setup for HVMotorCtrl+PFC Kit Projects* section in the *HVMotorCtrl+PFC Kit How to Run Guide* in:


C:\TI\controlSUITE\development\_kits\HVMotorCtrl+PfcKit\_v2.0\~Docs

1. Select the HVACI\_Sensorless\_CLA as the active project.
2. Verify that the build level is set to 1.
3. Ensure the code gen version 6.1.0 or later is installed.
4. Verify that the CCS environment recognizes the \*.cla extension (Windows -> Preferences -> C/C++ -> File Type)
5. Right-click on the project name and select "Rebuild Project".
6. Once the build completes, launch a debug session to load the code into the controller.
7. Open a watch window and add the critical variables as shown in [Figure 13](#).



| Name            | Value  | Address         | Type  | Format  |
|-----------------|--------|-----------------|-------|---------|
| (x)= IsrTicker  | 1253.0 | 0x00008A0C@Data | float | Natural |
| (x)= EnableFlag | 1.0    | 0x00001500@Data | float | Natural |
| (x)= lsw        | 2      | 0x00001504@Data | int   | Natural |
| (x)= IqRef      | 0.1    | 0x00001508@Data | float | Natural |
| (x)= IdRef      | 0.0    | 0x00001506@Data | float | Natural |
| (x)= SpeedRef   | 0.3    | 0x00001502@Data | float | Natural |
| <new>           |        |                 |       |         |

**Figure 13. Watch Window Variables**

- Click on Continuous Refresh button  on the top left corner of the graph tab to enable periodic capture of data from the microcontroller.

## 8 Incremental System Build for ACI Sensorless Project

### 8.1 Level 1 Incremental Build

Keep the motor disconnected at this step. Assuming the load and build steps described in the *HVMotorCtrl+PFC Kit How To Run Guide* completed successfully, this section describes the steps for a “minimum” system check-out, which confirms the operation of system interrupt, the peripheral and target independent IPARK\_CLA\_MACRO (inverse park transformation) and SVGEN\_CLA\_MACRO (space vector generator) modules, the peripheral dependent PWMDRV\_3PHINV\_CLA\_MACRO (PWM initializations and update) modules.

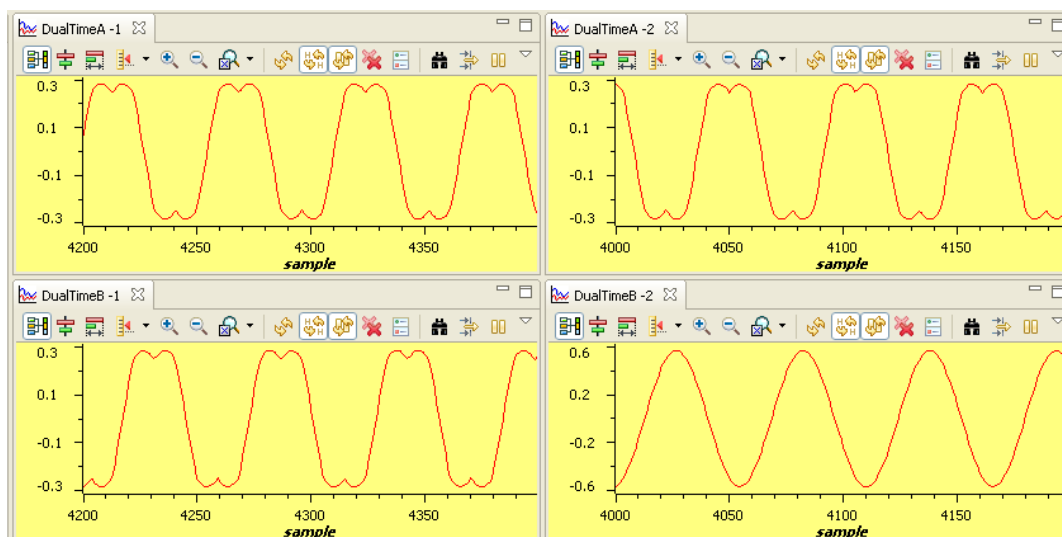
1. Open {App Name}\_CLA-Shared\_C.h and select level 1 incremental build option by setting the BUILDLEVEL to LEVEL1 (#define BUILDLEVEL LEVEL1).
2. Right-click on the project name and click Rebuild Project.
3. When the build is complete:
  - Click on the debug button.
  - Reset the CPU and restart.
  - Enable real-time mode and run.
  - Set the “EnableFlag” to 1 in the watch window. The variable named “IsrTicker” will now continue to increase, as seen in the watch window, to confirm the system interrupt is properly working.

In the software, the key variables to adjust are:

- SpeedRef (FLOAT): for changing the rotor speed in per-unit.
- VdTesting (FLOAT): for changing the d-qxis voltage in per-unit.
- VqTesting (FLOAT): for changing the q-axis voltage in per-unit.

### 8.2 Level 1A (SVGEN\_CLA\_MACRO Test)

In this level we would test the Space Vector Generator Macro (SVGEN\_CLA\_MACRO). The SpeedRef value is specified to the RG\_CLA\_MACRO module via RC\_CLA\_MACRO module. The IPARK\_MACRO module is generating the outputs to the SVGEN\_CLA\_MACRO module. Three outputs from SVGEN\_CLA\_MACRO module are monitored via the graph window, as shown in [Figure 14](#), where Ta, Tb, and Tc waveform are 120° apart from each other. Specifically, Tb lags Ta by 120° and Tc leads Ta by 120°. Check the PWM test points on the board to observe PWM pulses (PWM-1H to 3H and PWM-1L to 3L) and ensure that the PWM module is running properly.



**Figure 14. SVGEN Duty Cycle Outputs Ta, Tb, Tc and Tb-Tc**

**NOTE:** The graph window snapshots belong to C28x application. Please use PWMDACs to obtain the same graphs for debugging purposes while using CLA.

### 8.3 Level 1B (Testing The PWMDAC Macro)

To monitor internal signal values in real time, PWM DACs are very useful tools. Present on the HV DMC board are PWM DACs which use an external low pass filter to generate the waveforms ([Main]-J14, DAC-1 to 4). A simple first-order low-pass filter RC circuit filters out the high frequency components. The selection of R and C value (or the time constant,  $\tau$ ) is based on the cut-off frequency ( $f_c$ ), for this type of filter; the relation is as follows:

$$\tau = RC \frac{1}{2\pi f_c}$$

For example,  $R = 1.8 \text{ k}\Omega$  and  $C = 100 \text{ nF}$  results in  $f_c = 884.2 \text{ Hz}$ . This cut-off frequency must be below the PWM frequency. Use the formula above to customize low-pass filters used for the signal being monitored.

The DAC circuit low-pass filters ([Main]-R10 to13 and [Main]-C15 to18) are shipped with  $2.2 \text{ k}\Omega$  and  $220 \text{ nF}$  on the board. For more details, see *Using PWM Output as a Digital-to-Analog Converter on a TMS320F280x Digital Signal Controller* ([SPRAA88](#)).

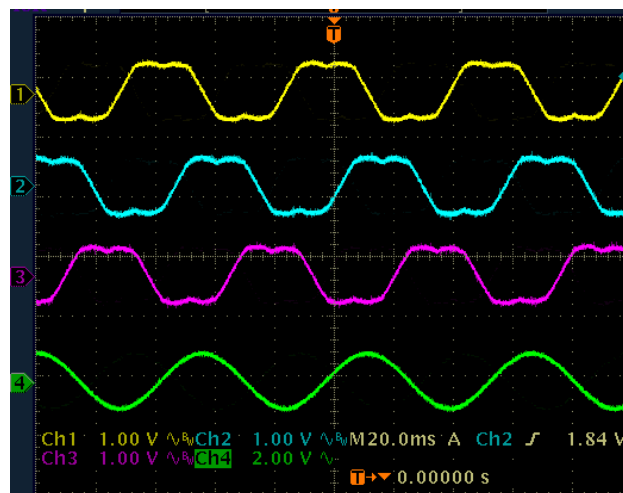



Figure 15. DAC-1-4 Outputs Showing  $T_a$ ,  $T_b$ ,  $T_c$  and  $T_b$ - $T_c$  Waveforms

### 8.4 Level 1C (PWMDRV\_3PHINV\_CLA\_MACRO and INVERTER Test)

After verifying the SVGEN\_CLA\_MACRO module in Level 1A, the PWMDRV\_3PHINV\_CLA\_MACRO software module and the 3-phase inverter hardware are tested by looking at the low-pass filter outputs. For this purpose, if using the external DC power supply gradually increase the DC bus voltage and check the Vfb-U, V and W test points using an oscilloscope or if using AC power entry slowly change the variac to generate the DC bus voltage. Once the DC bus voltage is greater than 15 V to 20 V, you will start observing the inverter phase voltage dividers and waveform monitoring filters (Vfb-U, Vfb-V, Vfb-W) enable the generation of the waveform, which ensures that the inverter is working appropriately. Note that the default RC values are optimized for AC motor state observers employing phase voltages.

**CAUTION**

After verifying the SVGEN\_CLA\_MACRO module:

1. Reduce the DC bus voltage.
2. Take the controller out of real-time mode (disable).
3. Reset the processor  (for more details, see the *HVMotorCtrl+PFC Kit How To Run Guide*).

Note that after each test, this process needs to be repeated for safety purposes. Also note that improper shutdown might halt the PWMs at some certain states where high currents can be drawn, therefore, caution needs to be taken while doing these experiments.

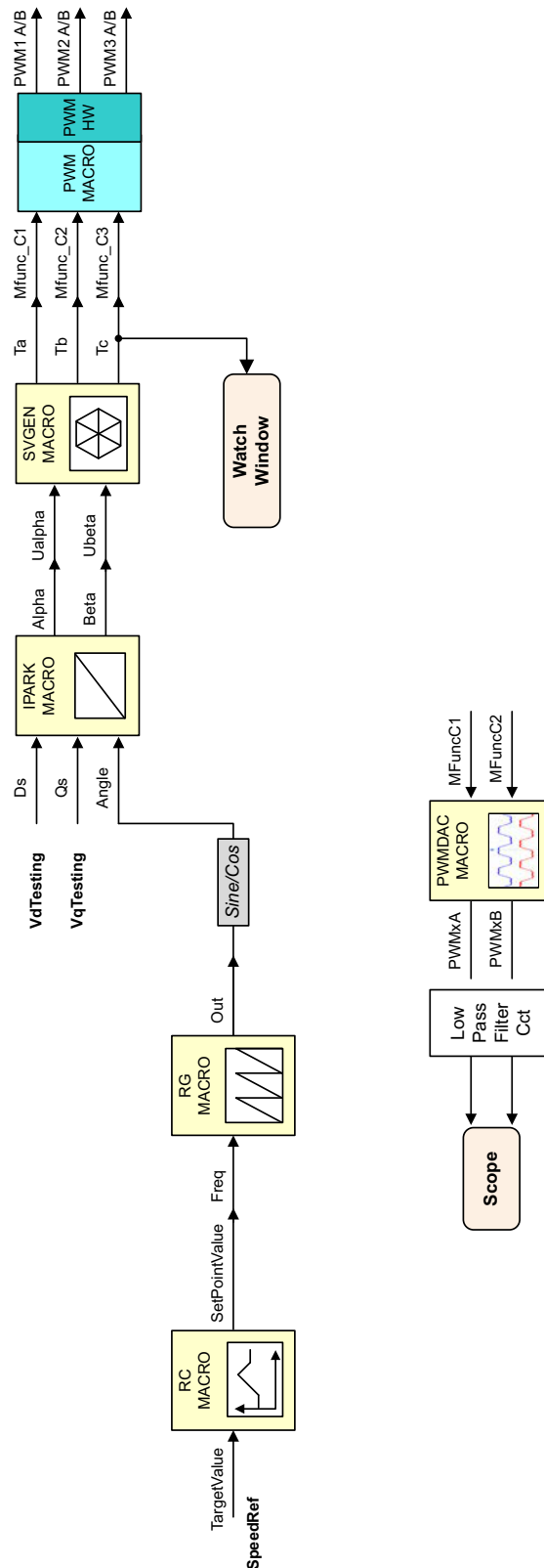


Figure 16. Level 1 — Incremental System Build Block Diagram

Level 1 verifies the target independent modules, duty cycles and PWM updates. The motor is disconnected at this level.



## 8.5 Level 2 - Incremental Build

Assuming the Level1 incremental build 1 is completed successfully, this section verifies the analog-to-digital conversion, Clarke/Park transformations and phase voltage calculations. Now the motor can be connected to the HVDMC board.

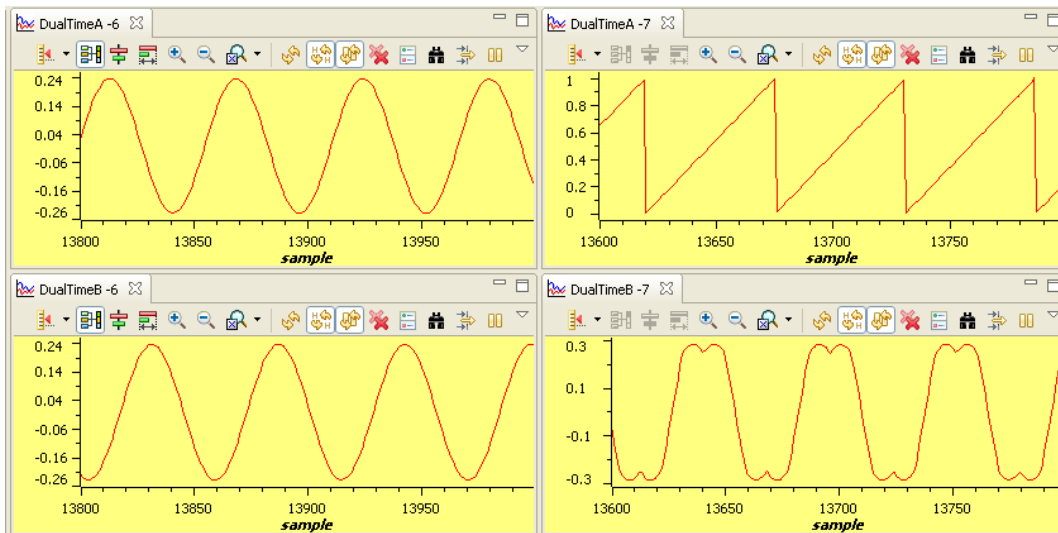
In the software, the key variables to adjust are:

- SpeedRef(FLOAT): for changing the rotor speed in per-unit.
  - VdTesting(FLOAT): for changing the d-axis voltage in per-unit.
  - VqTesting(FLOAT): for changing the q-axis voltage in per-unit.
1. Open {App Name}\_CLA-Shared\_C.h and select level 2 incremental build option by setting the BUILDLEVEL to LEVEL2 (#define BUILDLEVEL LEVEL2) and save the file.
  2. Right-click on the project name and click Rebuild Project.
  3. When the build is complete:
    - (a) Click on the debug button.
    - (b) Reset the CPU and restart.
    - (c) Enable real-time mode and run.
    - (d) Set "EnableFlag" to 1 in the watch window. The variable named "IsrTicker" will be incrementally increased as seen in watch windows to confirm the interrupt working properly.

## 8.6 Level 2A – Testing the Phase Voltage Module

In this part, the phase voltage calculation module, VOLT\_CALC\_CLA\_MACRO, will be tested. Gradually increase the DC bus voltage. The waveforms in [Figure 17](#) should be observed.

- The clarke1.Alpha waveform should be same as the clarke1.As waveform.
- The clarke1.Alpha waveform should be leading the clarke1.Beta waveform by 90° at the same magnitude.



**Figure 17. Calculated Phase A and B Voltages By Volt1 Module, rg1.Out, and svgen\_dq1.Ta**

The VphaseA, VphaseB, and VphaseC waveforms should be 120° apart from each other. Specifically, VphaseB lags VphaseA by 120° ([Figure 17](#)) and VphaseC leads VphaseA by 120°.

Alternatively, users can modify the datalog setting to verify the following relation between the signals:

- The Valpha waveform should be the same as the VphaseA waveform.
- The Valpha waveform should be leading the Vbeta waveform by 90° at the same magnitude.

Note that the open loop experiments are meant to test the ADCs, inverter stage, software modules, and so forth. Running the motor under load or at various operating points is not recommended.

## 8.7 Phase 2B – Testing the Clarke Module

In this part the Clarke module will be tested. The three measured line currents are transformed to two phase dq currents in a stationary reference frame. The outputs of this module can be checked from the graph window.

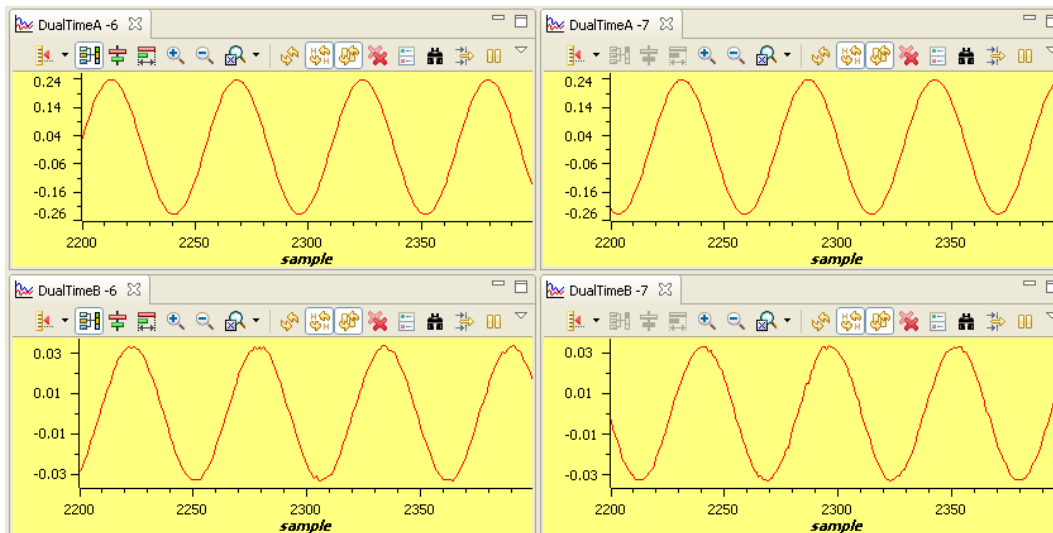
Verify the following:

- The clarke1.Alpha waveform leads the clarke1.Beta waveform by  $90^\circ$  at the same magnitude.
- The clarke1.Alpha waveform is the same as the clarke1.As waveform.

The measured line current must be lagging with the reconstructing phase voltage because of the nature of the ACI motor.

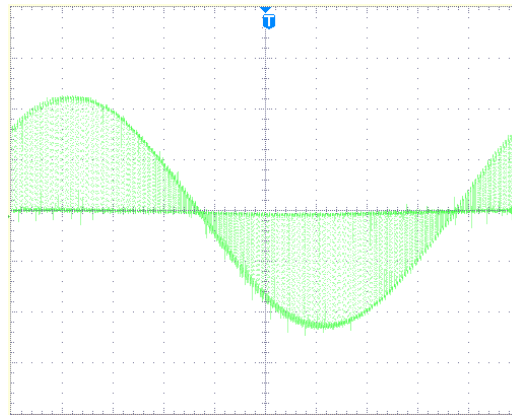
As mentioned in the previous section, three input switching functions may not be functioning correctly (see this module documentation for details). This can be easily checked as follows (Note: You may need to modify datalog settings and graph windows settings to observe these signals):

- The clarke1.Alpha waveform lags the Valpha waveform at an angle by nature of the reactive load of Induction motor.
- The clarke1.Beta waveform lags the Vbeta waveform at the same angle.
- If the clarke1.Alpha and Valpha or clarke1.Beta and Vbeta waveforms in the previous step are not truly affecting the lagging relationship, then set OutofPhase to 1 at the beginning of the VOLT\_CALC\_CLA\_MACRO module.



**Figure 18. The Waveforms of Phase A Voltage and Current and Phase B Voltage and Current**

Since the low side current measurement technique is used employing shunt resistors on inverter phase legs, the phase current waveforms observed from current test points ([M5]-lfb-U, and [M5]-lfb-V) are composed of pulses, as shown in [Figure 19](#).



**Figure 19. Amplified Phase A Current**

### 8.8 Level 2B – Adjusting PI Limits

Note that the vectorial sum of d-q PI outputs should be less than 1.0 which refers to maximum duty cycle for SVGEN macro. Another duty cycle limiting factor is the current sense through shunt resistors which depends on hardware/software implementation. Depending on the application requirements 3, 2 or a single shunt resistor can be used for current waveform reconstruction. The higher number of shunt resistors allow higher duty cycle operation and better DC bus utilization.

Run the system with default VdTesting, VqTesting and SpeedRef and gradually increase VdTesting and VqTesting values. Meanwhile, watch the current waveforms in the graph window. Increase until you notice distorted current waveforms and write down the maximum allowed VdTesting and VqTesting values. Ensure that these values are consistent with expected d-q current component maximums while running the motor. After this build level, PI outputs will automatically generate the voltage reference and determine the PWM duty cycle depending on the d-q current demand, therefore set pi\_id.Umax/min and pi\_iq.Umax/min according to recorded VdTesting and VqTesting values, respectively.

**Note:** Running the motor without proper PI limits can yield distorted current waveforms and unstable closed loop operations which may damage the hardware.

Bring the system to a safe stop, as described at the end of build 1 ([Section 8.1](#)), by reducing the bus voltage and taking the controller out of real-time mode and reset.

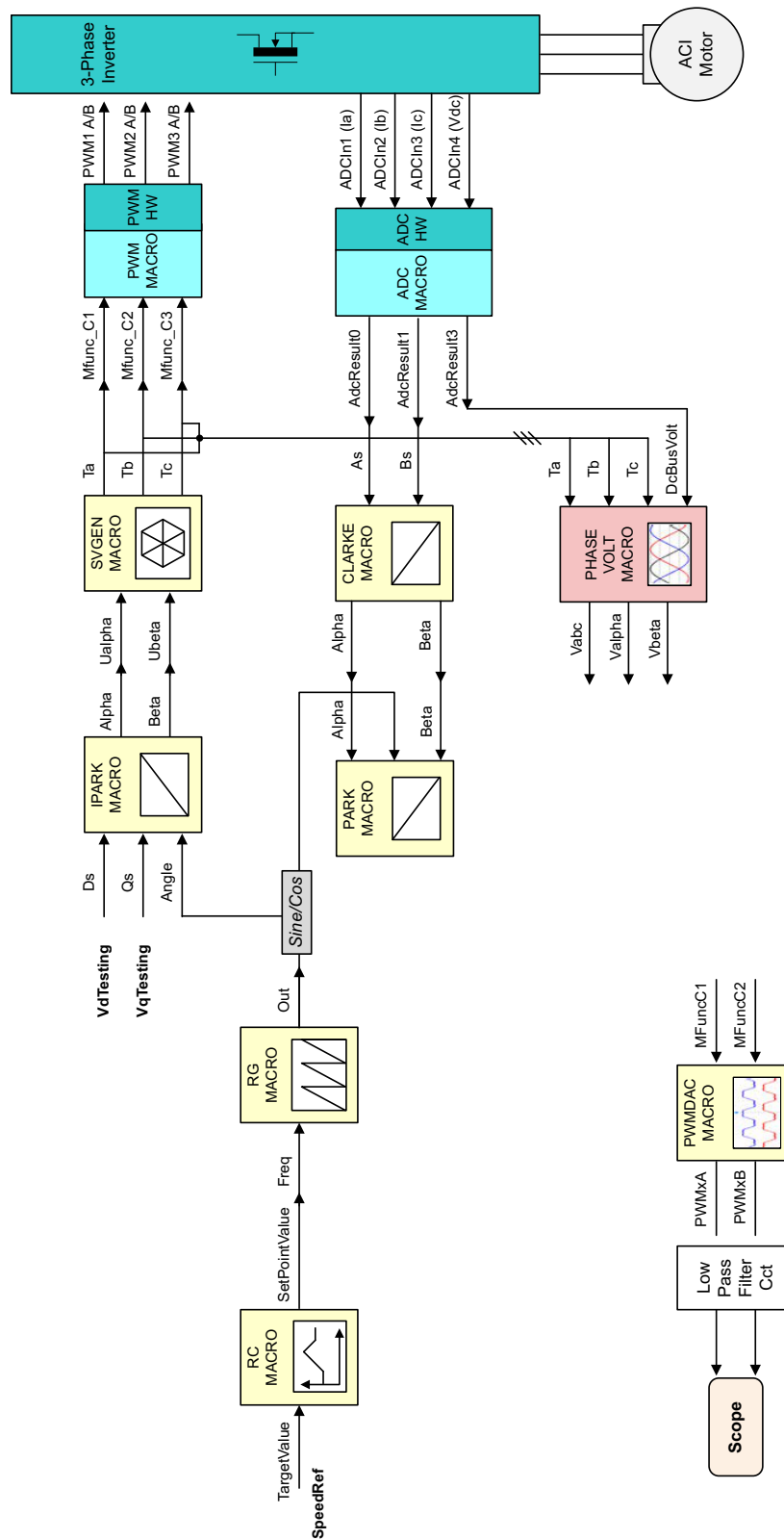


Figure 20. Level 2 — Incremental System Build Block Diagram

Level 2 verifies the analog-to-digital conversion, offset compensation, clarke / park transformations.

## 8.9 Level 3 Incremental Build

Assuming the previous section is completed successfully, this section verifies the dq-axis current regulation performed by PI modules and speed measurement modules (optional). To confirm the operation of current regulation, the gains of these two PI controllers are necessarily tuned for proper operation.

1. Open {App Name}\_CLA-Shared\_C.h and select level 3 incremental build option by setting the BUILDLEVEL to LEVEL3 (#define BUILDLEVEL LEVEL3).
2. Right-click on the project name and click Rebuild Project.
3. When the build completes:
  - (a) Click on the debug button.
  - (b) Reset CPU and restart.
  - (c) Enable Real-time mode and run.
  - (d) Set "EnableFlag" to 1 in the watch window. The variable named "IsrTicker" will be incrementally increased as seen in watch windows to confirm the interrupt working properly.

In the software, the key variables to adjust are:

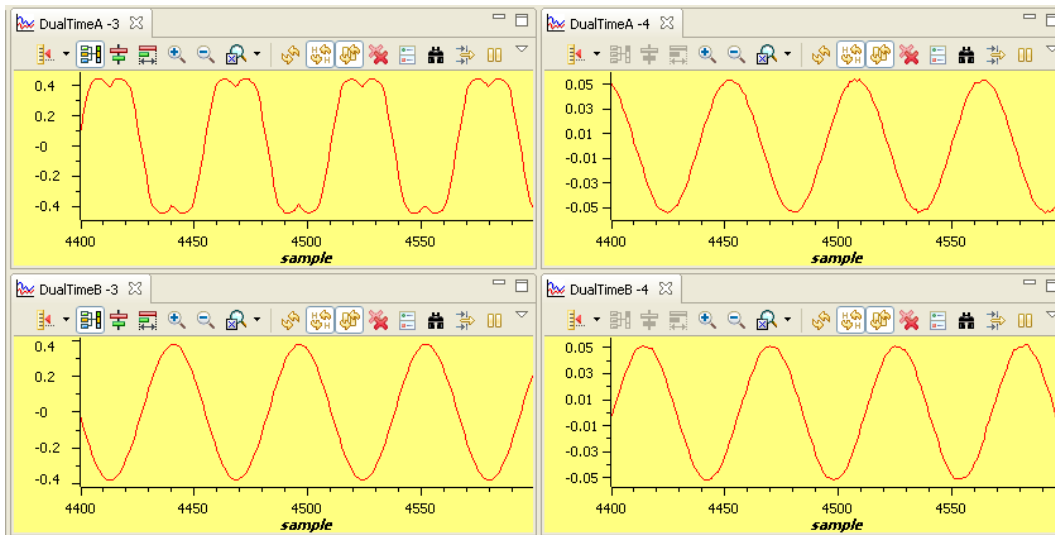
- SpeedRef (FLOAT): for changing the rotor speed in per-unit.
- IdRef (FLOAT): for changing the d-qxis voltage in per-unit.
- IqRef (FLOAT): for changing the q-axis voltage in per-unit.

In this build, the motor is supplied by AC input voltage and the (AC) motor current is dynamically regulated by using PI module through the park transformation on the motor currents.

The steps are:

1. Launch a debug session, enable time mode and run the project.
2. Set SpeedRef to 0.3 pu (or another suitable value if the base speed is different), Idref to a certain value to generate rated flux.
3. Gradually increase voltage at variac / dc power supply to get an appropriate DC-bus voltage.
4. Check pi\_id.Fdb in the watch windows with continuous refresh feature whether or not it should be keeping track pi\_id.Ref for PI module. If not, adjust its PI gains properly.
5. To confirm these two PI modules, try different values of pi\_id.Ref and pi\_iq.Ref or SpeedRef.
6. For both PI controllers, the proportional, integral, derivative and integral correction gains may be re-tuned to have the satisfied responses.
7. Bring the system to a safe stop, as described at the end of build 1 ([Section 8.1](#)), by reducing the bus voltage and taking the controller out of real-time mode and reset.

While running this build, the current waveforms in the CCS graphs appears as shown in [Figure 21](#).



**Figure 21. Svgen\_dq1.Ta, Phase A Voltage, and Phase A and B Current Waveforms**

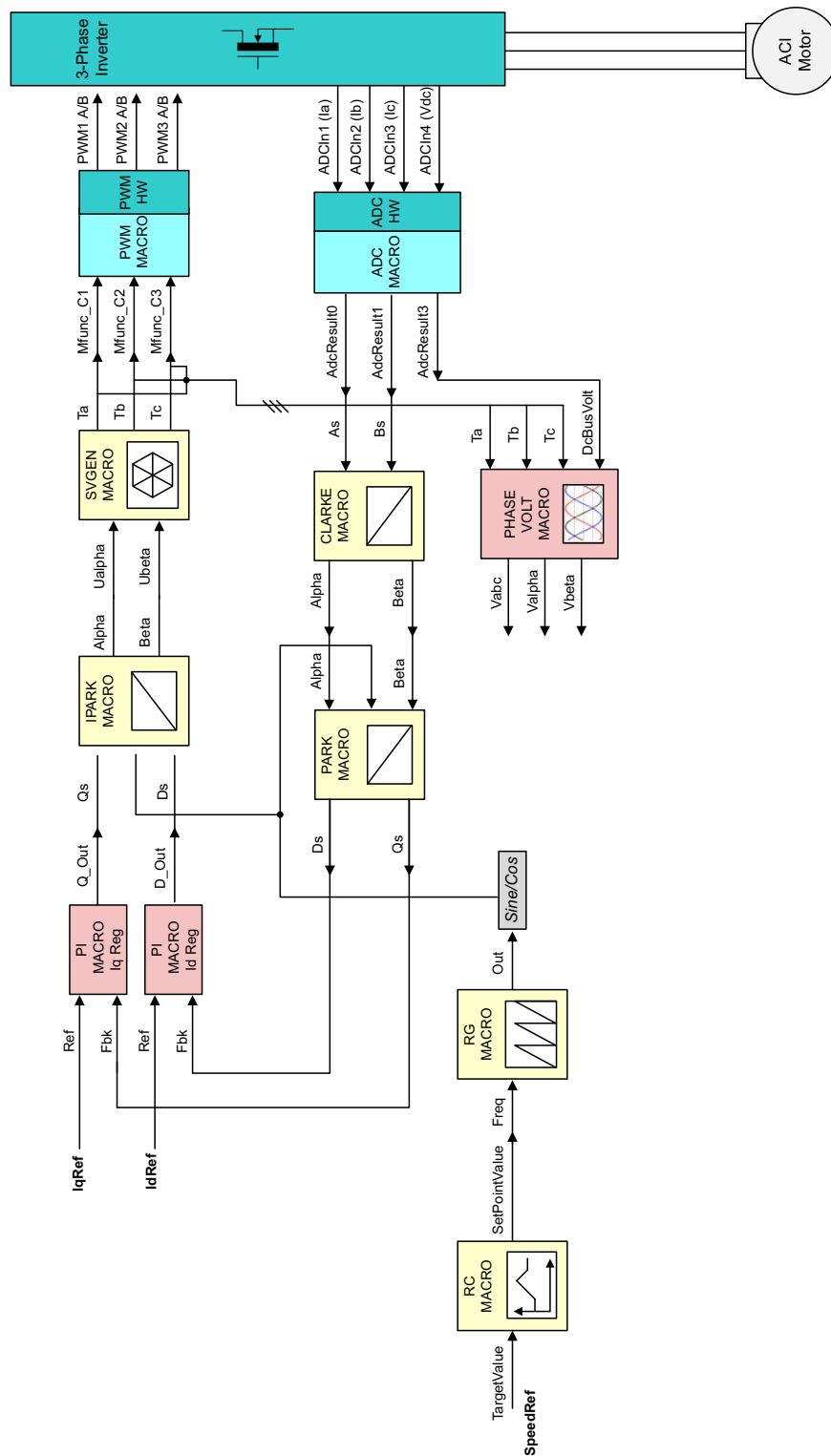


Figure 22. Level 3 — Incremental System Build Block Diagram

Level 3 verifies the dq-axis current regulation performed by PI macros and speed measurement modules.

### 8.10 Level 4 Incremental Build

Assuming the previous section is completed successfully; this section verifies flux estimation (ACI\_FE) and open-loop speed estimation (ACI\_SE), respectively.

1. Open {App Name}\_CLA-Shared\_C.h and select level 4 incremental build option by setting the BUILDLEVEL to LEVEL4 (#define BUILDLEVEL LEVEL4).
2. Right-click on the project name and click Rebuild Project.
3. When the build completes:
  - (a) Click on the debug button.
  - (b) Reset CPU and restart.
  - (c) Enable Real-time mode and run.
  - (d) Set "EnableFlag" to 1 in the watch window. The variable named "IsrTicker" will be incrementally increased as seen in watch windows to confirm the interrupt working properly.

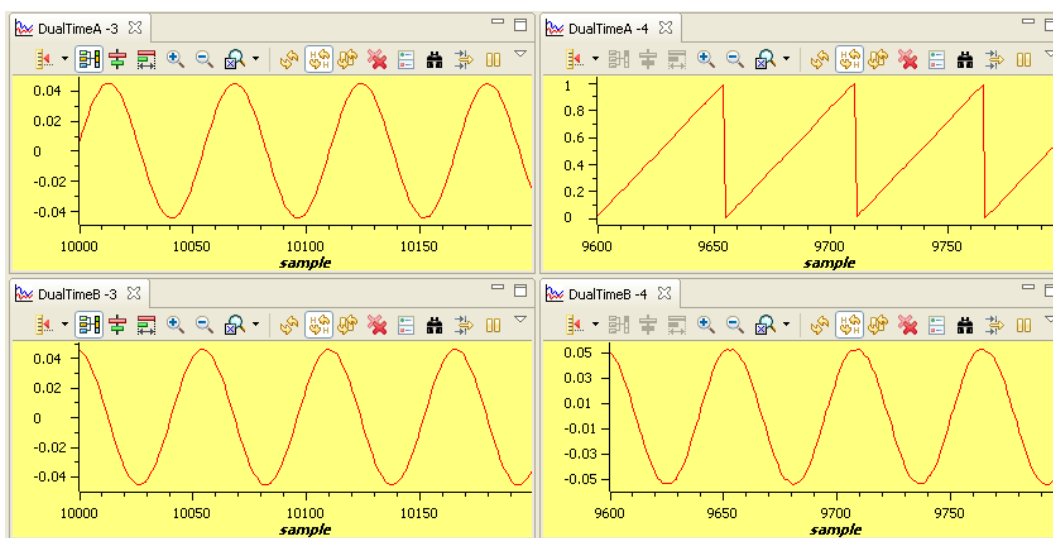
The key variables to adjust are:

- SpeedRef (FLOAT): for changing the rotor speed in per-unit.
- IdRef (FLOAT): for changing the d-qxis voltage in per-unit.
- IqRef (FLOAT): for changing the q-axis voltage in per-unit.

The tuning of proportional and integral gains (Kp\_fe and Ki\_fe) inside the flux estimator may be critical for very low speed operation. The key steps are:

1. Set SpeedRef to 0.3 pu (or another suitable value if the base speed is different).
2. Compile, load, and run program with real time mode and then increase voltage at variac / dc power supply to get the appropriate DC-bus voltage. Now the motor is running close to reference speed.
3. Compare fe1.ThetaFlux with rg1.Out via PWM DAC with external low-pass filter and an oscilloscope. They should be identical with a small phase shift.
4. If fe1.ThetaFlux does not give the ramp waveform, the Kp and Ki inside the flux estimator are required to be re-tuned (likely to be reduced).
5. To confirm this flux estimator, try different values of SpeedRef.
6. Compare se1.WrHat with reference speed or measured speed in the watch windows with continuous refresh feature whether or not it should be nearly the same.
7. To confirm this open-loop speed estimator, try different values of SpeedRef.

While running this build, the current waveforms in the CCS graphs should appear as shown in [Figure 23](#).



**Figure 23. Estimated d and q Fluxes With Estimated Theta and Phase A Current Waveform**



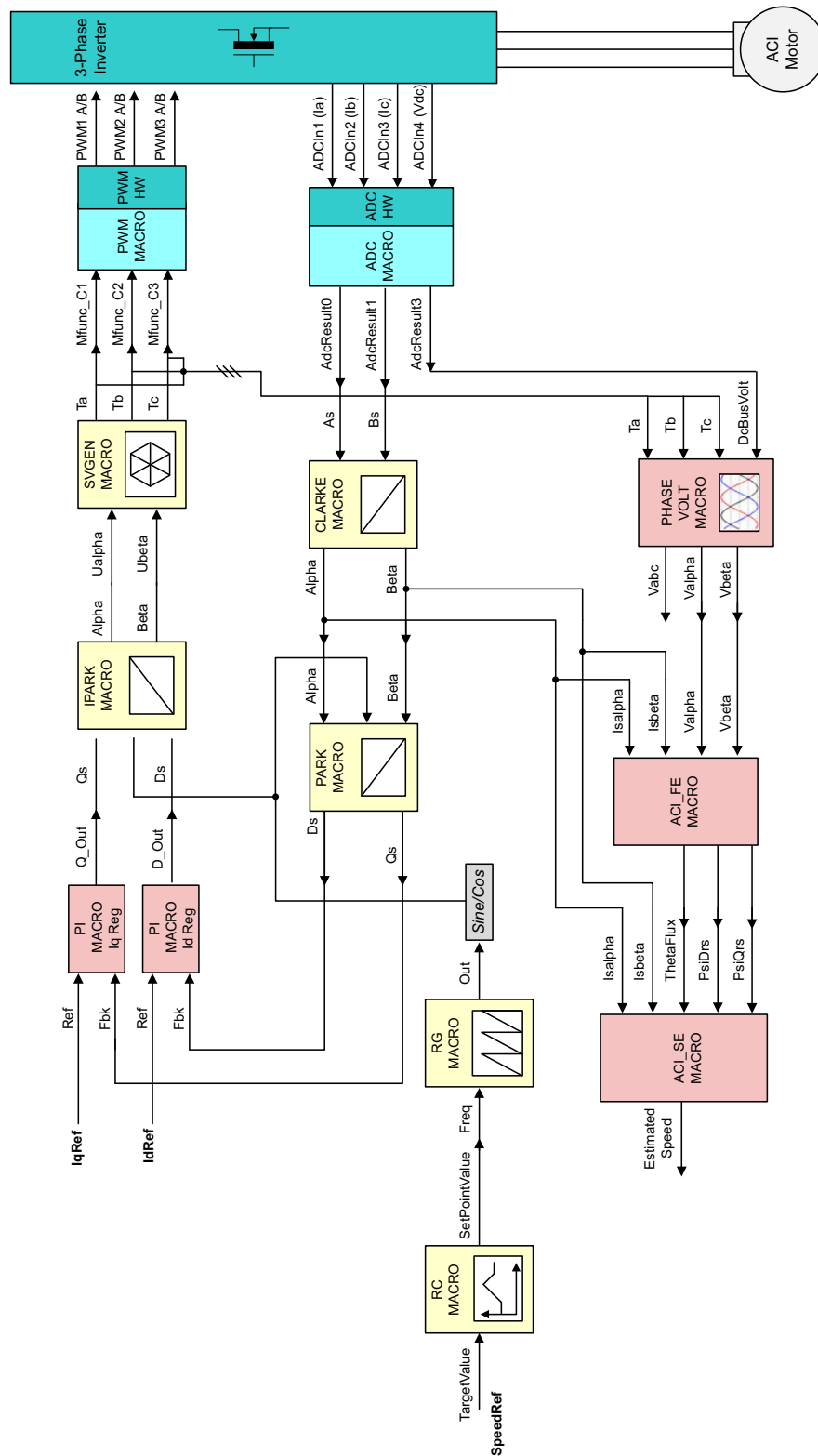


Figure 24. Level 4 — Incremental System Build Block Diagram

Level 4 verifies the flux and speed estimation performed by ACI\_FE and ACI\_SE.

## 8.11 Level 5 Incremental Build

Assuming the previous section is completed successfully, this section verifies the speed regulator performed by PI module. The system speed loop is closed by using the measured speed as a feedback.

1. Open {App Name}\_CLA-Shared\_C.h and select level 5 incremental build option by setting the BUILDLEVEL to LEVEL5 (#define BUILDLEVEL LEVEL5).
2. Right-click on the project name and click Rebuild Project.
3. When the build is complete:
  - (a) Click on the debug button.
  - (b) Reset CPU and restart.
  - (c) Enable Real-time mode and run.
  - (d) Set "EnableFlag" to 1 in the watch window. The variable named "IsrTicker" will be incrementally increased as seen in watch windows to confirm the interrupt working properly.

The key variables to adjust are:

- SpeedRef (FLOAT): for changing the rotor speed in per-unit.
- IdRef (FLOAT): for changing the d-qxis voltage in per-unit.

The speed loop is closed by using measured speed. The motor can spin only one direction when the measured speed (from capture driver) does not give information about the direction like QEP-based speed measurement. Therefore, if the speed sensor is not an incremental encoder, the SpeedRef is required to be positive. The key steps are:

1. Compile, load, and run the program with real-time mode.
2. Set SpeedRef to 0.3 pu (or another suitable value if the base speed is different).
3. Set Isw to 1. Gradually increase voltage at variac / dc power supply to get an appropriate DC-bus voltage and now the motor is running with this reference speed (0.3 pu).
4. Compare se1.WrHat with SpeedRef in the watch windows with continuous refresh feature whether or not it should be nearly the same.
5. To confirm this speed PI module, try different values of SpeedRef (positive or negative). For speed PI controller, the proportional, integral, derivative and integral correction gains may be retuned to have the satisfied responses.
6. At very low speed range, the performance of speed response relies heavily on the good rotor flux angle computed by flux estimator.
7. Bring the system to a safe stop as described at the end of build 1 by reducing the bus voltage, taking the controller out of realtime mode and reset.
8. Note that the IdRef is set to be constant at a certain value that is not too much for driving the motor. Practically, you can calculate IdRef from the rated flux condition and follow a flux weakening profile at high speed region.

---

**NOTE:** Using scheme 5B is recommended until completing the loop-tuning process to achieve smooth start-up. This scheme employs a soft loop-switch in the code for sensorless speed loop transient. For this purpose, add soft-switch variable "Isw" to watch window and set "Isw" to 1 in order close the speed loop. Each time close the speed loop earlier manually from watch window until achieving direct sensorless start-up.

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While running this build, the current waveforms in the CCS graphs should appear as shown in [Figure 25](#).

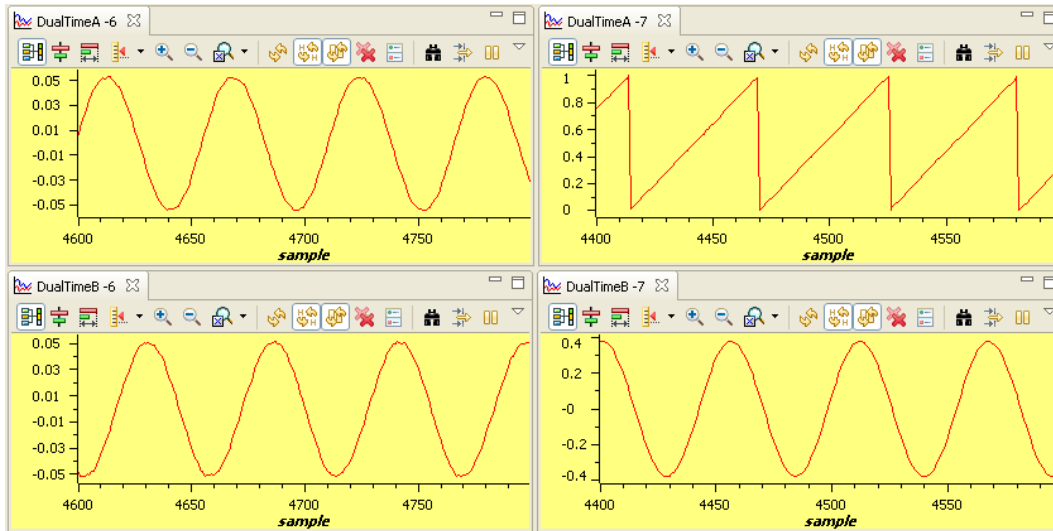


Figure 25. Phase A and B Current With Estimated Theta and Phase A Voltage Waveforms

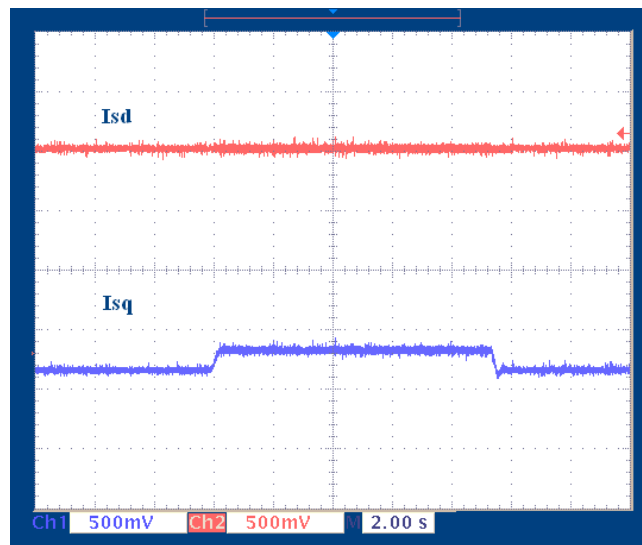


Figure 26. Flux and Torque Components of the Stator Current in the Synchronous Reference Frame

The flux and torque components of the stator current in the synchronous reference Frame under 1.0 pu step-load and 0.3 pu speed monitored from PWM DAC outputs.

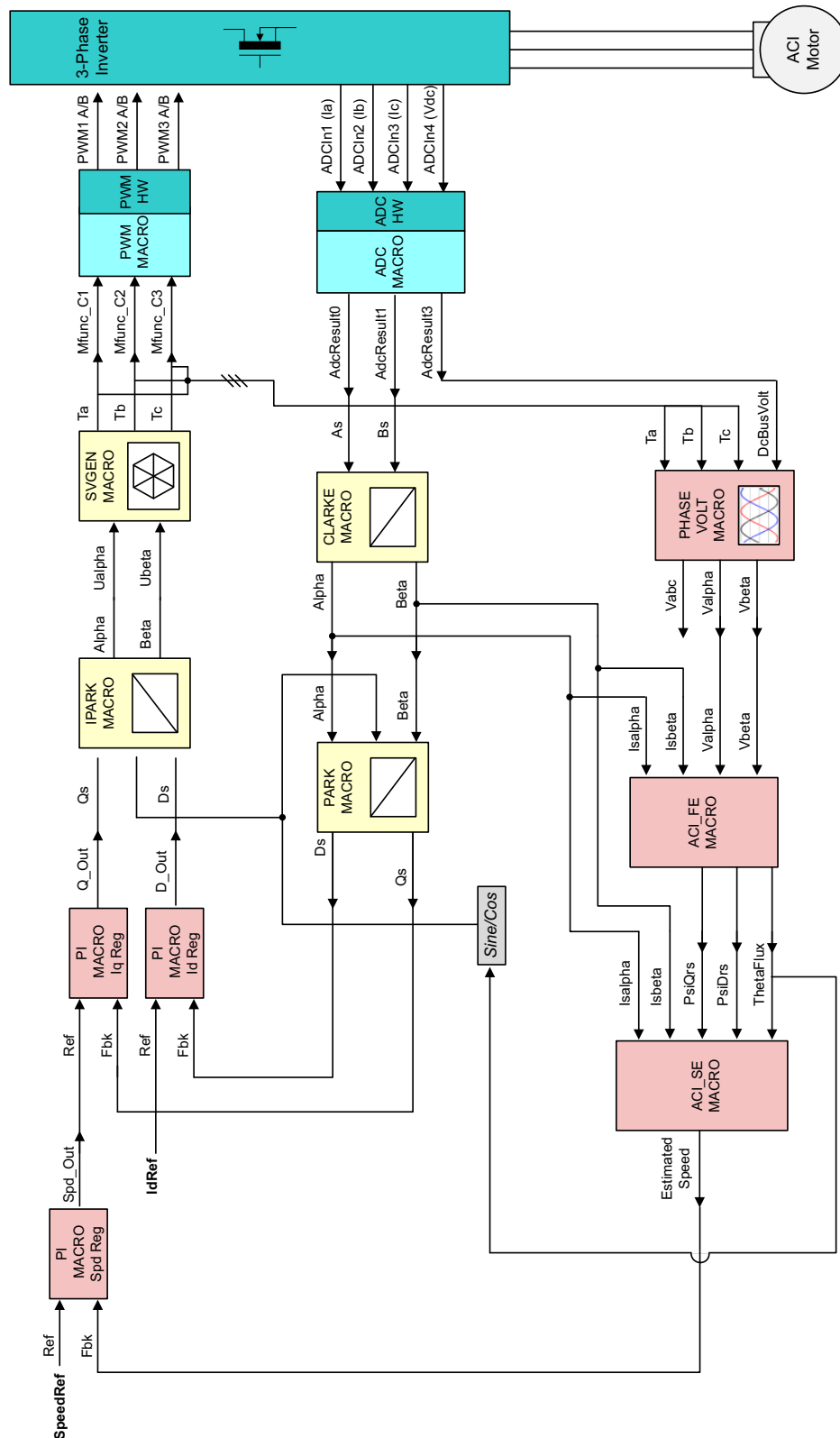


Figure 27. Level 5A — Incremental System Build Block Diagram

Level 5 verifies the speed PI module and estimated theta (lsw=1).

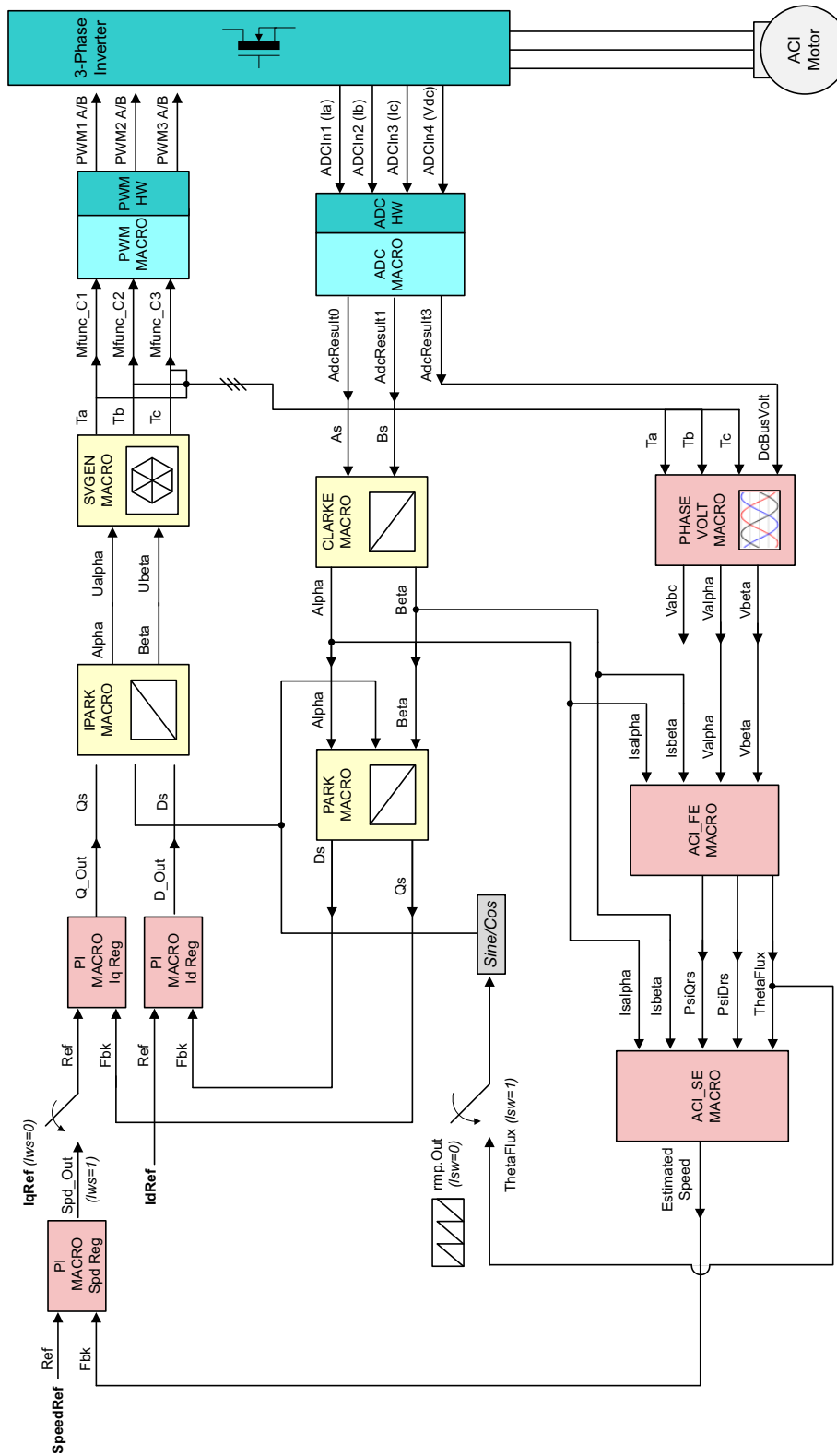


Figure 28. Level 5B — Incremental System Build Block Diagram

Level 5 verifies the estimated theta.

## 9 References

- *Using PWM Output as a Digital-to-Analog Converter on a TMS320F280x Digital Signal Controller* ([SPRAA88](#))

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