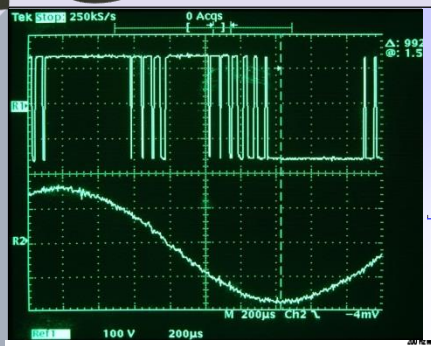
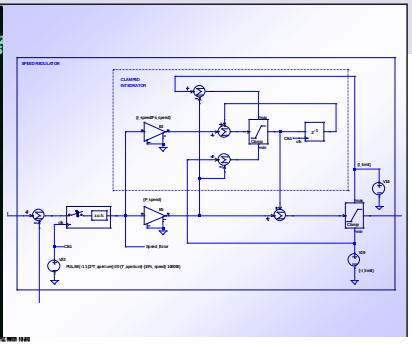
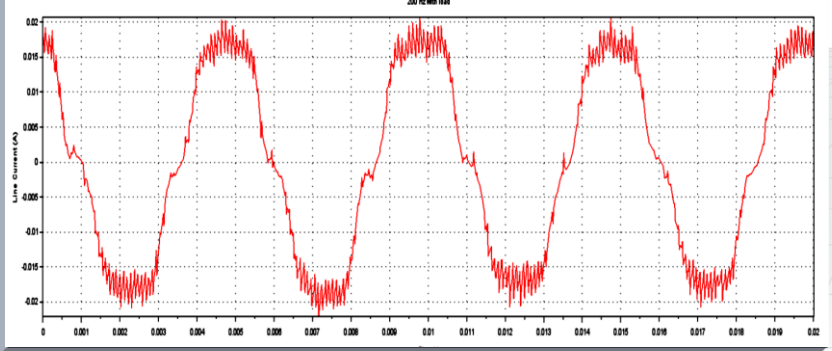
# Current Sensing

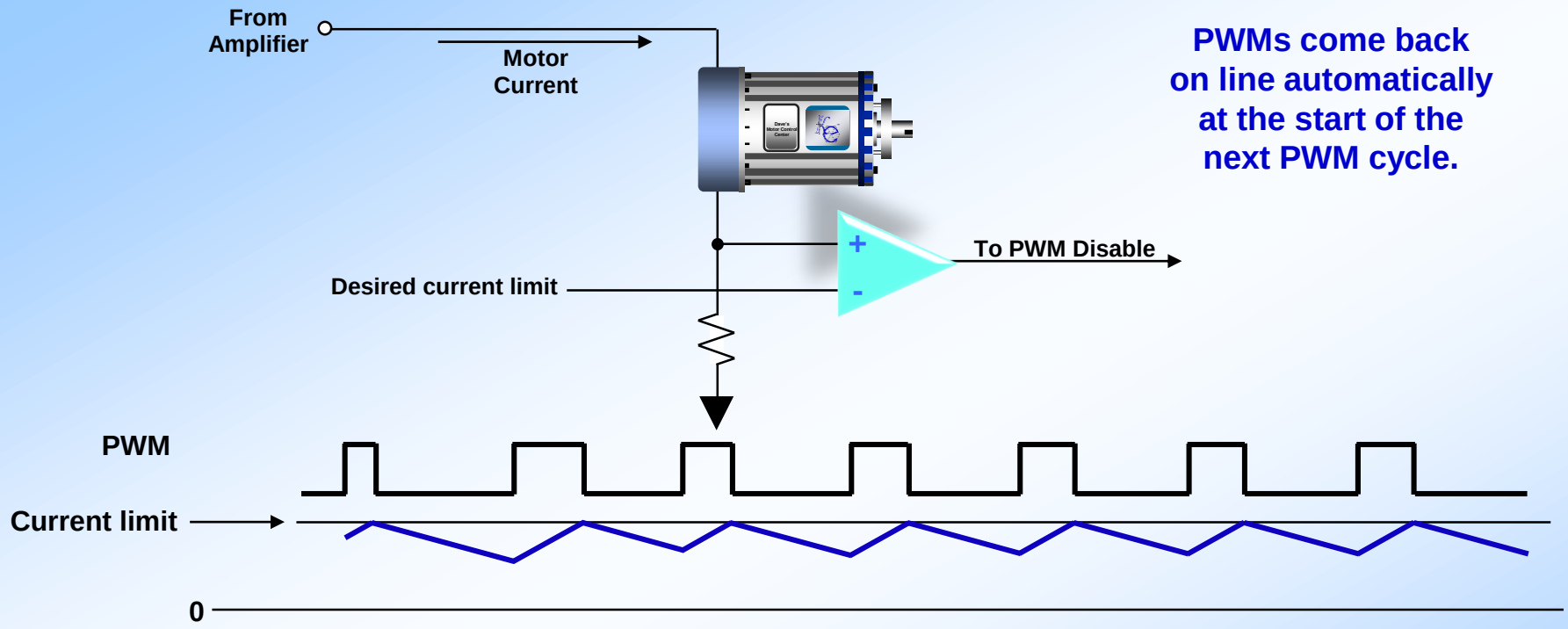





Dave Wilson
Co-Owner
Kappa Electronics
www.kappaiq.com

# Cycle-by-Cycle Current Limit

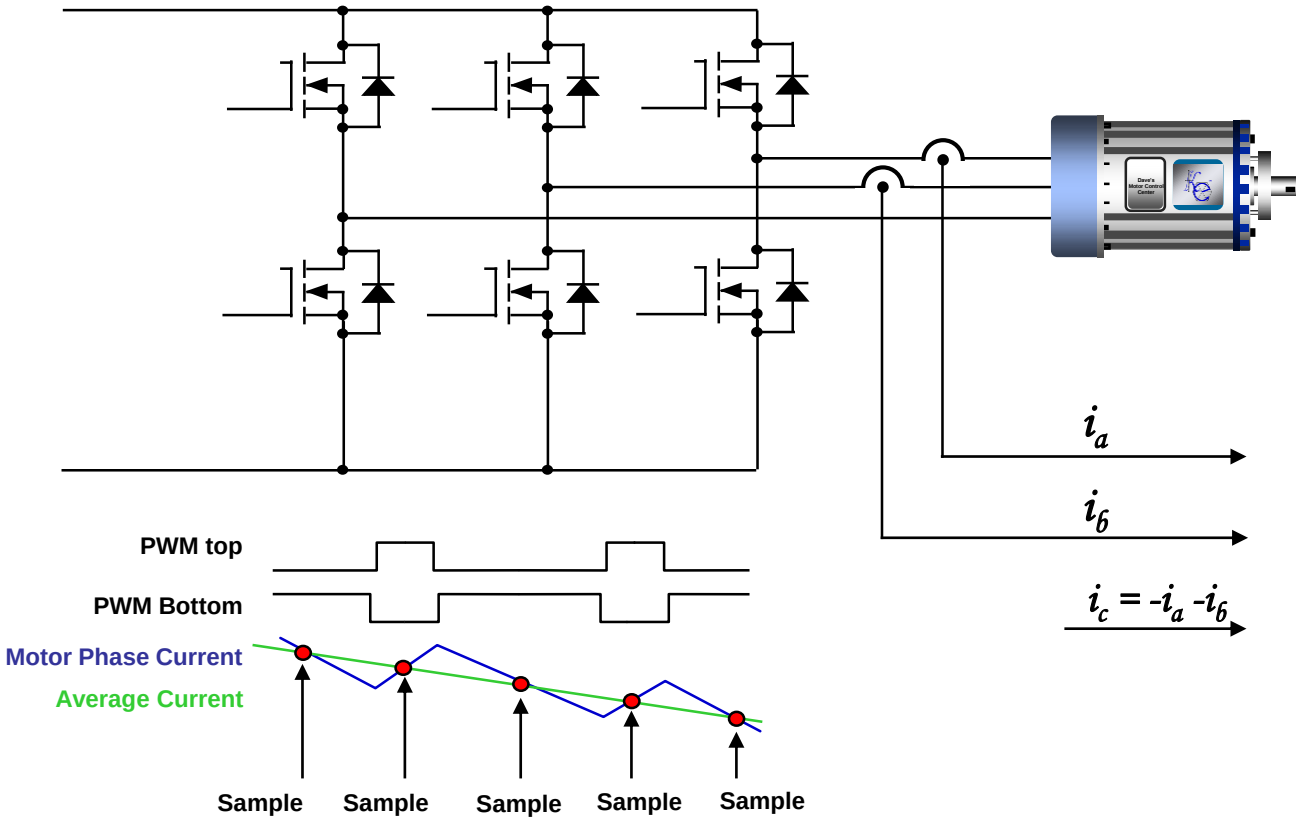



PWMs come back on line automatically at the start of the next PWM cycle.

**Pros:** Great for robust hardware over-current protection.
Can use on-board hardware comparator and fault inputs on most processors.
Simple. No software required.
Cost effective.

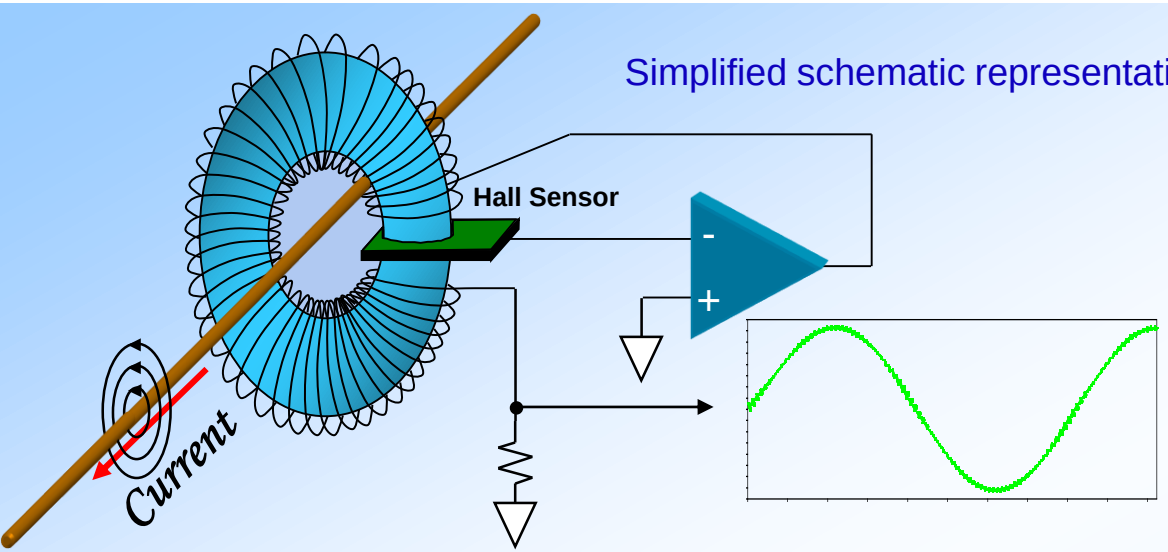
**Cons:** Not good for control, since it regulates peak current, not average current.
Unstable for duty cycles > 50% unless slope-compensation is used.

# In-Line Current Sensing




- ✓ Synchronous ADC Sampling helps to filter the measured current – anti-aliasing
- ✓ Noise free ADC sampling when the power transistor is not switching
- ✓ Current signal is ALWAYS visible
- ✓ Current can be sampled at TWICE the PWM frequency (null-vectors V0 AND V7)
- ✓ More expensive!

# LEM Sensors





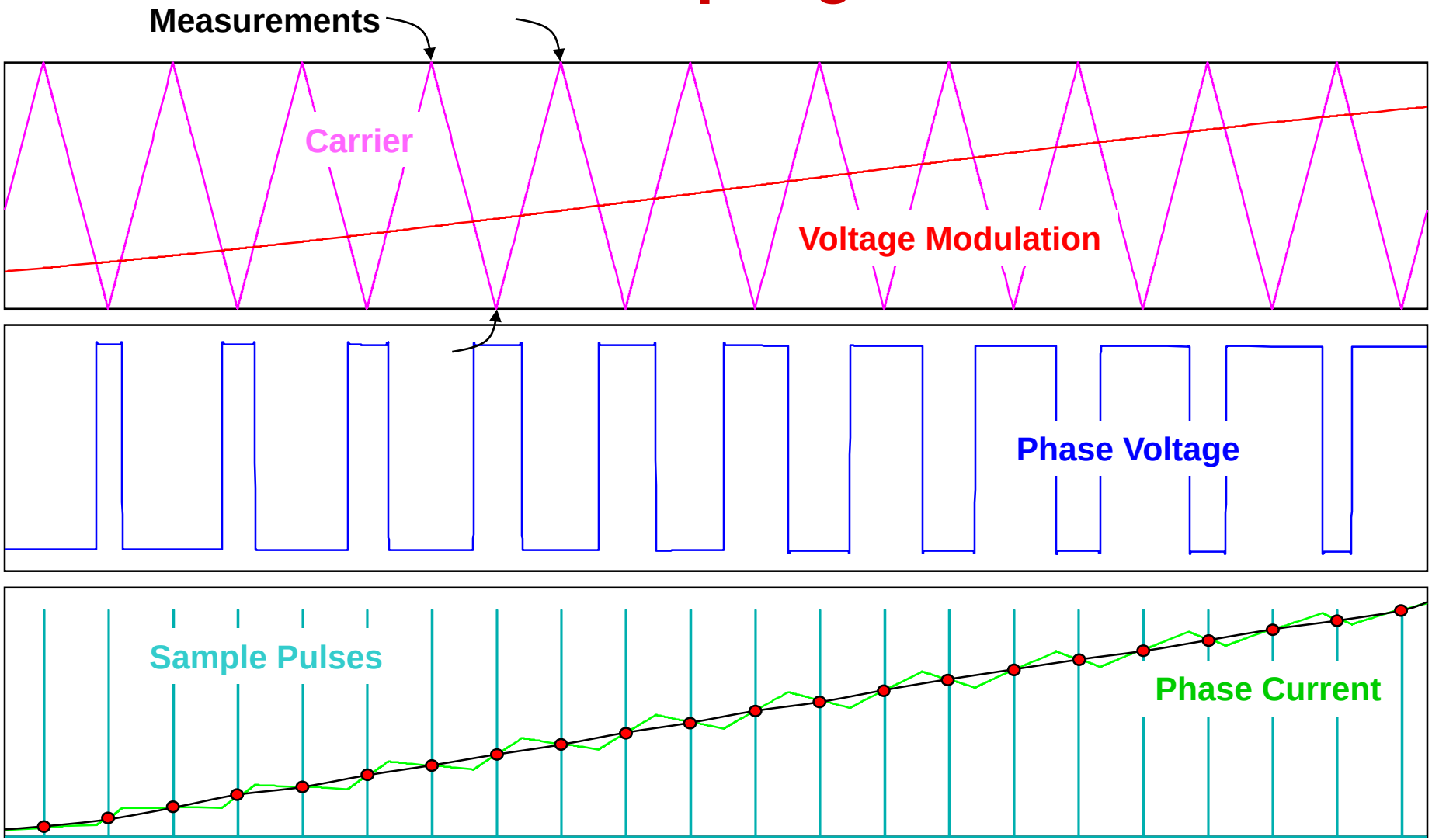
**Most popular in-line current sensing sensor.**

**Excellent linearity (flux is zero, so permeability variations of core material do not affect the linearity of the reading).**

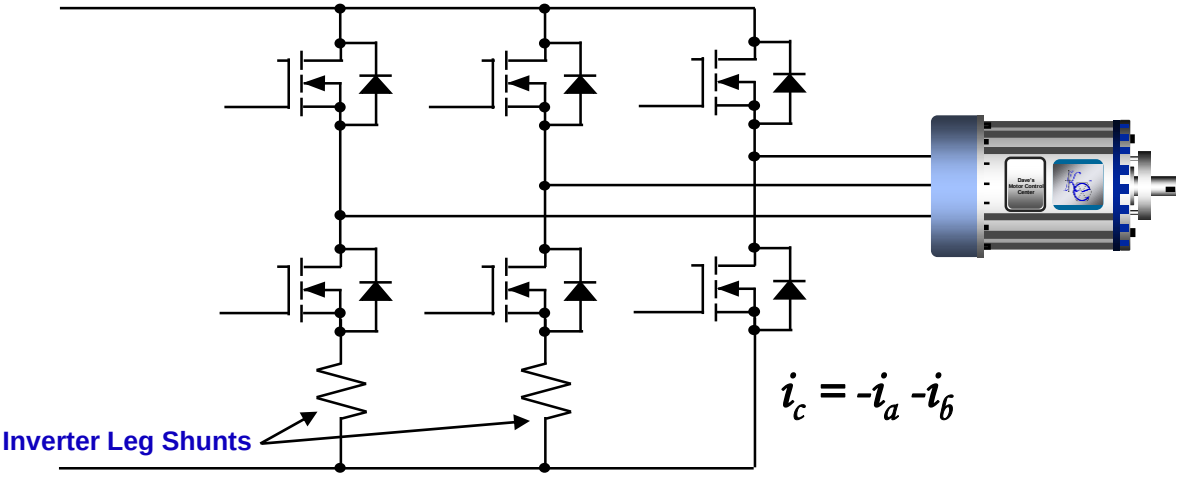
**Frequency response all the way down to DC.**

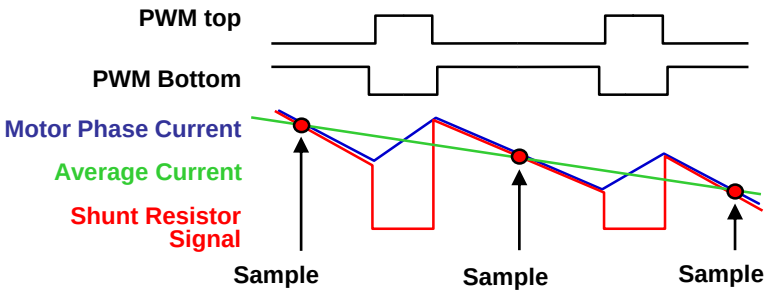
**Expensive**

# In-Line Current Sampling in Both V0 and V7



# 2-Shunt Current Sensing



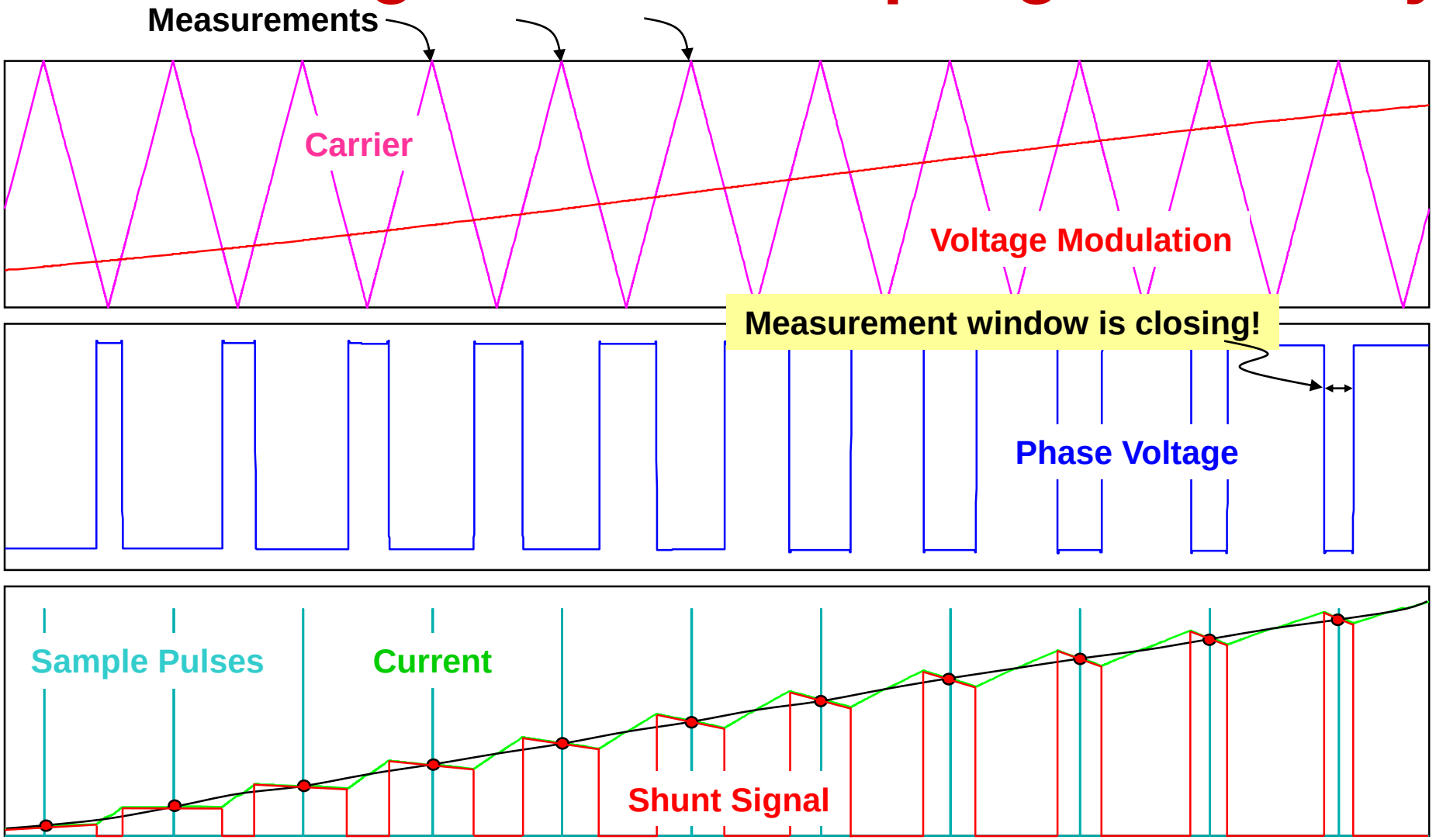




**In the d-q rotating reference frame:**

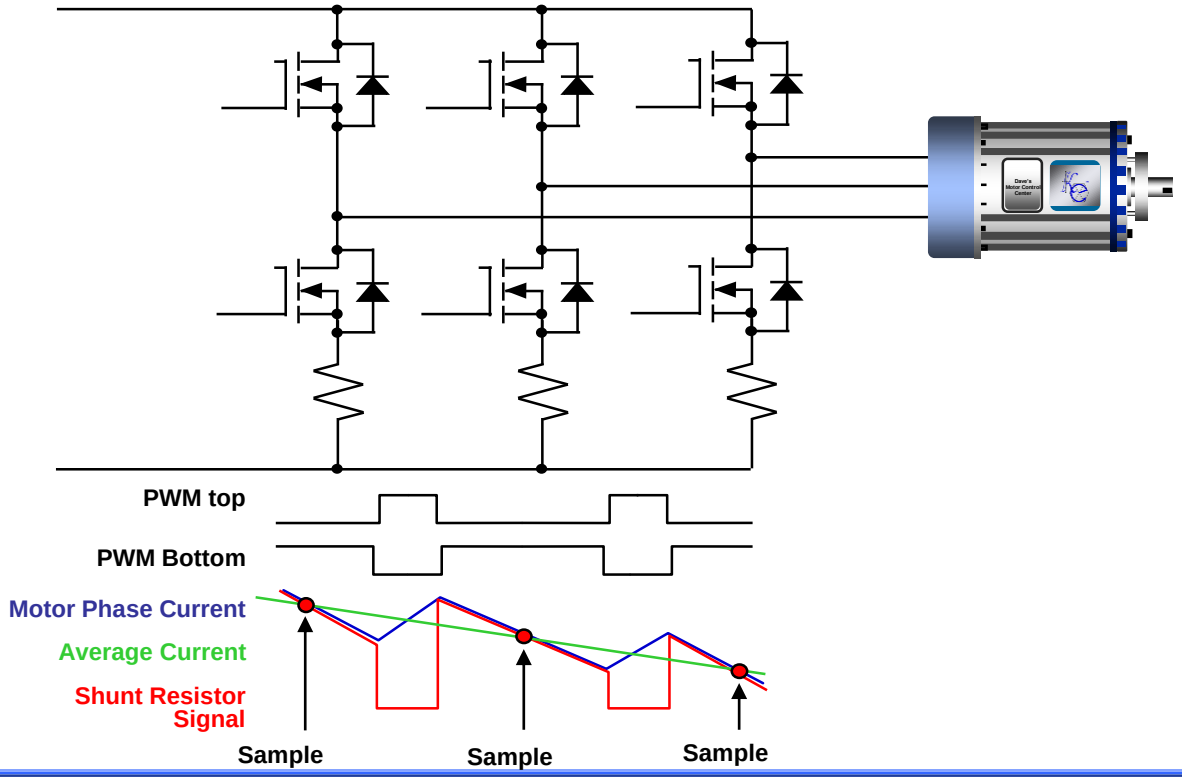
- **Gain differences manifest as a 2X harmonic distortion**
- **Offset errors manifest as a 1X harmonic distortion**

- ✓ Synchronous ADC Sampling helps to filter the measured current – anti-aliasing
- ✓ Noise free ADC sampling when the power transistor is not switching
- ✓ Current can be sampled at up to the PWM frequency (null-vector V0 only)
- ✓ Current samples are simultaneous.
- ✓ Not suitable for high power motors due to shunt power losses.
- ✓ Reading blackouts occur during high duty-cycle values

# Inverter Leg Current Sampling in V0 Only

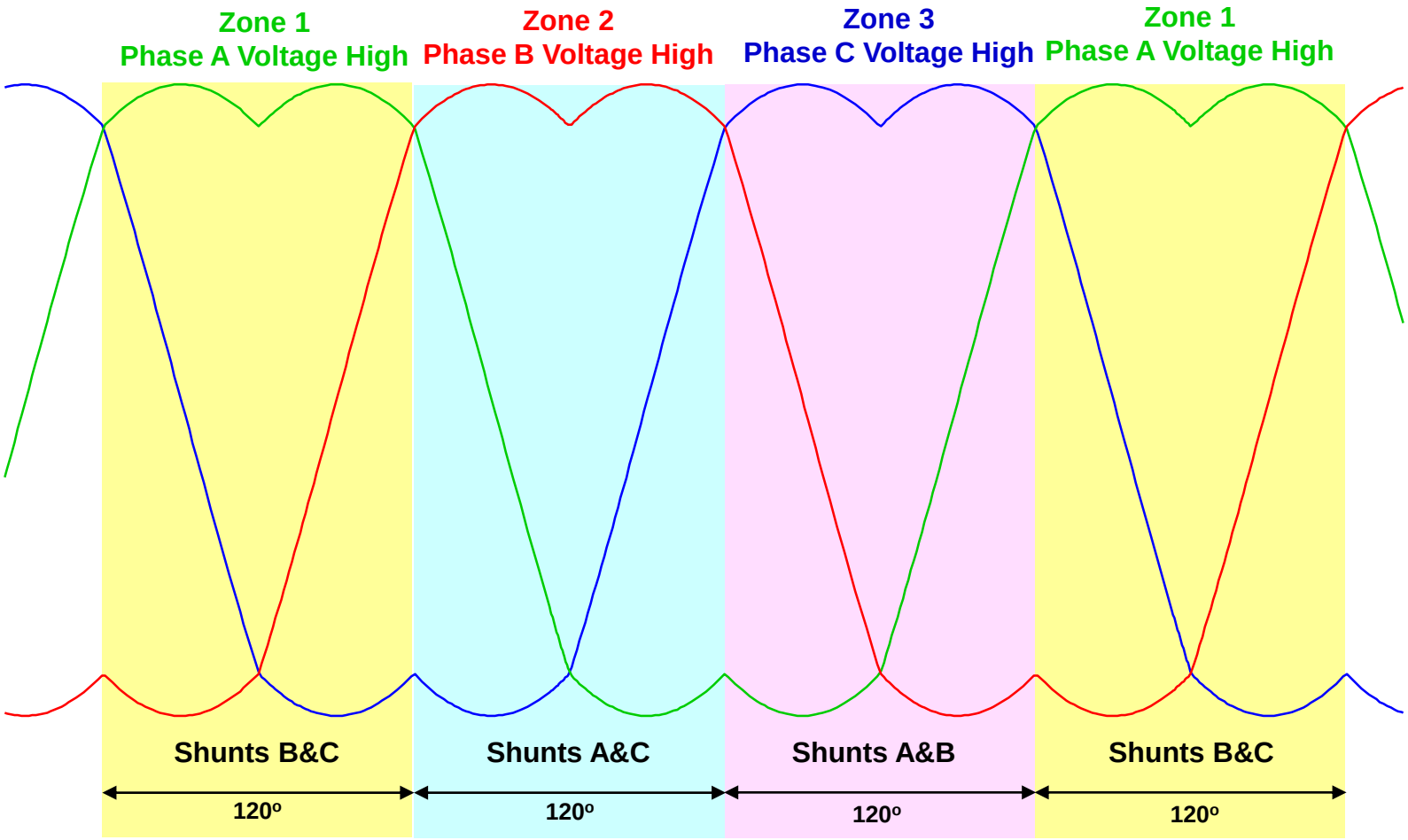


# 3-Shunt Current Sensing




- ✓ Synchronous ADC Sampling helps to filter the measured current – anti-aliasing
- ✓ Noise free ADC sampling when the power transistor is not switching
- ✓ Current can be sampled at up to the PWM frequency (null-vector V0 only)
- ✓ Current samples are simultaneous.
- ✓ 100% Modulation supported by switching between pairs of shunts.
- ✓ Extra shunt results in additional power loss.
- ✓ Channel gain differences can cause waveform discontinuities.

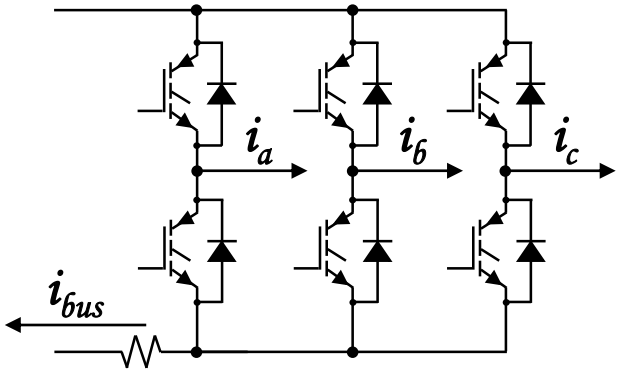
# Selecting Shunt Pairs Based on V-angle




**Shunt selections are based on the <u>voltage</u> zones, not the current angles.**

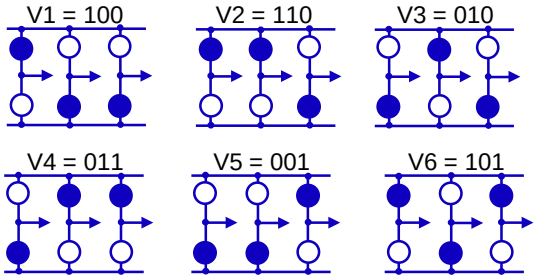
**Just a one percent gain change from one pair of shunts to the next represents a 41 count discrepancy on a 12-bit converter! Gain calibration may be required.**

# Phase Current Reconstruction from Single-Shunt Measurement

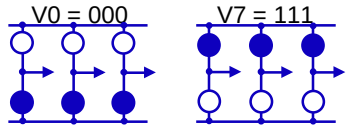



The inverter can be driven to 8 states.

- 6 voltage vectors

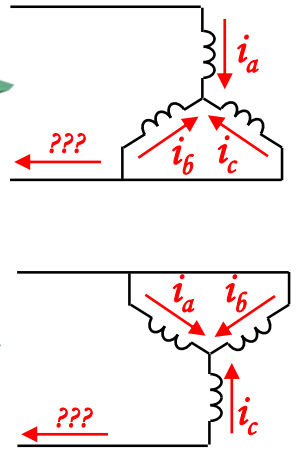



- 2 null vectors



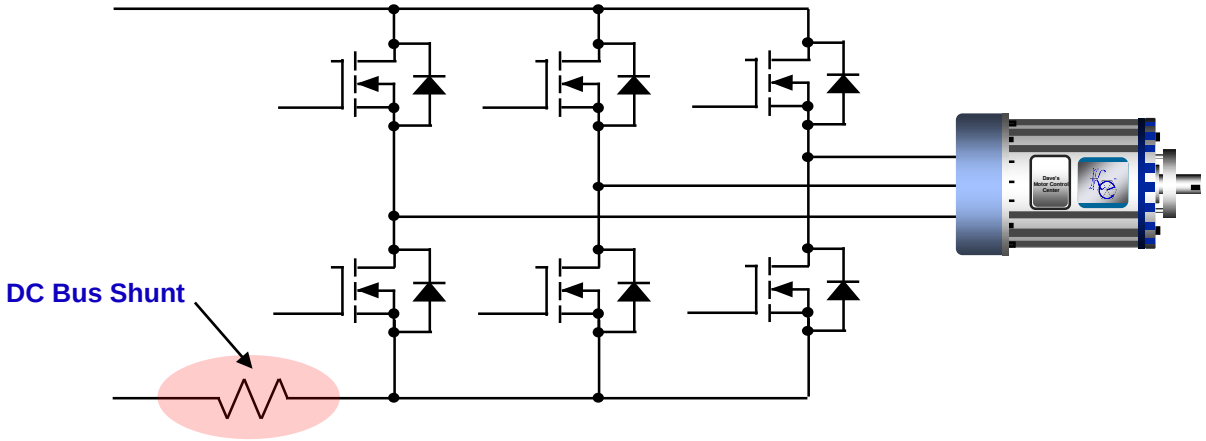

1 = Top Switch is on
0 = Bottom Switch is on

| Space Vector | $i_{bus}$ Value |
|---|---|
| V1 | $i_a$ |
| V2 | $-i_c$ |
| V3 | $i_b$ |
| V4 | $-i_a$ |
| V5 | $i_c$ |
| V6 | $-i_b$ |




**Assumes no ground currents in load**

# Single-Shunt Current Sensing

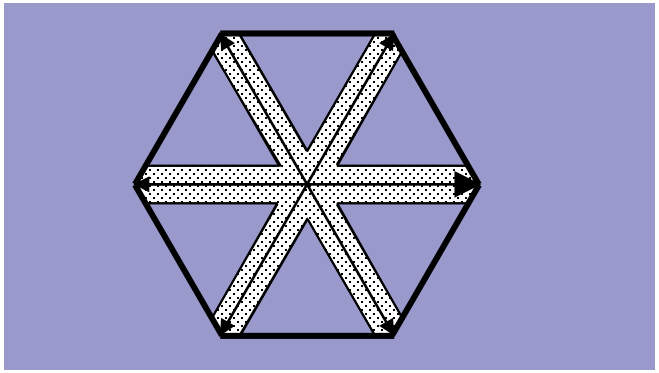



- ✓ Synchronous ADC Sampling helps to filter the measured current – anti-aliasing
- ✓ Noise free ADC sampling  when the power transistor is not switching
- ✓ Current can be sampled at SVM periodic rate (TWICE the PWM frequency).
- ✓ Lower power losses due to only one shunt.
- ✓ Only one current amplifier, so no waveform discontinuities due to gain mismatching.
- ✓ Only one shunt and one amplifier represents an economical solution.
- ✓ Op-amp must have much higher slew-rate characteristics.
- ✓ Shunt must be sampled during voltage vectors, NOT null vectors (timers required).
- ✓ ADC triggering is not fixed w.r.t. PWM waveform.  (Timer scheduling).
- ✓ Current readings are skewed in time.
- ✓ Reading blackouts occur during similar duty cycles on two or more phases (next slide…)

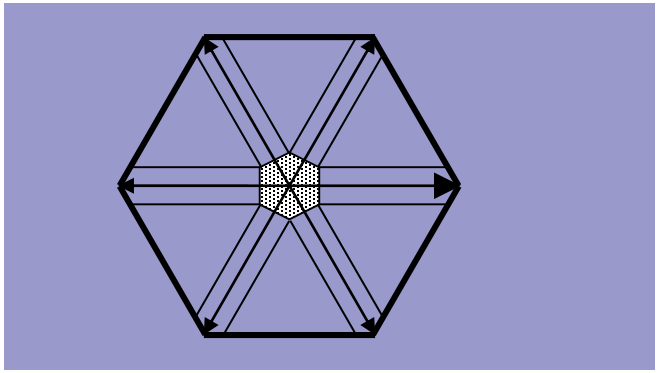
# Current Sampling Blackout Problem

- **Two current samples cannot be taken when:**
  1. voltage vector is crossing Space-vector boundary
     - only one sample can be taken
  2. low modulation indexes
     - sampling intervals are too short
     - none of current samples can be taken

1. **Areas where voltage vector is crossing SV boundary**

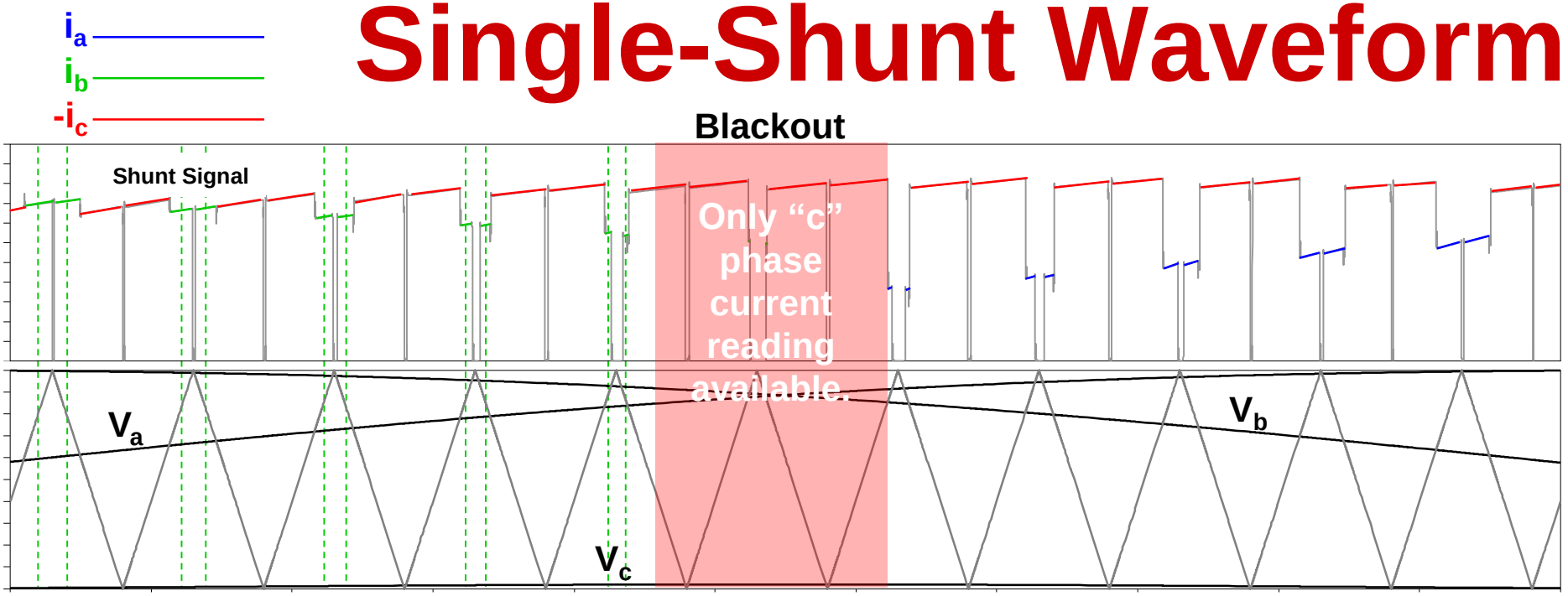


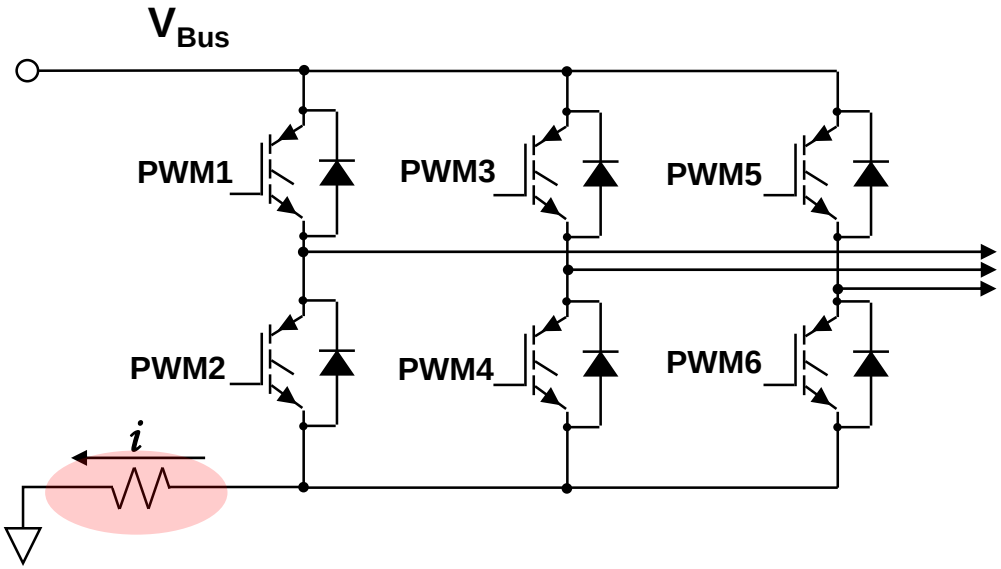
2. **Low Modulation Index**



***Source: Freescale Semiconductor***

# Single-Shunt Waveform



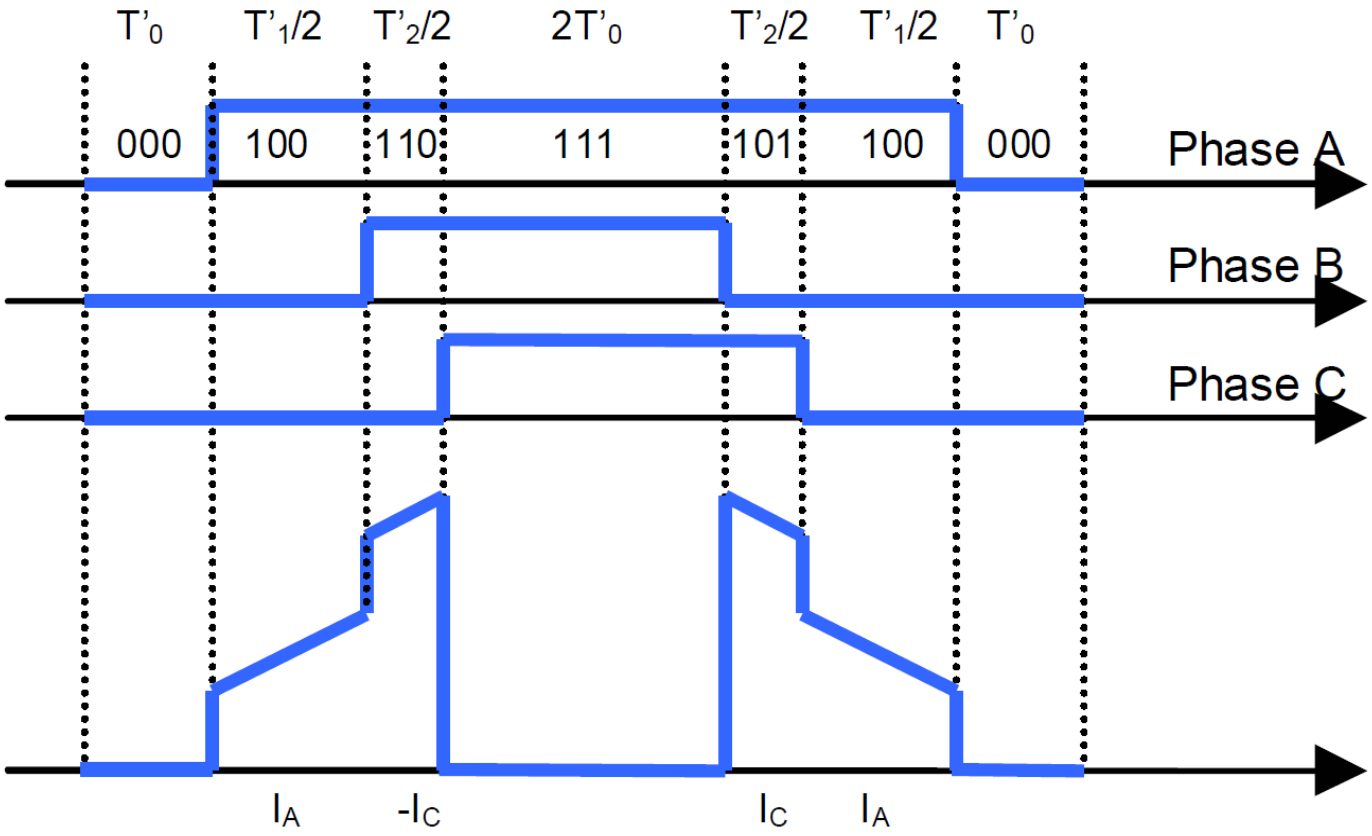



# Single-Shunt Blackout Solutions

## Solution 1:

### Asymmetrical PWM

- Modified ON/OFF times
- Duty cycles preserved




*Source: STMicroelectronics*

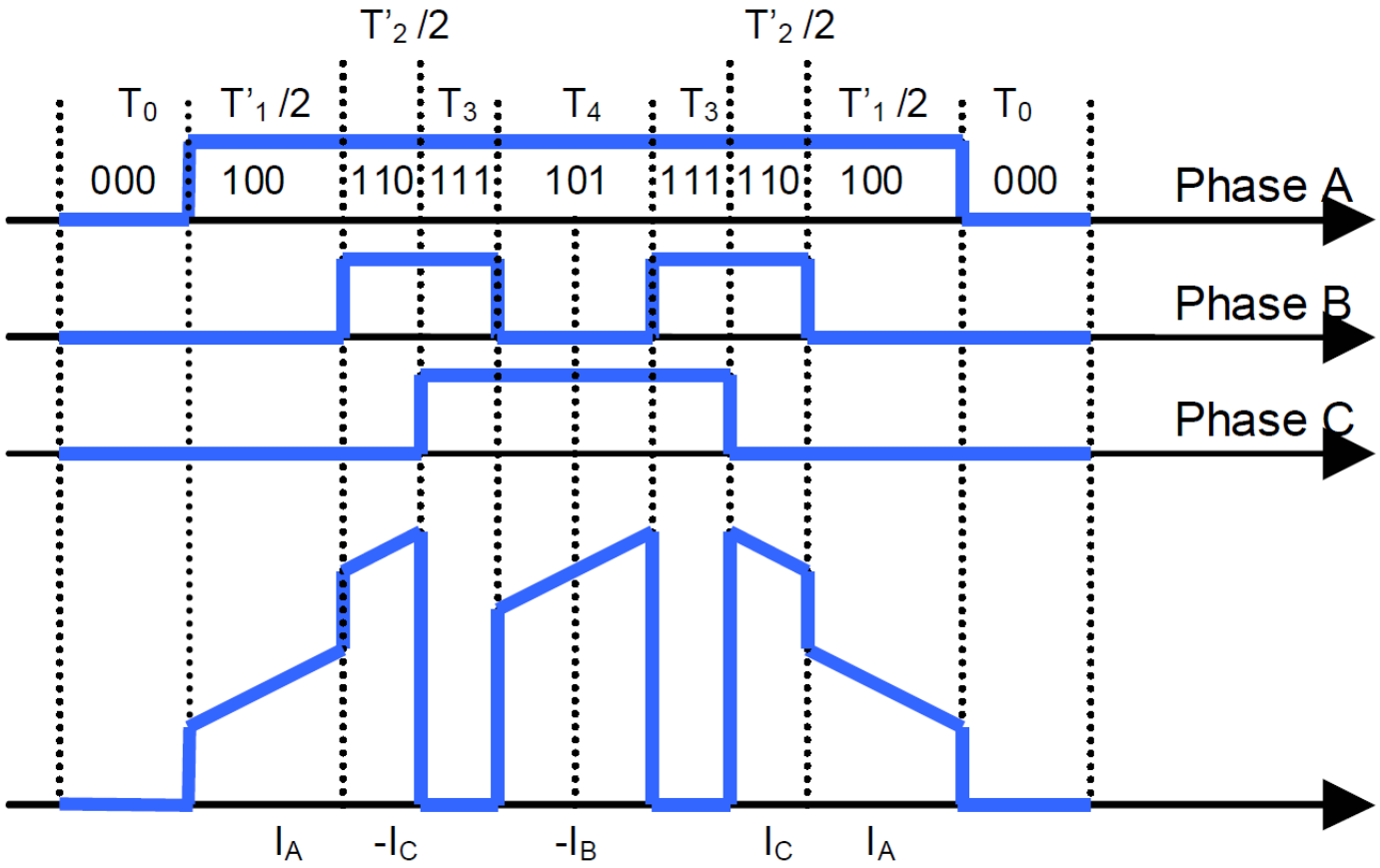
# Single-Shunt Blackout Solutions

## Solution 2:

**Symmetrical PWM – Double Pulse**

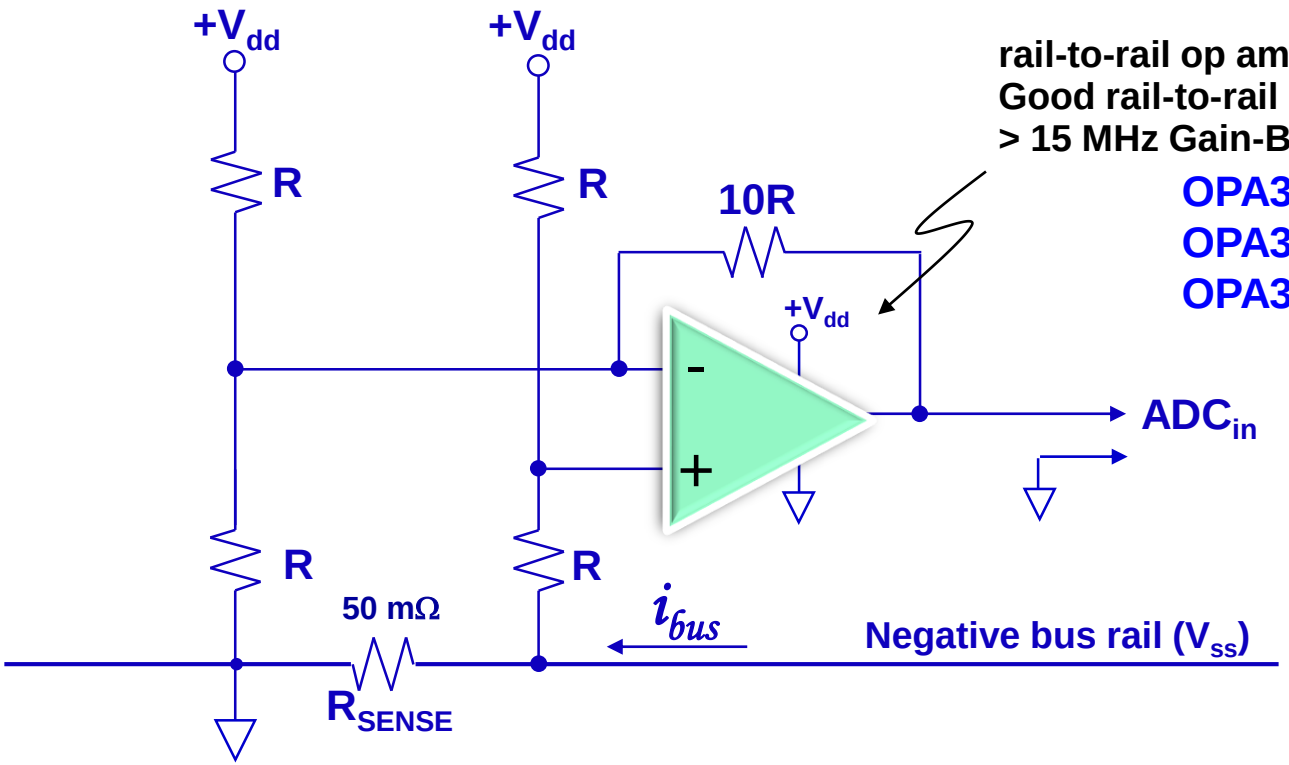
- Split duty cycle into 2 pulses
- Duty cycles preserved

**3-phase visibility!**




*Source: STMicroelectronics*

# Single Supply Bipolar Current Sensing




rail-to-rail op amp with >20V/uS slew rate
Good rail-to-rail performance
> 15 MHz Gain-Bandwidth Product

OPA320/2320
OPA350/2350
OPA365/2365

$I_0$ reading is taken during $V_{null}$ vectors, and then stored.