Attention

For additional information or use requests, please contact Jim Beneke at Avnet (jim.beneke@avnet.com)

FPGA-based Motor Control

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Course Objectives

- **Understand the challenges of designing integrated motor control applications**
- **Learn how Xilinx® FPGAs are used with partner analog solutions to increase performance and lower cost**
- **Explore the new Spartan-6 Motor Control Kit**
- **Discover Xilinx 7 series benefits for motor control**
- **Preview motor control IP and development tools**

Agenda

- Market Requirements and Challenges
- Motor Control Concepts
- Xilinx FPGAs for Motor Control
- Targeted Design Platform, Reference Designs & IP
- Demo Preview
- Closing Comments

Agenda

- **Market Requirements and Challenges**
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Who Uses FPGAs for Motor Control?

- **Industrial**
  - Industrial servos & drives
  - Manufacturing, assembly & automation
- **Transportation**
  - Power efficient drives
- **Medical**
  - Diagnostic (MRI, CAT, PET)
  - Automated test & analysis
  - Surgical assist robotics
  - Laser positioning
- **Integrated Applications**
  - Video surveillance & machine vision
  - ATM / Cash vending machines
  - Multi-motor synchronous control

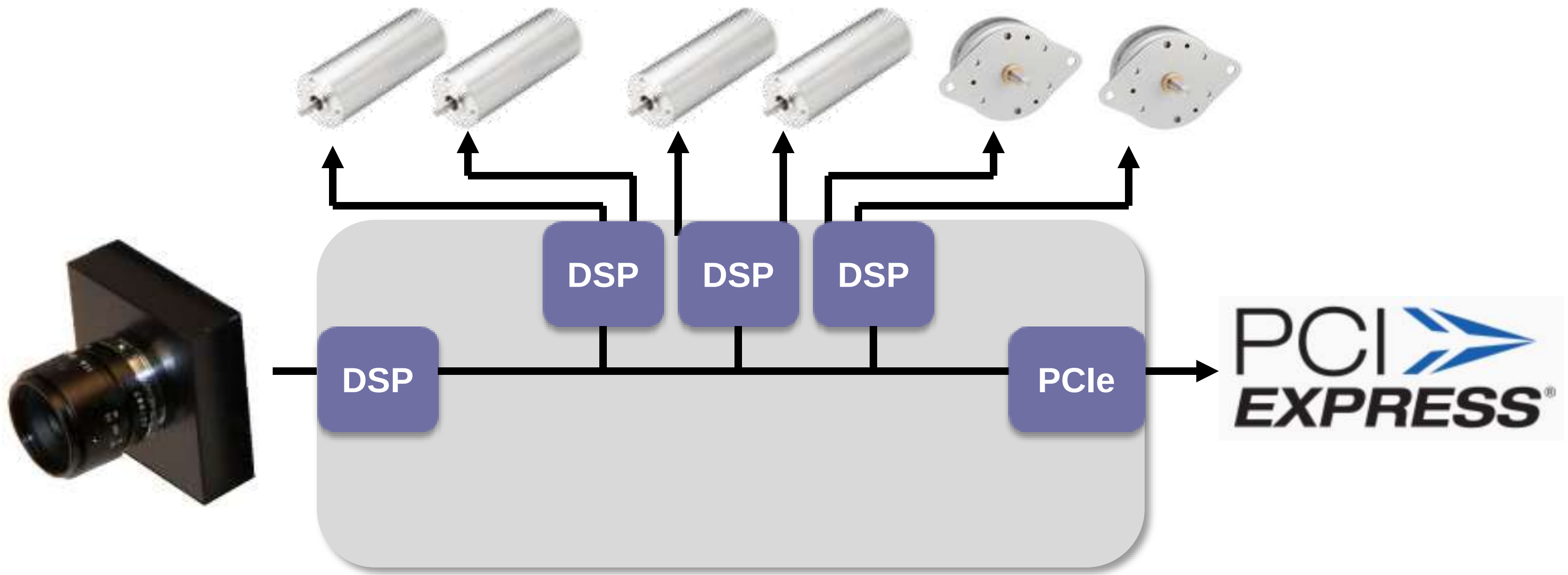
Challenges of Motor Control

- Accurately determining rotor speed/position without sensors or expensive encoders
- Delivering precise torque with PWM techniques
- Extracting extra performance from low cost motors
- Supporting multiple motors and motor types from one hardware platform
- Maintaining performance as motors are added to the system
- Real-time motion control for multi-axis systems
- System communication and synchronization

Why Use FPGAs for Motor Control?

- **Wider integration capabilities**
  - Industrial networking (Real-time Ethernet, CAN, PCIe)
  - Multiple motors and motor types
  - Custom interfaces and logic (i.e. camera sensors)
- **Higher Performance**
  - Parallel processing capabilities reduce latency
  - Real-time functions are deterministic in FPGA fabric
- **Reduced Total Cost of Ownership (TOC)**
  - Increase power efficiency by advanced modulation schemes (Space Vector Modulation, RPFM)
  - Eliminate encoder cost using Sensorless Field Oriented Control (SFOC)
  - Reduce board BOM by integration of industrial networking
  - Reduce motor BOM by using low cost Stepper instead of BLDC or PMSM

FPGA Integration Advantage

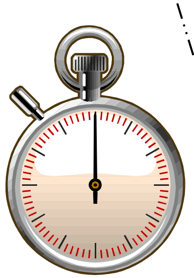


- **Traditional Solution**
  - Multiple DSP devices to control motors
  - Dedicated camera/video DSP
  - PCIe interface chip
- **Xilinx FPGA Solution**
  - Single Spartan-6 FPGA integrates all functions

FPGA Performance Advantage

XILINX SPARTAN 6

FPGA:
2.5us



MCU:
55-100us

+15x faster control loop means better precision, greater performance and higher efficiency

Clarke Transform:
Convert phase currents from 3-axis to 2-axis

ParkTransform:
Convert to rotating coordinate system

Slide Mode Controller:
Estimate motor position and speed

PI Controllers:
Estimate and correct error in speed & torque

Inverse Park Transform:
Convert rotating to stationary coordinates

Inverse Clarke Transform:
Convert 2-axis to 3-axis

Power Modulation:
PWM, SVM, RPFM

ADC

Sensorless Field Oriented Control

Drive Stage

Agenda

- Market requirements and challenges
- **Motor control concepts**
- Xilinx FPGAs for Motor Control
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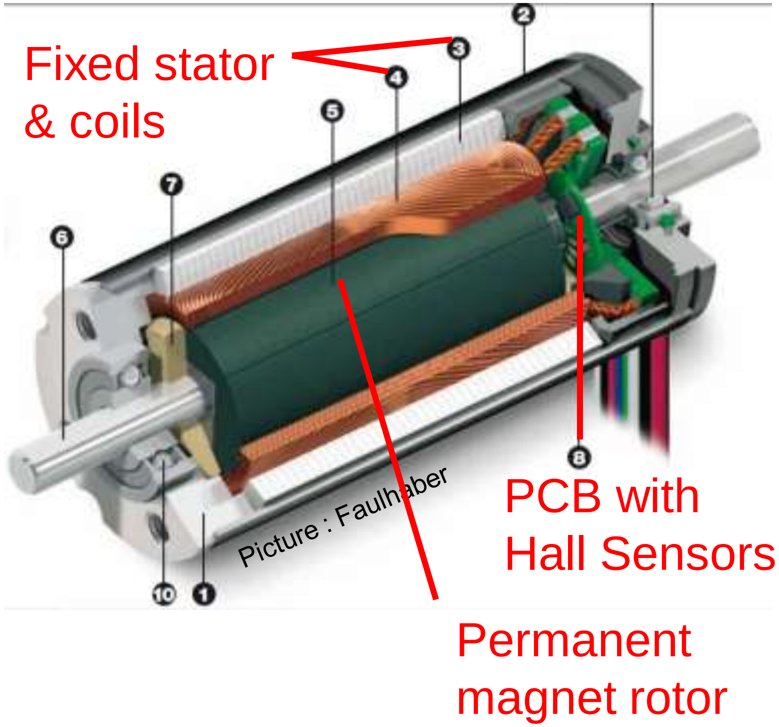
Types of DC Motors

- **Stepper**
  - Very low cost
  - Easy to control with open loop
  - Excellent holding torque
  - Undesirable cogging, unless modulation techniques are used
- **Brushed DC (BDC)**
  - Easy to spin
  - Short lifespan and high EMI
  - Not safe for all environments
- **Brushless Permanent Magnet**
  - Relatively higher cost
  - Robust
  - Require rotor position in order to control
  - Brushless DC (BLDC)
  - Permanent Magnet Synchronous Motors (PMSM)

Brushless PM Motor



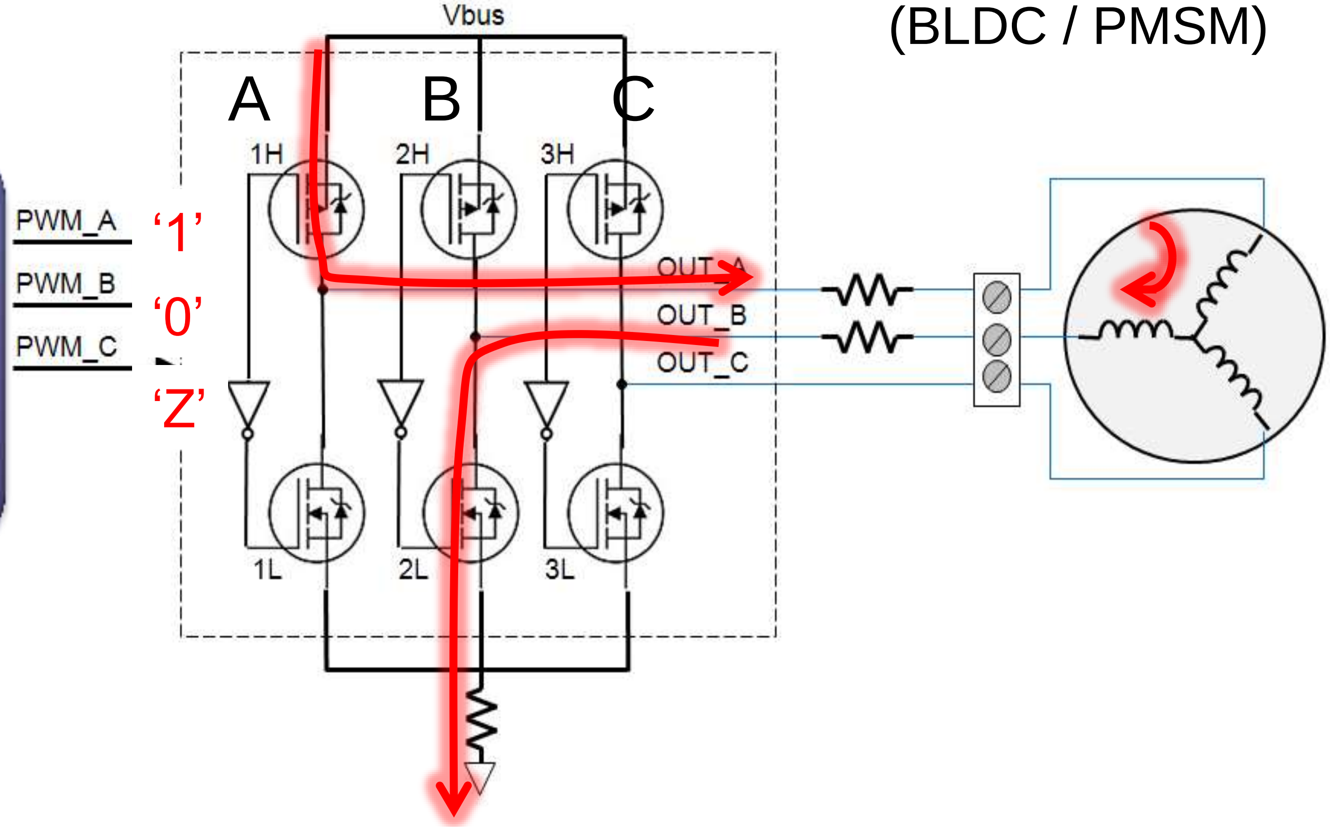
Typical 3-phase Brushless Drive

Controller

- Acquire & Filter
- Control
- Modulate
- Synchronize
- Network & IO

Half-bridge Drive

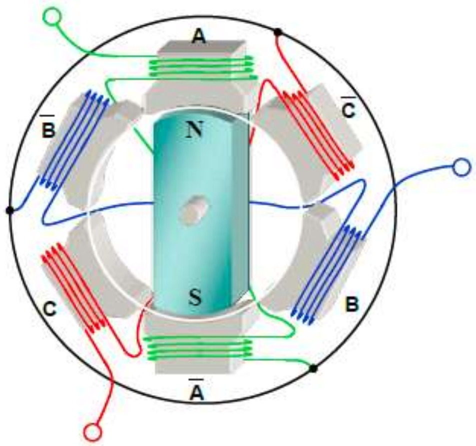
3-phase Motor
(BLDC / PMSM)

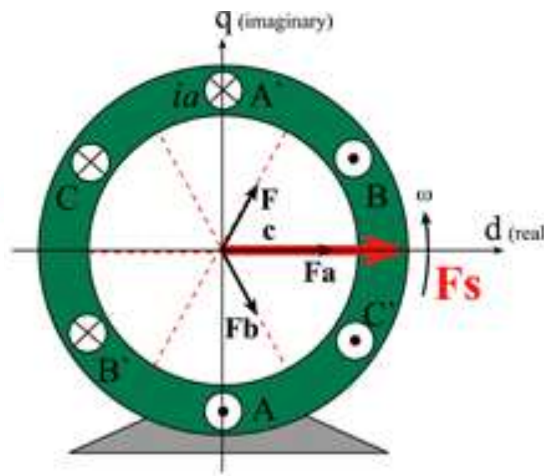


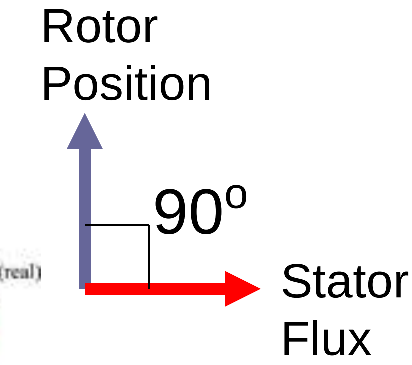
- FPGA commands PWM signals via FET gate driver ICs
- Galvanic or opto-isolation added for high power drives

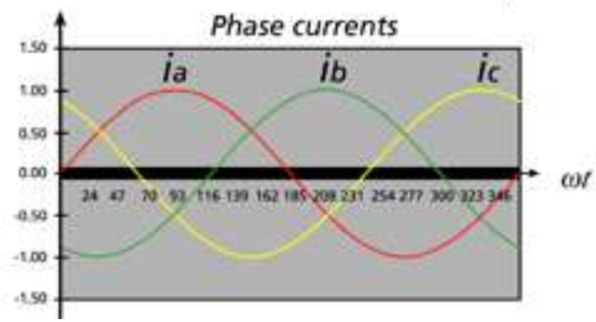
Generating a Rotating Field

Image: Wikipedia



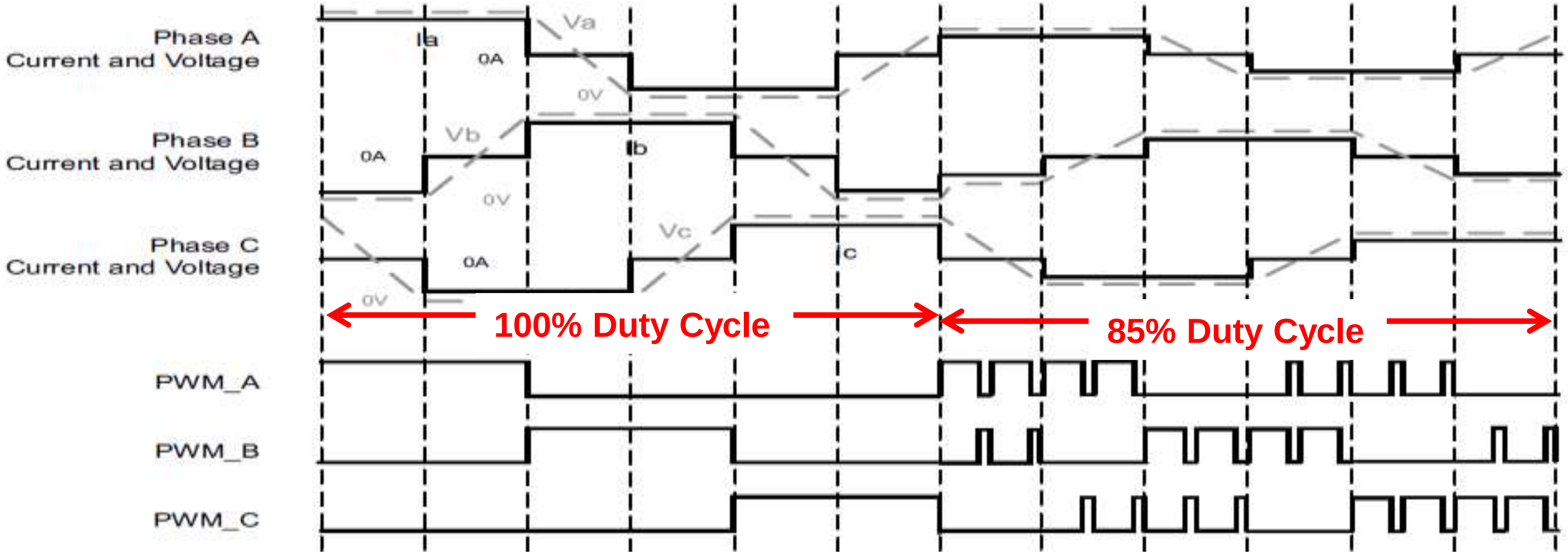






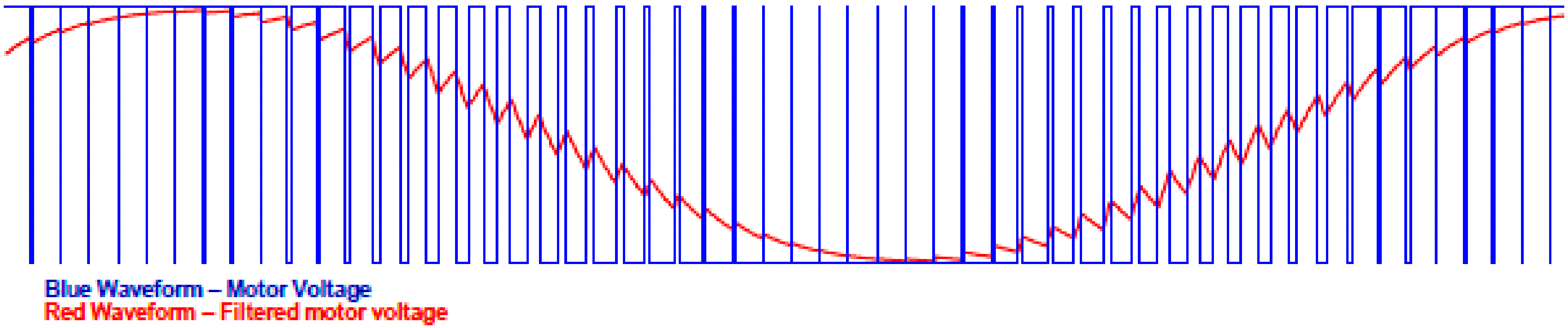
- **Alternating currents in stator windings cause rotating field in stator**
- **Rotor with permanent magnet follows rotating field**
- **Maximum torque when magnet flux angle is 90° from rotor**

6 State PWM Modulation (3-phase)



- **Drives two states per winding (on/off)**
  - 60 degrees phase shifted
  - Creates torque ripple (less smooth rotation)
- **Easily implemented with simple PWM techniques**

Sinusoidal Modulation

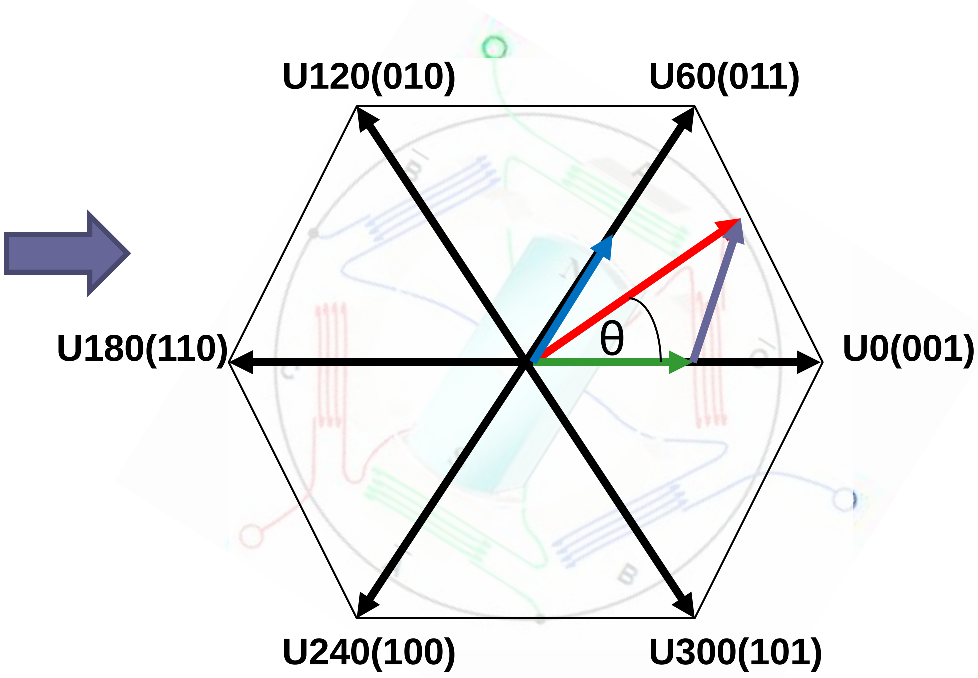


- **Use PWM to approximate a sinusoid**
- **Motor inductance filters binary pulses to create an averaged waveform**
- **Results in less torque ripple**
  - Smoother operation
  - Longer motor life
- **More complex waveforms achievable using Space Vector Modulation (SVM) techniques**

Space Vector Modulation (SVM)

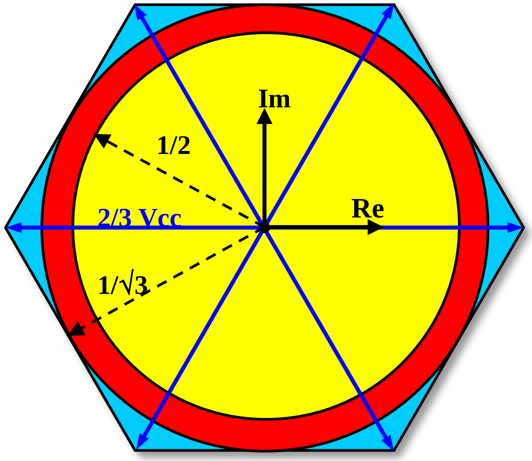
- **Map the h-bridge state table into vectors**
- **Drive adjacent vectors to make composite field vector**

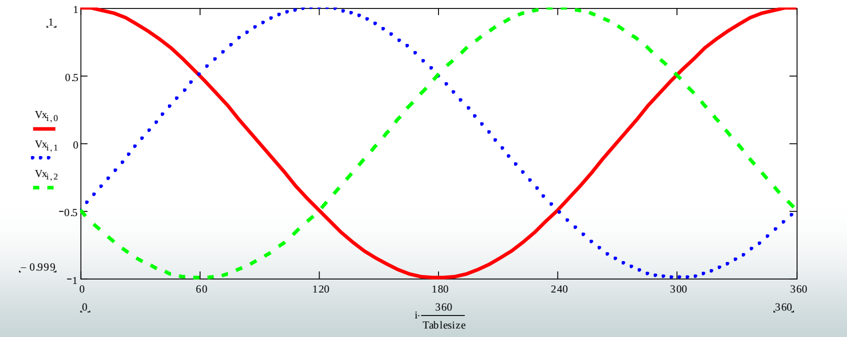
A	B	C	
0	0	0	null state
0	0	1	U0
0	1	0	U120
0	1	1	U60
1	0	0	U240
1	0	1	U300
1	1	0	U180
1	1	1	null state



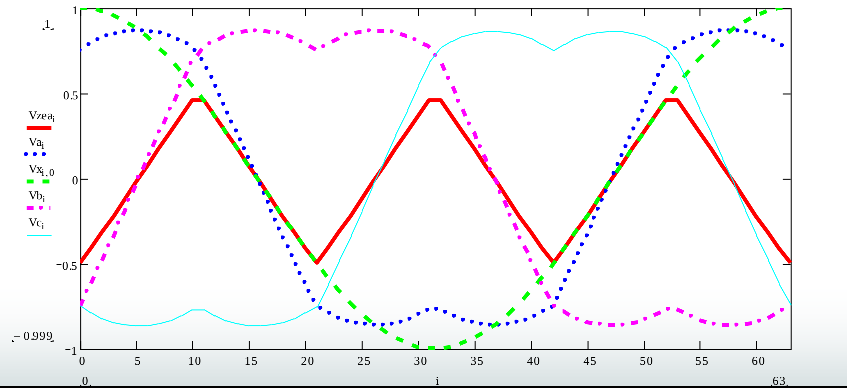
Modulation Efficiency Comparison

- **Simple PWM → 2Vdc/3**
- **Sinusoidal → Vdc/2**
- **SVM → Vdc/√3**
  - Greater efficiency
  - Low torque ripple





Voltage Waveforms of Sine Modulation

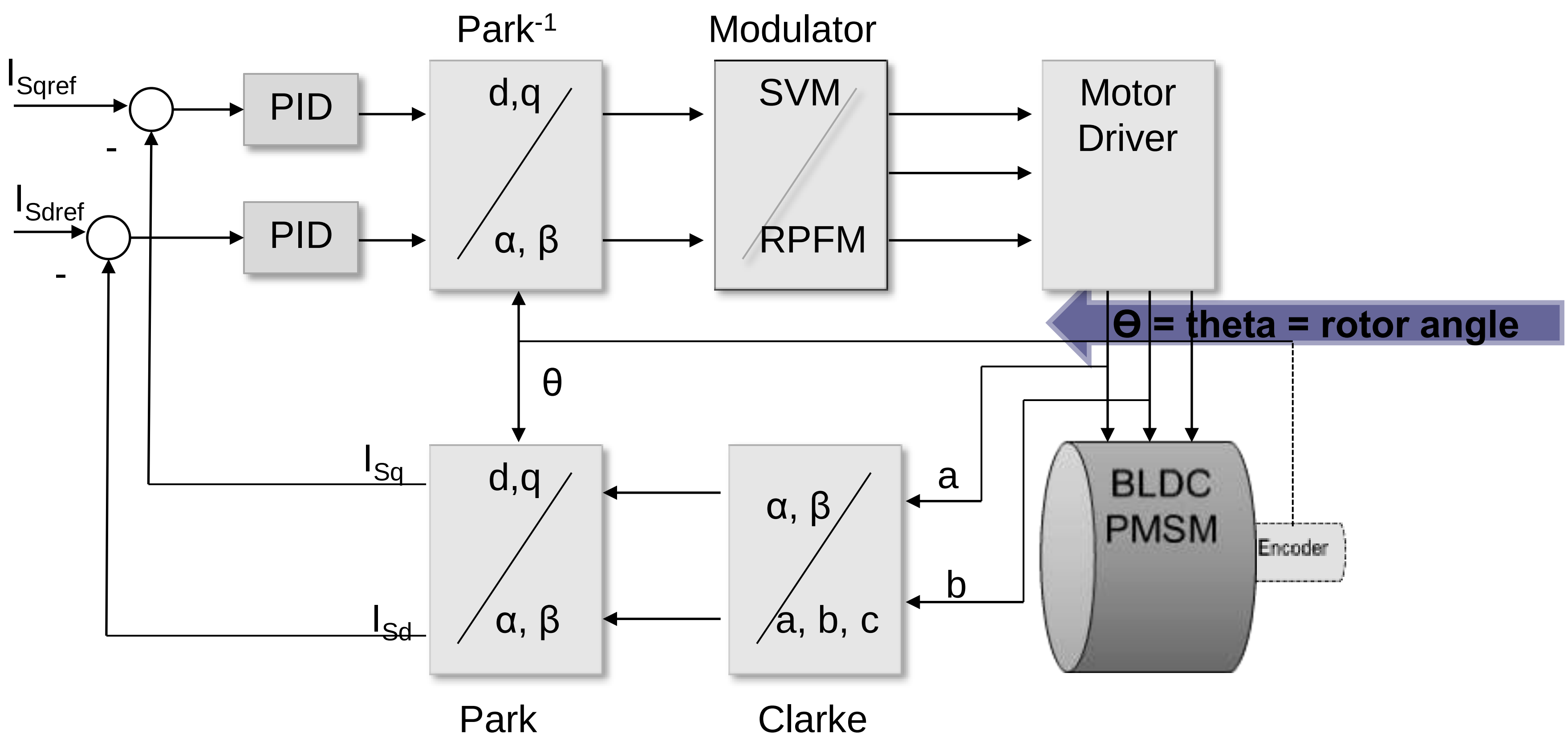


Voltage Waveforms of Space Vector Modulation

Modulation vs. Control

- **Modulation**
  - Determines voltage waveform delivered to the motor
  - Simplest is Pulse Width Modulation (PWM)
  - Space Vector Modulation (SVM) based on sinusoids
  - FPGA creates complex waveforms, easily changed on-the-fly
- **Control**
  - Speed, position and torque can be controlled
  - Field Oriented Control (FOC) used to precisely regulate torque
  - Add PID loops to control speed / position
  - FPGA has huge performance advantage

Field Oriented Control System



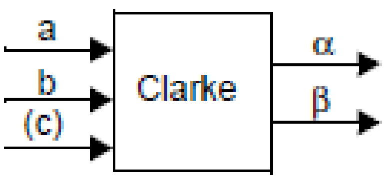
Measure Theta = FOC

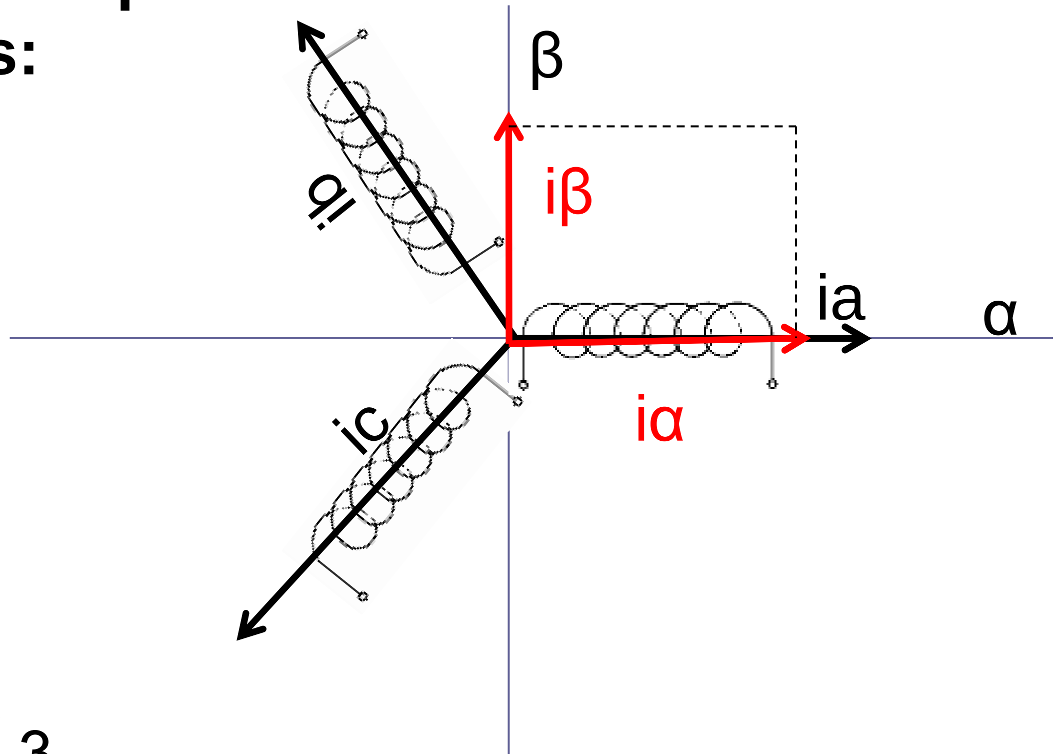
Estimate Theta = SFOC

Determining Rotor Position (θ)

- **Sensors**
  - Hall sensors detect the position of the permanent magnet in the rotor relative to the stator windings
  - Rotary encoders detect the position of the rotor
    - Absolute position
    - Relative position (incremental)
  - Resolvers generate sine / cosine relative to position
- **Sensorless**
  - BEMF Detection
    - Various approaches to detect rotor position by measuring BEMF voltage
      - Example: determine BEMF in un-driven stator winding
  - Observer
    - Measure stator current and compare against motor model (observer)
    - Measure stator voltage

- **Field Oriented Control (FOC) = Controlling the stator currents in a motor for torque regulation**
- **Mapping three phase stator currents into two dimensions:**





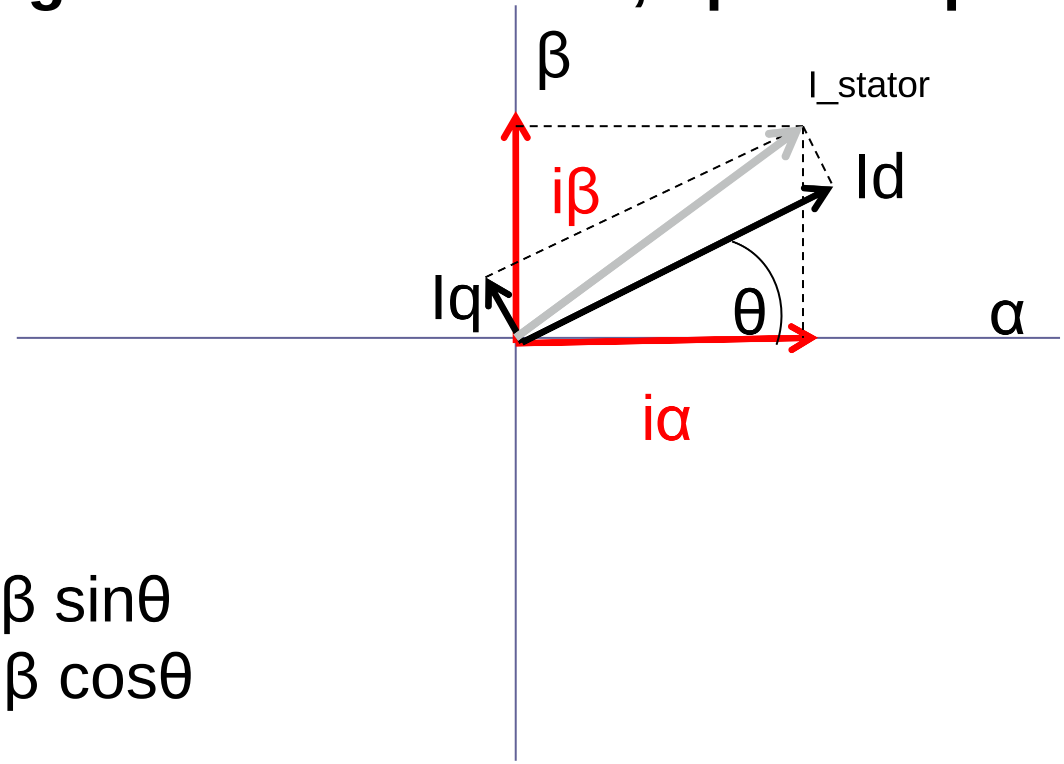
$ia + ib + ic = 0$

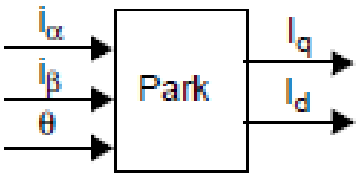
$i\alpha = ia$

$i\beta = (ia + 2ib)/\sqrt{3}$

Field Oriented Control - Park

- **Mapping the two phase orthogonal system (α,β) into the d,q rotating reference frame**
- **Id axis is aliged to the rotor flux, Iq axis represents torque**

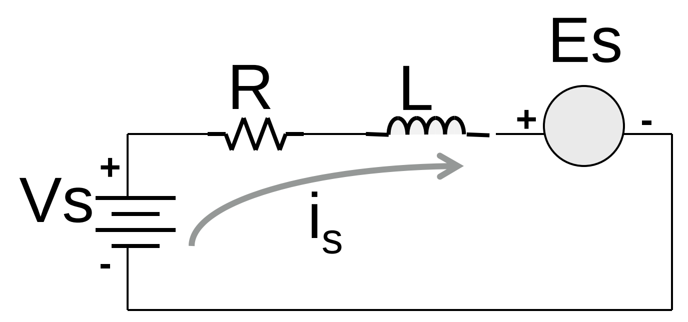




$$Id = i\alpha \cos\theta + i\beta \sin\theta$$
$$Iq = -i\alpha \sin\theta + i\beta \cos\theta$$

Slide Mode Current Observer & Controller

- **Motor electrical model has several components**
  - ✓ Resistance (datasheet)
  - ✓ Inductance (datasheet)
  - – BEMF voltage (Es - unknown)
  - ✓ Phase current (measured)
  - ✓ Bus voltage (measured)

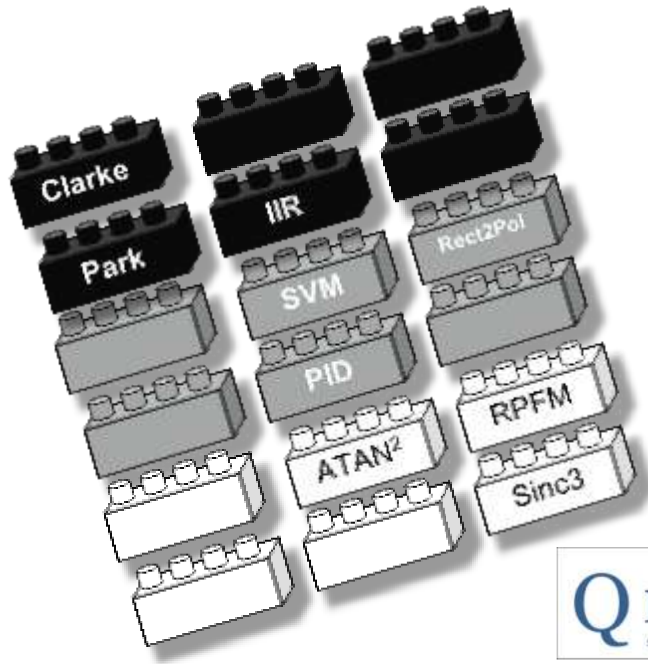


Simple Motor Model

- **Mathematical model estimates the unknown BEMF**
- **An "observer" is used to correct the model**
- **This non-linear control model requires tuning & expertise**

Xilinx Motor Control Library

- **15 Unique Building Blocks**
- **Easy Plug-and-Play Configuration**
- **Parallel processing for each motor control path**
- **Accelerated computations using Xilinx DSP48 slices**
  - 48-bit operations
  - 18-bit precision
  - Interpolated Sin/Cos/Atan2



Fully Documented IP

Agenda

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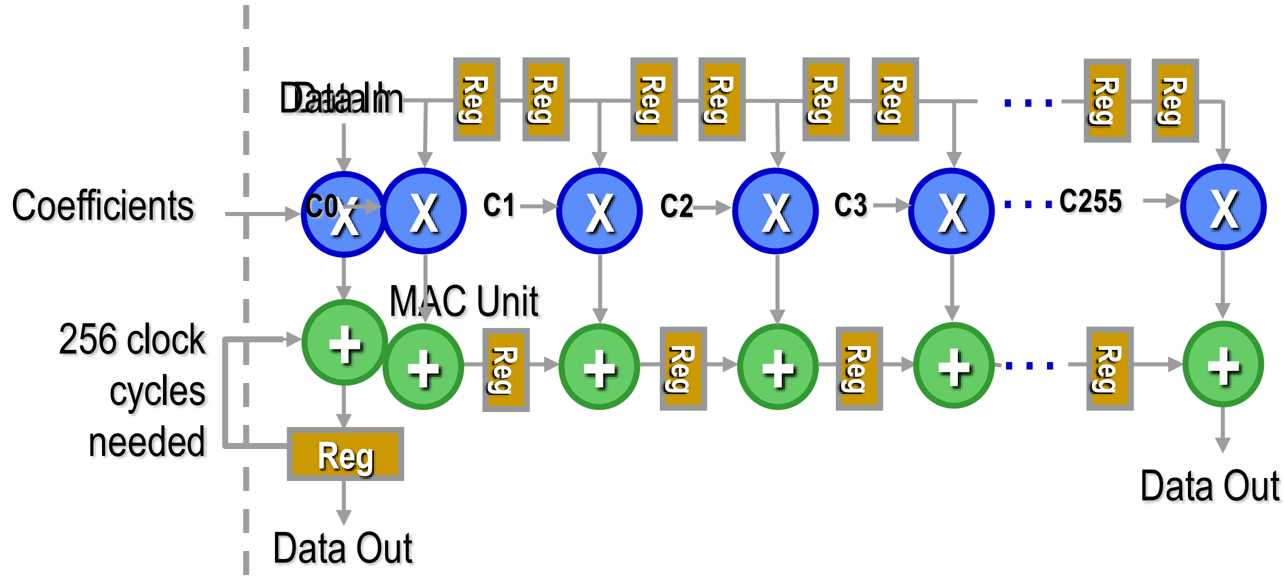
Power of Parallel Processing

Programmable DS FPGA - Fully Parallel Implementation

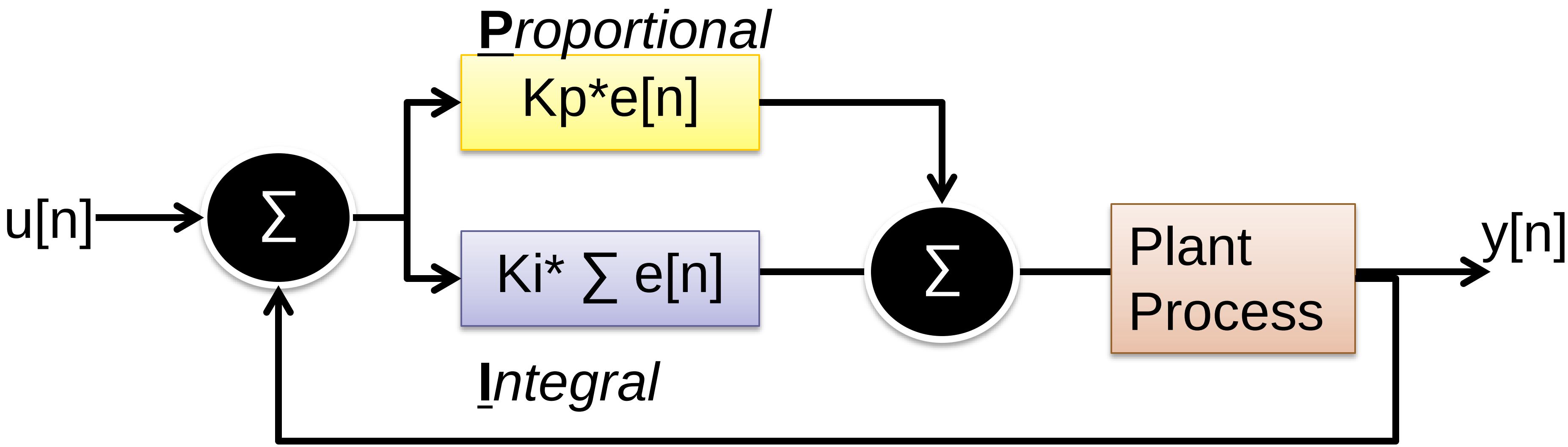


$\frac{\text{1 GHz}}{\text{256 clock cycles}}$

$\frac{\text{400 MHz}}{\text{1 clock cycle}}$ = 400 MSPS

256-tap filter implementation is 100 times faster

PI Controller with DSP48E1



$$y[n] = Kp*e[n] + Ki \sum e[n]$$

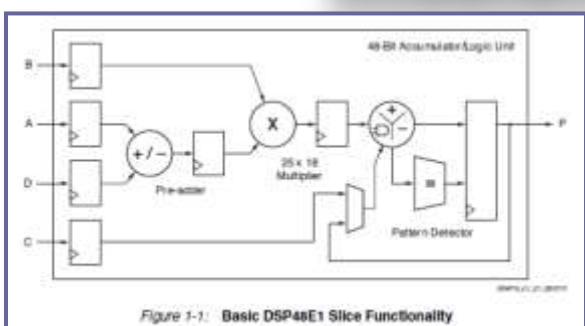
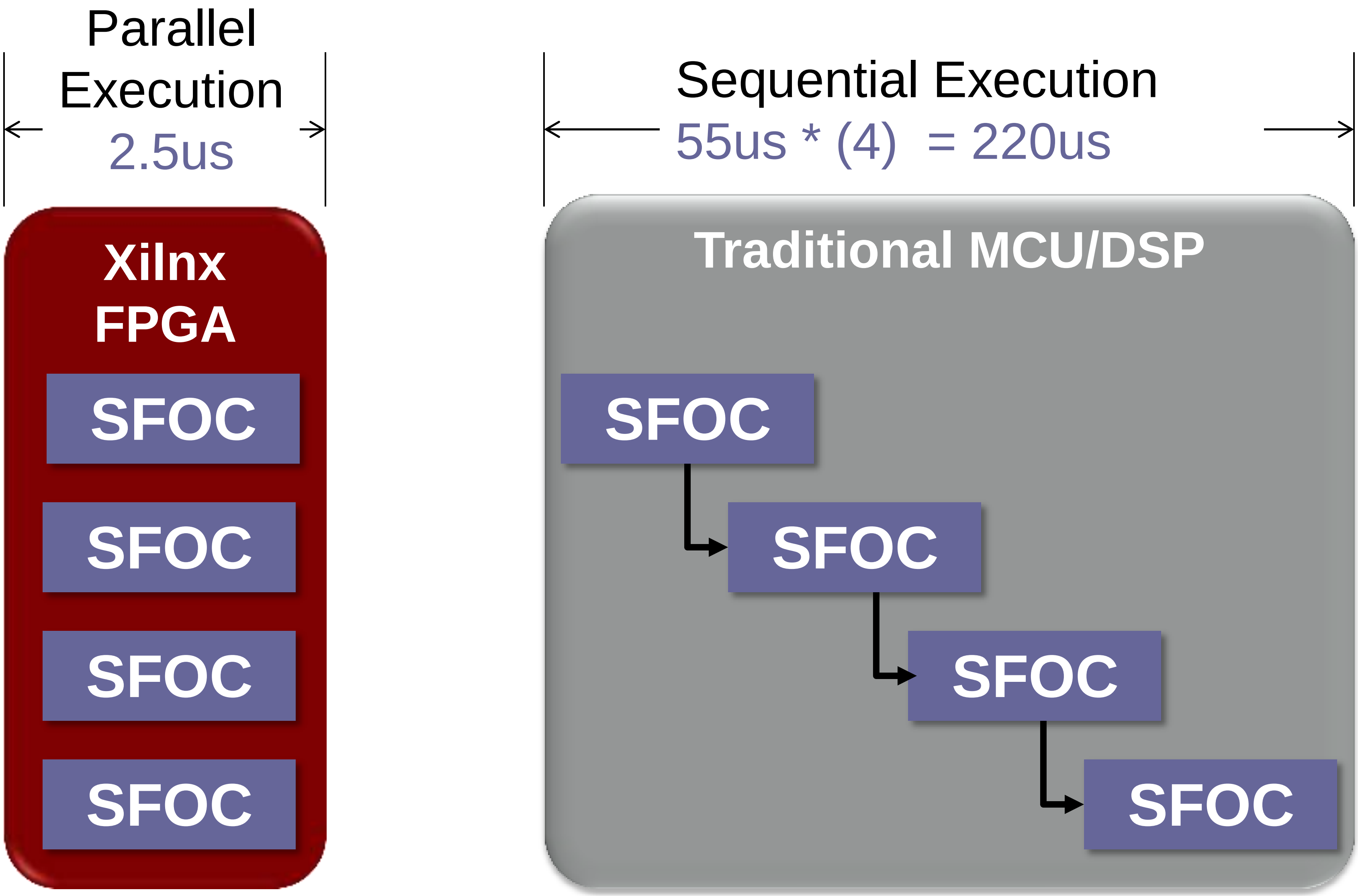


Figure 1-1: Basic DSP48E1 Slice Functionality

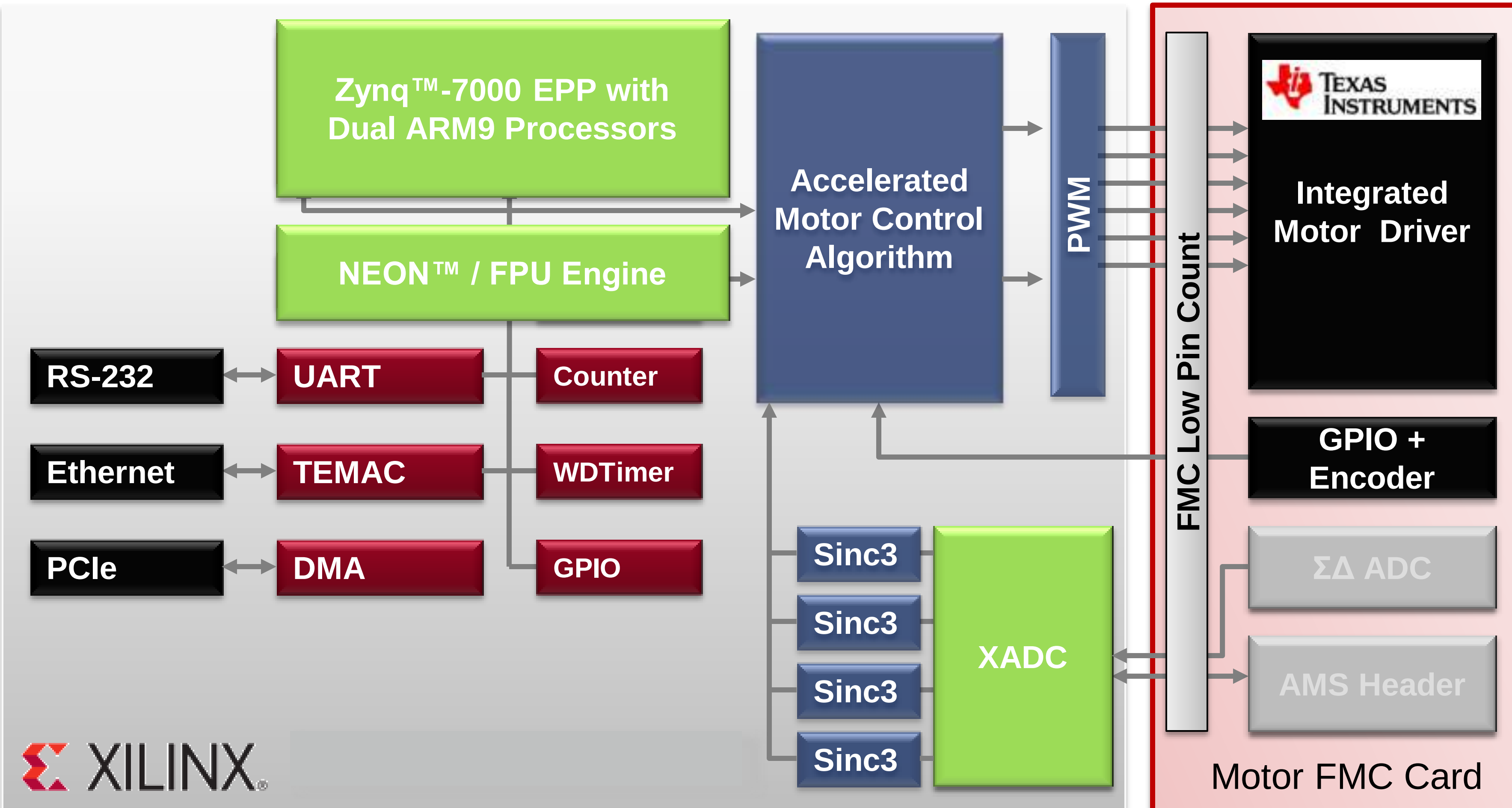
132 in Spartan-6 LX75T !!

- Xilinx DSP48 – dedicated ALU
- Many available in every device
- Fast parallel, deterministic paths
- 48-bit accumulators
- Floating point capable

FPGA Parallel Processing – Adding Control Loops Without Adding Latency



System Diagram with 7 Series FPGA

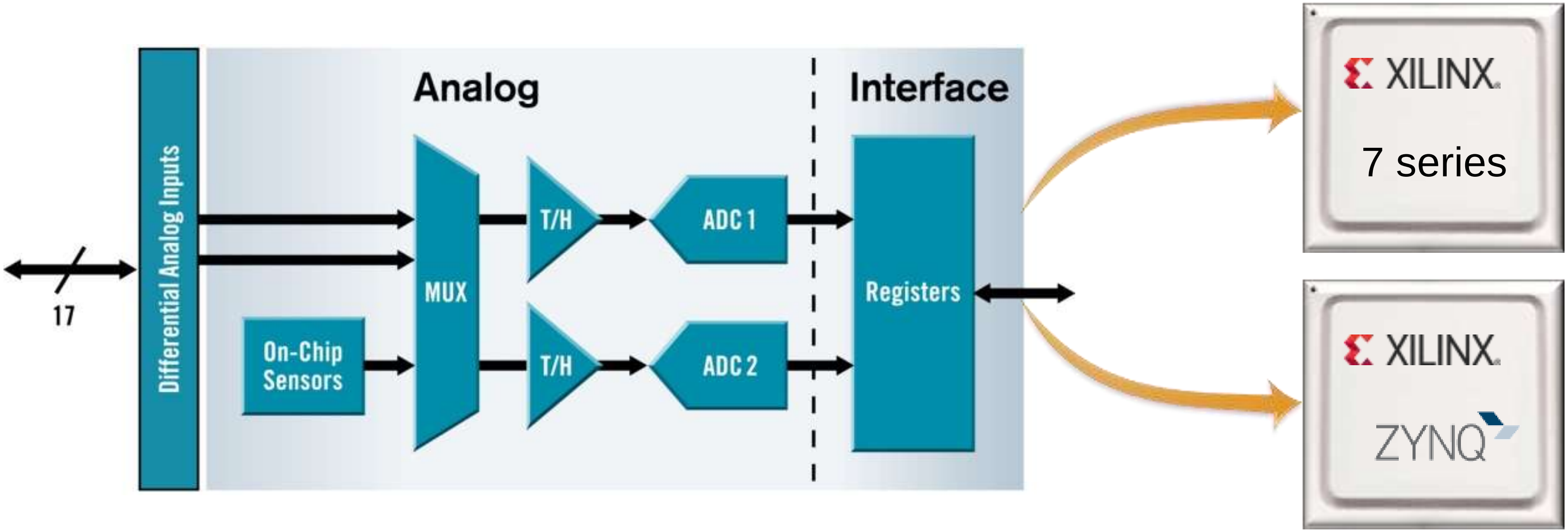


Xilinx Standard IP Library

7-series Features

Avnet Reference Design or Xilinx IP

Xilinx Agile Mixed Signal Integration



- **Flexible general purpose analog and interface**
  - Integrated with all 7 series FPGAs and Zynq
- **Dual 1Msps 12-bit ADC with 17-channel MUX**
- **Multiple modes and auto-sequencing options**
- **Embedded temperature and supply sensors**

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Spartan-6 FPGA Motor Control Kit

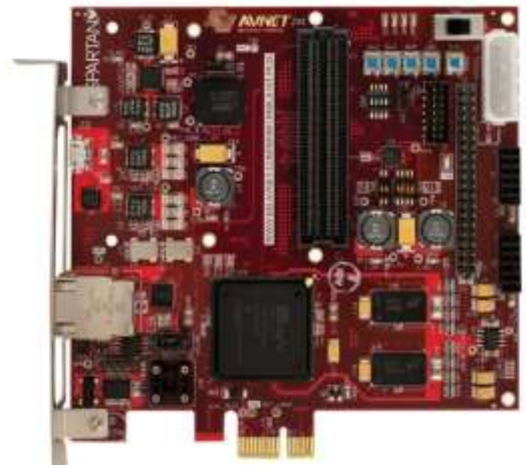
- **Hardware**
  – Avnet Spartan-6 LX75T baseboard
  – Avnet Motor Control FMC daughter card
  – Portescap Motors: 1 stepper, 1 BLDC
  – 12V power supply
- **Miscellaneous Cables**
  – USB A-mini-B Cable
  – Ethernet Cable
  – JTAG HS1 Programming Cable
- **Software Tools**
  – Xilinx ISE® Design Suite: System Edition, Device-locked to S6LX75T
- **Targeted Reference Designs**
  – Introductory Reference Stepper & BLDC Designs
  – VHDL Reference Design Tutorial
  – Xilinx Sensorless FOC Reference Design
- **Documentation**
  – Getting Started Guide
  – Downloadable Schematics, BOM, etc.

AES-S6MC1-LX75T-G
Price $1095 USD

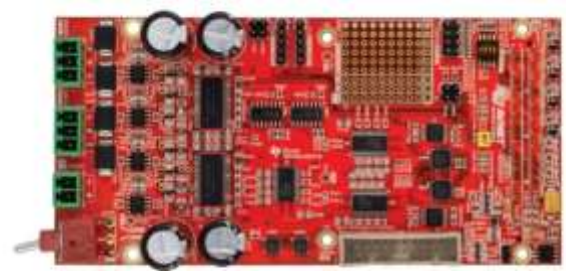
em.avnet.com/spartan6motor

Kit Features

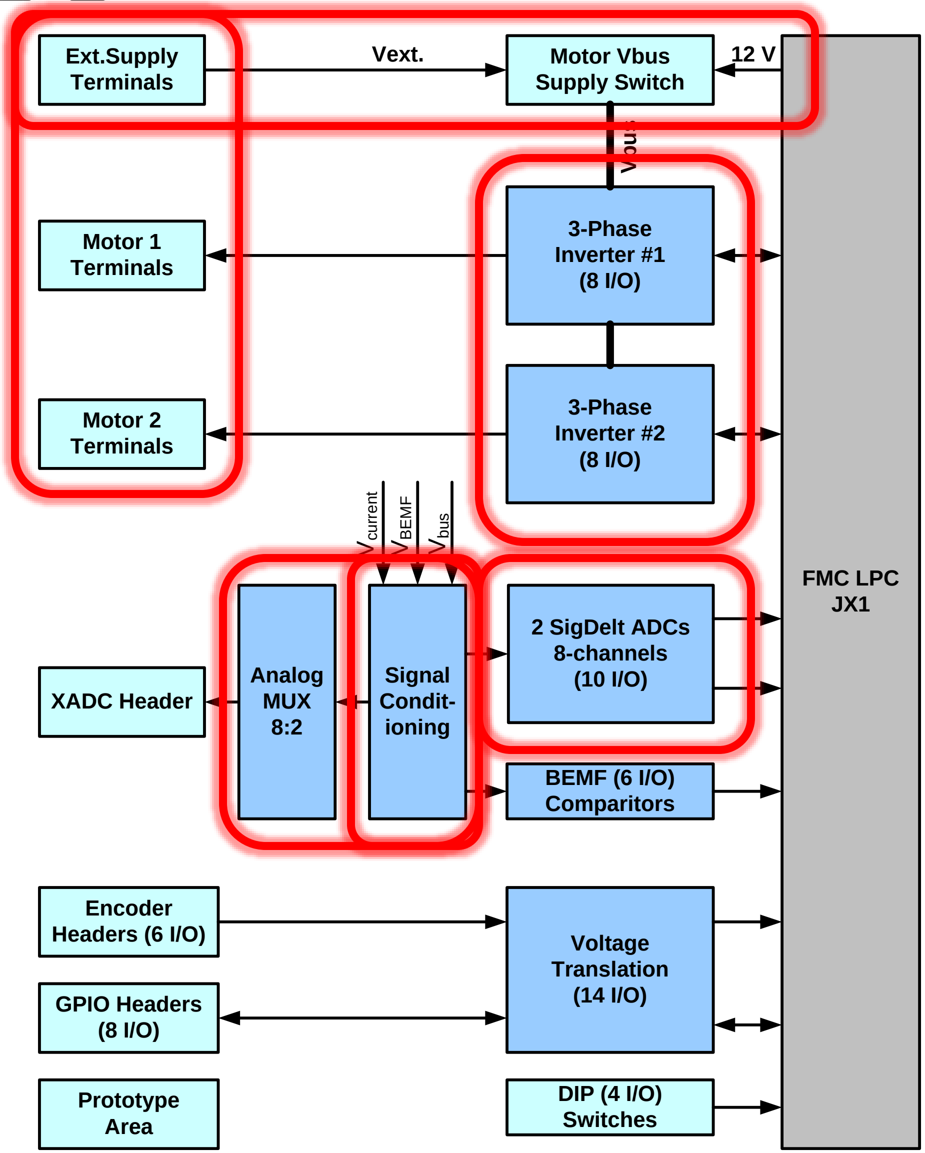
- **Avnet Spartan-6 LX75T carrier**
  - S6LX75T, 75K logic cells, 132 DSP48
  - 256 MB DDR3 SDRAM
  - 10/100 Ethernet PHY
  - PCIe x1 edge connector
  - PMOD expansion ports



- **Avnet Motor Control FMC**
  - Dual TI DRV8312 driving 2 motors simultaneously
    - Stepper
    - Brushed DC (BDC)
    - Brushless DC (BLDC) / PMSM
  - Dual TI ADS1204 Sigma-Delta ADC for high precision sensorless control algorithms
  - XADC header for low-cost 7 Series FPGA integration



Avnet Motor Control FMC Module



- FMC 12V or External Power

Texas Instruments

- Dual DRV8312 Integrated Motor Driver
- ADS1204 Sigma Delta Modulator
- THS4524 Differential OpAmp

Analog Devices

- AD8210 High CMRR Shunt Amp
- ADG759 Analog MUX

TE connectivity

- Compact flush-mount motor & power terminals

DRV8301 3-Phase Gate Driver

Features

- 3-phase gate driver
  - Supply voltage: 8 to 60V
  - Gate Drive Current: 1.7A source / 2.3A sink
  - Adjustable dead time/slew rate; 100% duty cycle
- Dual Bi-directional current shunt amplifiers
  - Adjustable gain (10, 20,40, 80) and offset (up to 3V)
  - DC Calibration
- Integrated buck converter
  - Up to 1.5A (3.5V to 60V) / RDSON of 200mR
- Fully protected
  - 2-stage thermal, CBC over current, UVLO, & shoot through protection with fault feedback
- SPI Management Interface

Benefits

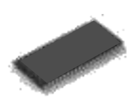
- Wide operating voltage and ability to drive up to 60A external FETs.
- Reduced board space and system cost; DC calibration allows MCU to adjust for DC offset & temperature drift
- Reduced board space and system cost; Buck can be used to power MCU and/or other systems power needs.
- Advanced on-chip protection reduces design complexity and enables higher system reliability
- Access detailed fault reporting and easily configure slew rate, sense amp gain & DC calibration, set overcurrent limit, etc via the SPI interface.

Applications

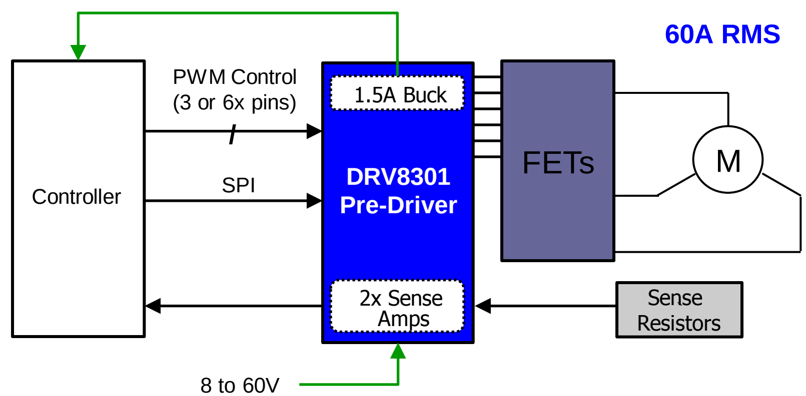
- Brushless DC & PMSM Motors
- Brushed DC (Use 2 of the 3 Half Bridges)

In Production

1K Pricing: $2.50



14 x 8.1mm, 56-pin HTSSOP package



DRV8312 3-Phase Motor Driver

Texas Instruments

Features

- The highest power heatsink-less drive on the market
  - Supply Voltage up to 52V (50V +/- 5%)
  - Output Current 3.5A RMS / 6.5A Peak (10ms)
- Advanced architecture with high efficiency up to 97%
  - PWM operation frequency up to 500kHz
  - Low Rdson MOSFETs (110mohm)
- Intelligent gate drive and cross conduction prevention
  - Short dead time (5ns)
  - Spike voltage control to reduce overshoot
- Integrated Protection Features
  - Short circuit and cycle-by-cycle current protection
  - Two stage thermal protection
- No External Snubber or Schottky Diode required

Benefits

- Minimized board space and design time while maximizing performance
- Ultra Low Rdson FETs and thermally efficient package with thermal pad allows for maximum heat dissipation without external heat-sinks
- High linearity of output signals to guarantee precise and smooth operation
- Advanced on-chip protection reduces design complexity and enables higher system reliability

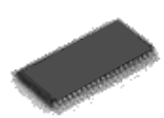
Applications

- Brushless DC Motors
- Permanent magnet synchronous motors

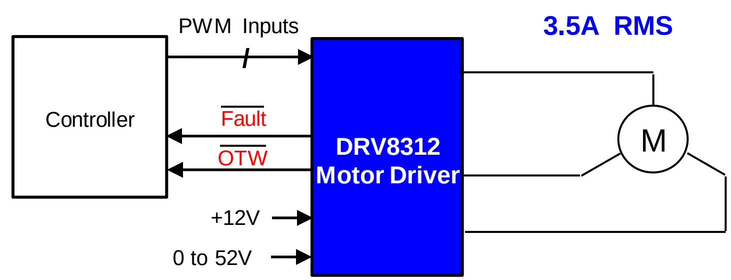
Calendar

In Production

1K Pricing: $3.30



14 x 8.1mm, 44-pin TSSOP, package (PP)



Sensing Small Signals in Large Noise

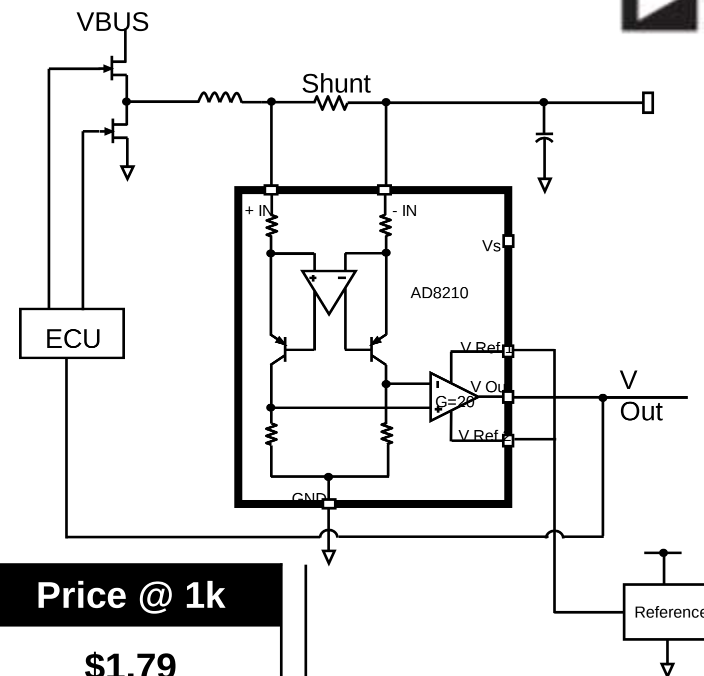
- **We want to measure stator currents**
  - Series 10mΩ shunt resistors
  - 100mA – 6A phase currents
  - 1mV – 60mV signal of interest (very small!)
- **Switching motor coils causes huge inductive spikes**
  - Quick but tall
  - > 3x bus voltage can be seen
- **Detecting the signal is challenging!**

AD8210 Current Sense Amplifier

ANALOG DEVICES

Key Features

- **Wide CMV Operating Range**
  - -2V to +65V (70V survival)
- **Fixed Gain of 20**
- **Sense Current In 1 or 2 Directions**
- **Voltage Out**
- **500kHz Frequency Range**
- **5MΩ Input Impedance**
- **Operating Temperature Range:**
  - SOIC: -40° C to +125° C



Price @ 1k
$1.79

Platforms

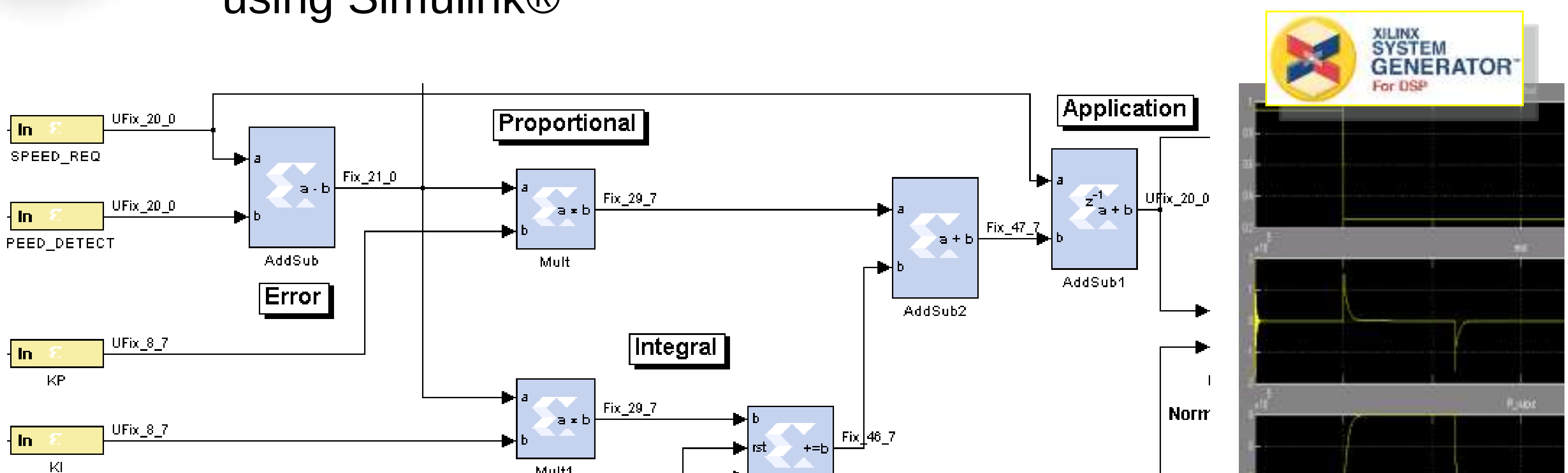
- Industrial and Automotive
  - Battery Charging
  - Motor Control
  - Industrial solenoid control
  - Switching Power Converter Control
  - Diagnostics

Key Specs

- Offset: ±1mV Max
- Offset Drift: 8μV/° C Max
- DC CMRR: 120 dB typ
- AC CMRR: 80dB Min up to 40kHz
- Gain Drift: 20ppm/° C

Avnet Motor Control Reference Designs

- **Avnet introductory "spin the motor" designs**
  - Stepper and BLDC
  - Hall Sensor & Sensorless 6-state speed control designs
  - Source HDL code and System Generator for DSP™ design, using Simulink®



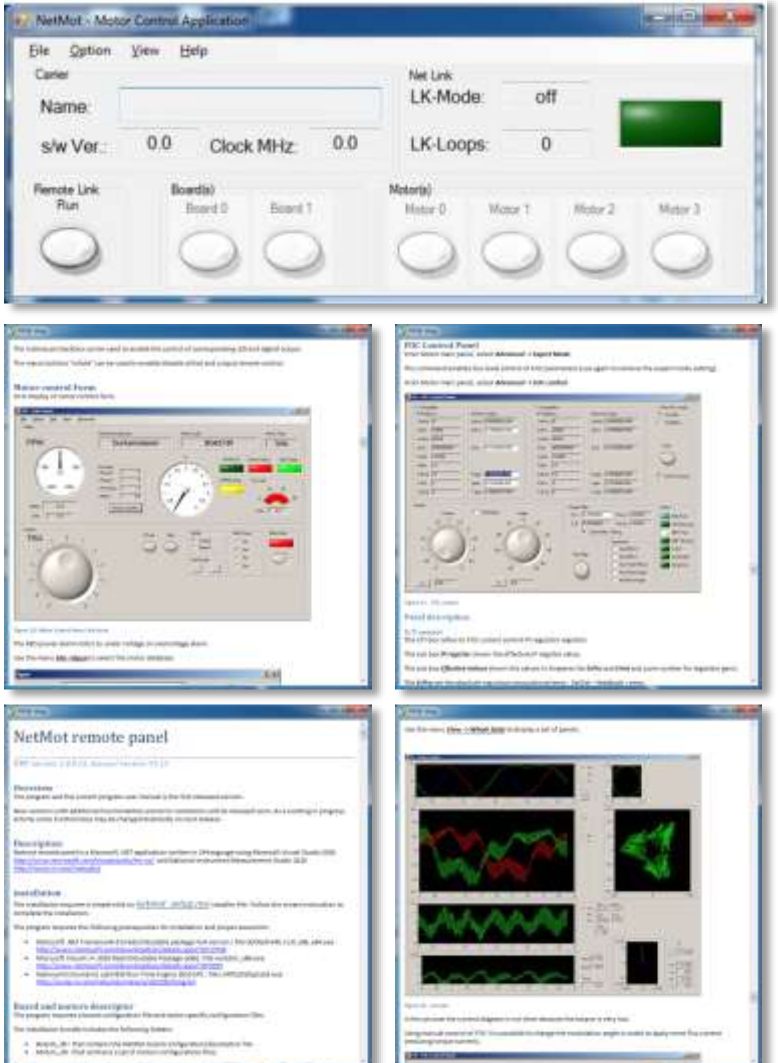
Download everything from www.em.avnet.com/spartan6motor

Qdesys Motor Control Reference Designs

- **Qdesys Field Oriented Control IP**
  - High performance, closed loop control (encoder or sensorless)
  - Advanced modulation schemes (SVPWM, RPFM)
  - Extensive, building block motor control IP library
  - Download to run on the Spartan-6 Motor Control Kit
  - Demonstration available for KC705 using XADC
  - IP available for Xilinx 7 series with XADC integration, Spartan-6, and Spartan-3A device families

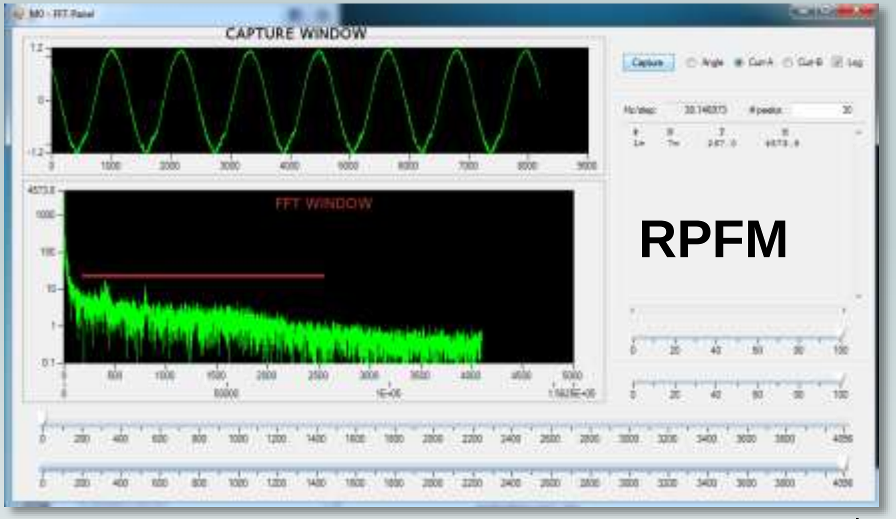
Download demo from www.em.avnet.com/spartan6motor

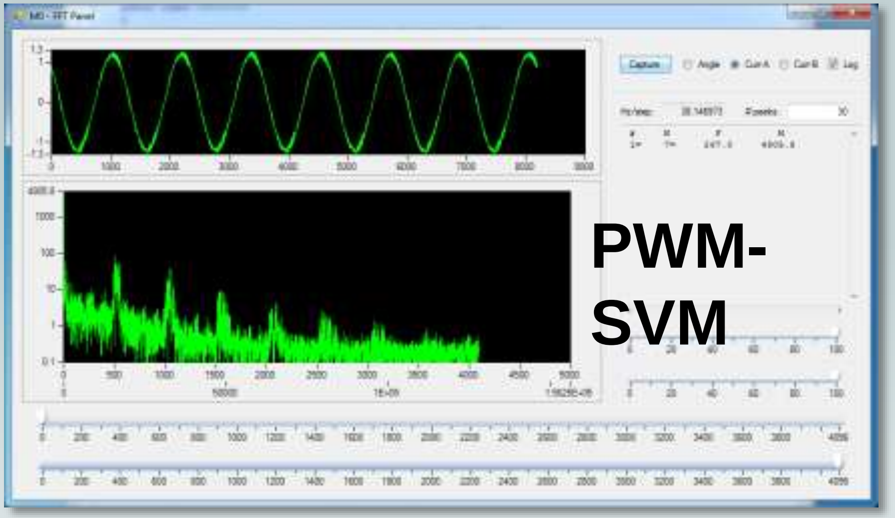
Qdesys Motor Control GUI



- **Data Acquisition**
  - Currents, Voltage, Angles
- **Switch Modulation Profiles On-the-fly**
  - SVM – Sinusoidal
  - PWM – RPFM
  - PWM frequency
  - RPFM repetition
- **Vector Space Display**
  - Diagnosis
  - Tuning
- **FFT for noise measurement**
- **Easily Add New Motors via XML file**
- **Supports Netmot V2.0 and AVNET-AES-FMC-MC1-G**
- **On-line Documentation**

RPFM and Space Vector Modulation





Motor Dunkermotoren BG65x50

Regenerative Pulse Frequency Modulation *

** Xilinx Patent Pending*

- Less harmonics
- Less switching

Pulse Width Space Vector Modulation

- Spectral peaks on harmonics

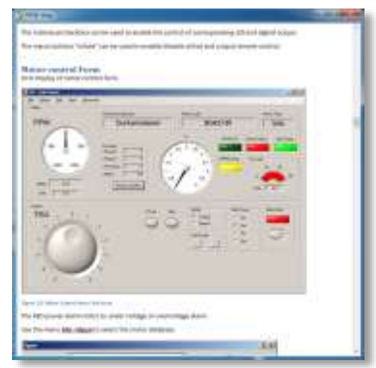
Excellent Noise Reduction = Less EMI

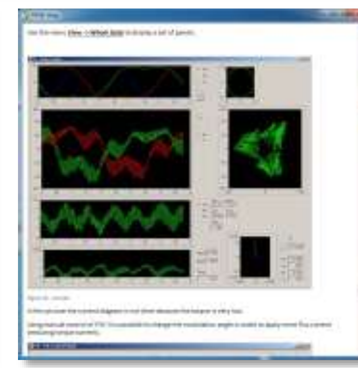
Agenda

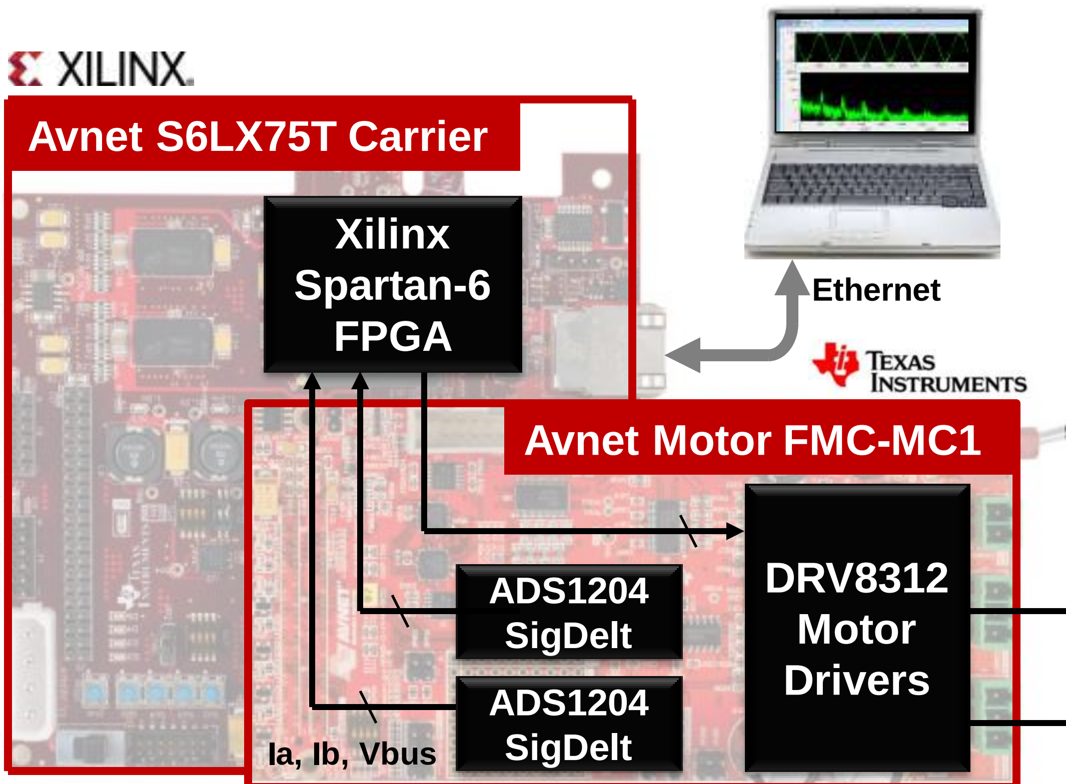
- Market requirements and challenges
- Motor control concepts
- Xilinx FPGAs for Motor Control
- Targeted Design Platform, Reference Designs & IP
- Design flows
- **Demo Preview**

Demo1: Sensorless Field Oriented Control

- **Sensorless Field Oriented Control (FOC)**
- **Switch Modulation Profiles On-the-fly**
  - PWM, SVM, RPFM
- **Measure currents, voltage, angles, FFT**

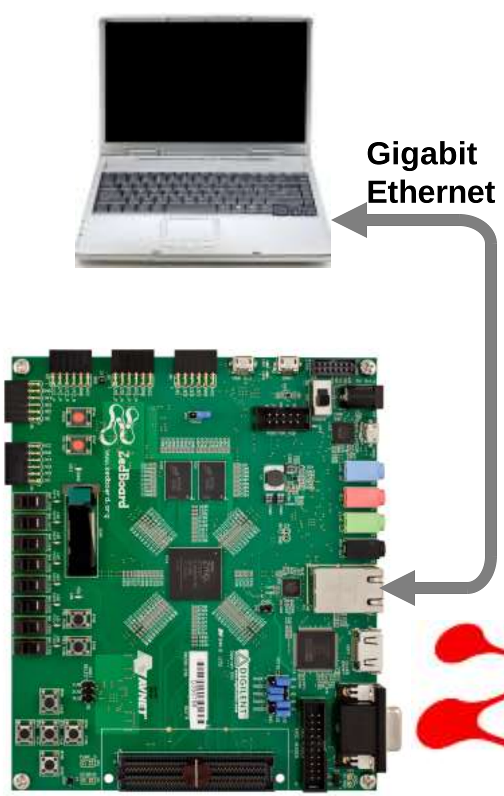




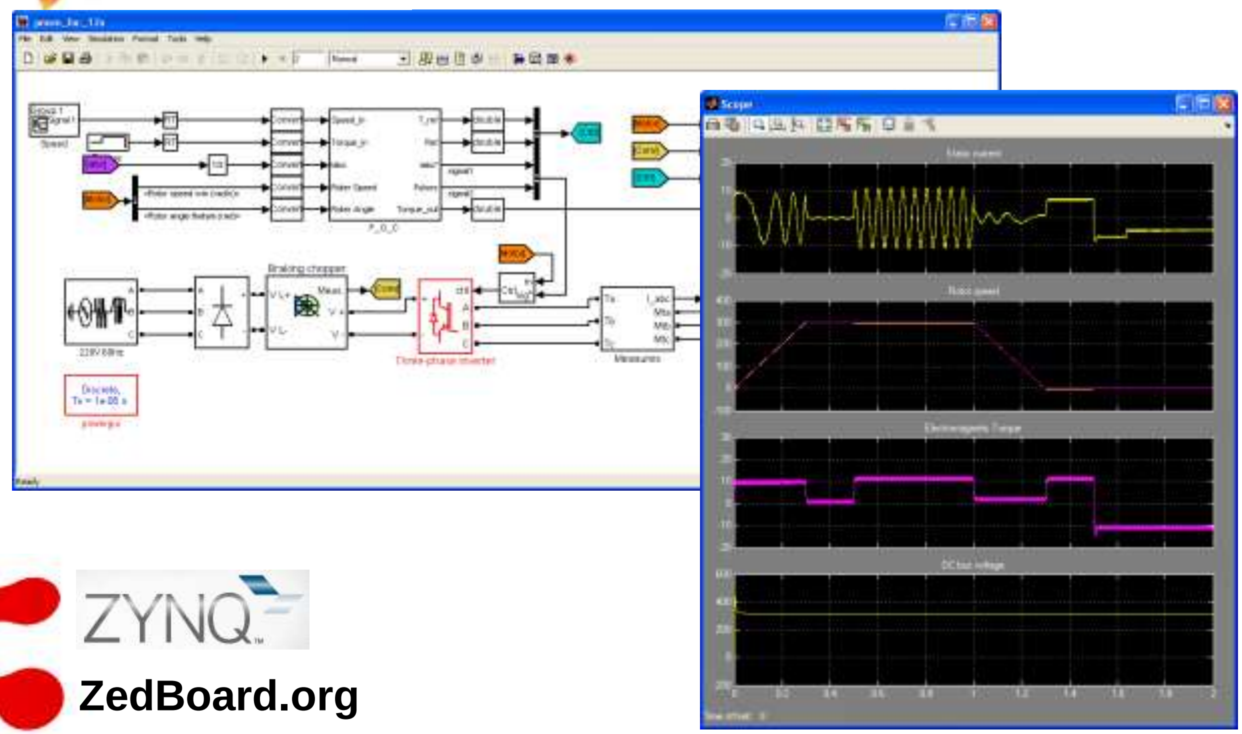


Demo2: Simulink Support for Xilinx Zynq-7000 EPP

- Field Oriented Control (FOC) Simulation in Simulink
- Embedded Coder™ generates C code for motor plant model executed on Cortex-A9
- HDL Coder™ generates VHDL/Verilog for motor control model executed on FPGA
- Verify Zynq EPP target execution with Simulink via Gigabit Ethernet connection

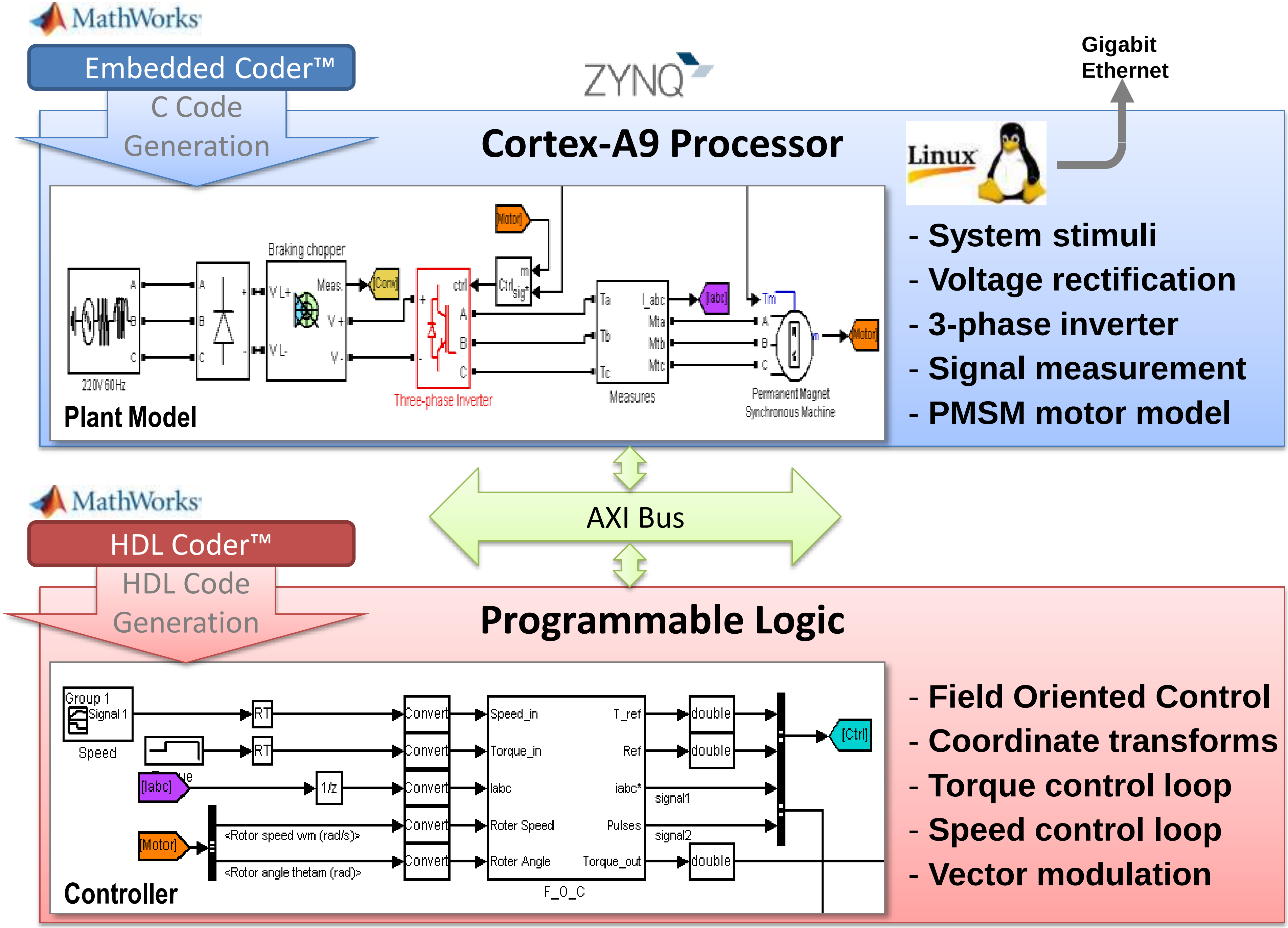


MathWorks

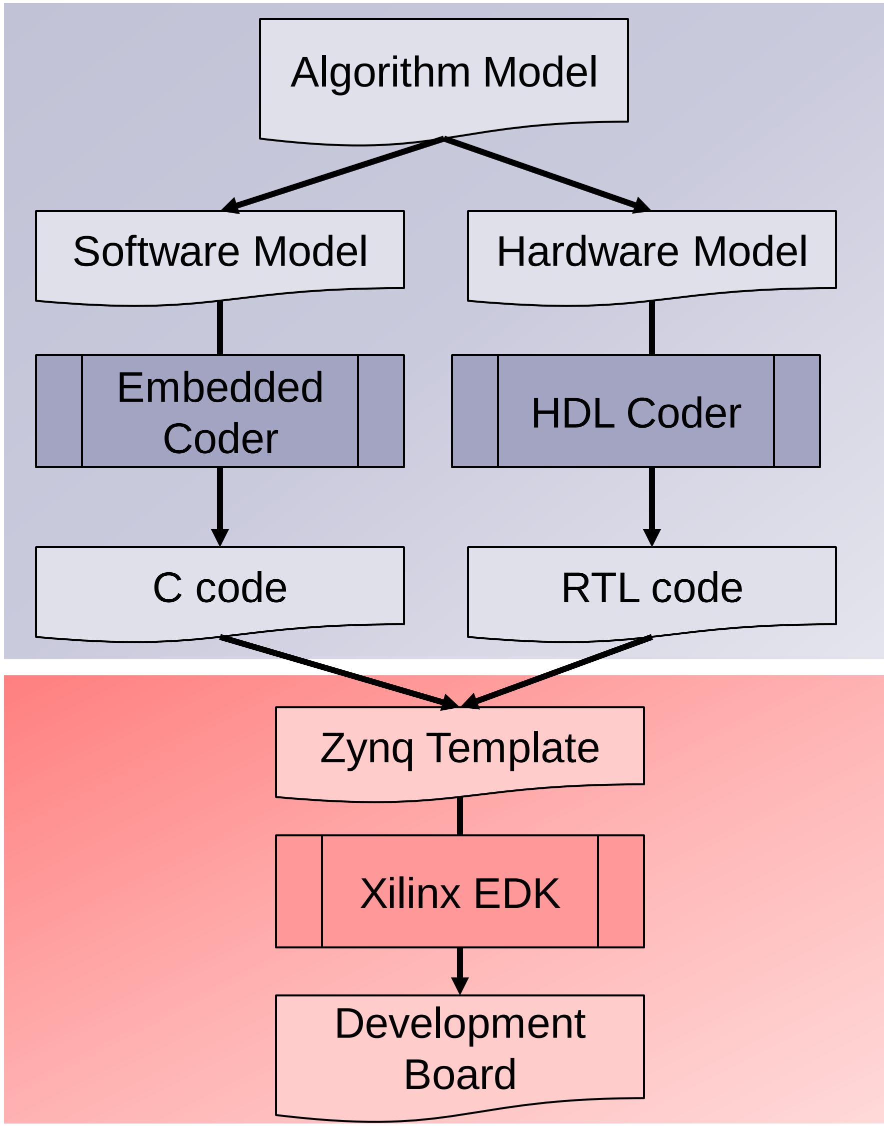


ZYNQ

ZedBoard.org


MathWorks
Embedded Coder™
C Code Generation
ZYNQ
Gigabit Ethernet
Cortex-A9 Processor
Linux
Braking chopper
220V 60Hz
Three-phase Inverter
Measures
Permanent Magnet Synchronous Machine
Plant Model
- System stimuli
- Voltage rectification
- 3-phase inverter
- Signal measurement
- PMSM motor model
AXI Bus
MathWorks
HDL Coder™
HDL Code Generation
Programmable Logic
Speed
Speed_in
Torque_in
Iabc
Roter Speed
Roter Angle
T_ref
Ref
iabc*
Pulses
Torque_out
signal1
signal2
<Rotor speed wm (rad/s)>
<Rotor angle thetam (rad)>
F_O_C
Controller
- Field Oriented Control
- Coordinate transforms
- Torque control loop
- Speed control loop
- Vector modulation

Simulink Design Flow for Zynq-7000 EPP



Next Steps

- **Visit www.em.avnet.com/spartan6motor**
  - Purchase the Spartan-6 FPGA Motor Control Development Kit
  - Download reference designs
- **Order ZedBoard and Motor FMC bundle for Zynq motor control development**
- **Ask your Avnet/Xilinx FAE for an on-site demo**
- **Register for FPGA-based Motor Control Speedway coming Fall 2012**

Thank You!
Please visit the demo area.

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2012 X fest

APPENDIX

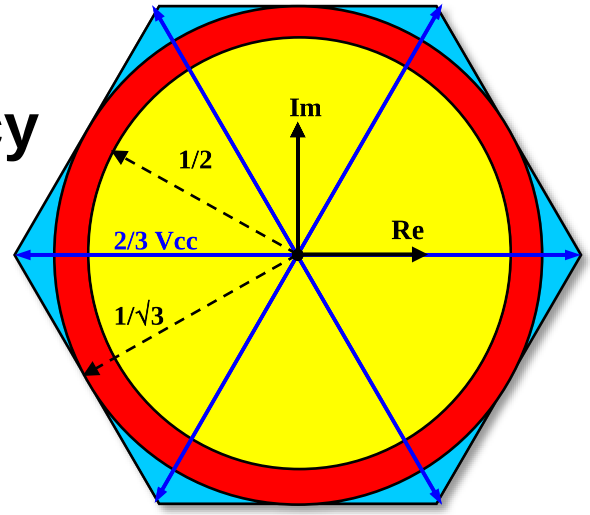
PMSM vs. BLDC Motors

Comparison of BLDC and PMSM motors	
BLDC	**PMSM**
Synchronous machine	Synchronous machine
Fed with direct currents	Fed with sinusoidal currents
Trapezoidal Bemf	Sinusoidal Bemf
Stator Flux position commutation each 60 degrees	Continuous stator flux position variation
Only two phases ON at the same time	Possible to have three phases ON at the same time
Torque ripple at commutations	No torque ripple at commutations
Low order current harmonics in the audible range	Less harmonics due to sinusoidal excitation
Higher core losses due to harmonic content	Lower core loss
Less switching losses	Higher switching losses at the same switching freq.
Control algorithms are relatively simple	Control algorithms are mathematically intensive

Source: Texas Instruments "Sensorless Trapezoidal Control of BLDC Motors"

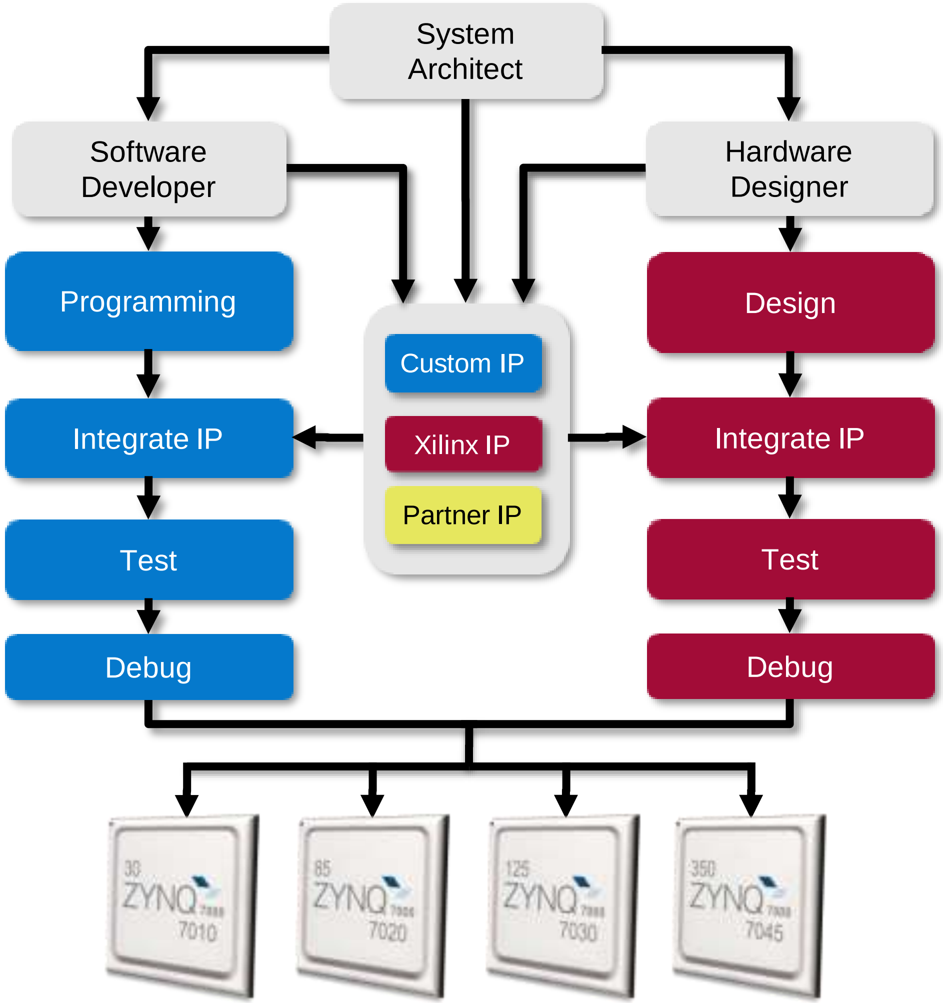
Modulation Effeciency Comparison

- **Vector space diagram**
- **Comparison of modulation efficiency**
- **Hexagon (blue)**
  - 6 step PWM control
  - Non-linear mode of motor operation
  - Inferior torque ripple and precision
- **Circles (red, yellow)**
  - Sinusoidal modulation max voltage to the motor is Vcc/2
  - Space vector modulation max voltage to the motor is Vcc/√3
  - Linear modulation, into the circle inscribed within the hexagon



Zynq-7000 EPP – Embedded Design Flow

- **Industry-Leading Tools**
  - Xilinx SDK (Eclipse IDE, GNU)
  - ARM Ecosystem
  - Virtual Platform
- **Many Sources of SW IP**
  - Xilinx, ARM libraries
  - 3rd Parties
  - open-source



- **Industry-Leading Tools**
  - C-Gates / AutoESL
  - System Generator
  - VHDL/Verilog
- **Many Sources of HW IP**
  - Standardized around AXI
  - 3rd Parties