Power Electronics and Electric Motor Research at ORNL

A Seminar for the
Wisconsin Electric Machines and
Power Electronics Consortium
at
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December 6, 2002
by

J. W. McKeever
ORNL's Power Electronics and
Electric Machinery Research Center

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DOE/USCAR
Cooperative Research Commitment

The structure for government electric vehicle research was revised and announced early this year by DOE and the U.S. Council for Automotive Research composed of automakers Ford, General Motors, and DaimlerChrysler.

- Name - FreedomCAR = "Freedom" and "Cooperative Automotive Research"
- Represents DOE's commitment to developing public/private partnerships to fund high risk, high-payoff research into advanced automotive technologies.
- Emphasizes fuel cells to power automobiles without air pollution.
- Progenitor is the Partnership for a New Generation of Vehicles (PNGV) initiative that ran from 1993 through 2001.

FreedomCAR Goals

Since transportation consumes 67% of our nation's petroleum and steady growth of imported oil needed to meet U.S. requirements (current levels of 10 million barrels each day) is not sustainable over the long term the research partnership goals are to develop cars and trucks that are:

- Free from imported oil
- Cheaper to operate
- Pollution free
- Competitively priced

Power Electronics and Electric Machinery Research Center

PEEMRC is *the* U.S. Department of Energy's broad-based power electronic and electric machinery research center.

www.ornl.gov/etd/peemrc

The center has advanced technology in:

- Soft-switched inverters
- Multilevel inverters
- Non-active power compensation
- Motor control techniques
- Efficient, compact electric machines

The PEEMRC's National Laboratory Role

- Conducts fundamental research
- Evaluates commercially supplied prototype hardware
- Assists in technical direction of the DOE's FreedomCAR and Vehicle Technologies' Power Electronics and Electric Machinery Program
  - Serves on FreedomCAR Electrical and Electronics Technical Team
  - Evaluates proposals for DOE
  - Lends technological expertise to help direct projects and evaluate developing technologies.

National User Facility

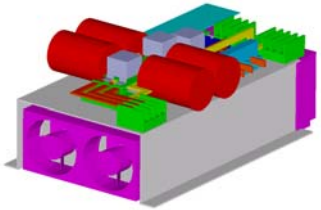
PEEMRC has been designated a DOE National User Facility.

> 700 square meters of laboratory space for developing prototype inverters, rectifiers, and electric machine technology.

Center has had 25 patents granted with several more pending.

20 personnel, 10 with advanced degrees in electrical engineering, mechanical engineering, physics, nuclear engineering.

Power Electronics Research Areas



Interface with **distributed energy resources** such as microturbines and fuel cells

Multilevel converters for utility applications such as static var compensation, voltage sag support, HVDC intertie, large variable speed drives

Harmonics, **power quality**, and **power filters**

Hybrid electric vehicle (HEV) applications such as motor drives or dc-dc converters

Soft-switching inverters and dc-dc converters

Application of **wide-band gap power electronics**

Simulation, modeling and **analysis of power electronics** for transportation and utility applications

Electric Machine Technology Research

Novel electric machine technology

- *Permanent magnet* (axial and radial gap)
- *Switched reluctance*
- *Induction* (novel designs and rotor bar technology)
- *DC machines* (advanced brush technology, soft-commutated, homopolar)
- *Superconducting generator*

Motor control – sensorless motor drive techniques, circuits and dual mode inverter control for extended constant power range at high speeds

Design, thermal, efficiency, and **performance models** for AC machines

Prognostics and **failure diagnostic** techniques

FY 2002 PEEMRC Research

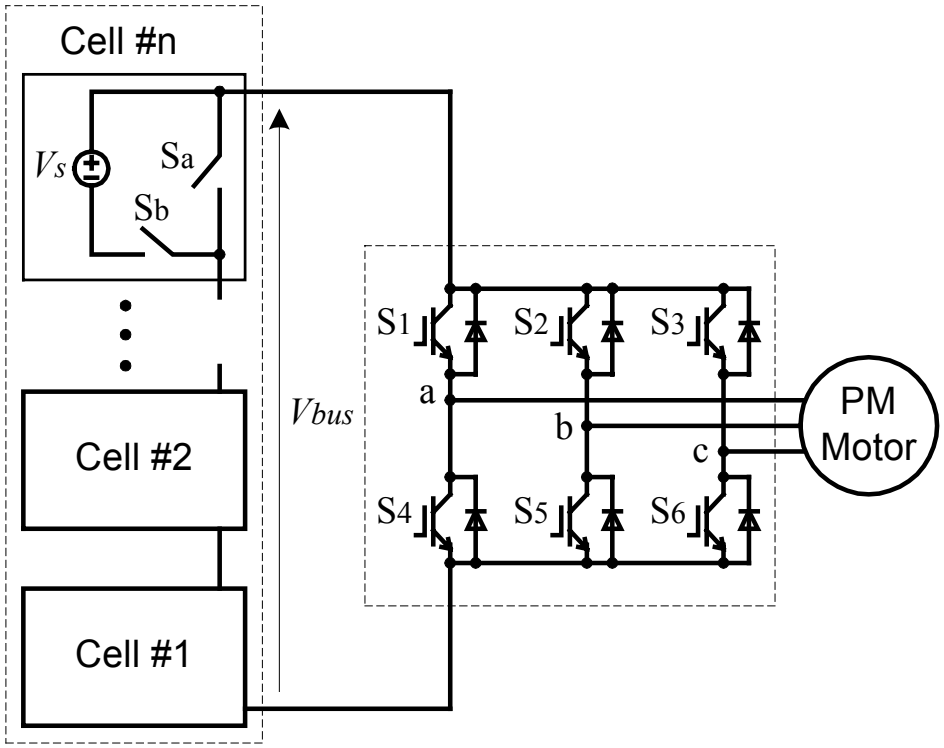
This past year the PEEMRC research and test activities have included:

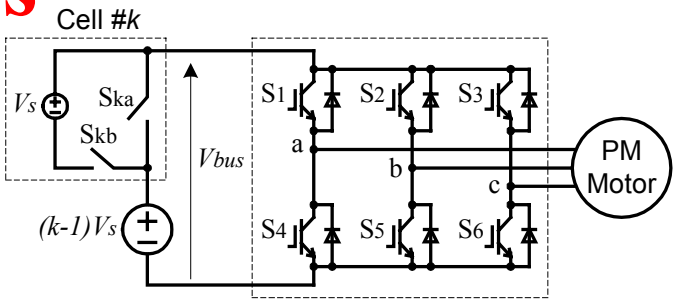
- Development of inverter/converter topologies - Multilevel DC Link Inverter
- Development of field weakening by flux control - HSUB motor
- Development of Field Weakening by inverter control - Dual Mode Inverter Control for low inductance PM motors
- Evaluation of Switched Reluctance Motors for HEVs
- Motor/Inverter Modeling - SRM model on LabVIEW platform

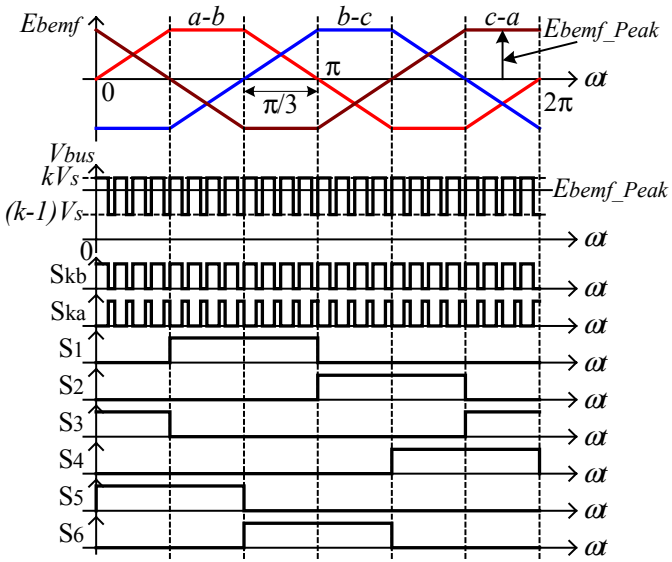
FY 2002 PEEMRC Research
(continued)

- Automotive Electric Motor Drive (AEMD) validation testing and contract support
- Automotive Integrated Power Module (AIPM) validation testing and contract support
- Development of micro-sensors for automotive power electronics
- Modeling silicon carbide for transportation applications.
- Developed a real-time platform for evaluation of electric machinery control algorithms

Multilevel DC Link Inverter to Reduce Current Ripple in Low Inductance PM Motors







Developed and patented by Dr. Gui-Jia Su, ORNL

MLDCLI Current Ripple Analysis

$$I_{m_ripple} = \frac{k^2 V_s}{4 L_m f_{SW}} \left(1 - \frac{K_{bemf} N}{k V_s}\right)\left(\frac{K_{bemf} N}{k V_s} - \frac{k-1}{k}\right)$$

$L_m =$ per-phase stator leakage inductance,

$f_{SW} =$ inverter cell switching frequency,

$V_S =$ inverter cell voltage, and

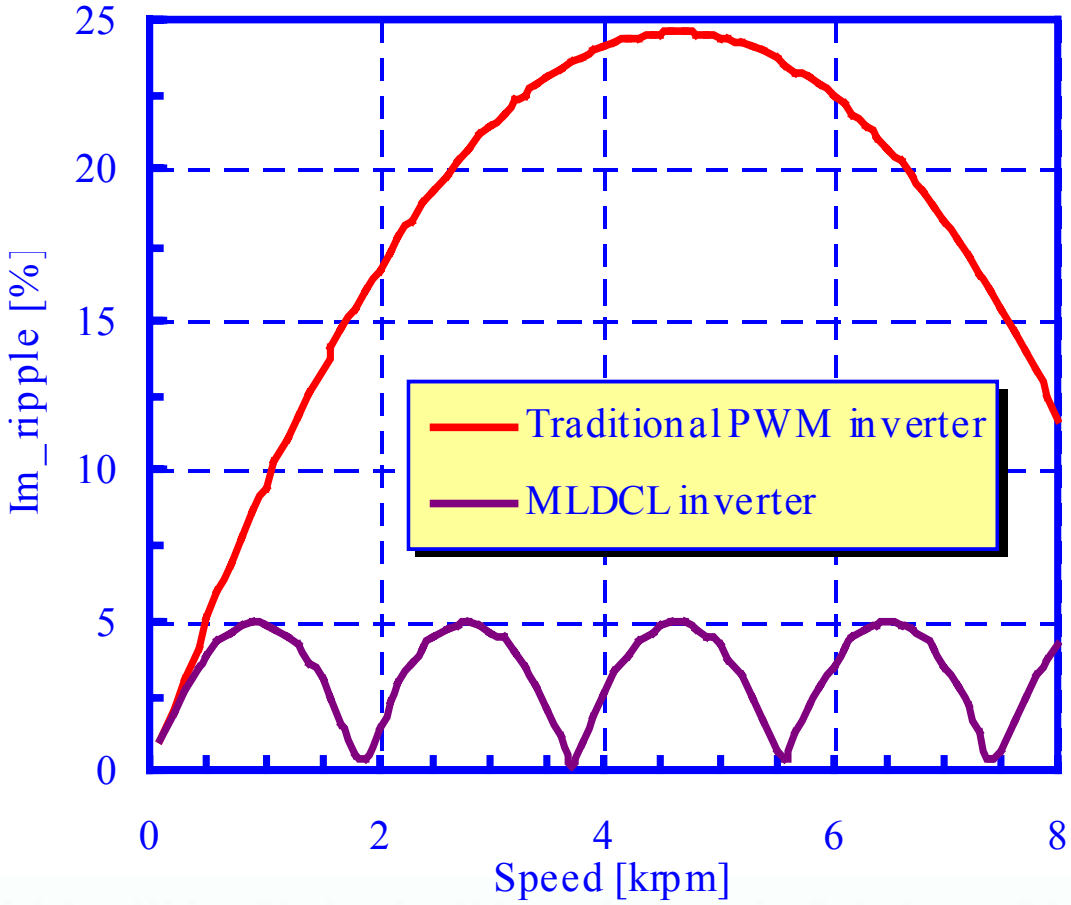
$K_{bemf} =$ back-emf constant determined by the motor.

The maximum current ripple can be determined by

$$I_{m_ripple}(\max) = \frac{V_s}{16 L_m f_{SW}}$$

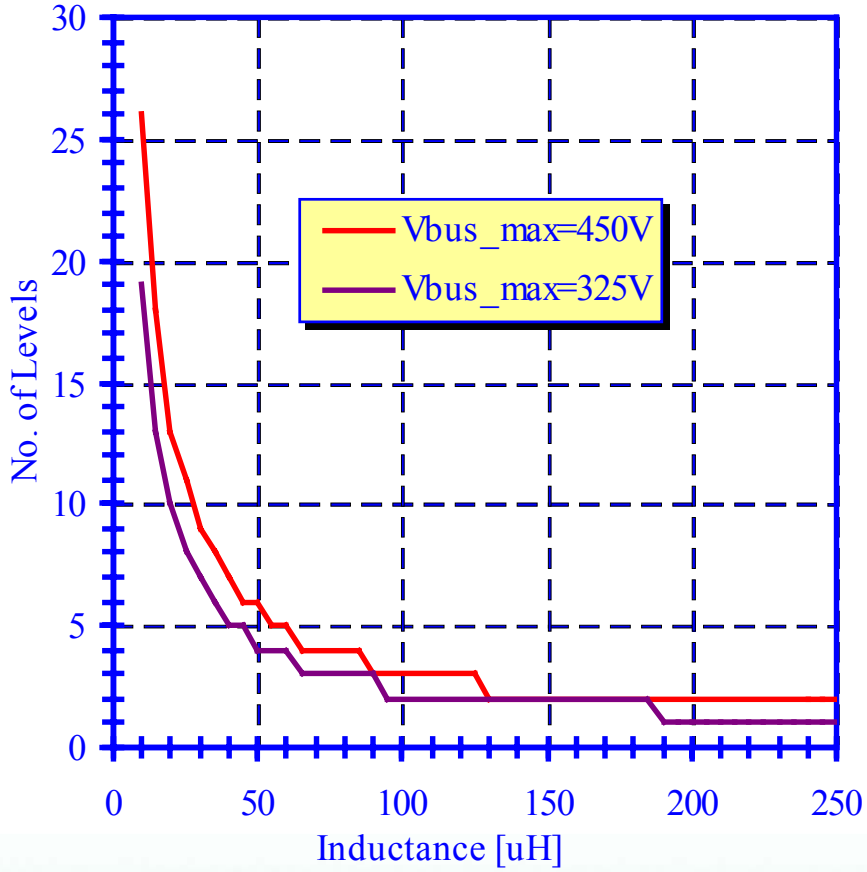
at $$N = \frac{(2k-1)V_s}{2K_{bemf}}$$

Comparison of Traditional and MLDCL Current Ripple

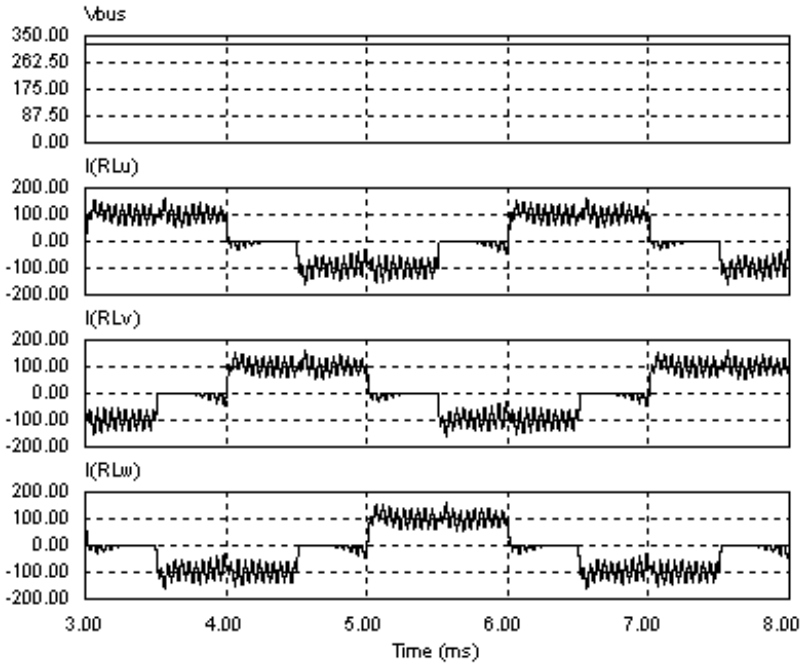


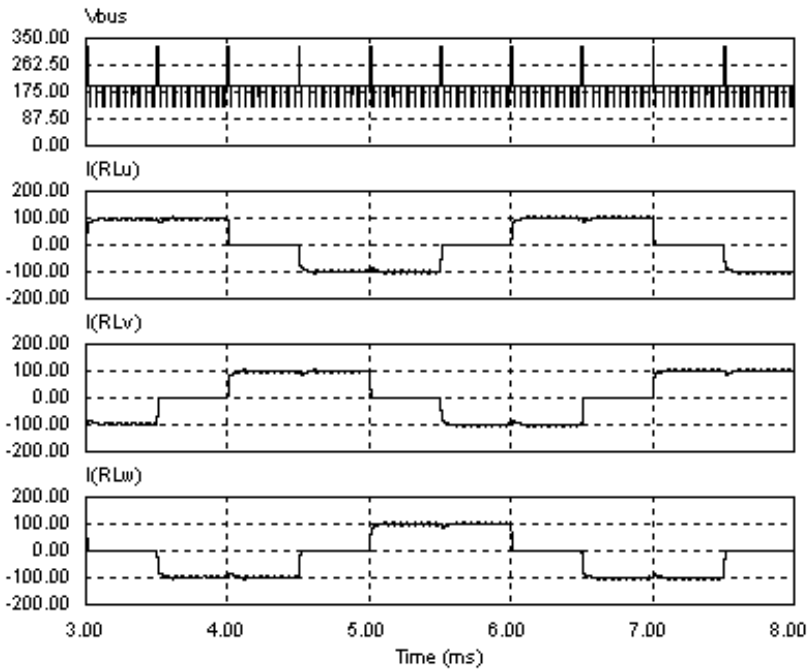
Number of Levels to Limit Current Ripple to 5%

(20 kHz Switching Frequency)



Comparison of Simulated Current Waveforms at 5000 rpm

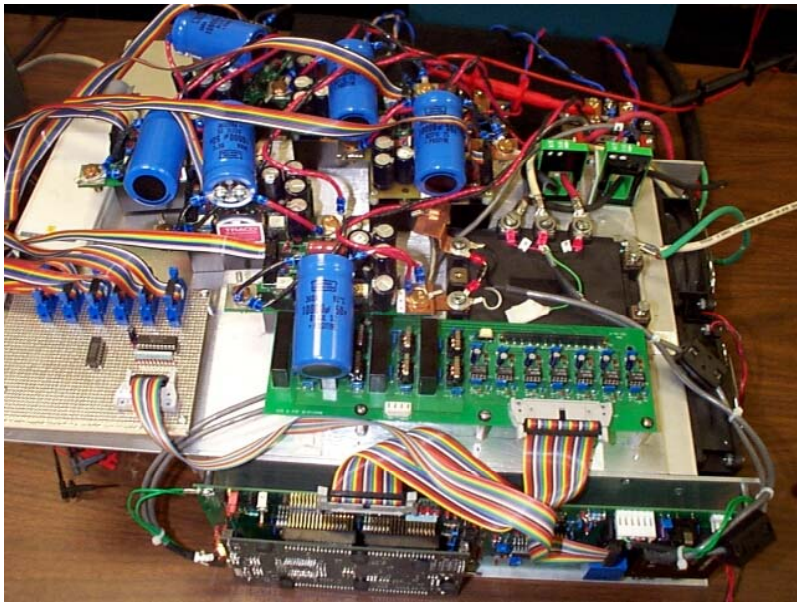


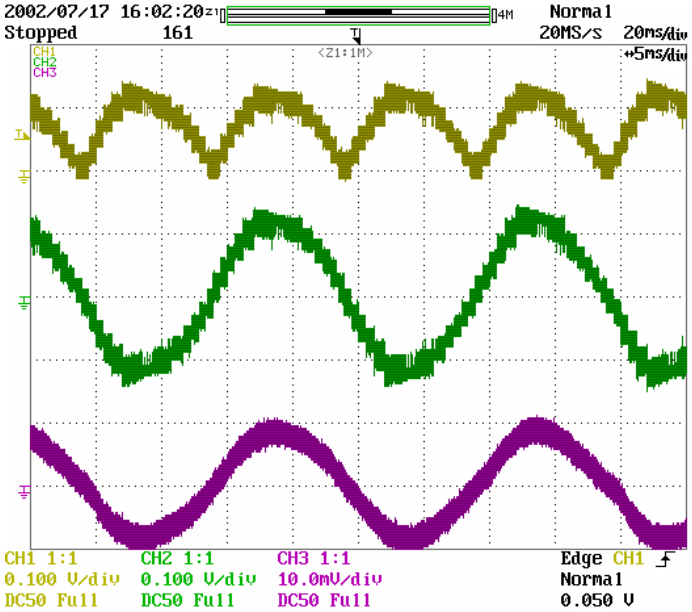


Traditional PWM inverter

5-level MLDCLI PWM Inverter

Six-Level MLDCLI Proof-of-Concept Testing





DC bus voltage 100V/div

Output voltage 100V/div

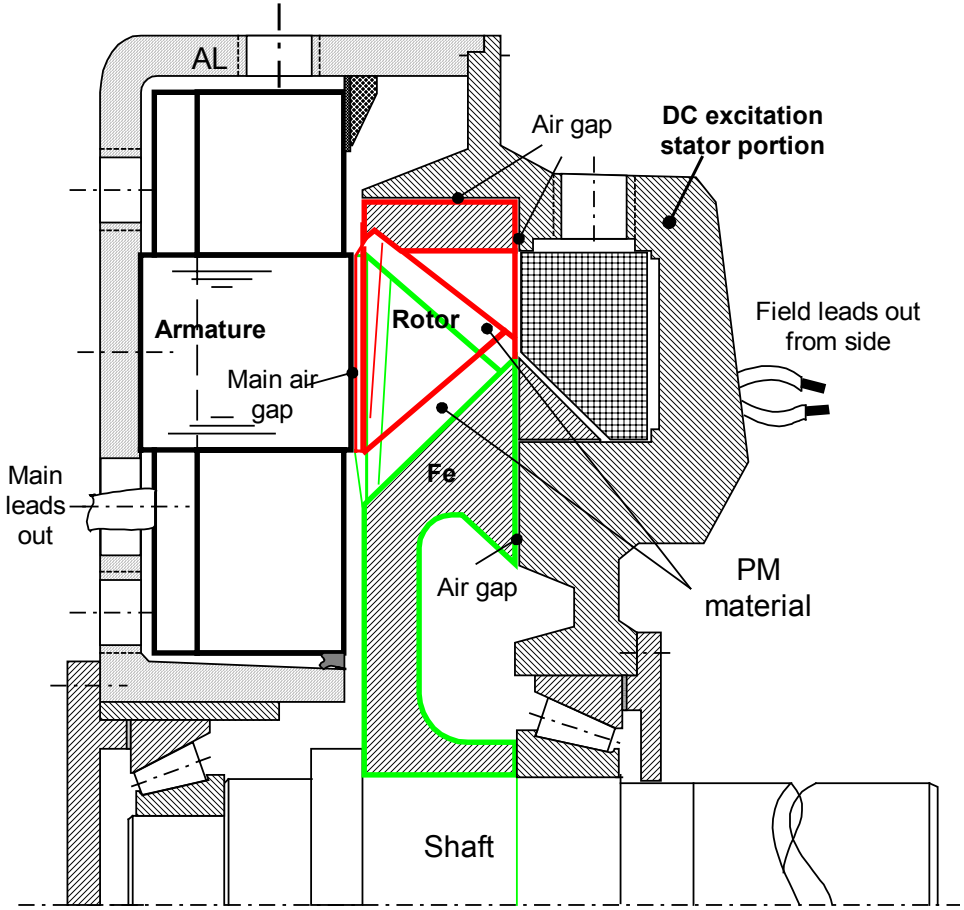
Load current 5A/div

Test setup

Waveforms

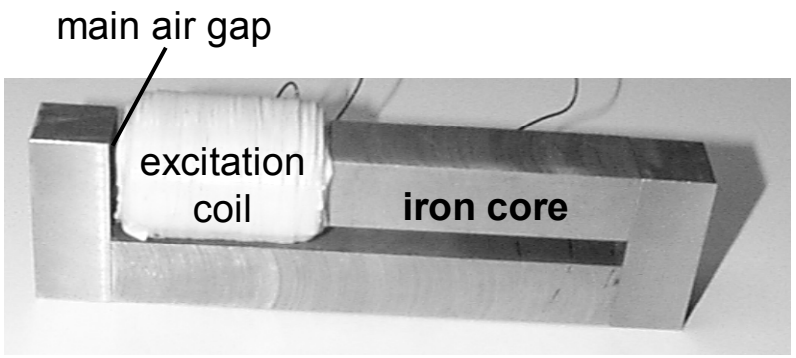
Field Weakening by Flux Control

The High-Strength Undiffused Brushless (HSU-B) Motor

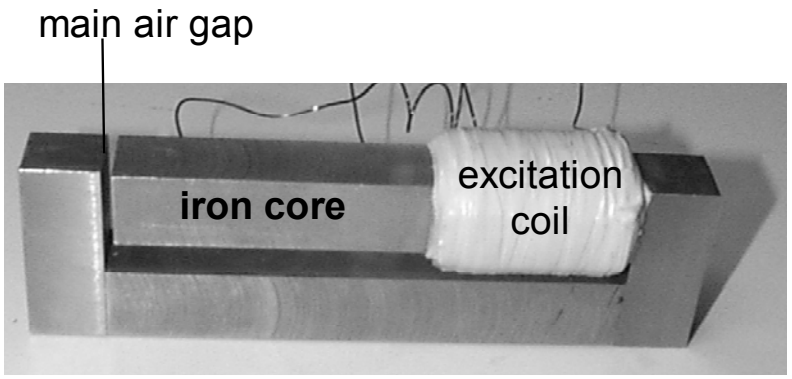


Developed and patented by Dr. John Hsu, ORNL

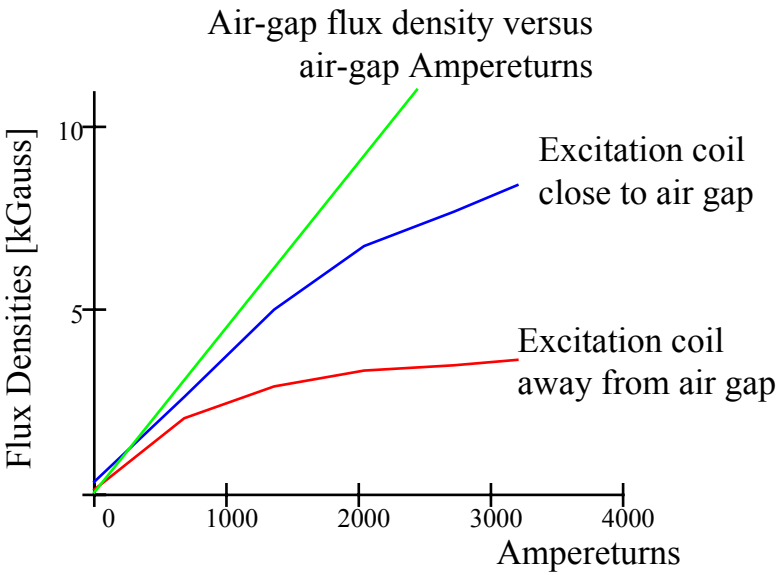
Diffused (rotor leakage) Flux Reduces "Payoff" Air-gap Flux



(a)



(b)



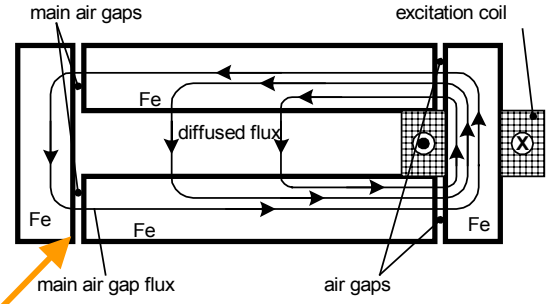
Use of PM* to Reduce Flux Diffusion

a) Diffuse flux leaks lowering main gap field.

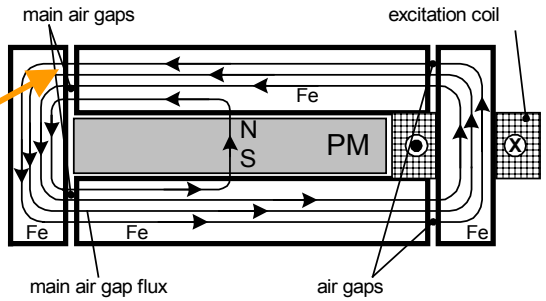
b) PM redirects leaks to increase main gap field

c) Excitation field reverses to weaken main gap field.

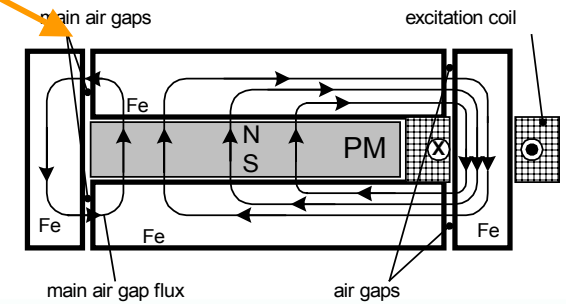
*PM powders mixed with small amount of epoxy, injected and magnetized in place.



(a). Main air gap flux and diffused flux

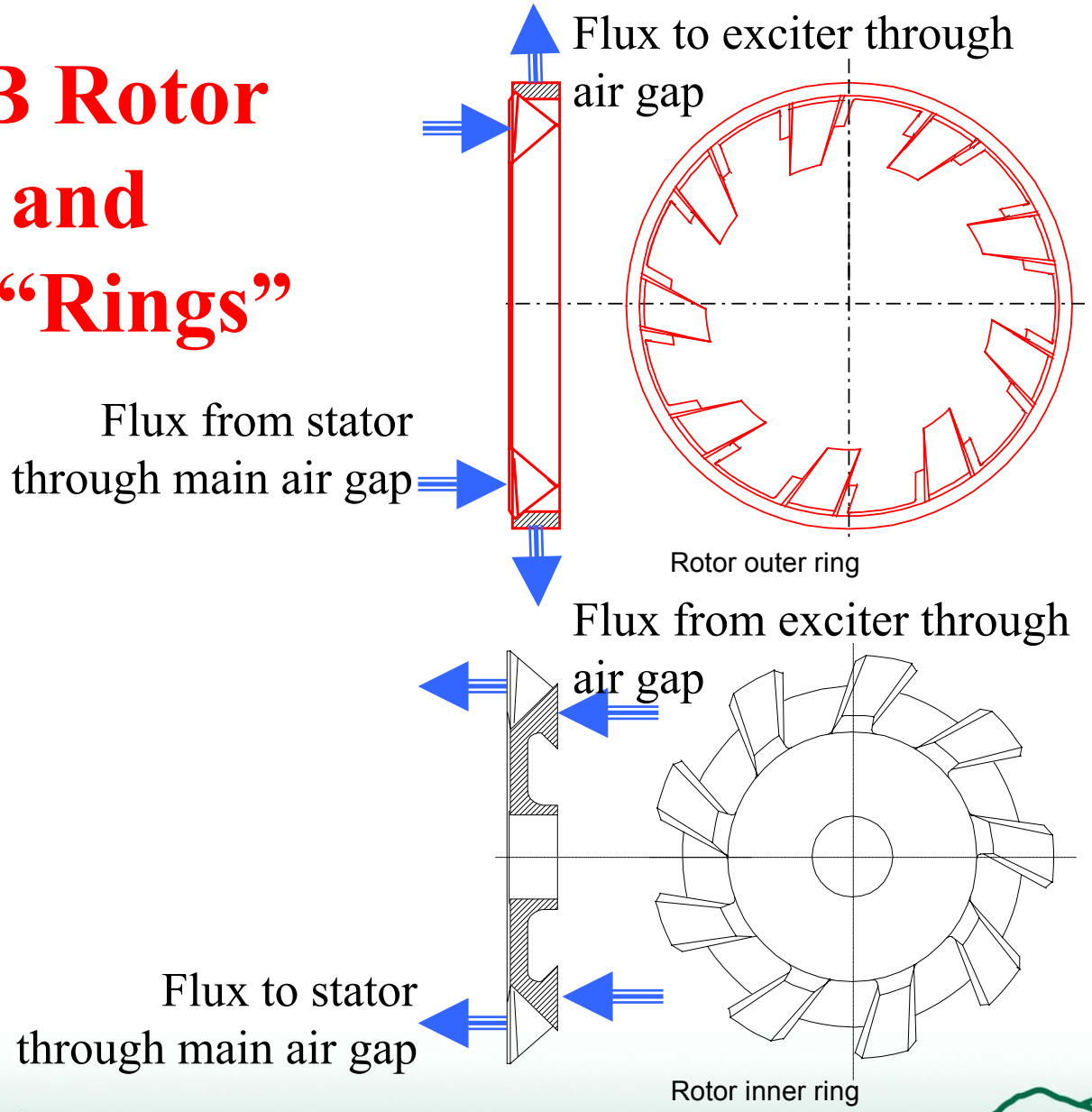


(b). Enhanced main air gap flux due to undiffused blocking provided by permanent magnet

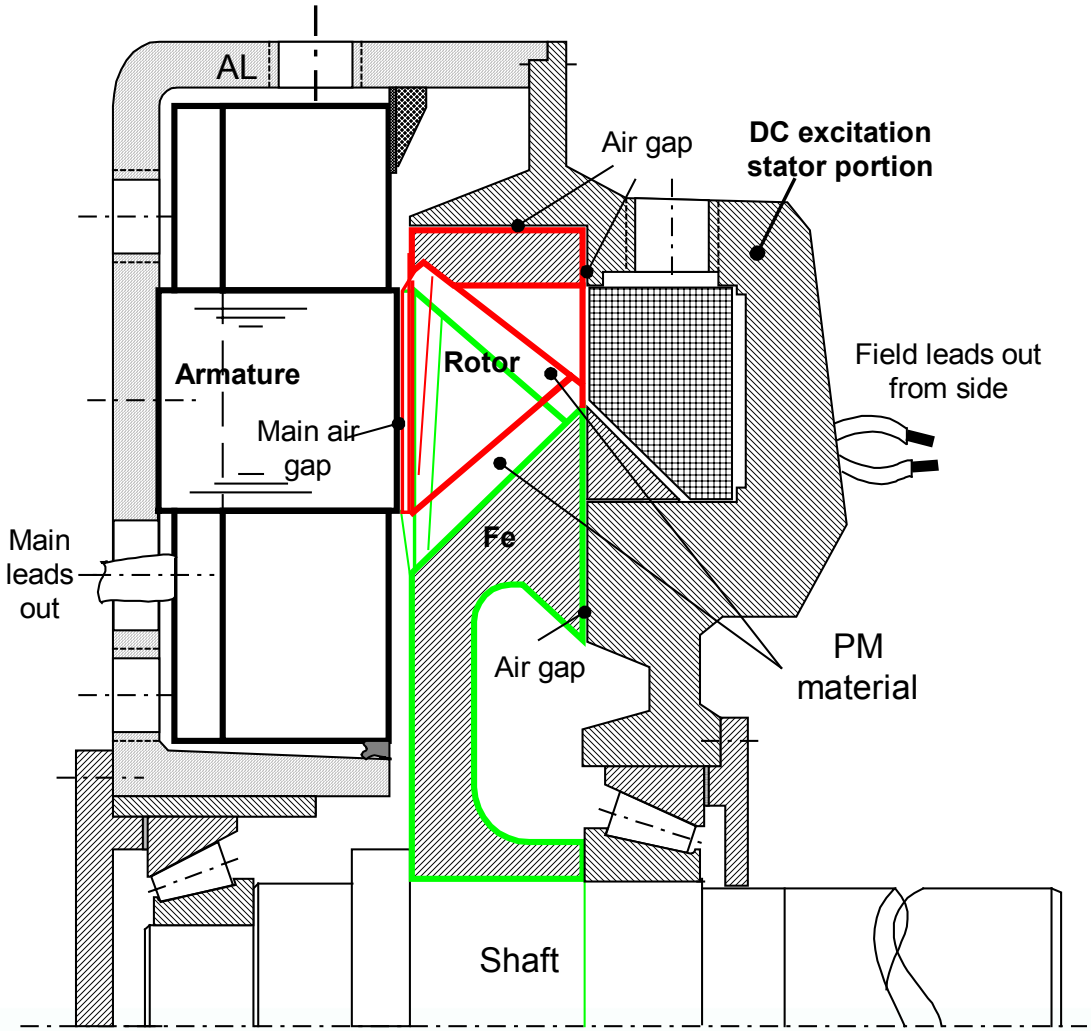


(c). Weakened main air gap flux due to reversed excitation

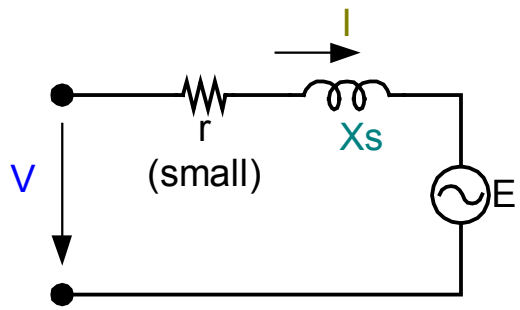
HSU-B Rotor Outer and Inner "Rings"



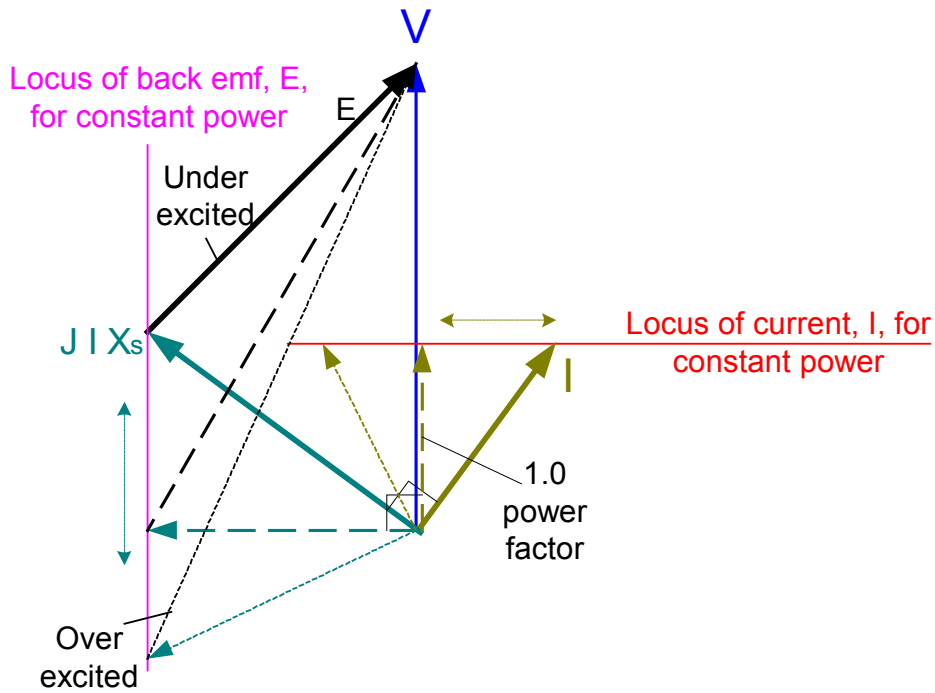
Cut View of an Axial-gap HSU-B Motor



HSU-B Equivalent Circuit and Control for Constant Power



Equivalent circuit of HSUB motor



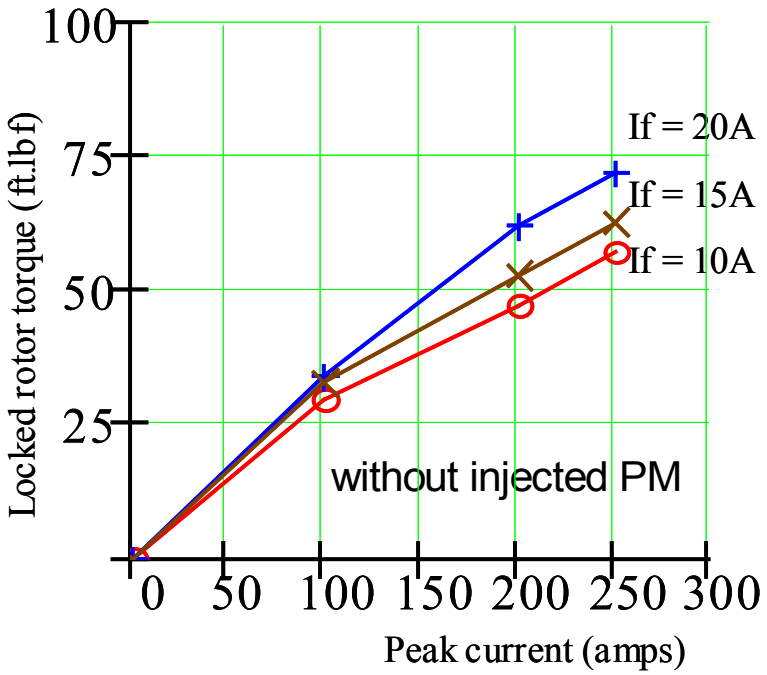
The phase current, I can be adjusted through E to give unity power factor

(V-curve of Current vs Excitation)

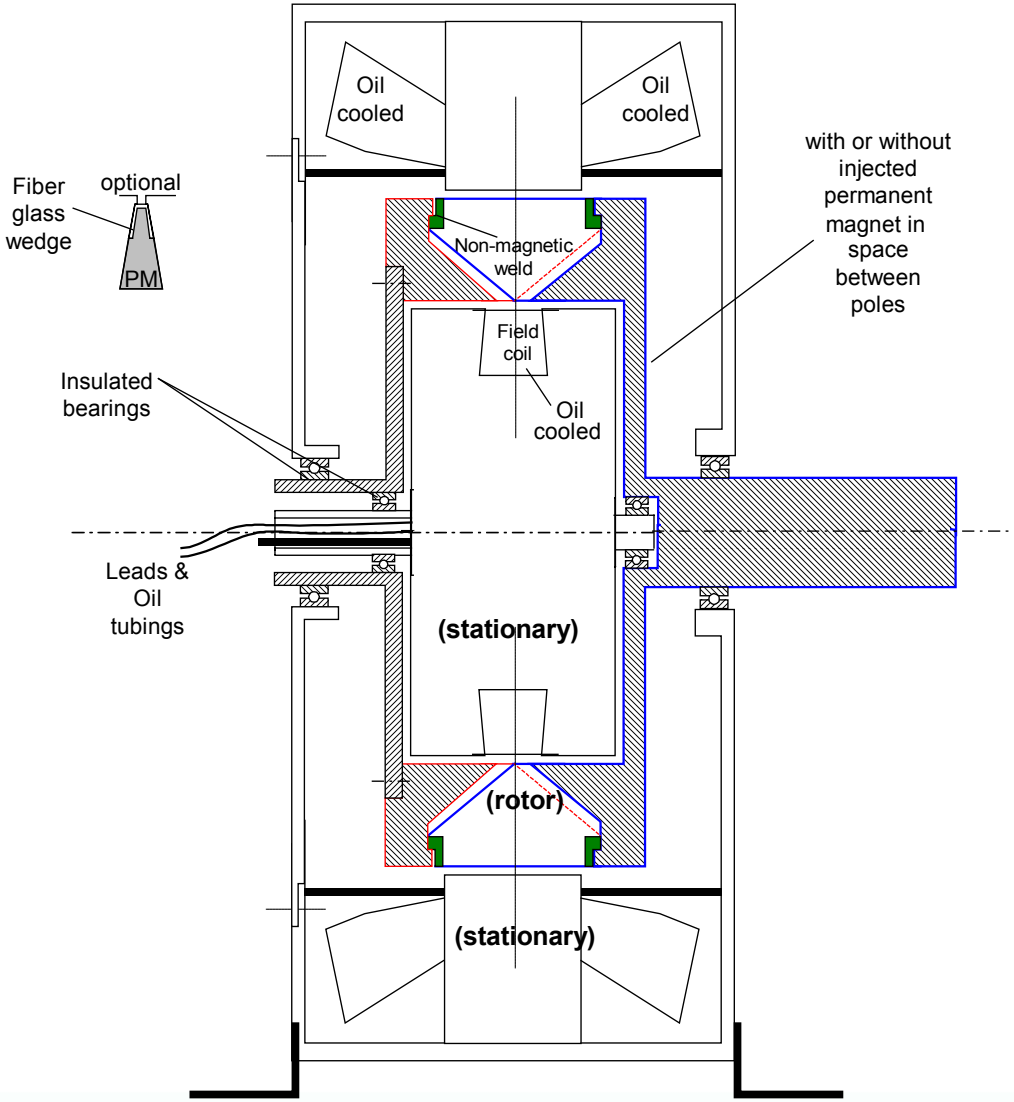
Attributes of the HSU-B Motor

- Allows high current density by directly cooling stationary armature and excitation windings.
- Strengthens "payoff" field in main gap by reducing fringing flux with strategically placed PMs, which combine with dc flux to produce high torque.
- Achieves direct field weakening and strengthening by flux control without danger of demagnetization.
- Delivers dc flux through air gap for brushless operation.
- Simplifies the power electronics drive to reduce its cost.
- Uses injected PMs magnetized in place to reduce manufacturing costs.

HSU-B Prototype Motor and Early Test Results

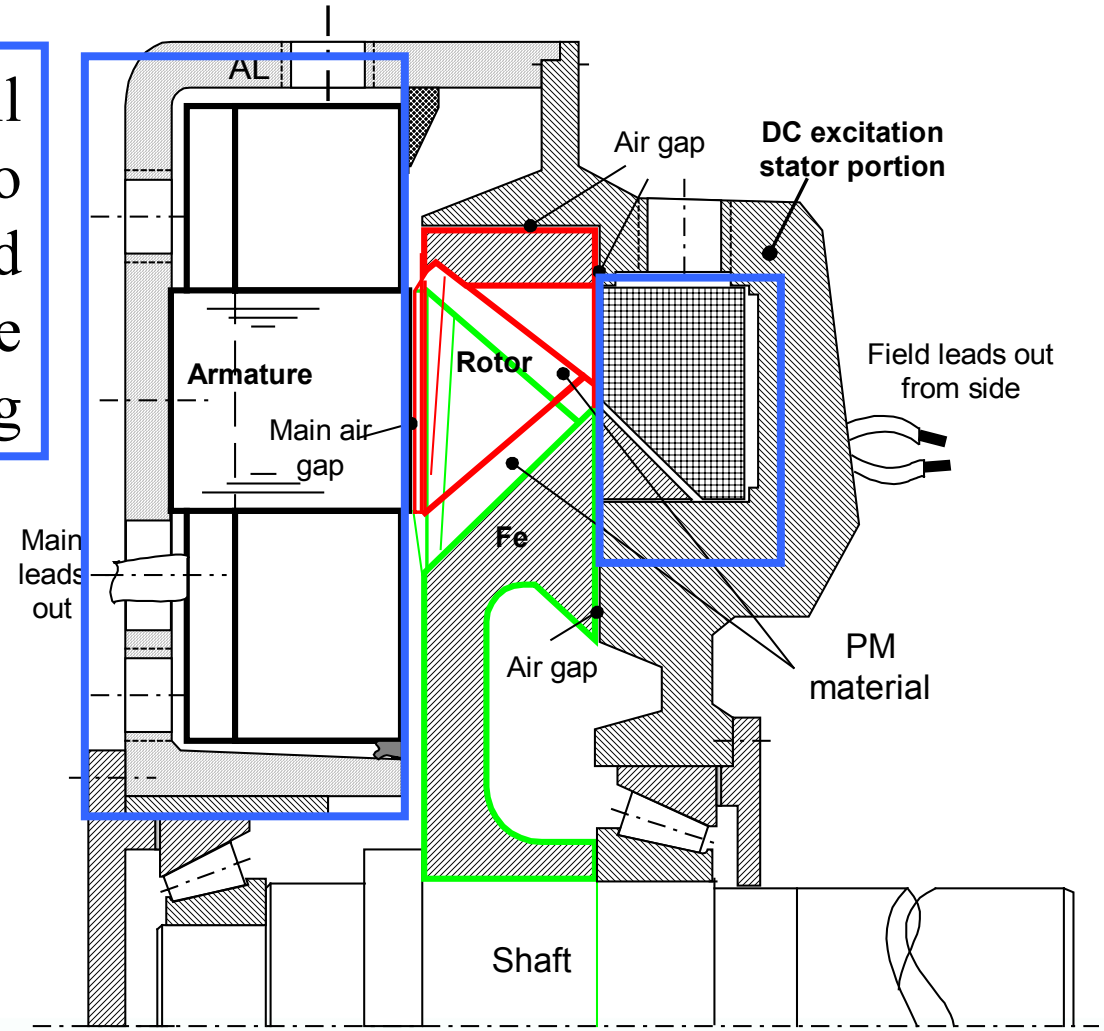


Conceptual Radial-Gap HSU-B Motor

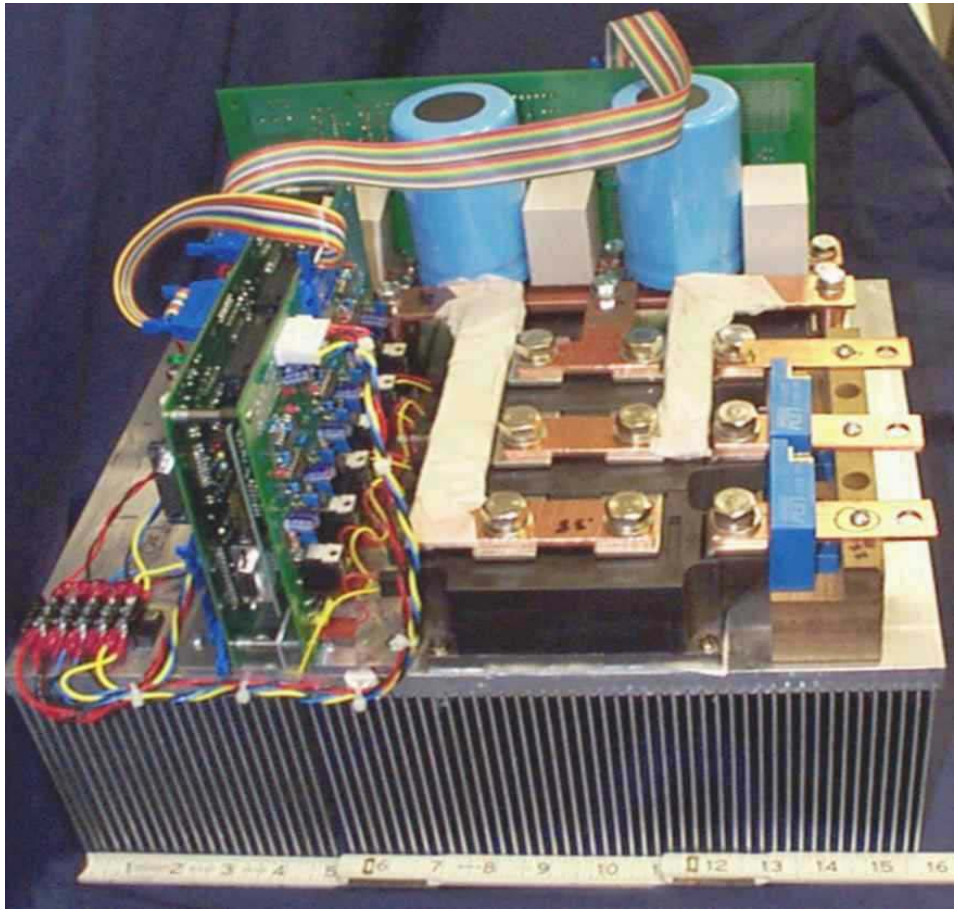


HSU-B Superconducting Motor

Excitation coil and armature do not move and may be superconducting



Field Weakening by Inverter Control

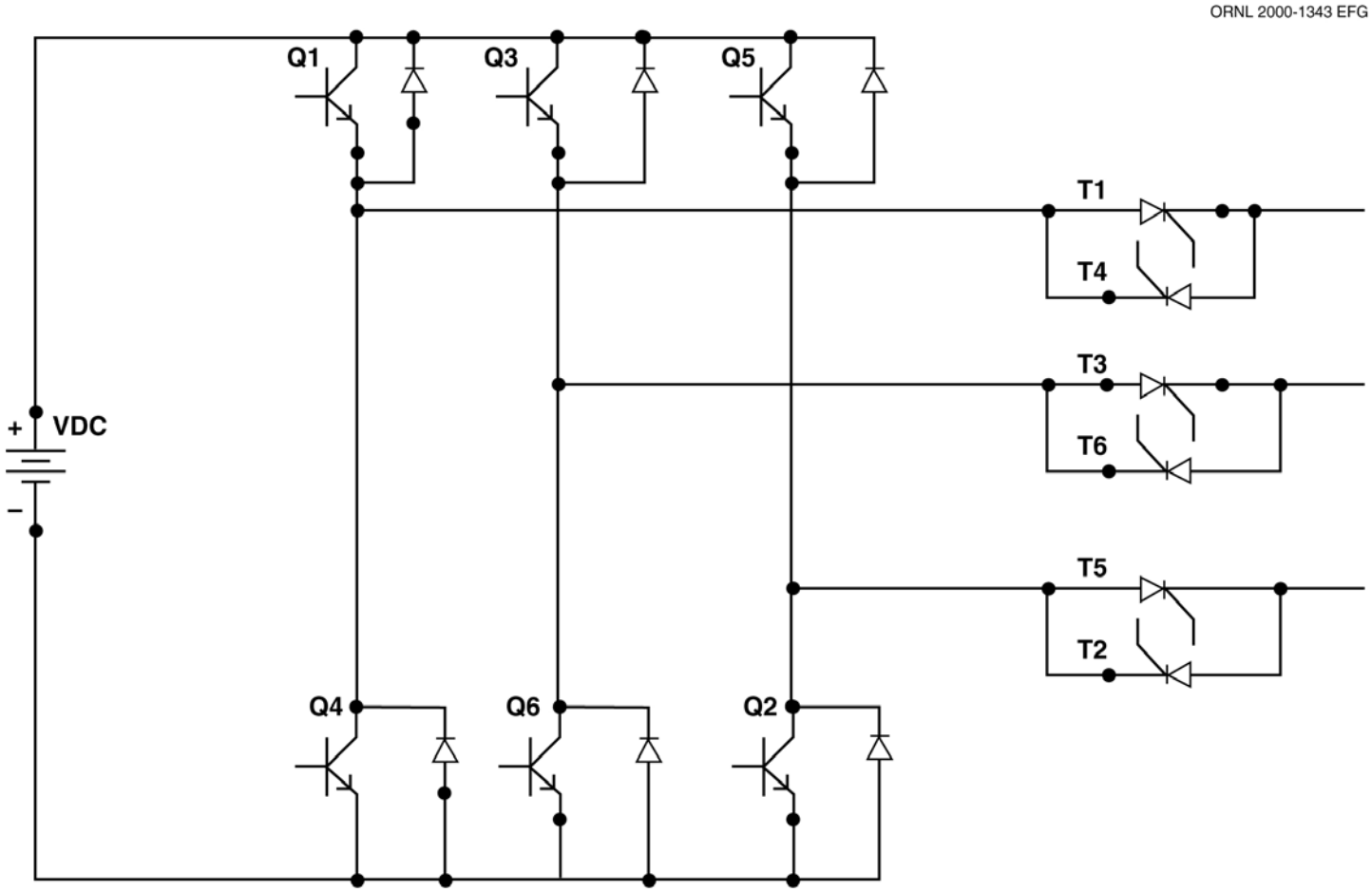


Voltage fed 3-phase bridge with 6 transistors, each having an anti-parallel bypass diode, interfaced to the motor through a pair of anti-parallel SCRs in each phase.

Developed by J. S. Lawler, UTK and J. M. Bailey, ORNL

patented by ORNL

Topology of the DMIC



Features of the DMIC

- **Thyristors prevent the detrimental mixture of motoring and regeneration during high speed operation in motoring mode.**
- **Can drive a "low" inductance BDCM over a wide CPSR without exceeding the rated (base speed) rms motor current.**
- **Can drive a "high" inductance BDCM over a wide CPSR without exceeding the rated rms current. May expect up to 50% more power at high speed.**
- **Can tolerate large changes in the dc supply voltage. As the dc supply voltage decreases motor power is reduced but the rated rms motor current can be maintained.**
- **Can control both motoring and regenerative braking over the entire speed range.**

Features of the DMIC (continued)

- **Each phase "idles" twice during one electrical cycle allowing position estimation schemes developed for conventional operation below base speed to be extended to operation above base speed. May eliminate the need for an encoder.**
- **Motor current can be extinguished within 1/2 electrical cycle if the transistor inverter or dc supply system short circuits.**
- **Loss of semiconductor firing signals while motoring at high speed results in rapid extinction of motor current rather than deep regenerative braking.**
- **"Coasting" at high speed does not involve any stator copper losses since the motor current is cut off.**
- **Achieves functional equivalent of field weakening without supplementary field windings or exotic rotor/magnet configuration.**

Impact of Motor Inductance on dc Supply Voltage and Peak Power

- **Neglecting winding resistance the dc supply required to drive rated current into the motor at base speed without employing phase advance is** $V_{dc} = 2E_b + \frac{6\sqrt{6}}{\pi^2}\Omega_b L_{eq} I_{rms}$ **, showing how larger inductance requires a greater dc supply voltage to support rated conditions at base speed.**
- **Without considering motor current rating, the peak powers that can be developed by CPA and DMIC are,**

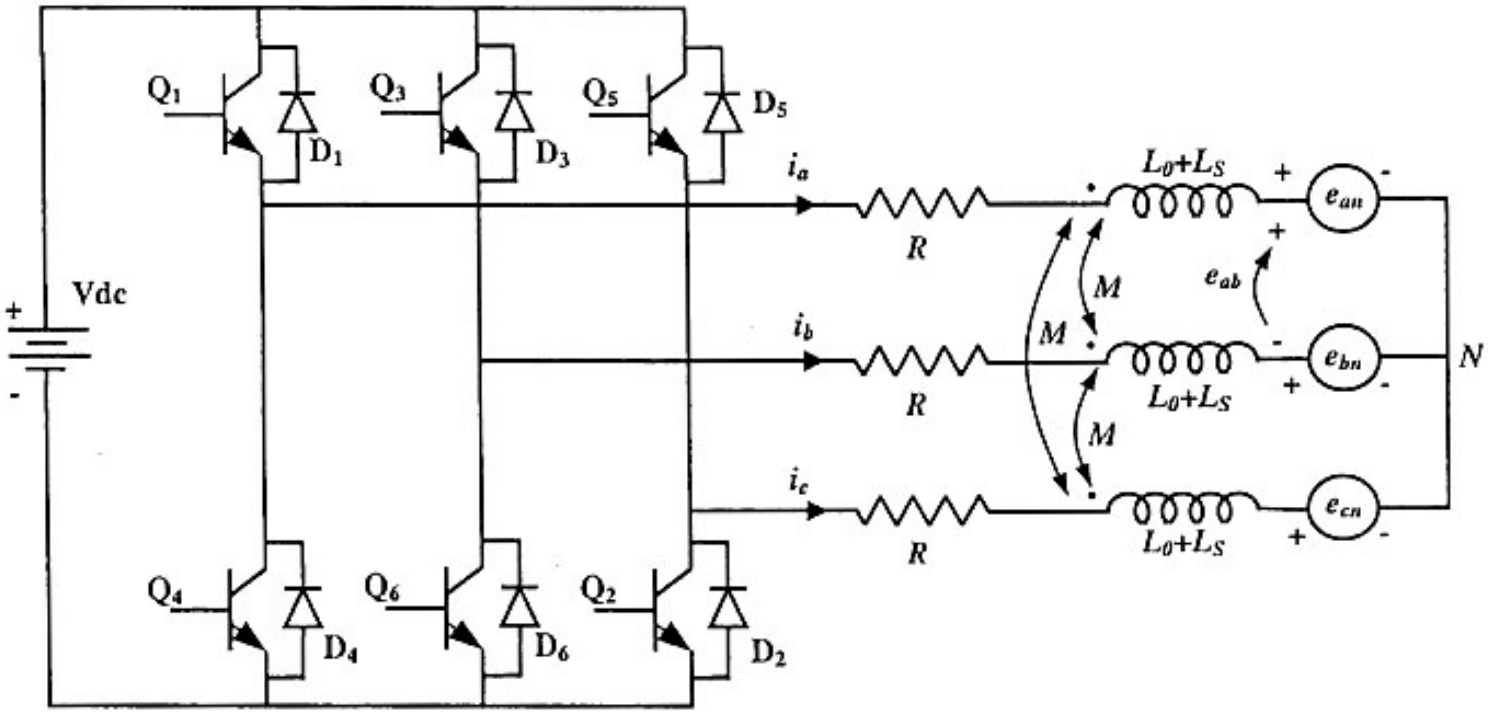
$$P_{pk-CPA} = \frac{36 V_{dc} E_b}{\pi^3 \Omega_b L_{eq}} = 1.1611 \frac{V_{dc} E_b}{\Omega_b L_{eq}} \text{ and } P_{pk-DMIC} = \frac{10\pi V_{dc} E_b}{27 \Omega_b L_{eq}} = 1.1635 \frac{V_{dc} E_b}{\Omega_b L_{eq}} .$$

- **For both control methods** $P_{pk} = \text{const}\frac{V_{dc}}{L_{eq}} = \text{const} \times \left(\frac{2E_b}{L_{eq}} + \frac{6\sqrt{6}}{\pi^2}\Omega_b I_{rms} \right)$ **, showing how peak power decreases with increasing inductance.**

Solution to a Problem

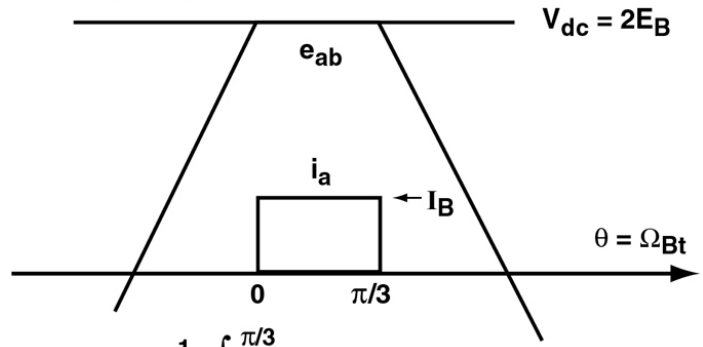
- Low inductance BDCMs are desirable because they require lower dc supply voltage and produce higher peak power.
- Low inductance motors are incompatible with the conventional phase advance method for high CPSR operation.
- The DMIC is a special inverter topology and control scheme that allows a low inductance BDCM to be driven over a wide CPSR.

Conventional Phase Advance Inverter Topology and Motor Model



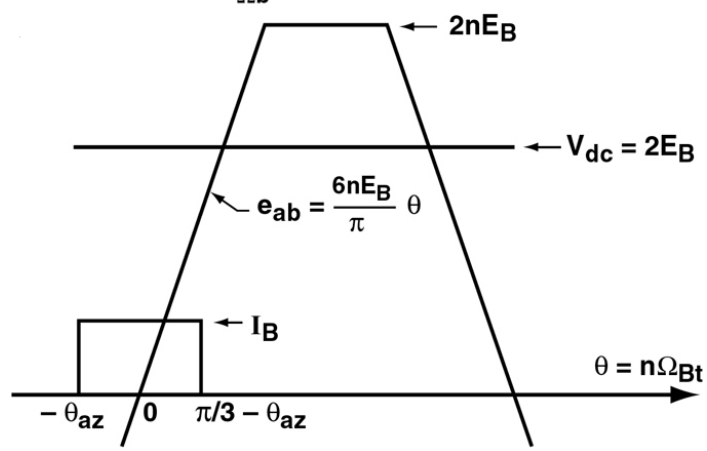
Conventional Phase Advance Method

At Base Speed (n = 1)



$$P_{avg} = \frac{1}{\pi/3}\int_0^{\pi/3} I_B \bullet 2E_B \, d\theta = 2\, I_B\, E_B$$

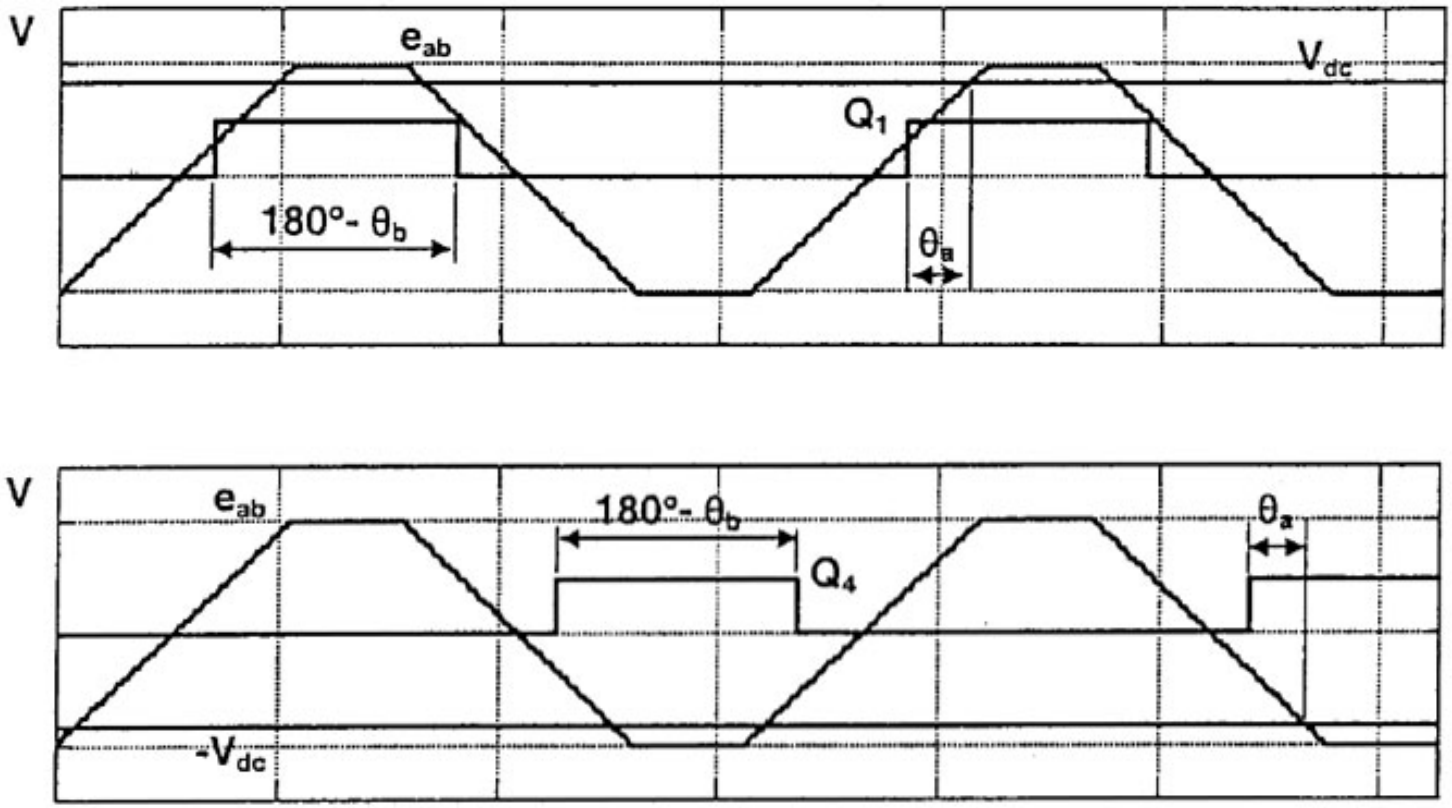
At High Speed ($n = \frac{\Omega}{\Omega b} > 1$)



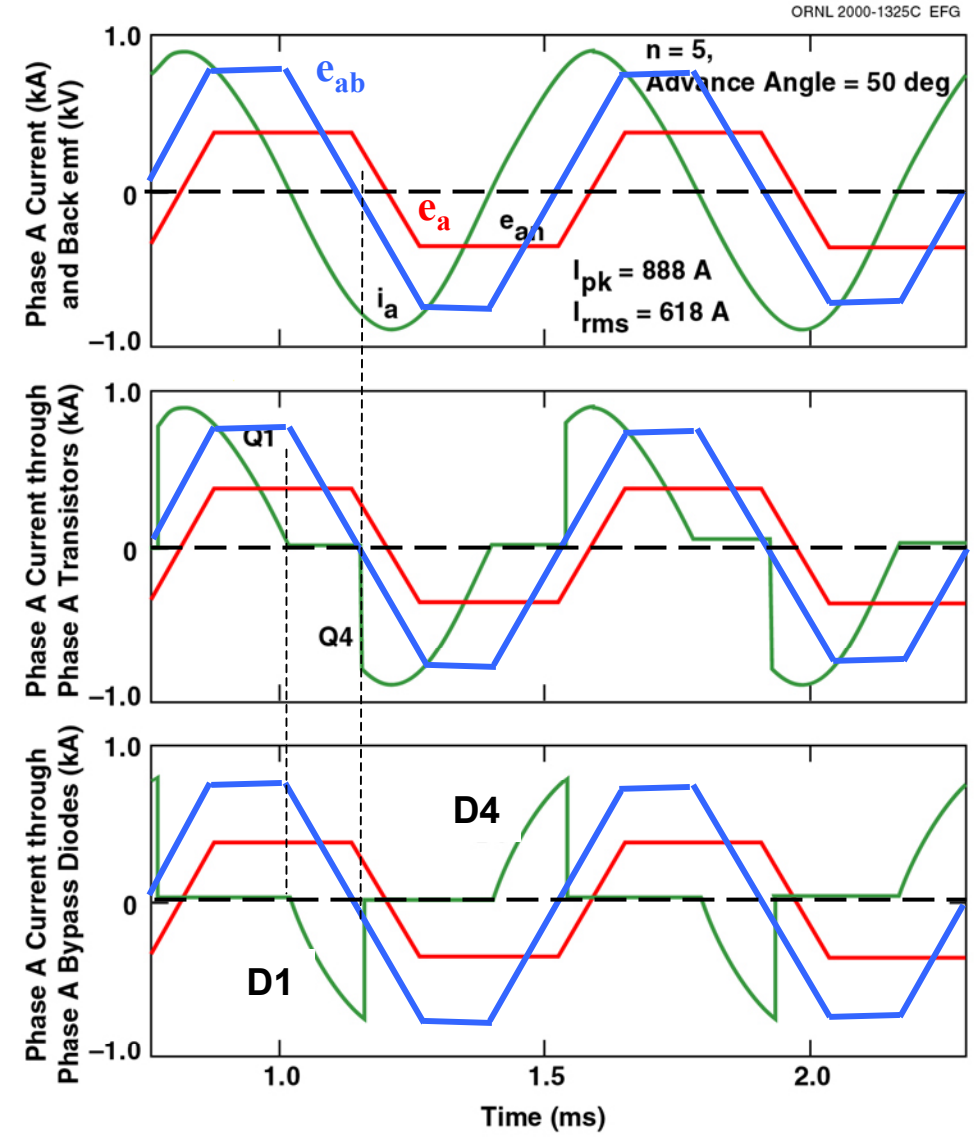
$$P_{avg} = \frac{1}{\pi/3}\int_{-\theta_{az}}^{\pi/3-\theta_{az}} I_B \bullet \frac{6nE_B}{\pi}\theta \, d\theta$$

$$= 2\, I_B\, E_B \quad \text{when} \quad \theta_{az} = \frac{\pi}{6} - \frac{\pi}{6n}$$

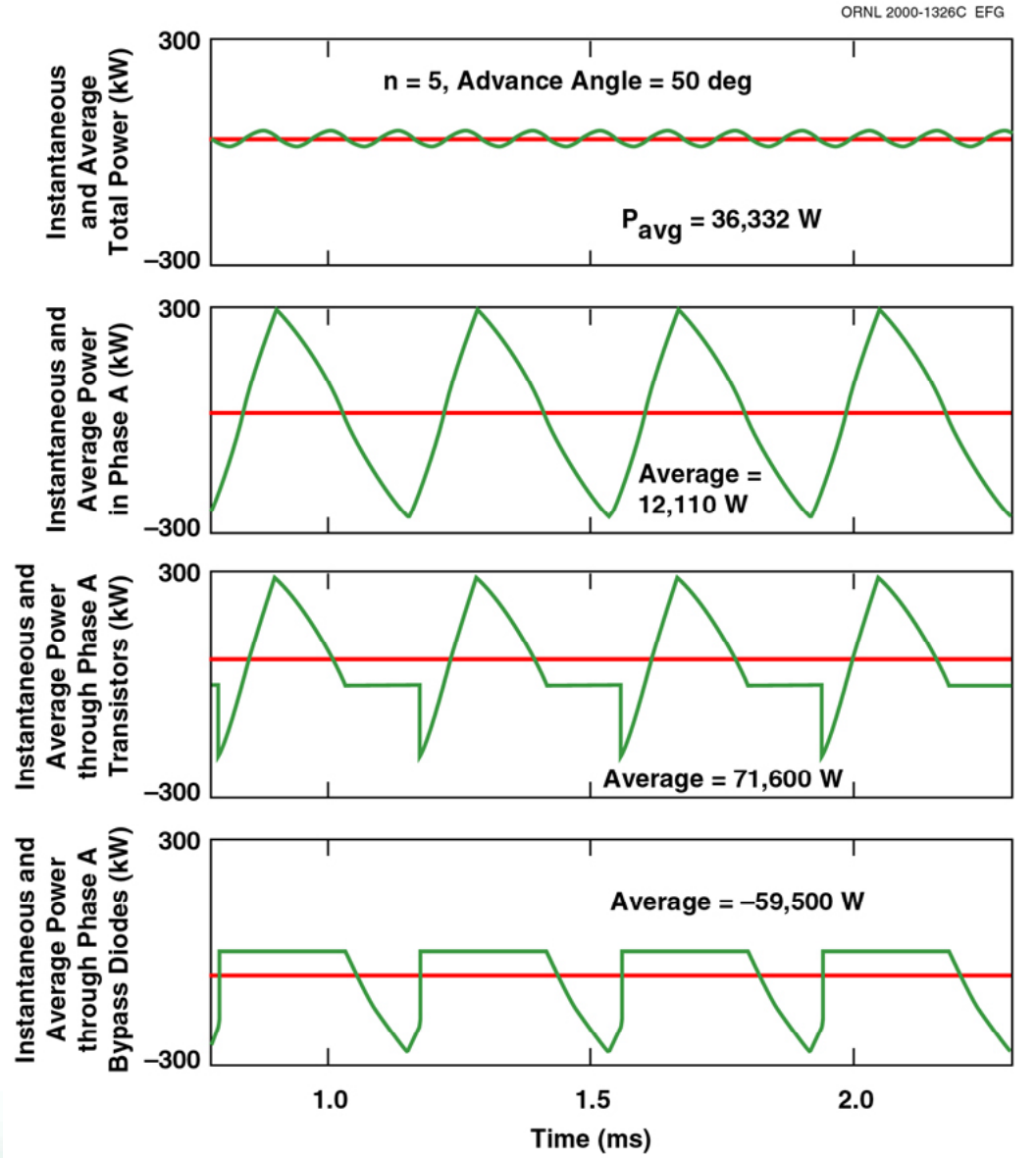
Conventional Phase Advance Firing Scheme



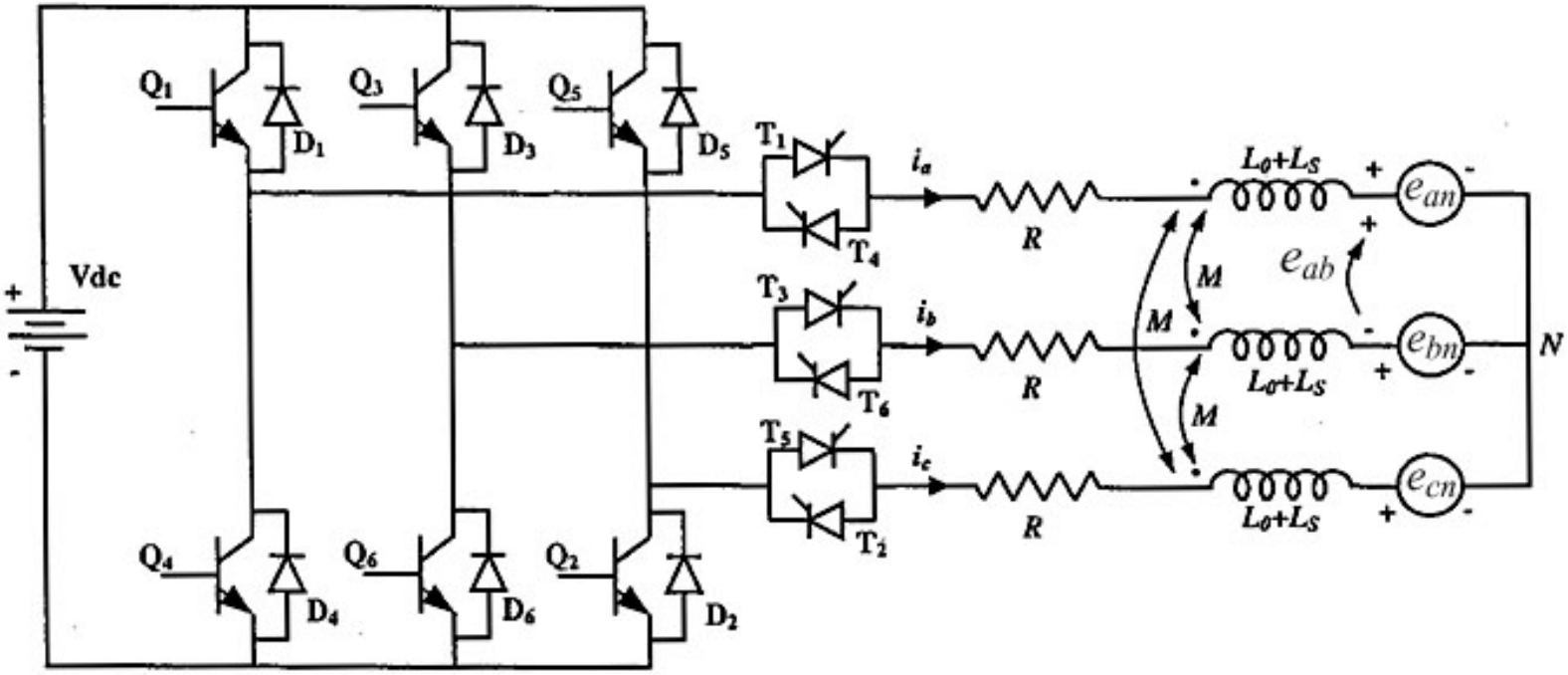
Back emf and Phase Current Flow in Conventional Phase Advance



Detrimental Power Flow during Conventional Phase Advance



DMIC Inverter Topology and PM Motor Model



Example Motor Parameters

N_b = base speed = 1000 rpm

p = 18 poles

L = 158 μH per phase

R = 0.026 ohms

E_b = peak phase-to-neutral back emf at base speed

= 46.96 volts

P_r = rated power = 20,092 watts (26.9 horsepower)

T_r = rated torque = 191.9 Nm

V_{dc} = dc supply voltage = 130 volts

$$I_{pk} = \text{peak current} = \frac{P_r}{2E_b} = 213.9 \text{ amps}$$

$$I_{rms} = \text{rms current} = I_{pk}\sqrt{\frac{2}{3}} = 174.7 \text{ amps}$$

Phase Equations for a BDCM

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} L_o + L_s & -M & -M \\ -M & L_o + L_s & -M \\ -M & -M & L_o + L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$+ \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_{an} \\ e_{bn} \\ e_{cn} \end{bmatrix}$$

Analytical Solution for the BDCM Phase Currents

With Ω_b = base speed, n = relative speed = Ω/Ω_b and the change of variable, $\Theta = n\Omega_b t$

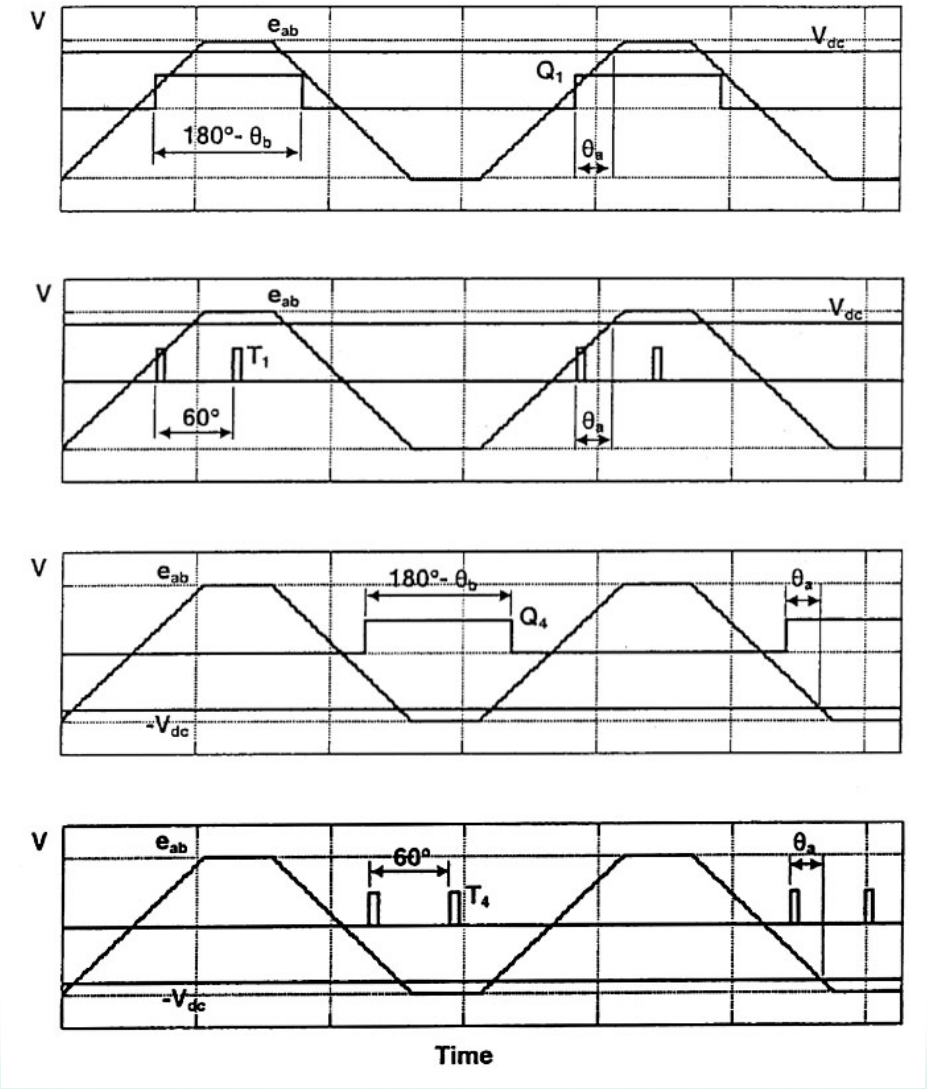
For current in three phases the equations are:

$$\frac{d}{d\theta}\begin{bmatrix} i_a \\ i_c \end{bmatrix} = \frac{-R}{n\,\Omega_b\,L}\begin{bmatrix} i_a \\ i_c \end{bmatrix} + \frac{1}{3\,n\,\Omega_b\,L}\begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}\begin{bmatrix} v_{ab} - e_{ab} \\ v_{cb} - e_{cb} \end{bmatrix}$$

For current in two phases the equation is:

$$\frac{d}{d\theta} i_a = \frac{-R}{n\,\Omega_b\,L}\, i_a + \frac{1}{2\,n\,\Omega_b\,L}\left[v_{ab} - e_{ab}\right]$$

DMIC Firing Scheme - Phase A



EMF Waveforms

Considering the phase transition where c is outgoing and a is incoming,

$$e_{ab}(\theta) = \frac{6nE_b}{\pi}(\theta - \theta_a + \frac{\pi V_{dc}}{6nE_b}) \qquad 0 \le \theta \le \pi/3$$

$$e_{cb}(\theta) = \frac{6nE_b}{\pi}(\theta - \theta_a + \frac{\pi V_{dc}}{6nE_b} + \frac{\pi}{3}) \qquad 0 \le \theta \le \theta_a - \frac{\pi V_{dc}}{6nE_b}$$

$$= 2nE_b \qquad \theta_a - \frac{\pi V_{dc}}{6nE_b} \le \theta \le \pi/3$$

Commutation Phase Currents for 180° Dwell

Line voltages: → $v_{ab} = v_{cb} = +V_{dc}$

Initial currents:

$$i_a(0) = 0$$

$$i_b(0) = -\frac{E_b}{\Omega_b L}(2\theta_a - \frac{\pi}{3})$$

$$i_c(0) = \frac{E_b}{\Omega_b L}(2\theta_a - \frac{\pi}{3})$$

Phase currents during commutation interval:

$$i_a(\theta) = \frac{E_b}{\Omega_b L}\left\{\left[\frac{2\theta_a}{\pi} + \frac{2}{3}\right]\theta - \frac{1}{\pi}\theta^2\right\}$$

$$i_b(\theta) = \frac{E_b}{\Omega_b L}\left\{\left[\frac{\pi}{3} - 2\theta_a\right] + \left[\frac{2}{3} - \frac{4\theta_a}{\pi}\right]\theta + \frac{2}{\pi}\theta^2\right\}$$

$$i_c(\theta) = \frac{E_b}{\Omega_b L}\left\{2\theta_a - \frac{\pi}{3} + \left[\frac{2\theta_a}{\pi} - \frac{4}{3}\right]\theta - \frac{1}{\pi}\theta^2\right\}$$

$$0 \le \theta \le \theta_c = 2\theta_a - \pi/3$$

Two-phase Currents after Commutation for 180° Dwell

$$\mathrm{i_a}(\theta) = \mathrm{i_a}(\theta_c)$$

$$+\frac{\mathrm{E_b}}{\Omega_b \mathrm{L}}\left\{\frac{3}{\pi}\theta_\mathrm{c}\left(\frac{1}{2}\theta_\mathrm{c} - \theta_\mathrm{a}\right) + \frac{3\theta_\mathrm{a}}{\pi}\theta - \frac{3}{2\pi}\theta^2\right\}$$

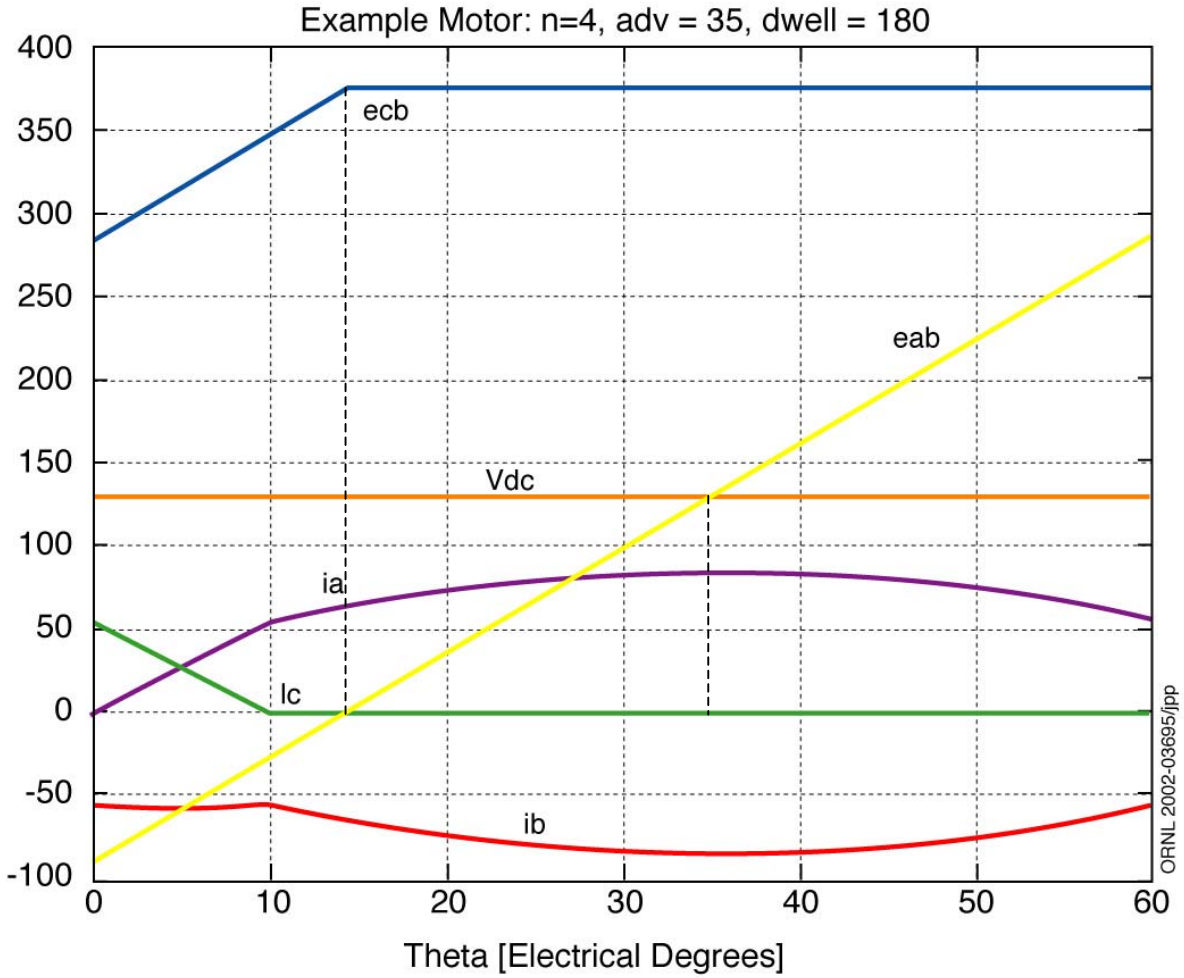
$$= \frac{\mathrm{E_b}}{\Omega_b \mathrm{L}}\left\{\left(\theta_\mathrm{a} - \frac{\pi}{6}\right) + \frac{3\theta_\mathrm{a}}{\pi}\theta - \frac{3}{2\pi}\theta^2\right\}$$

$$\mathrm{i_b}(\theta) = -\mathrm{i_a}(\theta)$$

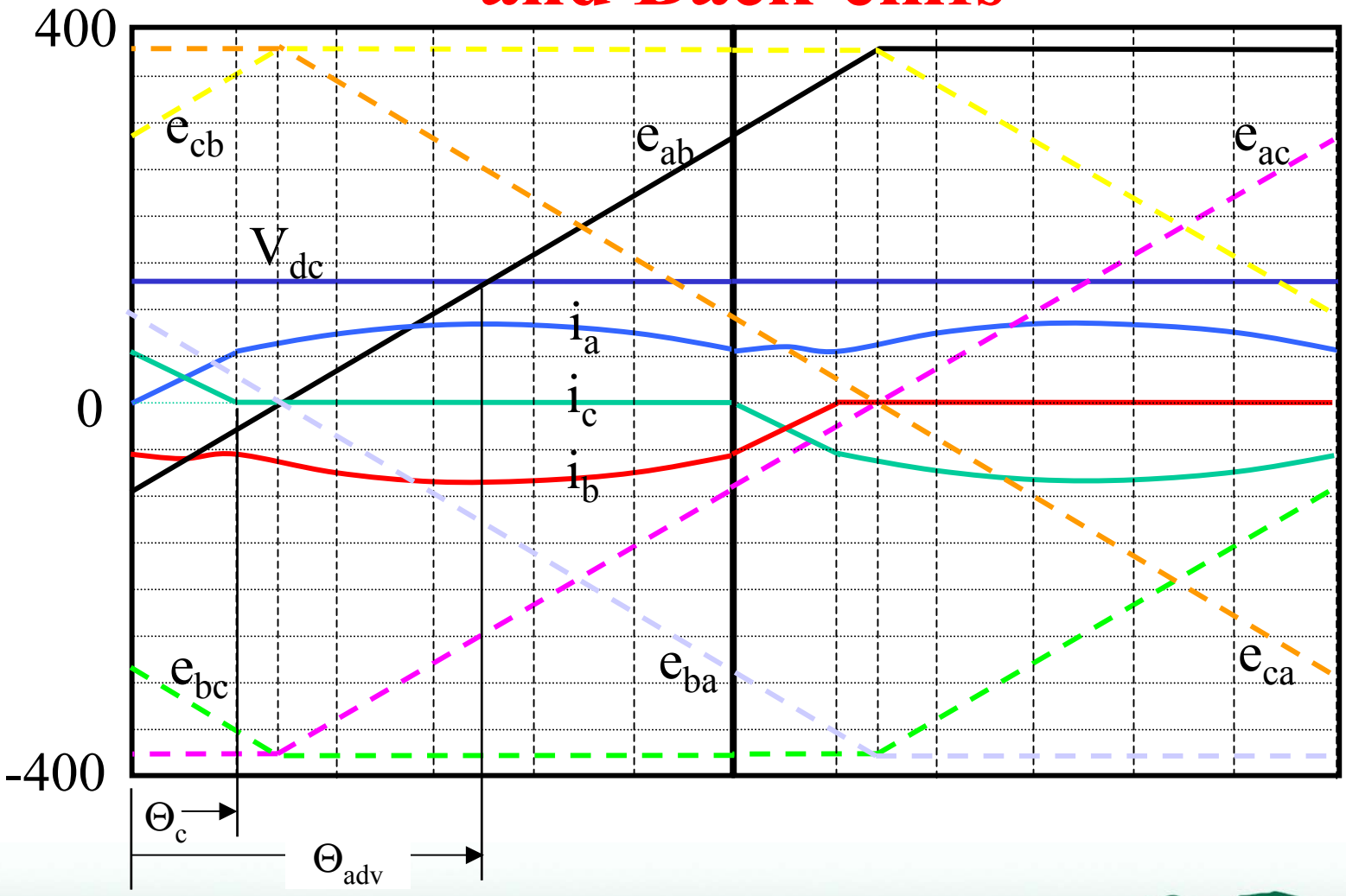
$$\mathrm{i_c}(\theta) = 0$$

$$\theta_\mathrm{c} \le \theta \le \frac{\pi}{3}$$

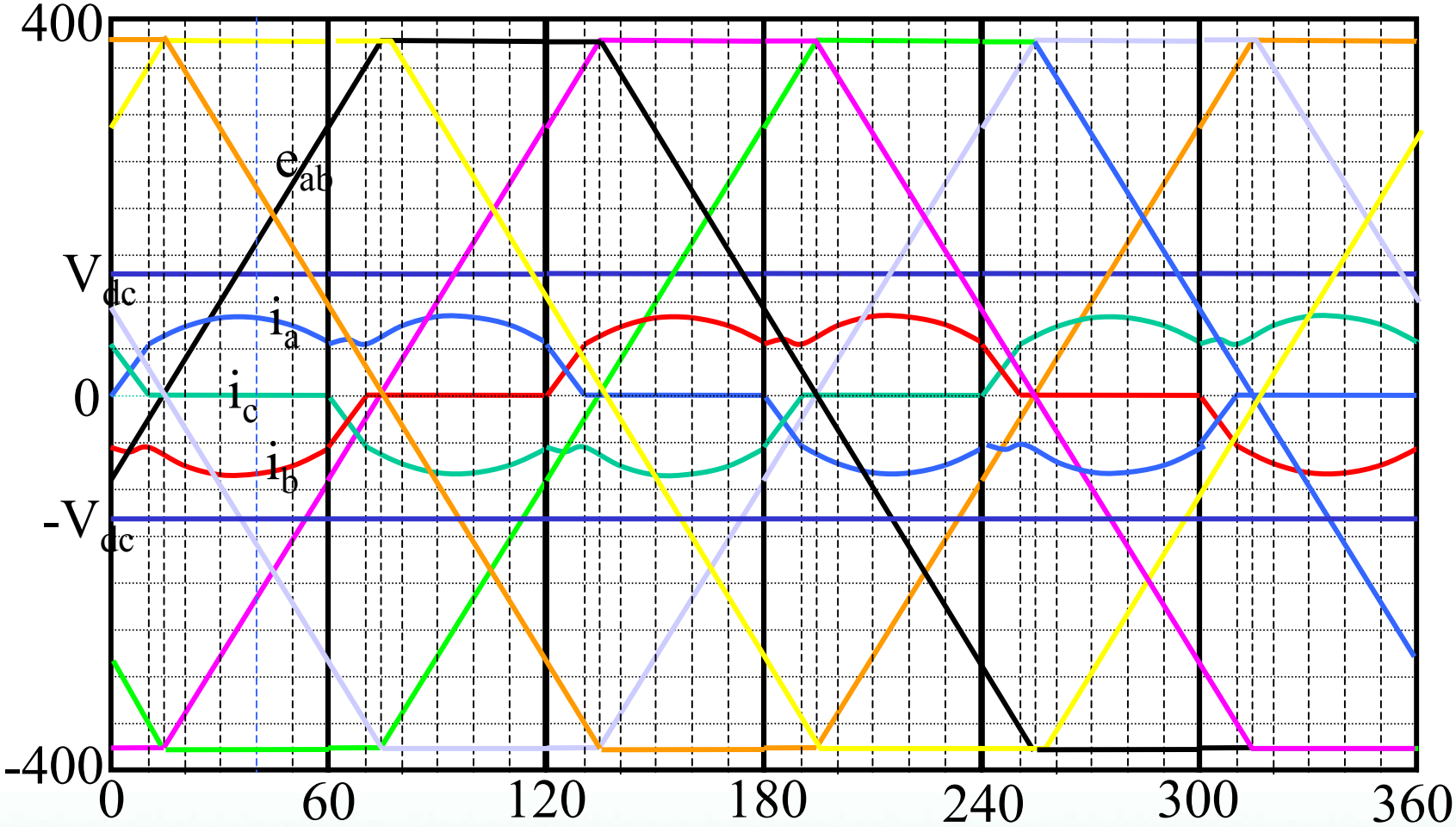
Analytical Waveforms in one 60° Interval



Third Cycle of DMIC Currents and Back-emfs



Full Cycle of DMIC Currents and Back-emfs



Average DC Link Power for a dwell of 180°

$$P_{avg} = \frac{3}{\pi}\int_0^{\pi/3} V_{dc}\ i_{dc}(\theta)\, d\theta$$

$$= \frac{3}{\pi}\int_0^{\pi/3} V_{dc}\ \left[i_a(\theta) + i_c(\theta)\right] d\theta$$

$$= \frac{3\ V_{dc}\ E_b}{\pi\ \Omega_b\ L}\left\{\frac{2}{3\pi}\theta_a^{\ 3} + \frac{2}{3}\theta_a^{\ 2} + \frac{2\pi}{9}\theta_a - \frac{4\pi^2}{81}\right\}$$

Average Power Delivered by Outgoing Phase

$$P_c = \frac{3}{\pi} \int_0^{\theta_c} V_{dc}\ i_c(\theta)\ d\theta$$

$$= \frac{3\ V_{dc}\ E_b}{\pi\ \Omega_b\ L} \left[\frac{4}{3\ \pi}\ \theta_a^3 + \frac{4}{3}\ \theta_a^2 - \frac{5\ \pi}{9}\ \theta_a + \frac{4\ \pi^2}{81} \right]$$

Peak and RMS Motor Current for 180° Dwell

$$I_{pk} = \max\{i_a(\theta), -i_b(\theta)\}$$

$$= \frac{E_b}{\Omega_b L} * \max\left\{\left[\frac{3\theta_a^{\ 2}}{2\pi} + \theta_a - \frac{\pi}{6}\right], \left[\frac{2\theta_a^{\ 2}}{\pi} + \frac{4\theta_a}{3} - \frac{5\pi}{18}\right]\right\}$$

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i_a(\theta)^2 \, d\theta}$$

$$= \frac{E_b}{\Omega_b L}\left\{\sqrt{\frac{1}{\pi}\left[\begin{array}{l}\frac{8}{5\pi^2}\theta_a^{\ 5} + \frac{8}{3\pi}\theta_a^{\ 4} + \frac{16}{9}\theta_a^{\ 3} \\ + \frac{4\pi}{27}\theta_a^{\ 2} - \frac{16\pi^2}{81}\theta_a + \frac{23\pi^3}{1215}\end{array}\right]}\right\}$$

Commutation Phase Currents for 120° Dwell

Line voltages: → $v_{ab} = V_{dc} \qquad v_{cb} = 0$

Initial currents:

$$i_a(0) = 0$$

$$i_b(0) = -\frac{E_b}{\Omega_b L}(2\theta_a - \frac{\pi}{3})$$

$$i_c(0) = \frac{E_b}{\Omega_b L}(2\theta_a - \frac{\pi}{3})$$

Phase currents during commutation interval:

$$i_a(\theta) = \frac{E_b}{\Omega_b L}\left\{\left[\frac{2\theta_a}{\pi} + \frac{2}{3} + \frac{V_{dc}}{3nE_b}\right]\theta - \frac{1}{\pi}\theta^2\right\}$$

$$i_b(\theta) = \frac{E_b}{\Omega_b L}\left\{\left[\frac{\pi}{3} - 2\theta_a\right] + \left[-\frac{4\theta_a}{\pi} + \frac{2}{3} + \frac{V_{dc}}{3nE_b}\right]\theta + \frac{2}{\pi}\theta^2\right\}$$

$$i_c(\theta) = \frac{E_b}{\Omega_b L}\left\{2\theta_a - \frac{\pi}{3} + \left[\frac{2\theta_a}{\pi} - \frac{4}{3} - \frac{2V_{dc}}{3nE_b}\right]\theta - \frac{1}{\pi}\theta^2\right\}$$

$$0 \le \theta \le \theta_c = \theta_a - \frac{2\pi}{3} - \frac{\pi V_{dc}}{3nE_b} + \sqrt{(\theta_a - \frac{2\pi}{3} - \frac{\pi V_{dc}}{3nE_b})^2 + \pi(2\theta_a - \frac{\pi}{3})}$$

Two Phase Currents after Commutation for 120° Dwell

$$i_a(\theta) = i_a(\theta_c) + \frac{E_b}{\Omega_b L}\left\{\frac{3}{\pi}\theta_c\left(\frac{1}{2}\theta_c - \theta_a\right) + \frac{3\theta_a}{\pi}\theta - \frac{3}{2\pi}\theta^2\right\}$$

$$i_b(\theta) = -i_a(\theta)$$

$$i_c(\theta) = 0.$$

$$\theta_c \le \theta \le \frac{\pi}{3}$$

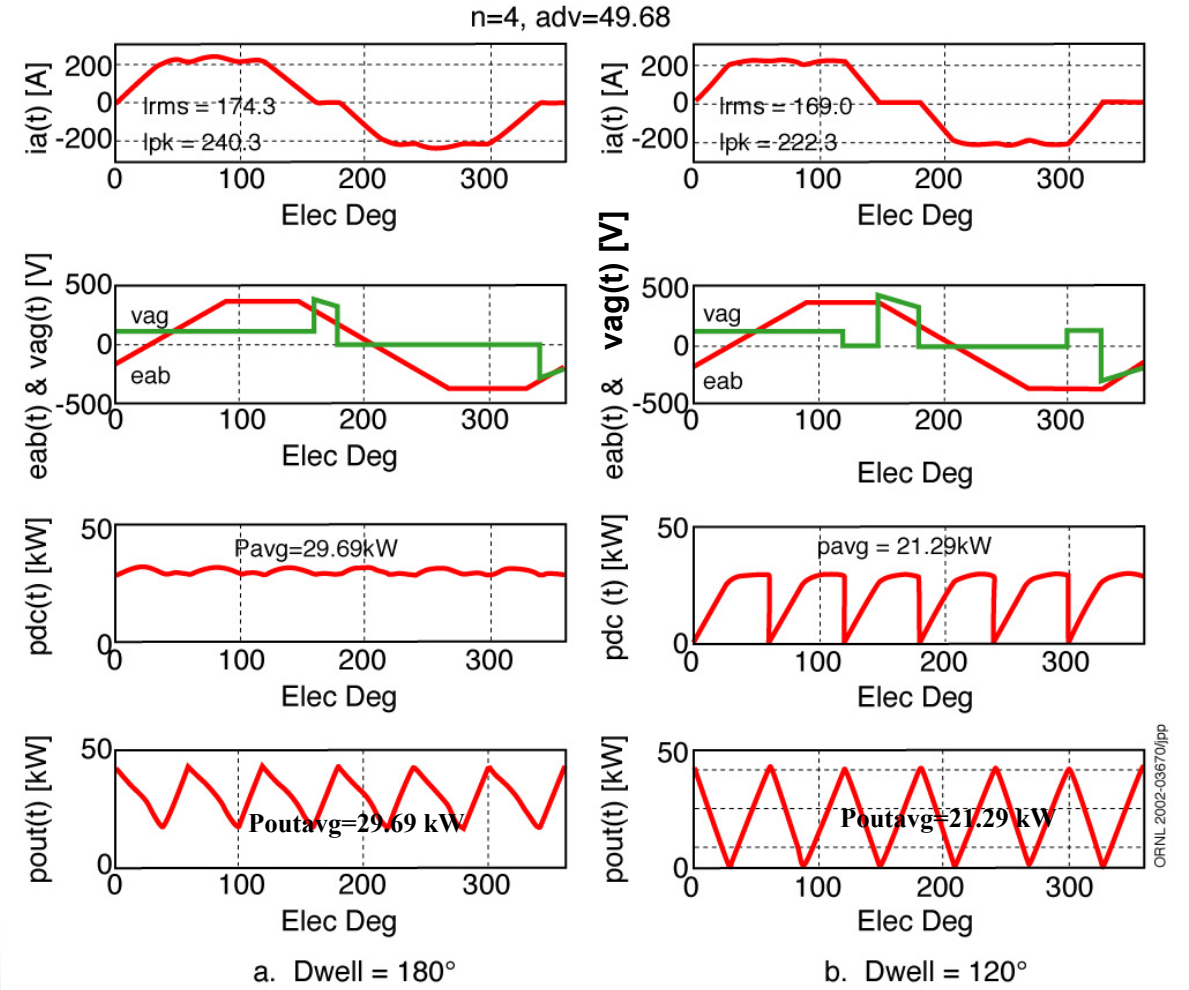
Average DC Link Power for a dwell of 120°

$$P_{avg} = \frac{3}{\pi}\int_0^{\pi/3} V_{dc}\ i_{dc}(\theta)\, d\theta$$

$$= \frac{3}{\pi}\int_0^{\pi/3} V_{dc}\ i_a(\theta)\, d\theta$$

$$= \frac{3V_{dc}E_b}{\pi\Omega_b L}\left\{\begin{array}{l}\frac{\pi}{6}\theta_a - \frac{\pi^2}{54} + (\frac{2\pi}{9} - \frac{1}{3}\theta_a + \frac{\pi V_{dc}}{9nE_b})\theta_c \\ +(\frac{-1}{6} + \frac{1}{2\pi}\theta_a - \frac{V_{dc}}{6nE_b})\theta_c^{\ 2} - \frac{1}{3\pi}\theta_c^{\ 3}\end{array}\right\}$$

Impact of Dwell Angle on DMIC Performance



Effect of Dwell on Performance

The impact of dwell on performance is:

- **The current waveforms differ primarily in the commutation time.**
- **There is a dramatic difference in the average power developed by the motor, 29.6 kW for 180° dwell compared to 21.3 kW for 120° dwell. Base speed power is 20.1 kW.**
- **The instantaneous supply power and the instantaneous power output of the motor have different wave shapes but have the same average value.**

Effect of Dwell on Performance (continued)

The dc link current has the same wave shape as the instantaneous supply power.

- **For the 120° dwell case, the dc current drops to zero at the beginning of each commutation interval. The incoming phase current is initially zero and the outgoing phase current is transferred from the dc supply to a circulating path through a bypass diode.**
- **For the 180° dwell case the outgoing phase is left connected to the dc supply and the dc link current is much smoother.**

Average High-speed DC Link Power for a dwell of 120°

$$P_{avg}(n \to \infty) = \frac{3V_{dc}E_b}{\pi\Omega_b L}\left[\frac{-2}{3\pi}\theta_a^{\,3} - \frac{2}{3}\theta_a^{\,2} + \frac{7\pi}{9}\theta_a - \frac{8\pi^2}{81}\right]$$

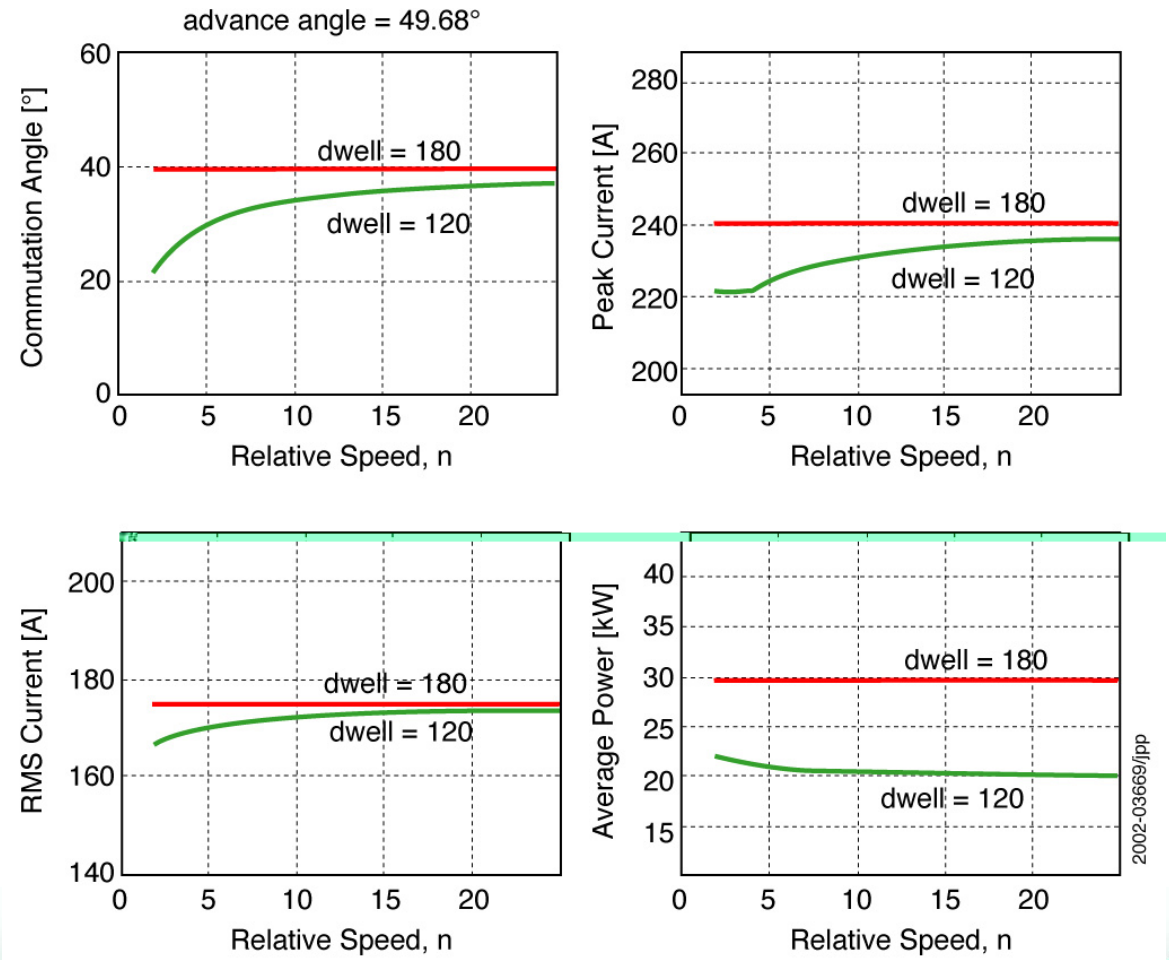
This is the average power developed by a 180° dwell minus the power contributed by the outgoing phase.

Conclusion:
Although the current waveforms at infinite speed are identical for 120° and 180° dwells, the 180° dwell delivers significantly more power.

Neglecting Resistance, CPSR is Infinite

- **Advance angle is defined with respect to the intersection of back-emf (i.e. e_{ab}) and V_{dc}.**
- **Commutation and conduction waveforms do not depend explicitly on V_{dc}.**
- **Shape of waveform depends solely on advance angle.**
- **Therefore, if motor produces rated power at rated current for a low speed (i.e. n=2) then it will exhibit the same performance at any higher speed.**

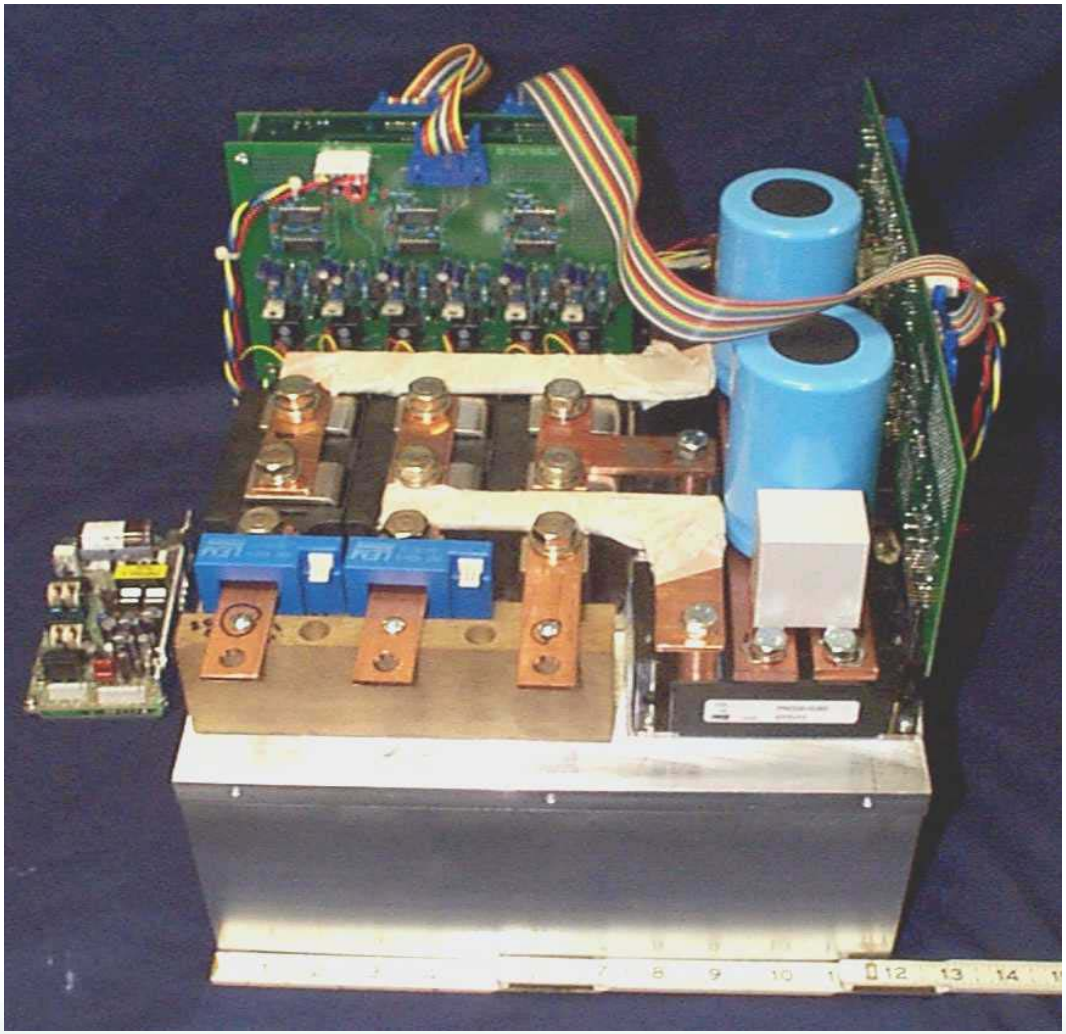
Effect of Dwell and Speed on Commutation Angle, Peak Current, RMS Current, and Average Power



Conclusions Regarding the DMIC

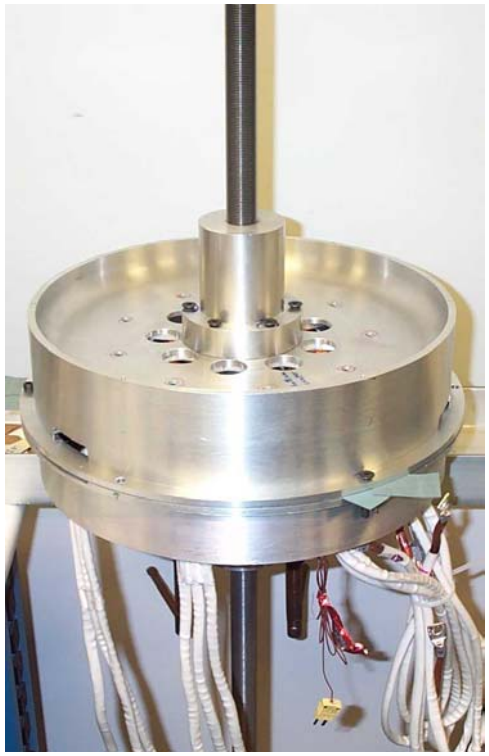
- **Differential equations of the loss-less BDCM driven by the DMIC have been solved.**
- **Analysis shows no inherent limit to the constant power speed ratio of a BDCM when driven by the DMIC.**
- **Analytic expressions have been developed for the dependence of peak and rms current and average power on motor inductance and dc supply voltage.**

Dual Mode Inverter Controller, DMIC-1

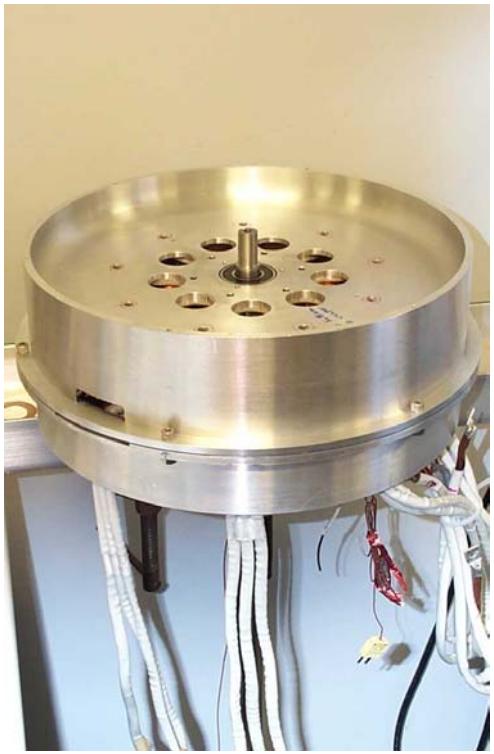


Rotor Assembly
(20-kW Axial-gap PM Motor)

Pre-closure



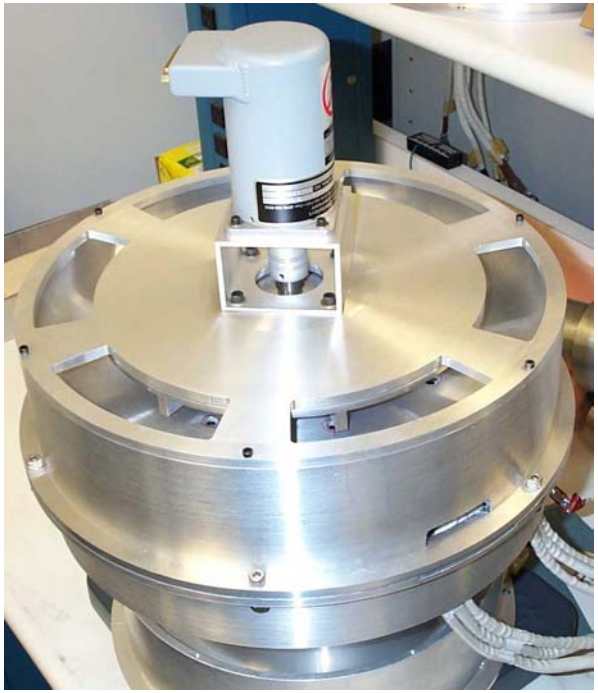
Post-closure



Jig removed

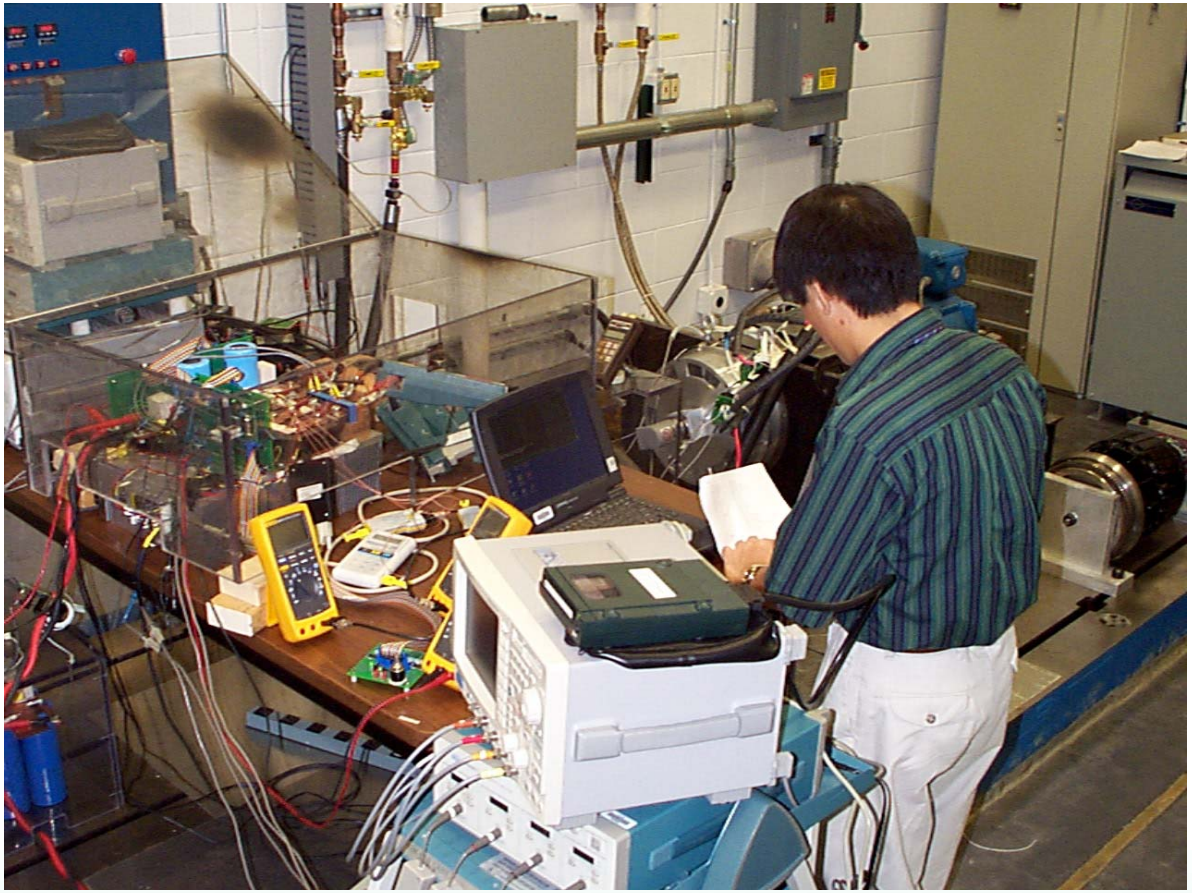
Fan and Encoder Assembly
(20-kW axial-gap PM motor)

Fan view

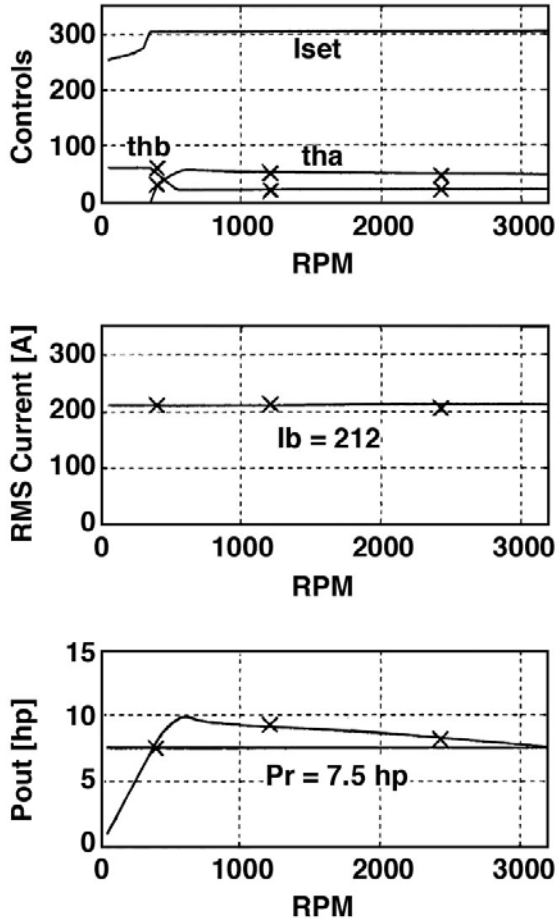


Cooling spider and encoder

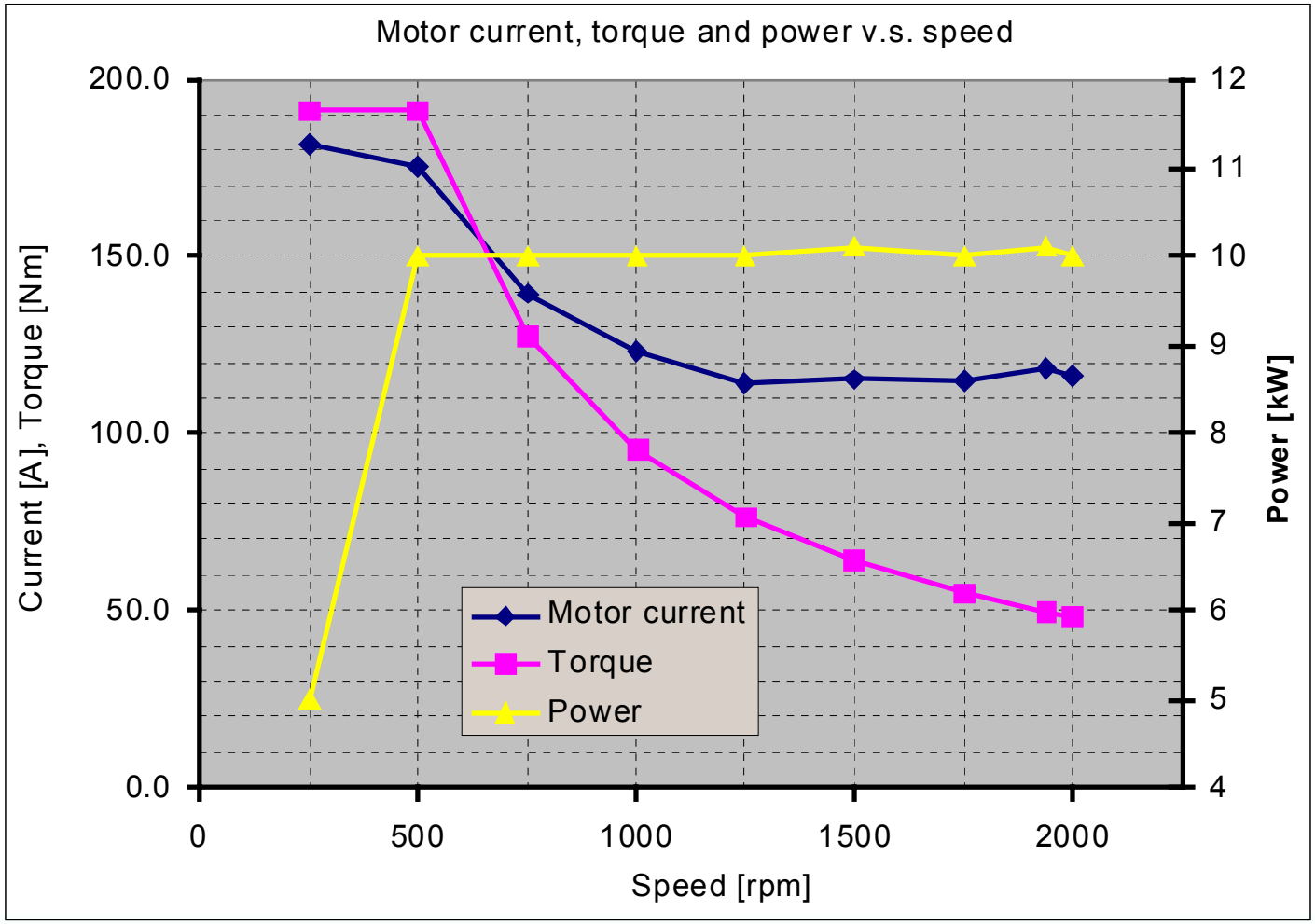
Preliminary testing of DMIC Inverter and Motor in Test Cell 1



DMIC-0 - Experimental and Simulated Performance of Lab Verification Test



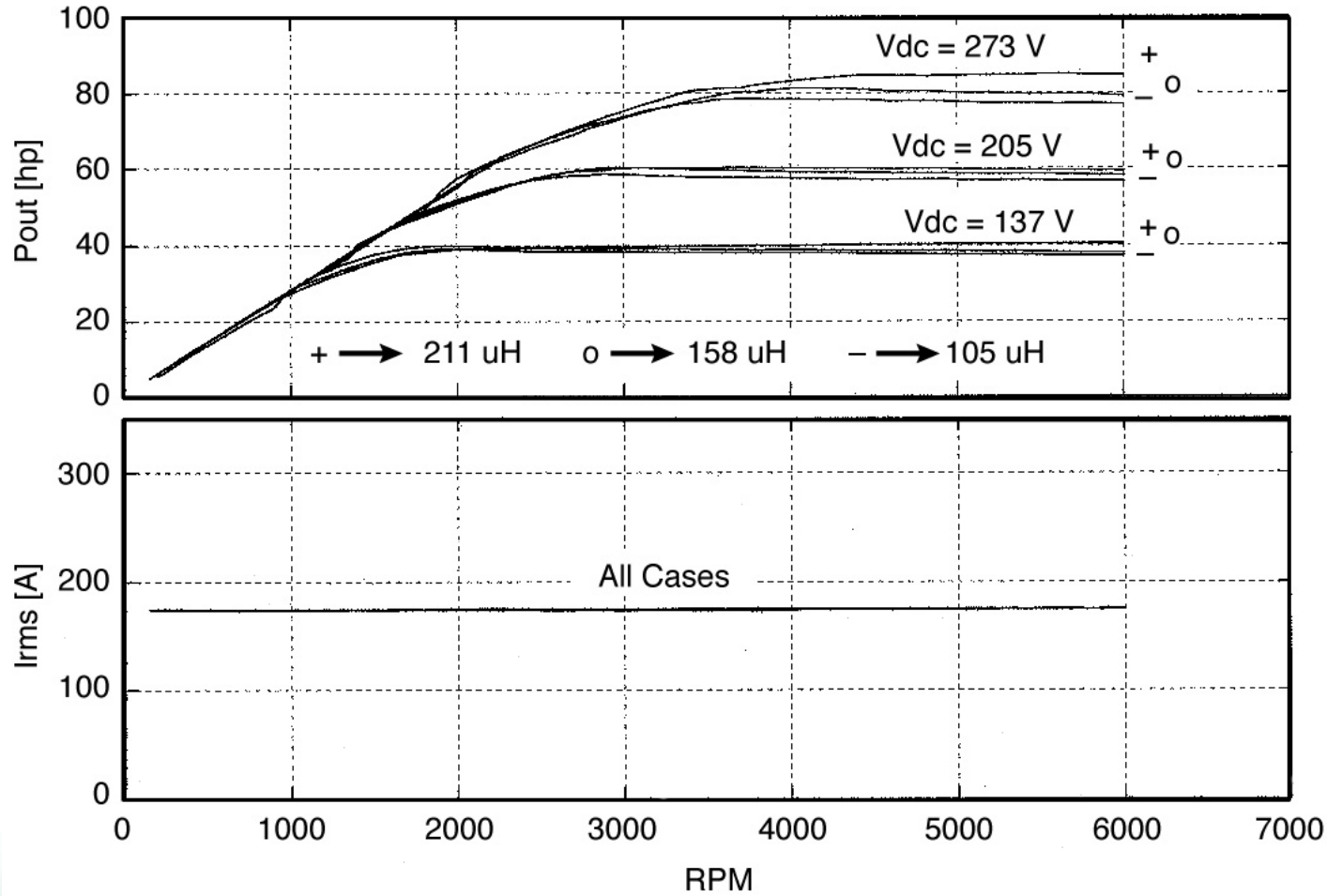
Results DMIC Testing at Half-speed



Conclusions

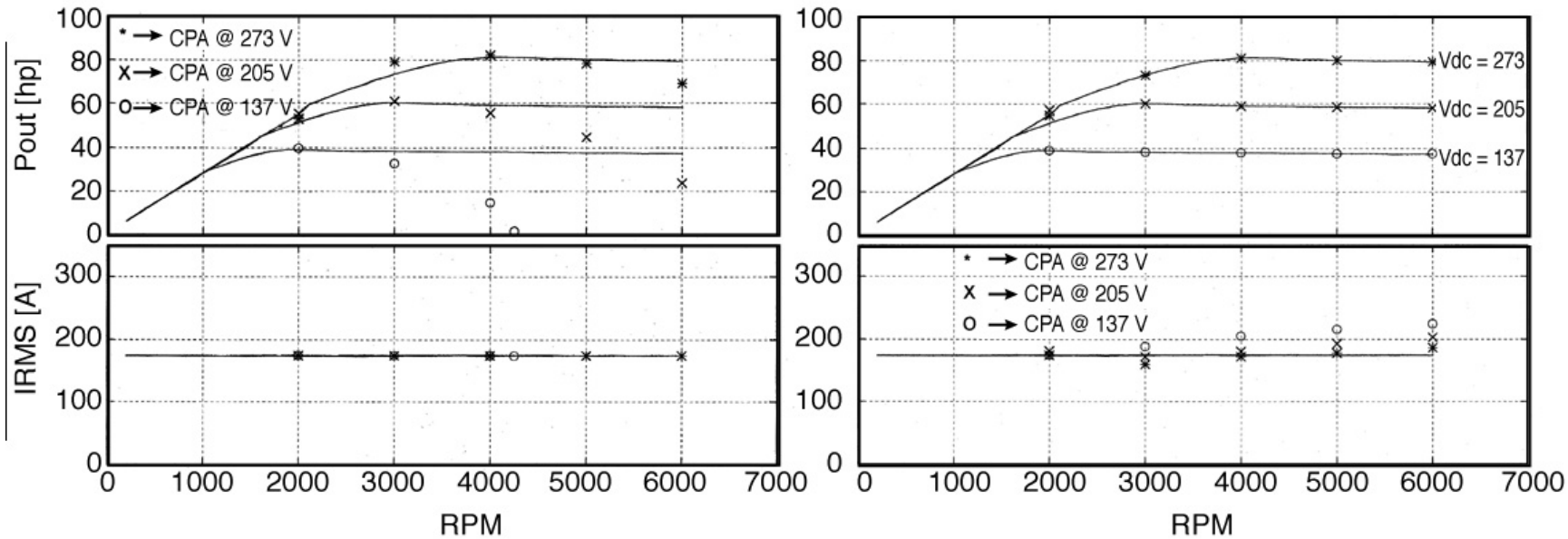
- **The DMIC can tolerate very large inductance and voltage variations.**
  - **Allows motor designer to optimize his design based on machine concerns likely to lead to low inductance.**
  - **Lower inductance decreases dc supply voltage requirements and increases peak power capability.**
  - **Unnecessary to oversize the dc supply, the electric motor, the electronics, and the cooling system when using this technology.**
- **Coasting losses with the DMIC are solely the hysteresis and eddy current losses of the motor. When CPA is used coasting losses may be an order of magnitude greater.**
- **The thyristors in the DMIC inverter protect against**
  - **shorting the dc bus**
  - **loss of the dc bus**
  - **loss of firing signals.**

Simulated Effect of Variations in Parameters, V_{dc} and L_{eq}, on DMIC



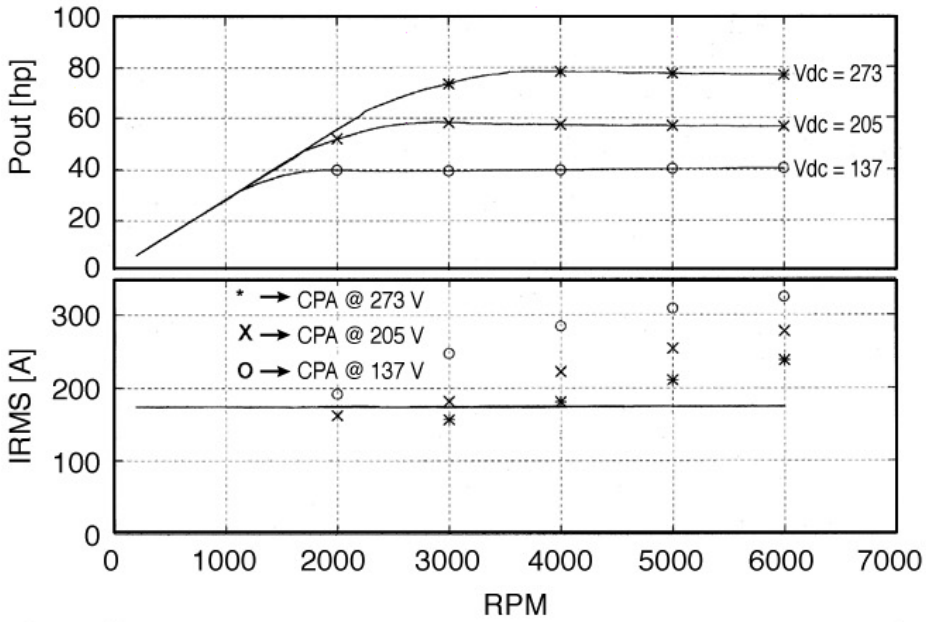
Comparative Response to V_{dc} Variations (1)

(L_{eq}= 158 μH)

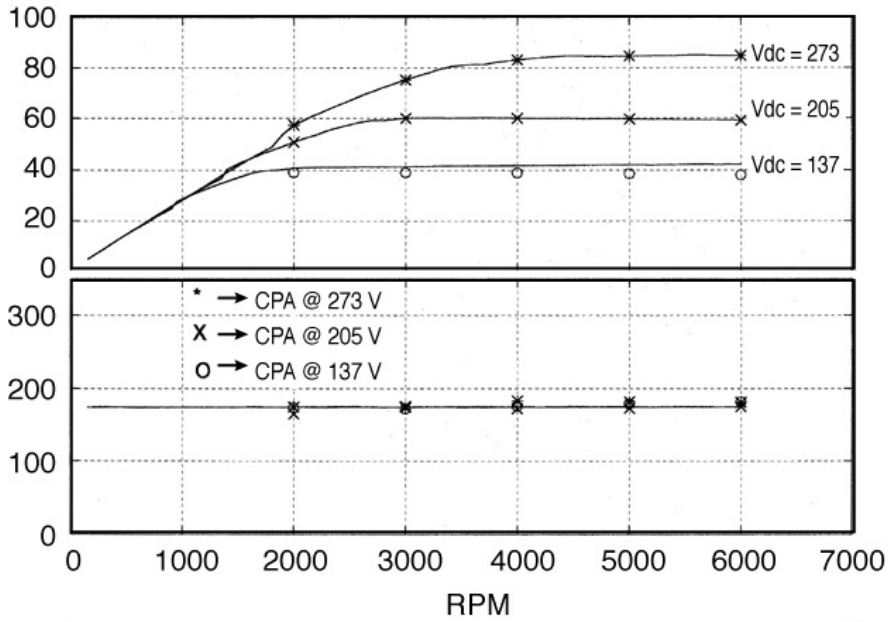


a. Equal current **b. Equal power**

Comparative Response to V_{dc} Variations (2)

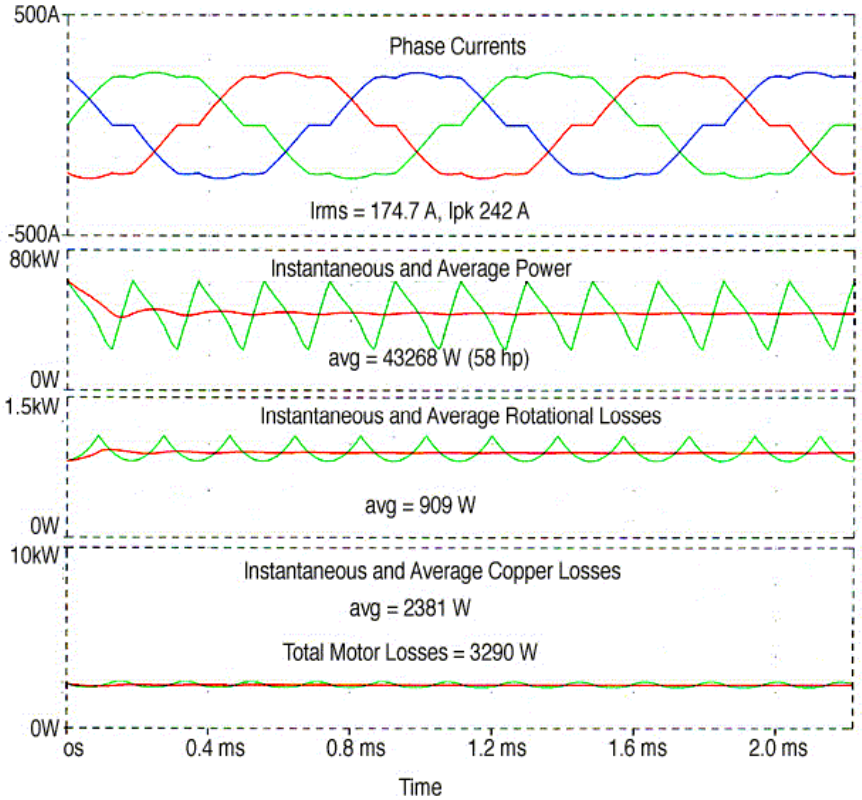


a. Low inductance

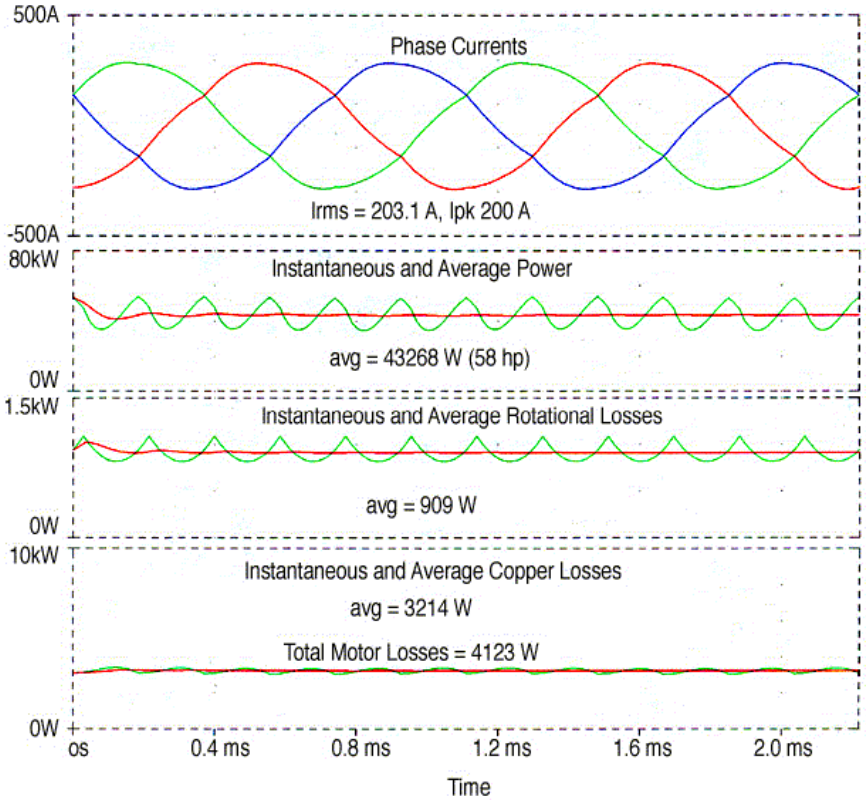


b. High inductance

Motor Current and Power Waveforms (58 hp operating at n=4)



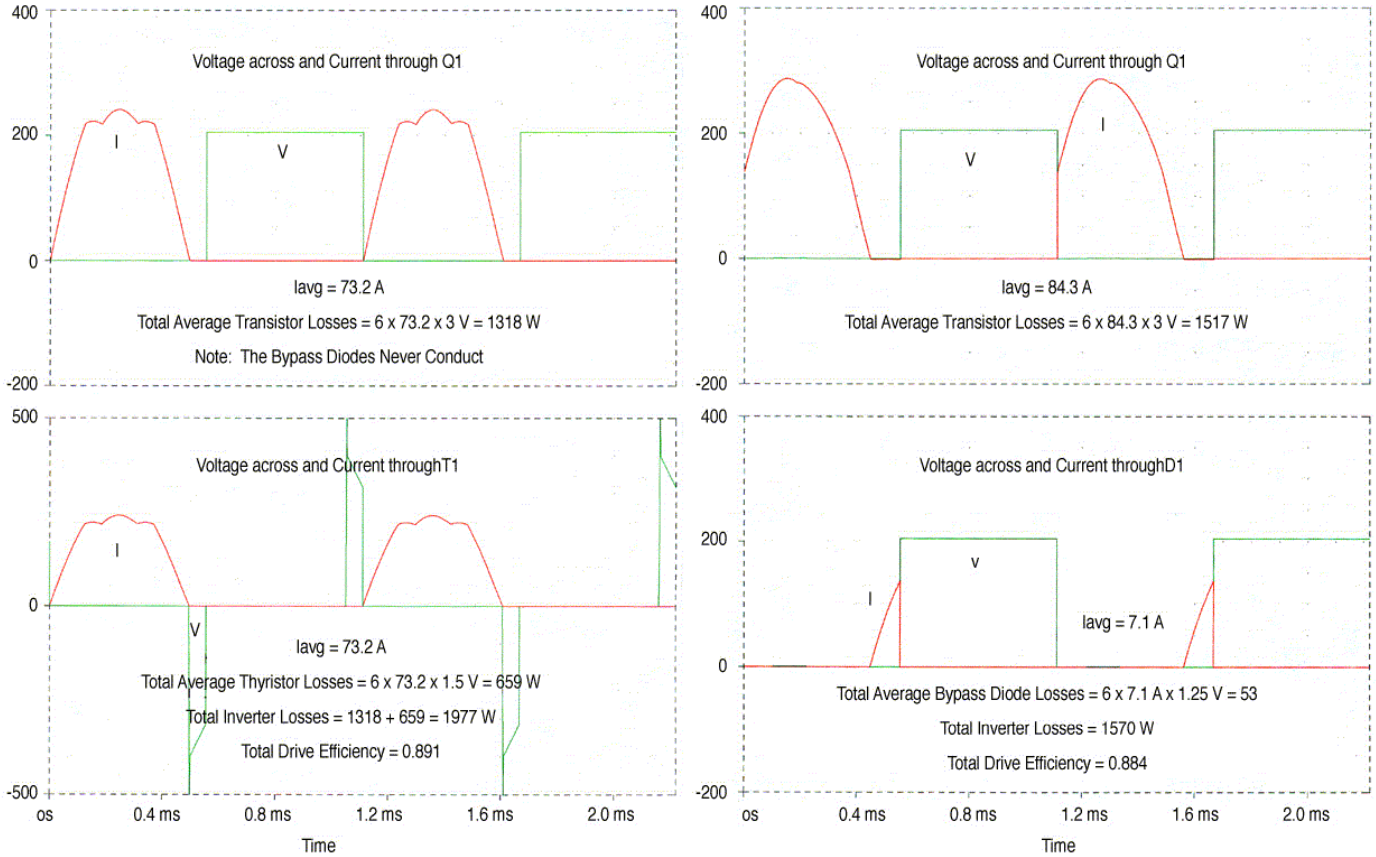
a. Dual mode inverter control **(I_{rms}=175A, I_{pk}=242A)**



b. Conventional phase advance control

(I_{rms}=203A, I_{pk}=288A)

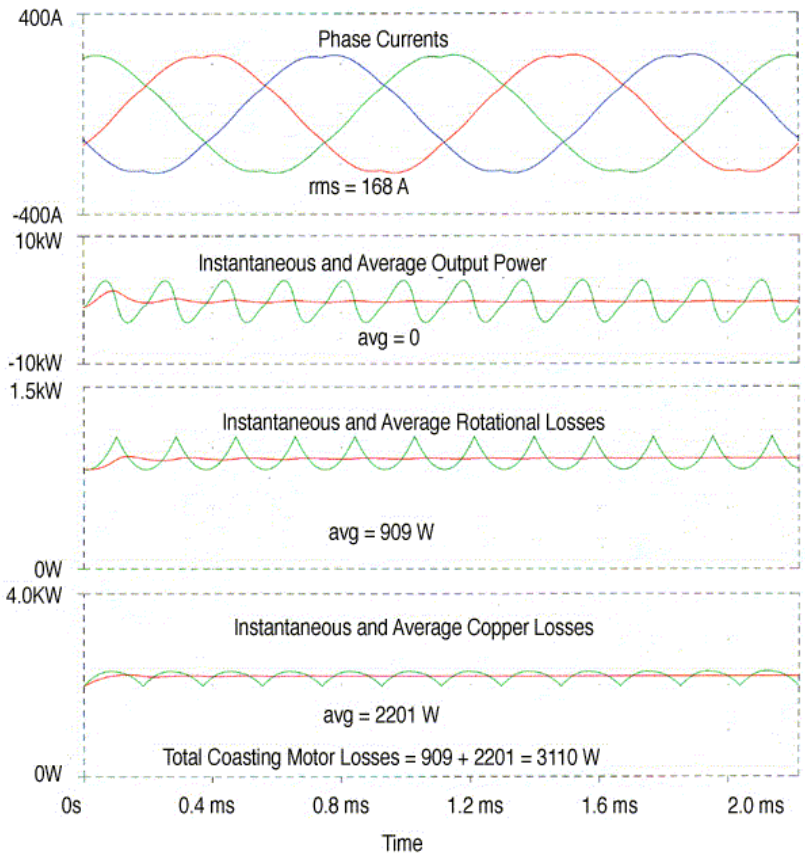
Inverter Voltage and Current Waveforms (58 hp operating at n=4)



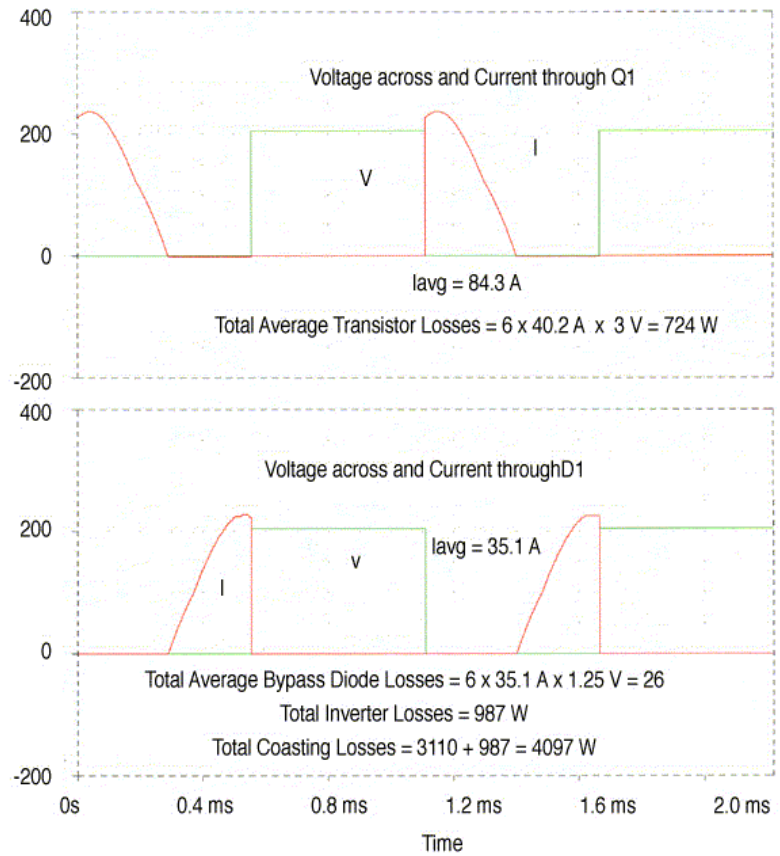
a. Dual mode inverter control

b. Conventional phase advance control

CPA Coasting Losses at n=4



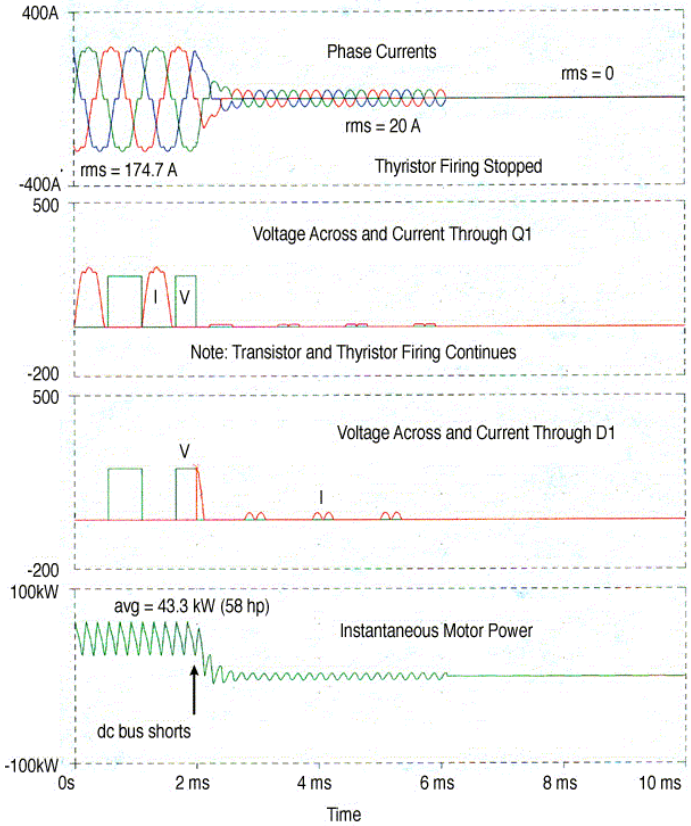
a. Motor current and power waveforms



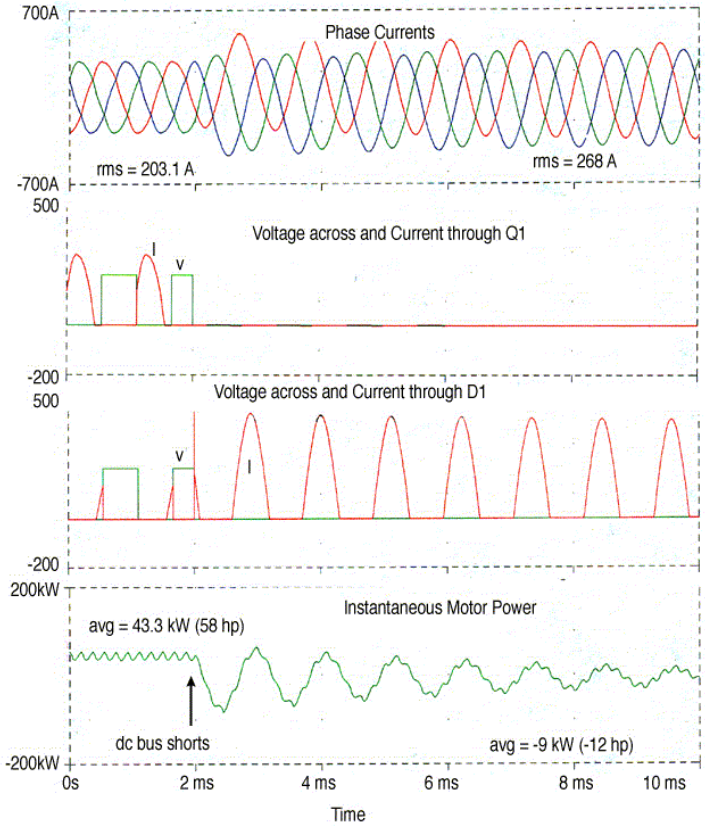
b. Inverter voltage and current waveforms

Short Circuiting the DC Bus

(Motor Phase Current and Power Waveforms and Inverter Voltage and Current Waveforms)



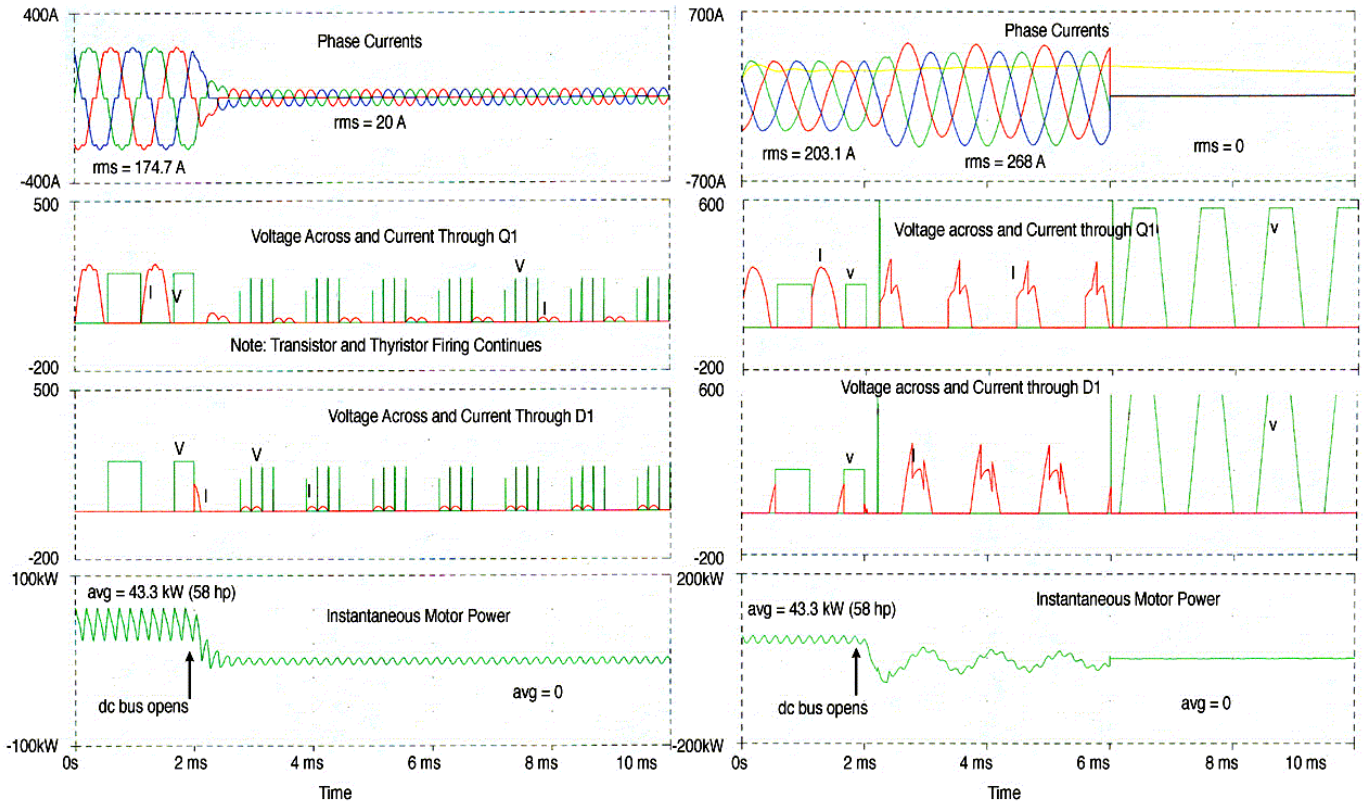
a. **Dual mode inverter control**



b. Conventional phase advance control

Open Circuiting the DC Bus

(Motor Phase Current and Power Waveforms and Inverter Voltage and Current Waveforms)

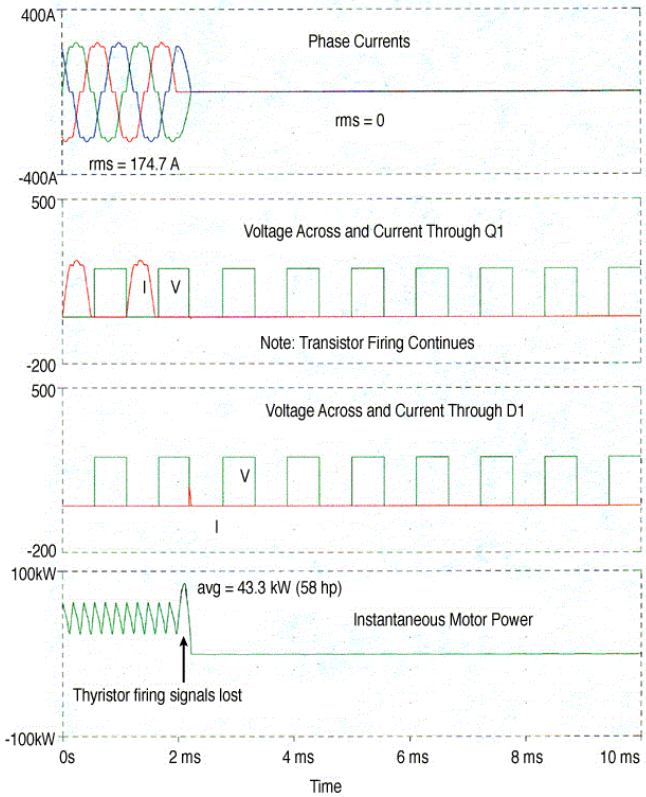


a. Dual mode inverter control

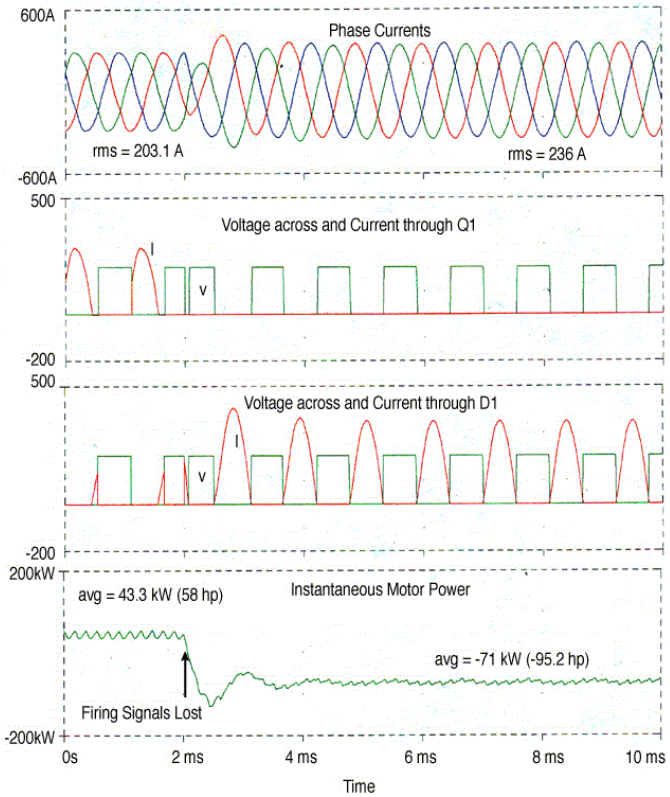
b. Conventional phase advance control

Loss of Firing signals

(Motor Phase Current and Power Waveforms and Inverter Voltage and Current Waveforms)



a. Dual mode inverter control



b. Conventional phase advance control

Example: Impact of Motor Inductance on dc Supply and Peak Power

Example using DMIC Prototype:

- L=158 μH YV$_{dc}$=199.0 V YP$_{pk\text{-}CPA}$ = 72,861 W
  P$_{pk\text{-}DMIC}$= 73,012 W

- L=211 μH YV$_{dc}$=218.5 V YP$_{pk\text{-}CPA}$ = 59,904 W
  (+33.5%) (+9.8%) (-17.8%)
  P$_{pk\text{-}DMIC}$= 60,028 W
  (-17.8%)