Energy. Don’t loose it…REUSE it!

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Quadrants of Operation

- **First Quadrant**: Positive speed - positive torque, "forward-accelerating" - Motoring
- **Second Quadrant**: Negative speed - positive torque, "reverse-braking" - Generating
- **Third Quadrant**: Negative speed - negative torque, "reverse-accelerating" - Motoring
- **Fourth Quadrant**: Positive speed - negative torque, "forward-braking" - Generating
Example 4-Quadrant System
DC Motor Regeneration

Q1 (Forward)

Motor Back-emf

Q4 (Forward)

Motor Back-emf

Motor Voltage

Motor Current

DC Bus Current

Applied average PWM voltage greater than back EMF voltage

Applied average PWM voltage less than back EMF voltage

Positive average implies motoring

Negative average implies generating

Motoring

Generating
Bus regen. can only occur when applied voltage is smaller in magnitude than the motor back-EMF, and of the same polarity.
AC Motor Regeneration

\[ P = \frac{1}{2} V_{emf} I_L \cos(\theta) \]

MOTORING (unity PF)

SPICE SIMULATION

GENERATING (unity PF)
Regeneration in Toyota Prius

Panasonic Ni-MH battery stack
7.2V x 28 = 202V
6.5 amp-hours

Regenerative Boost Converter

1 kW Buck Converter

1.2 kW Variable Speed AC Compressor

8100 µF

200 - 500 V

50 kW 3-phase Traction Motor

30 kW 10k RPM 3-phase Starter/Alternator

1 kW AC Compressor

205 x 81 = 202V
6.5 amp-hours

12V

System 12V

Brush DC EPS Motor

One Third of Kinetic Energy Recaptured!
Where Does the Energy Go?

Rectifiers block current flow back on to AC line from the dc bus, thus preventing line regeneration. All motor energy gets dumped in the bus capacitor.

Options
- Limit deceleration rate
- Bigger capacitor
- Turn PWMs off and coast
- Brake resistor
- Dump energy onto AC line input
Regeneration to a Single Phase AC Line

Energy Flow

AC In

Energy Flow

Designing with Freescale
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Single Phase
AC Line Regeneration

VAC
Vbus

Current Reference Waveform

PWM

Carrier

PWM Module

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Simulation Results of Single-Phase Regenerative System
Regeneration to a 3-Phase AC Line

Freescale offers several controller solutions with the required MIPS and peripherals for this application.
D and Q Axes Representation

Field Oriented Techniques applied to three-phase system

Power Factor = Cos(φ)

Where φ is the angle between the voltage and current space vectors

Put current vector on this axis for unity PF.
Step 1: Voltage Measurement

Measure the instantaneous AC line voltages. These scalar values represent the instantaneous magnitudes of the vectors along the A, B, C axes.

Assuming equal phase voltages,

\[-V_c = V_a + V_b\]
Step 2: 3-phase to 2-phase transformation

This is sometimes referred to as the FORWARD CLARK transformation

\[ V_\alpha = \frac{3}{2} V_a \]

\[ V_\beta = \frac{\sqrt{3}}{2} V_b - \frac{\sqrt{3}}{2} V_c \]
Step 3: Angle Demodulation

\[ \theta_d = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right) \]

Difficult to evaluate, especially on a fixed-point machine.
Tracking Filter Used for Angle Demodulation

\[ \sin(\theta(n) - \hat{\theta}(n)) = \sin(\theta(n))\cos(\hat{\theta}(n)) - \cos(\theta(n))\sin(\hat{\theta}(n)) \]

\[ \text{error}(n) = \sin(\theta(n) - \hat{\theta}(n)) \]
Step 4: Bus Voltage Regulator

Bus voltage (commanded) + error(t) PI Regulator

Bus voltage (measured)

V_{Bus}

3-Phase AC supply
Step 5. Establish $i_d$ and $i_q$

$$i_d = \sqrt{2/3} \times (\cos(\theta) \cdot i_a + \cos(\theta - 2\pi/3) \cdot i_b + \cos(\theta - 4\pi/3) \cdot i_c)$$

$$i_q = \sqrt{2/3} \times (-\sin(\theta) \cdot i_a - \sin(\theta - 2\pi/3) \cdot i_b - \sin(\theta - 4\pi/3) \cdot i_c)$$

Forward Clark-Park Transformation
Step 6. Synchronous Frame Current Regulation

Output from bus voltage regulator

\[ i_d (\text{commanded}) \]
\[ i_d (\text{measured}) \]
\[ i_q (\text{commanded}) \quad (0 \text{ amps}) \]
\[ i_q (\text{measured}) \]

P or PI regulators work well.
Step 7: Synchronous to Stationary Frame Transformation

\[
V_1 = \sqrt{2/3} \cdot (\cos(\theta) \cdot V_d - \sin(\theta) \cdot V_q)
\]

\[
V_2 = \sqrt{2/3} \cdot (\cos(\theta - 2\cdot\pi/3) \cdot V_d - \sin(\theta - 2\cdot\pi/3) \cdot V_q)
\]

\[
V_3 = \sqrt{2/3} \cdot (\cos(\theta - 4\cdot\pi/3) \cdot V_d - \sin(\theta - 4\cdot\pi/3) \cdot V_q)
\]

Reverse Clark-Park Transformation
Step 8. Output Voltage Modulation

6 transistor converter

Vbus

PWM1
PWM2
PWM3

V1 amplified
V2 amplified
V3 amplified

V_a
V_b
V_c

AC Line

PWM

V_1
V_2
V_3
Three-Phase System Overview

AC Line

6 transistor converter

PWM A
PWM B
PWM C

Vbus

Desired Bus Voltage

PI

PWM A
PWM B
PWM C

Dave Wilson
Simulation Results of 3-Phase Regenerative System

- **D-axis Current**
- **Bus Load Current**
- **Q-axis Current**
- **Phase A Voltage**
- **Phase A Current**
- **Bus Voltage**
Standby Power Supplies

Connecting asynchronous power sources

Hybrid vehicles

Combined starter/alternator

Elevator Drives

Driving high inertial loads

Wind Energy

Variable Speed Generator

Variable Frequency AC

Power Processing Unit

50 or 60 Hz

AC Utility

Energy Flow

Inverter

Static Disconnect Switch

Load

AC Utility

High-Performance Power Architecture sockets
System Benefits

- **Bidirectional control of power**

- **Sinusoidal Currents**

- **Unity Power Factor (or ANY Power Factor for that matter)**

- **Since Vbus is regulated, and currents are sinusoidal, the semiconductor volt-amp ratings are reduced**

- **Vbus is less sensitive to AC line fluctuations**

- **For three-phase AC systems, FOC algorithms can be used for both converter and inverter control**
Matrix Converters

Direct AC to AC waveform conversion

No energy storage elements required

Inherent regeneration to input supply

Sinusoidal line currents possible

Unity (or any) power factor is possible
Matrix Converter Topology

Inputs

Outputs
Matrix Converter Output Waveform Example

Unfiltered

Filtered

SWITCHING FREQUENCY IS 3 KHZ

TIME(SEC)
## Dual Converter-Inverter DSC Solutions

### All devices are 60 MHz, (-40, +125)°C

<table>
<thead>
<tr>
<th>Voltage (Core / I/O)</th>
<th>2.5/3.3V</th>
<th>2.5/3.3V</th>
<th>2.5/3.3V</th>
<th>2.5/3.3V</th>
<th>2.5/3.3V</th>
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<td>PWM Current Sense</td>
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<td>GPIO (Ded./Shrd/Tot)</td>
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<td>JTAG/EOnCE</td>
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<td>Yes</td>
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<td>Package</td>
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<td>160LQFP</td>
<td>128LQFP</td>
<td>144LQFP</td>
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</tbody>
</table>
Cost Effective 56F8000 Solutions
56F8011/56F8013/56F8014

- 32 MIPS Performance
- 16 K Bytes Program FLASH
- 4 K Bytes Program/Data RAM
- Tunable Internal Relaxation Oscillator
- Software Programmable Phase Locked Loop
- Up to 96 MHz Peripherals – Timers and PWMs
- Up to 6-Output PWM Module with up to 4 Programmable Fault Inputs
  - Selectable PWM frequency for each complementary PWM signal pair
- Two 12-bit ADCs with up to 8 Inputs, 1.125us conversion rate
- Synchronization between PWM and ADC
- Four 16-bit General Purpose Programmable Timers
- Computer Operating Properly Timer
- Serial Ports: SCI, SPI, I2C
- Up to 26 GPIOs – Versatile pin usage
- Low Power Consumption – 59mA Max and .026mA Min
- JTAG/EOnCE™ Debug Port
- MSRP starting at $2.92 for 1K units

- Packages: 32LQFP
**56F8000 Family Expansion**

**56F8023/56F8025/56F8036/56F8037 Features**

- 32 MHz/32 MIPS 56800E Core
- 3.0-3.6V Operation
- 32K-64K Bytes Program FLASH
- 4K-8K Bytes Program/Data RAM
- Flash security
- Tunable Internal Relaxation Oscillator
- Software Programmable Phase Locked Loop
- Up to 96 MHz Peripherals – Timers and PWMs
- 6 Output PWM Module with 4 Programmable Fault Inputs
- 2-12-bit ADCs for 6-8 Inputs w/ Int. or External Vref
- **Up to 2 12-bit Digital to Analog Converters**
- **2 - Analog Comparators**
- Synchronization between PWM and ADC
- 4 or 8 16-bit General Purpose Programmable Timers
- **1 or 3 Programmable Interval Timers**
- Computer Operating Properly Timer
- **2-Queued Serial Communications Interface**
- **2-Queued Serial Peripheral Interface**
- Optional MSCAN
- I²C Communications Interface
- Up to 53 GPIOs
- JTAG/EOnCE™ Debug Port
- 4 Lead Free Packages
- Up to -40 to 125°C temperature range
- MSRP starting at $3.30 for 1K units

**56800E Core**

- 32 MIPS
- 32 MHz

**System Clock Control (PLL, SIM, Osc)**

- 64KB Flash
- 8KB RAM

**3-PIT**

**MSCAN**

**COP**

**Power Supervisor**

**Interrupt Controller**

**Voltage Regulators**

**JTAG/EOnCE™**

**6 Output PWM**

**8 16bit Timers**

**Two 12bit ADCs**

Up to 2x8 Input

**2-QSPI**

**2-QSCI**

**I²C**

**2-12bit DACs**

**2-Analog Comparators**

**Up to 53 GPIOs**
### Anguilla White: Ultra Low Cost Product: 56F8002, 56F8006

<table>
<thead>
<tr>
<th>Feature</th>
<th>56F8002, 56F8006</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-16KB Program Flash</td>
<td></td>
</tr>
<tr>
<td>System Integration Module (SIM)</td>
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</tr>
<tr>
<td>Interrupt Controller</td>
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<tr>
<td>PLL</td>
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<tr>
<td>Relaxation OSC</td>
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<tr>
<td>Crystal OSC</td>
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<tr>
<td>1 Period Int Timer</td>
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<tr>
<td>Up to 40 GPIOs</td>
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<tr>
<td>1 SCI</td>
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<tr>
<td>1 SPI</td>
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<td>2 x 16bit Timers</td>
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<tr>
<td>3 x Analog Comparators</td>
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<tr>
<td>2 x Programmable Gain Amplifiers</td>
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<td>12ch 12bit ADC</td>
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<td>12ch 12bit ADC</td>
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<td>Programmable Delay Block</td>
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<td>Synch</td>
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<td>6-ch PWM Output</td>
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<td>56800E Core 32Mhz</td>
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<td>Voltage Regulator</td>
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<td>COP</td>
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<tr>
<td>Power-On-Reset</td>
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<tr>
<td>Power Supervisor</td>
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<tr>
<td>JTAG/EOnCE</td>
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</tr>
</tbody>
</table>

- **28SOIC, 32SDIP, 32LQFP, 48 LQFP**

**Sampling Now!**

MSRP is $1.50 in 10K quantities!

- 32 MHz/32 MIPS 56800E Core
- 1.8-3.6V Operation
- 12K - 16K Bytes Program FLASH with Flash security
- 2K Bytes Program/Data RAM
- Tunable Internal Relaxation Oscillator and 32KHz clock
- Phase Locked Loop (PLL)
- Up to 96 MHz Peripherals – Timers, PWM & Hi-SCI
- 6 Output PWM Module with 4 Programmable Fault Inputs
  - Programmable Dead timer insertion
  - Programmable PWM generation for Power supply apps
  - Multiple PWM Frequency outputs
- Two Programmable Gain Amplifiers with x2, x4, x8, x16 gains (Clocked in order to cancel input offset)
- Two 12-bit ADCs with up to 24 Inputs, 2.5us Per conversion
- Programmable Delay Block provides precise control of ADC/PGA sample times relative to PWM reload cycles
- Three High Speed Analog Comparators
- 2 multiple function Programmable Timers
- Computer Operating Properly Timer
- One Periodic Interval Timer (PIT)
- 1 High Speed Serial Communication Interface (Hi-SCI)
- 1 Serial Peripheral Interface (SPI)
- I²C Communications Interface
- Up to 40 GPIOs – Versatile pin usage
- JTAG/EOnCE™ Debug Port
- Lead Free “Green” Packages
- Industrial temp: -40C – 105C
Pictus: MPC560xP

Core
- up to 60 MHz PowerPC ISA e200 zen0h core (64MHz at 105°C)

Memory
- 192k to 512k byte Program Flash with ECC
- 4x16k byte Data Flash with ECC
- 12k to 40k byte SRAM with ECC

I/O
- 1 x FlexCAN with 32MB
- 1 x Safety port (can be used as additional FlexCAN - 32MB)
- 1 x FlexRay Dual Channel with 32MB
- 2 x LinFlex
- 4 x DSPI (4 independent chip selects each)
- 1 x FlexPWM (4x3 channels with 4 Fault Inputs)
- 1 x eTimer (6 channels incl. quad decode)
- 1 x eTimer (6 channels for general purpose)
- 2 x ADC
  - 2x13 Ch.(4 shared channels), 10bit, conversion time 760 nsec (2x6ch, 4shared on 100 pin package)
- 1 x ADC triggering unit: 8 events

System
- 2 x PLL (one FM-PLL, one for Flexray)
- 16Ch eDMA
- Fault Collection Unit
- 16MHz internal RC OSC
- Junction Temperature Sensor
- JTAG (2 pin or 5 pin) / Nexus Class 2+
- 3.3V single supply (5V mask option) with external ballast transistor
  - 100 and 144 pins TQFP package
- 145°C ambient temperature option with Slugdown package