Accurate Power Conversion Measurements on High Power Motor Drives

Presented by:
Ian Walker
GMW Associates
ian@gmw.com

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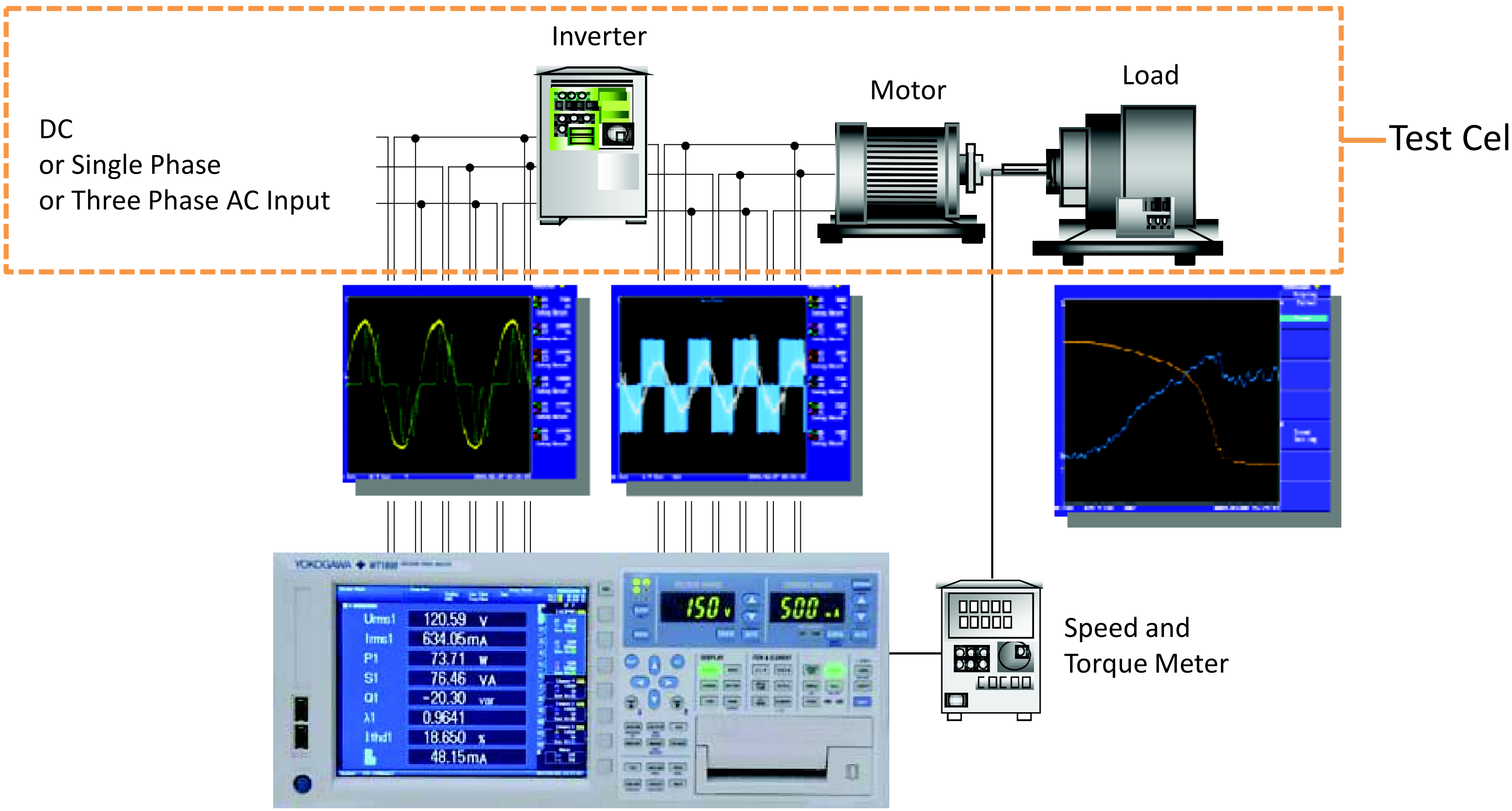
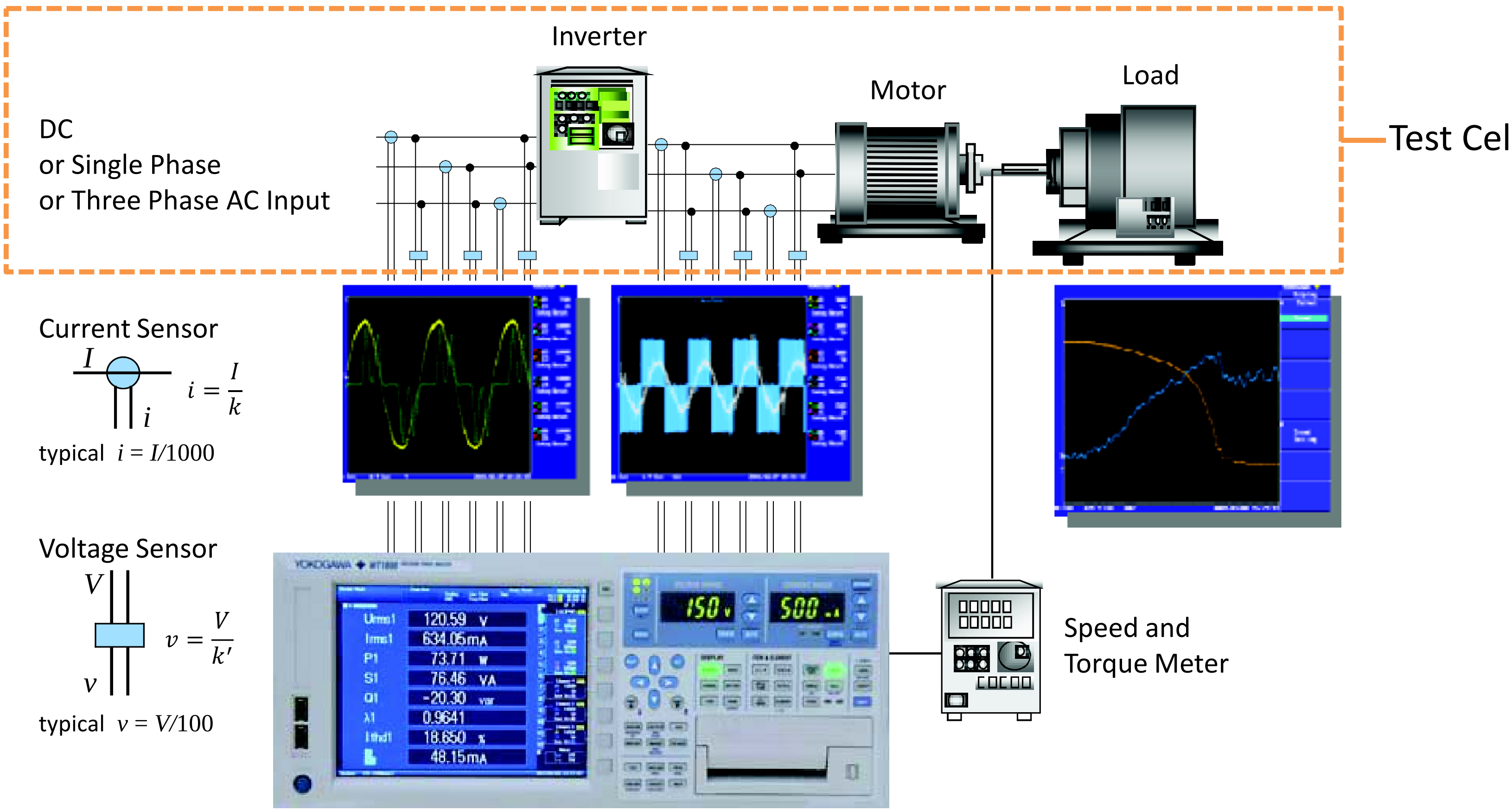
Interconnections for the test of a low power AC Motor with Variable Speed Drive



From: Yokogawa

Current and Voltage Transduces provide electrical isolation in testing high power Variable Speed Drives

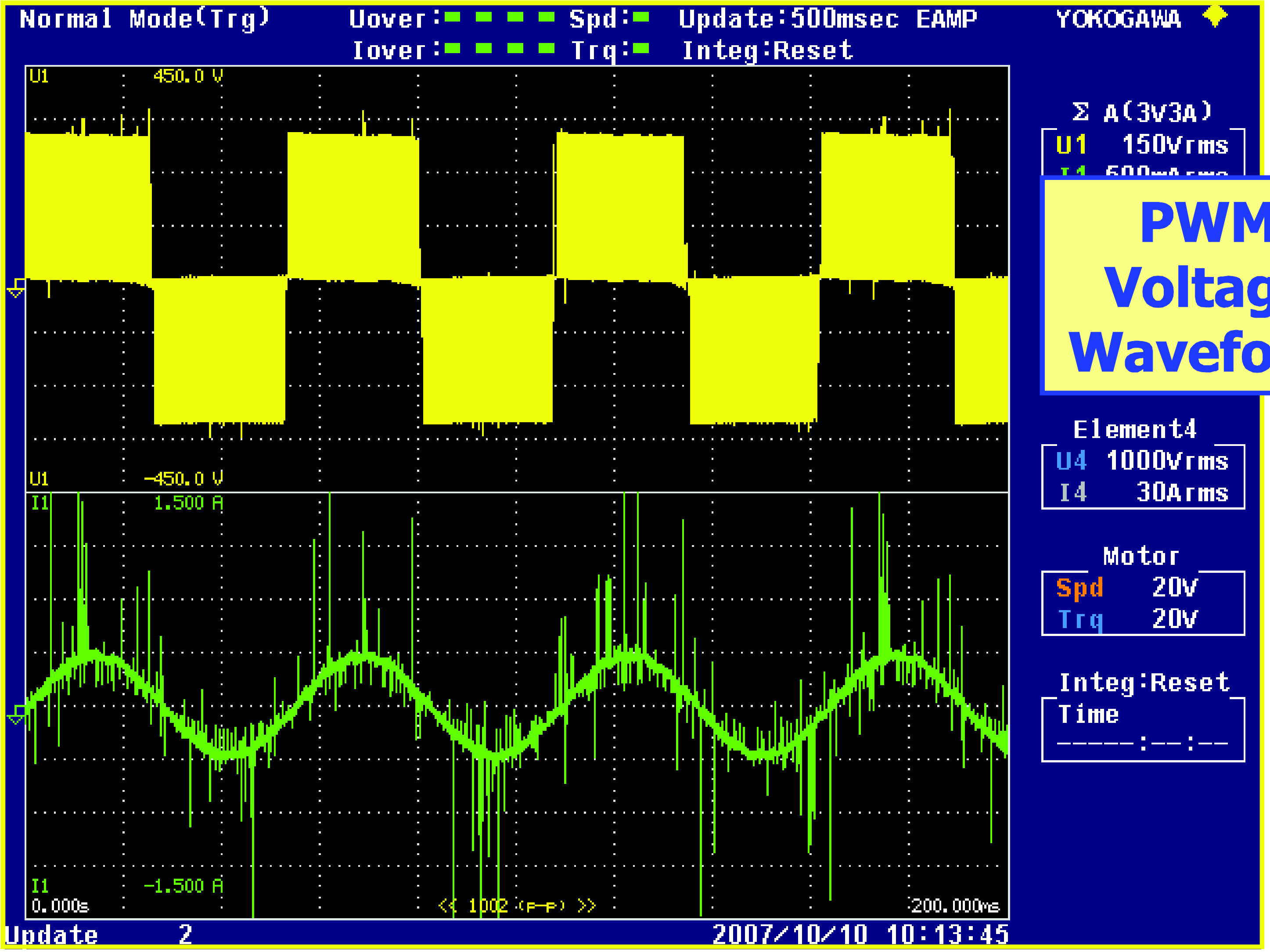


From: Yokogawa

Voltage and Current Waveforms on one phase of a low power, variable speed AC Motor Drive

V

I



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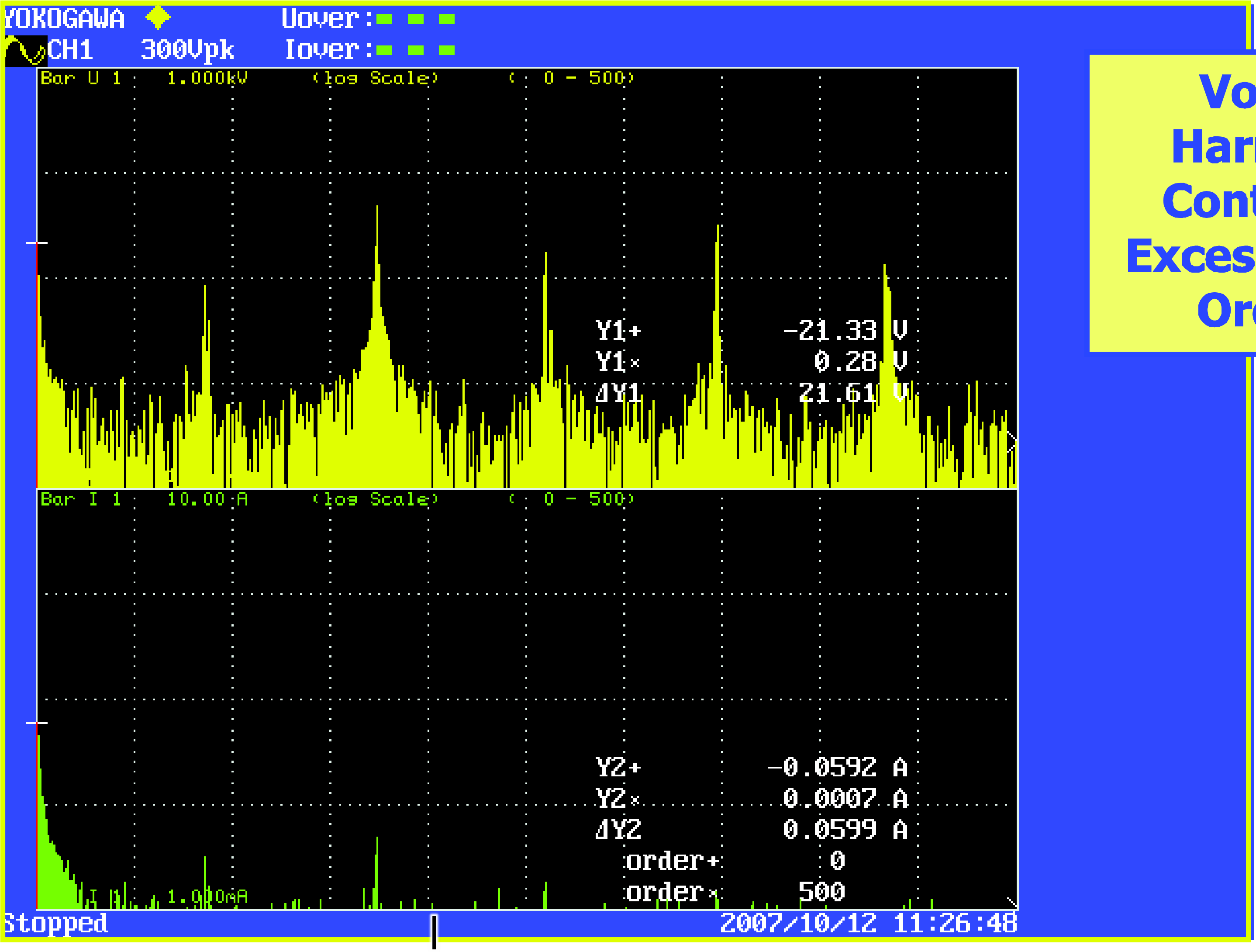
Voltage and Current Spectra for the previous Voltage and Current Waveform



Voltage Harmonic Content in Excess of 500 Orders

~200 harmonic

From: Yokogawa

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Power Measurement

For any voltage and current phase pair:

$$P_{total} = 1/T \int_0^T V(t) \cdot I(t) dt$$

When Voltage and Current Transducers are used:

$$V(t) = k' \cdot v(t) \;\text{ with } k' \text{ typically about } 100$$
$$I(t) = k \cdot i(t) \;\text{ with } k \text{ typically about } 1000$$

$$P_{total} = k \cdot k' \, 1/T \int_0^T v(t) \cdot i(t) dt$$

This calculation provides **True Power** measurement of any waveform, including all the harmonic content, limited by the bandwidth of the transducers and the processing instrument.

Note also: $\frac{dv\,(t)}{dt} = \frac{1}{k'} \frac{dV\,(t)}{dt}$ and $\frac{di\,(t)}{dt} = \frac{1}{k} \frac{dI\,(t)}{dt}$

dramatically reducing the capacitive and inductive coupling from long cables.

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The Total Power can also be calculated from the harmonic content

$$P_{total} = V_0 \cdot I_0 + V_1 \cdot I_1 \cdot cos\theta_1 + V_2 \cdot I_2 \cdot cos\theta_2 + V_3 \cdot I_3 \cdot cos\theta_3 + \cdots + V_n \cdot I_n \cdot cos\theta_n$$

or

$$P_{total} = V_0 \cdot I_0 + \sum_1^{max} V_n \cdot I_n \cdot cos\theta_n$$

V_0 and I_0 are the dc components of Voltage and Current.

or

$$P_{total} = k \cdot k' v_0 \cdot i_0 + k \cdot k' \sum_1^{max} v_n \cdot i_n \cdot cos\theta_n$$

Voltage and Current Transducers must have accurate amplitude and phase response for all the harmonics that contribute to P_{total}. Any "False" harmonics, v_n or i_n , introduced by cross-talk, will generate an error in the P_{total} if $cos\theta_n$ is $\neq 0$ and may be significant if θ_n approaches 0 and $cos\theta_n$ is = 1.

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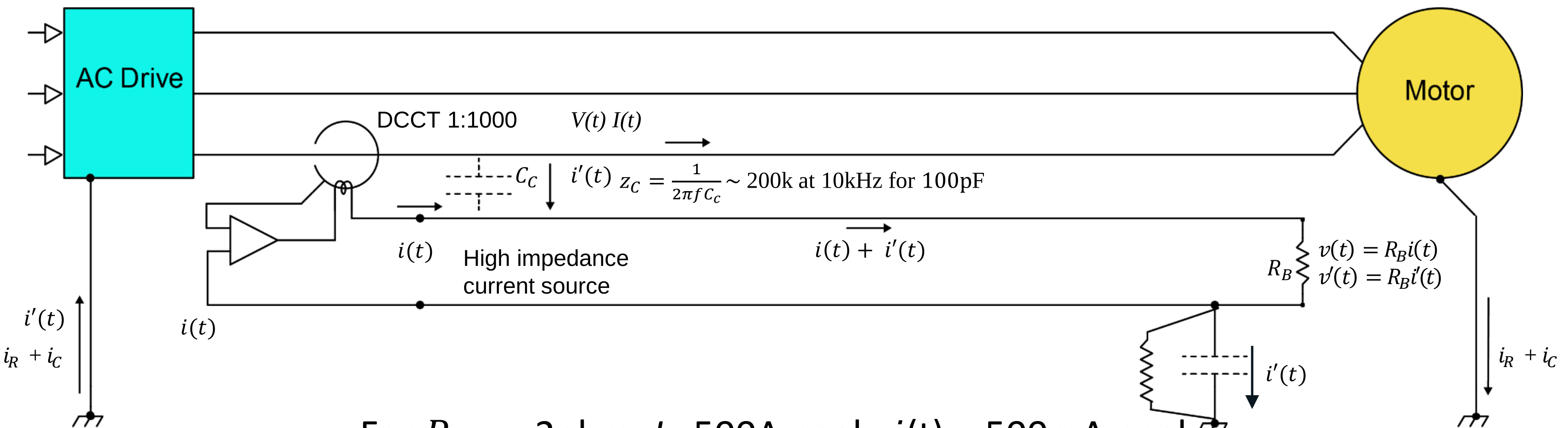
Cross Talk Mechanisms

For a variable speed motor drive used in transport applications, the voltage signal rise and fall times can be as short as 50ns, implying significant spectrum components to 6MHz. The wavelength of the electromagnetic radiation at 6MHz is about 50m. In a Motor Drive Test Cell, the dimensions of possible “antennas” within the signal measurement cables are typically less than 5m so simple capacitance and inductive coupling models, rather than electromagnetic wave coupling, can be used for a simplified analysis.

$$\lambda \sim \frac{c}{f} \sim \frac{3\ x\ 10^8}{6\ x\ 10^6} \sim \frac{1}{2} \times 10^2 \sim 50m$$

Capacitive Cross Coupling from the high voltage, high current cables



For $R_B =$ 2ohm, I =500A peak, i(t) = 500mA peak

$v(t) = R_B i(t) = 1000\text{mV peak}$

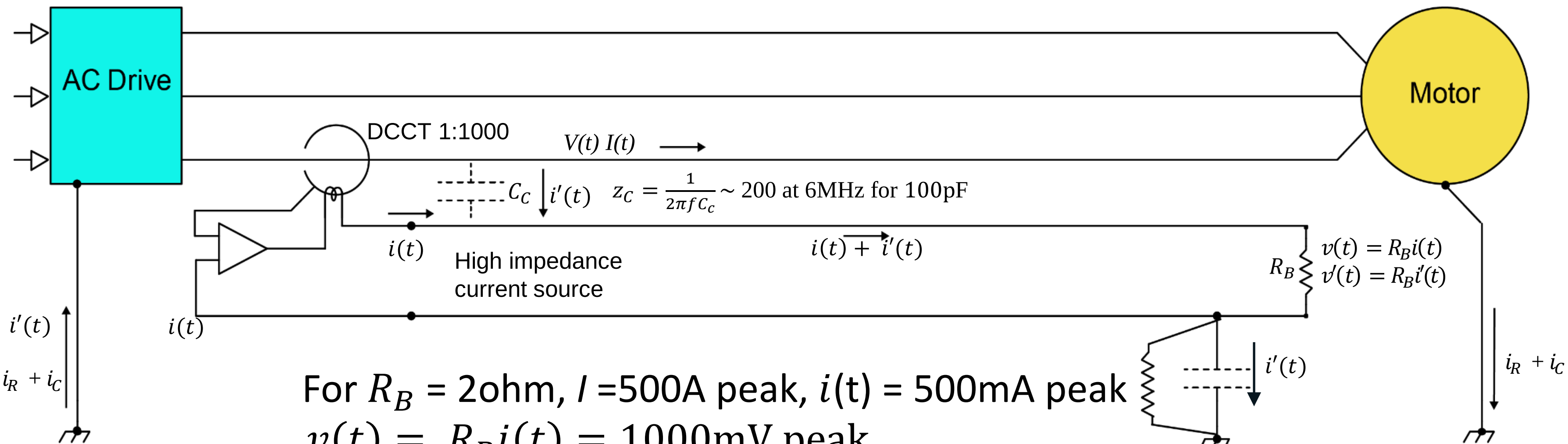
At low frequency, ~10kHz, capacitive cross-coupling is low with $C_C \sim 100\text{pF}$ and $V_n \sim 100\text{V}$at 10kHz, $z_C \sim 200\text{kohm}$.

$$i'(t) \sim \frac{V_n}{(z_C + R_B)} \sim \frac{100V}{200\text{k}} \sim 0.5\text{mA}$$

$$v'(t) \sim R_B i'(t) = 2\ x\ 0.5\text{mA} \sim 1\text{mV peak}$$

$\sim$0.1% of the “true” current output signal of 1000mV peak.

Capacitive Cross Coupling from the high voltage, high current cables



For R_B = 2ohm, *I* =500A peak, i(t) = 500mA peak

$$v(t) = R_B i(t) = 1000\text{mV peak}$$

At high frequency, ~1MHz, capacitive cross-coupling is high with $C_C \sim 100\text{pF}$ and $V_n \sim 100\text{V}$at 1MHz, $z_C \sim 1\text{kohm}$.

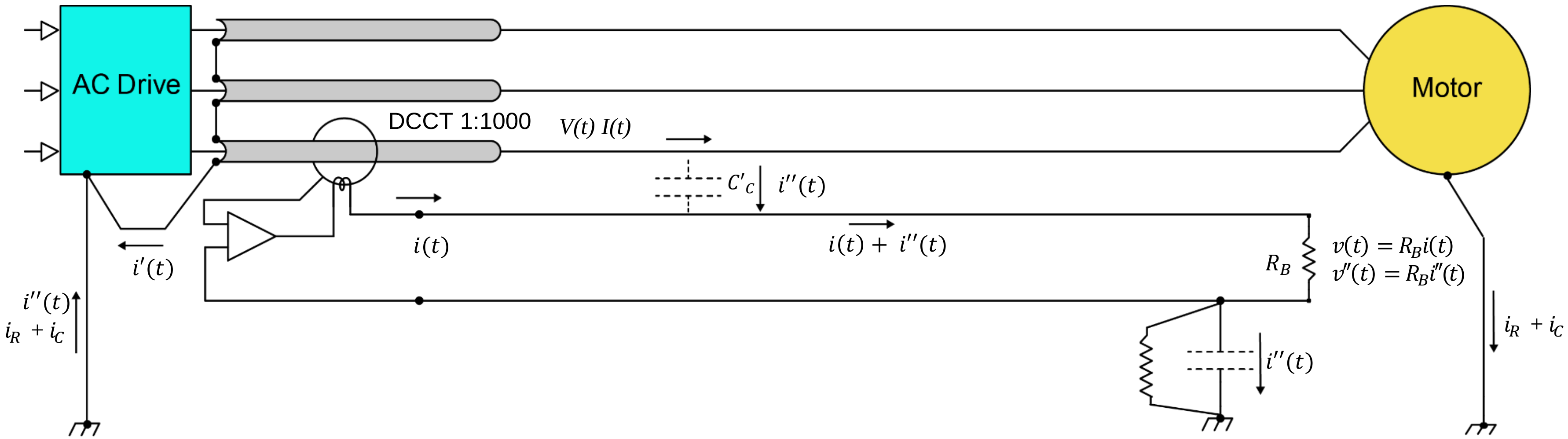
$$i'(t) \sim \frac{V_n}{(z_C + R_B)}$$

$$v'(t) \sim R_B i'(t) = \frac{R_B V_n}{(z_C + R_B)} \sim \frac{2 \times 100}{1\text{k}} \sim 100\text{mV peak}$$

~10 % of the "true" current output signal of 1000mV peak.

Note that $v'(t)$ on the current signal is approximately in phase with $V(t)$.

Capacitive Cross Coupling from the high voltage, high current cables



Capacitive Cross Coupling from the high voltage $V(t)$ on the motor drive cables can be substantially reduced by shielding the drive-to-motor cables in the vicinity of the Current Transducer and signal cables. Self adhesive copper tape can be wrapped around the cables for a length of greater than three Current Transducer Head diameters. The shielding must be grounded at one end only and near the AC Drive so that the shield high frequency current, $i'(t)$, is returned to the AC drive in a short, low inductance path.

There will still be some capacitive coupling between the Drive-to-Motor cables and signal cables giving rise to a cross coupling current $i''(t)$ with $i''(t) << i'(t)$. This can be reduced by shielding the signal cables.

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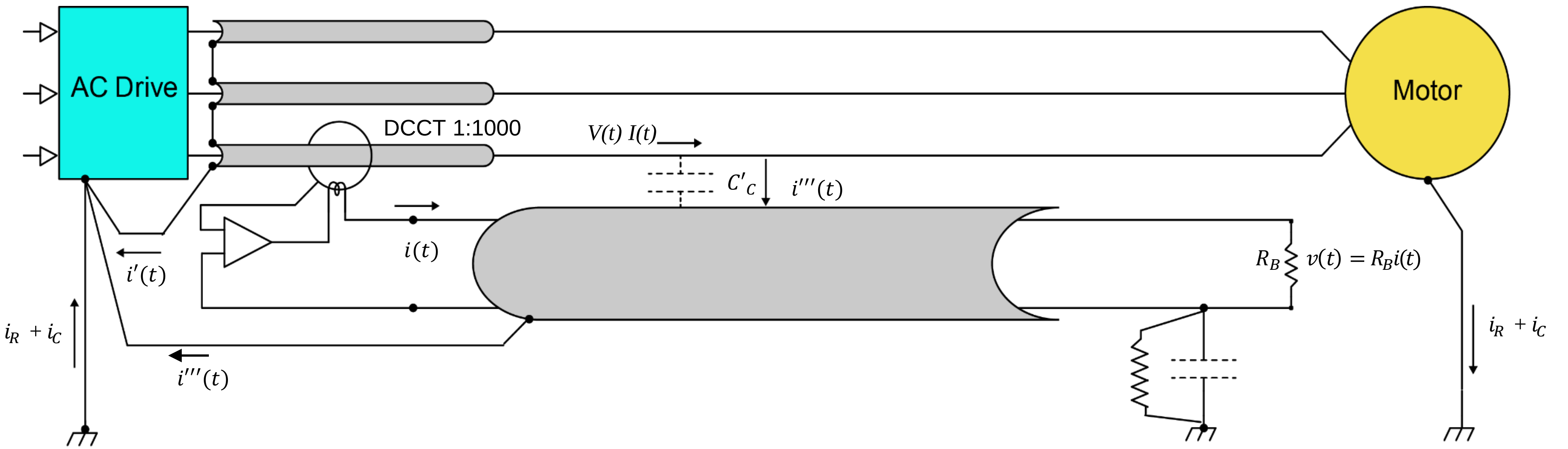
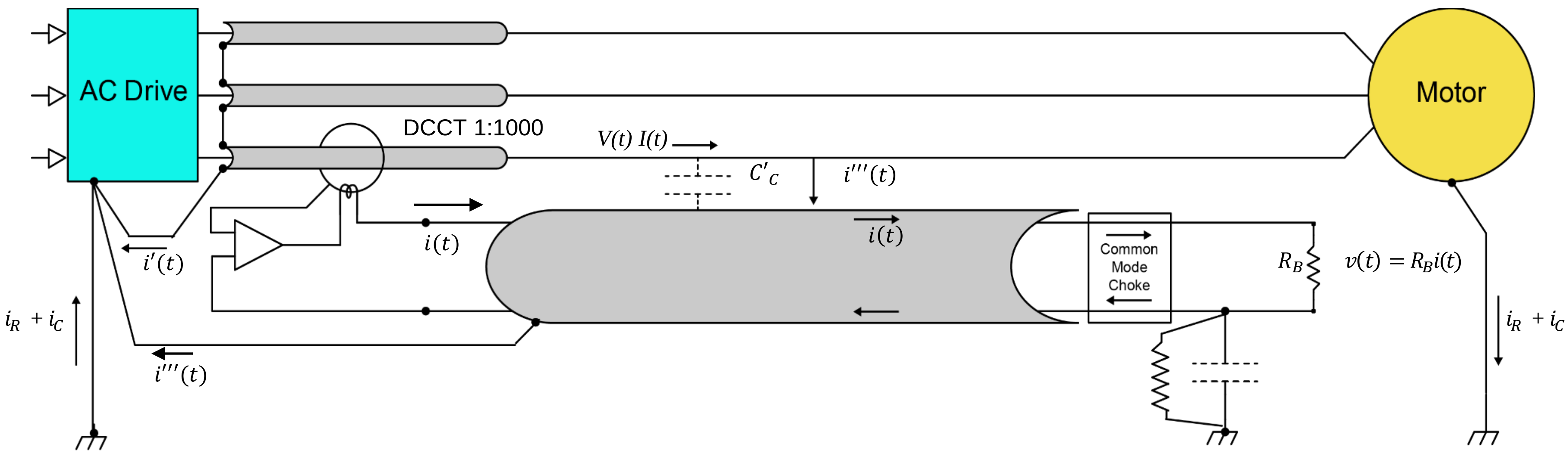
Capacitive Cross Coupling from the high voltage, high current cables



The Current Transducer to Burden Resister signal cable should be a twisted pair (to reduce magnetic pickup) with the outer shield returned to the AC drive in a short, low inductance path.

Capacitive Cross Coupling from the high voltage, high current cables.

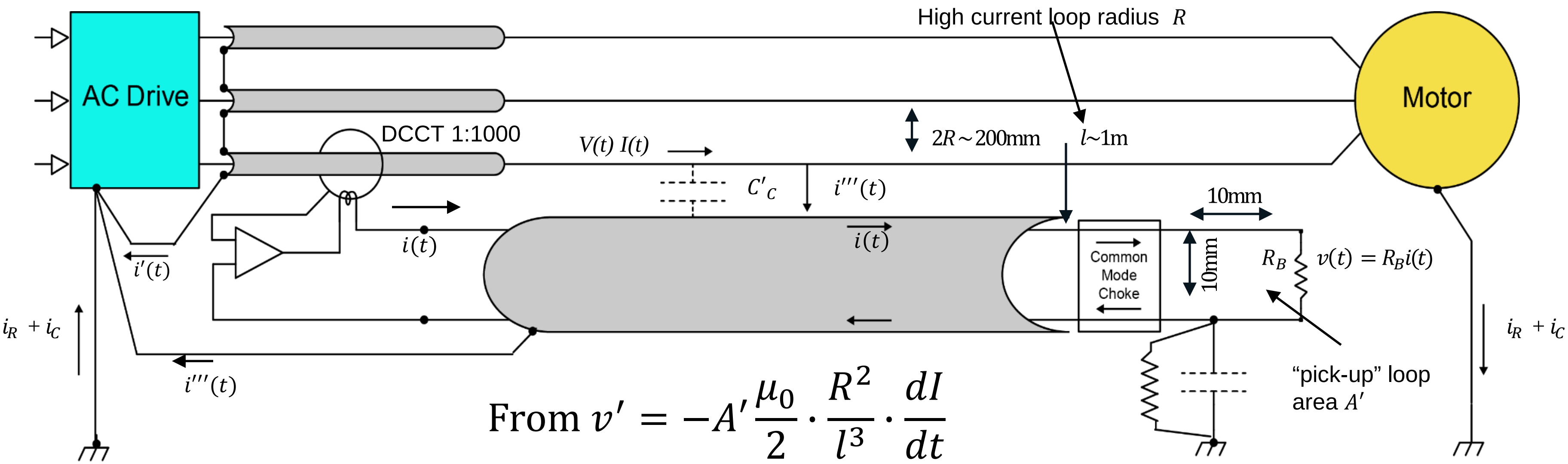
Addition of a Common-Mode Choke to a Signal Pair.



Even with a shielding of the drive-to-motor cables and shielded signal cables, there still can be a residual cross-talk, particularly at higher frequencies. A common-mode choke is effective in providing a relatively high impedance to a current on only one line of the signal pair. Single turn, clamp-on, common-mode shunts can have an impedance of about 10ohm at 1MHz and 30ohm at 6MHz to give a reduction of spurious signals at a 2ohm Burden Resistor of between 5 and 15 times. This demonstrates one benefit of using a current source Current Transducer with a remote, low resistance Burden Resistor, R_B.

Inductive Cross Coupling from the High Current Motor Drive Cables.

Signal induced in a small "pick-up" loop at the Burden Resistor.



$$\text{From } v' = -A'\frac{\mu_0}{2}\cdot\frac{R^2}{l^3}\cdot\frac{dI}{dt}$$

$$A' \sim 10 \times 10\text{mm} \sim 10^{-4}\text{m}^2$$

$$R \sim 100\text{mm} \quad \sim 10^{-1}\text{m}$$

$$l \sim 1\text{m}$$

$$\frac{dI}{dt} \sim \frac{400\text{A}}{2\text{ms}} \sim 2x10^5\ A/sec\ \ (f \sim 150\text{Hz})$$

Then the voltage induced in the loop at the Burden Resistor is

$$v' \sim -10^{-4}\cdot\frac{4\pi\times10^{-7}}{2}\cdot\frac{10^{-2}}{1}\cdot 2\times10^5$$

$\sim 0.1\mu$V. At low frequencies and with good layout the direct magnetic coupling is small and the developed voltage leads the current *I*(t) by about 90°.

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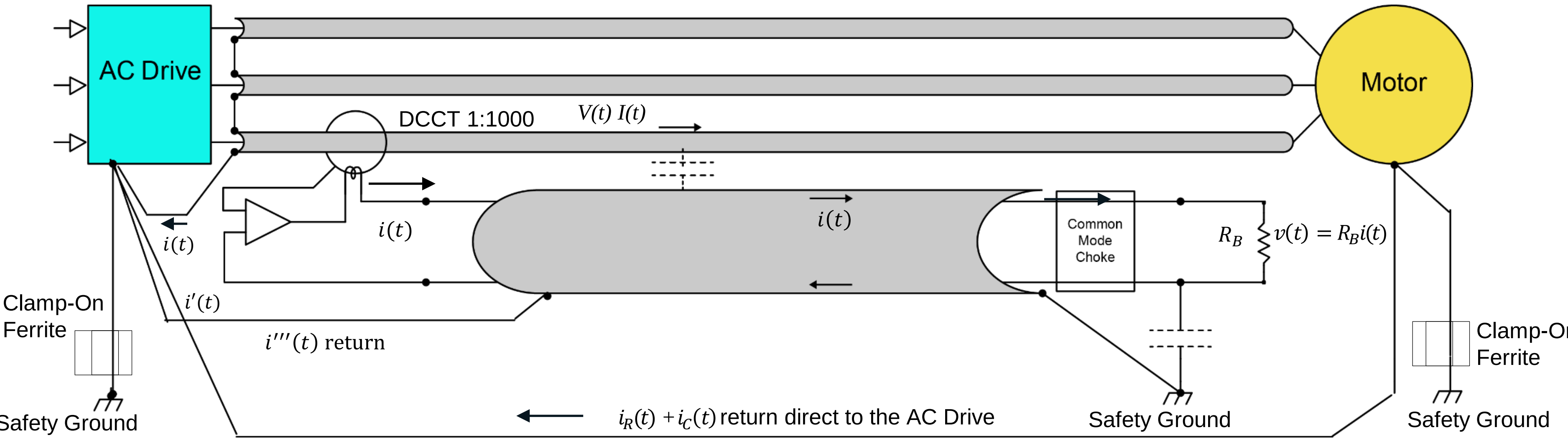
Capacitive Cross Coupling from the high voltage, high current cables.

"Grounding" of high frequency capacitively coupled currents.



To minimize capacitive coupling from the high frequency voltages and for safety, it is often preferable to use shielded Drive to Motor Cables. The parasitic currents $i_R(t) + i_C(t)$ are returned by the cable shields. However, to measure the phase currents requires the shields be broken so the parasitic currents return outside the Current Transducer aperture. A separate low impedance return from the Motor to the Drive must be added. This direct return combines with the safety grounds to generate a potentially large "ground loop" in which current can be induced by changing magnetic fields. As far as feasible the loop area should be minimized. High frequency current can be reduced by clamp-on ferrite on the safety ground leads.

Summary

1. In the measurement of power transfer in high power variable speed motor drives a significant source of error in the power calculation can be the generation of "false" current harmonics arising from capacitive coupling to the current channel from the high frequency voltage harmonics.
2. Shield all cables carrying high voltage to reduce capacitive coupling to the Current Transducer and associated signal lines.
3. To minimize the effects of capacitive coupling from the high frequency voltage harmonics, use current source (high impedance) Transducers rather than voltage source Transducers. This is particularly important for the Current Transducers.
4. Locate Transducers near the Drive rather than the Motor to avoid magnetic fields from the Motor generating cross-talk signals in the Transducers.
5. Capacitively induced currents in the cable shields should be explicitly returned to the source common with short, low impedance return leads. Low frequency magnetic fields from the motor currents can be reduced by minimizing the area enclosed by high currents.
6. Grounding for electrical safety compliance should be separately considered from the return of high frequency, capacitively coupled currents.
7. High frequency currents reduced in ground loops can be reduced by clamp on ferrites on the safety ground leads.

References Page

- Weston, David A. *Electromagnetic Compatibility, Principles and Application.* 2nd ed. CRC Press, 2001.

Thank You

Questions?

Ian Walker

ian@gmw.com

www.gmw.com

650-802-8292