Flux Weakening, Flux Enhancement, and CPSR Enhancement Techniques

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FY 2005 AOP Task: 3.3

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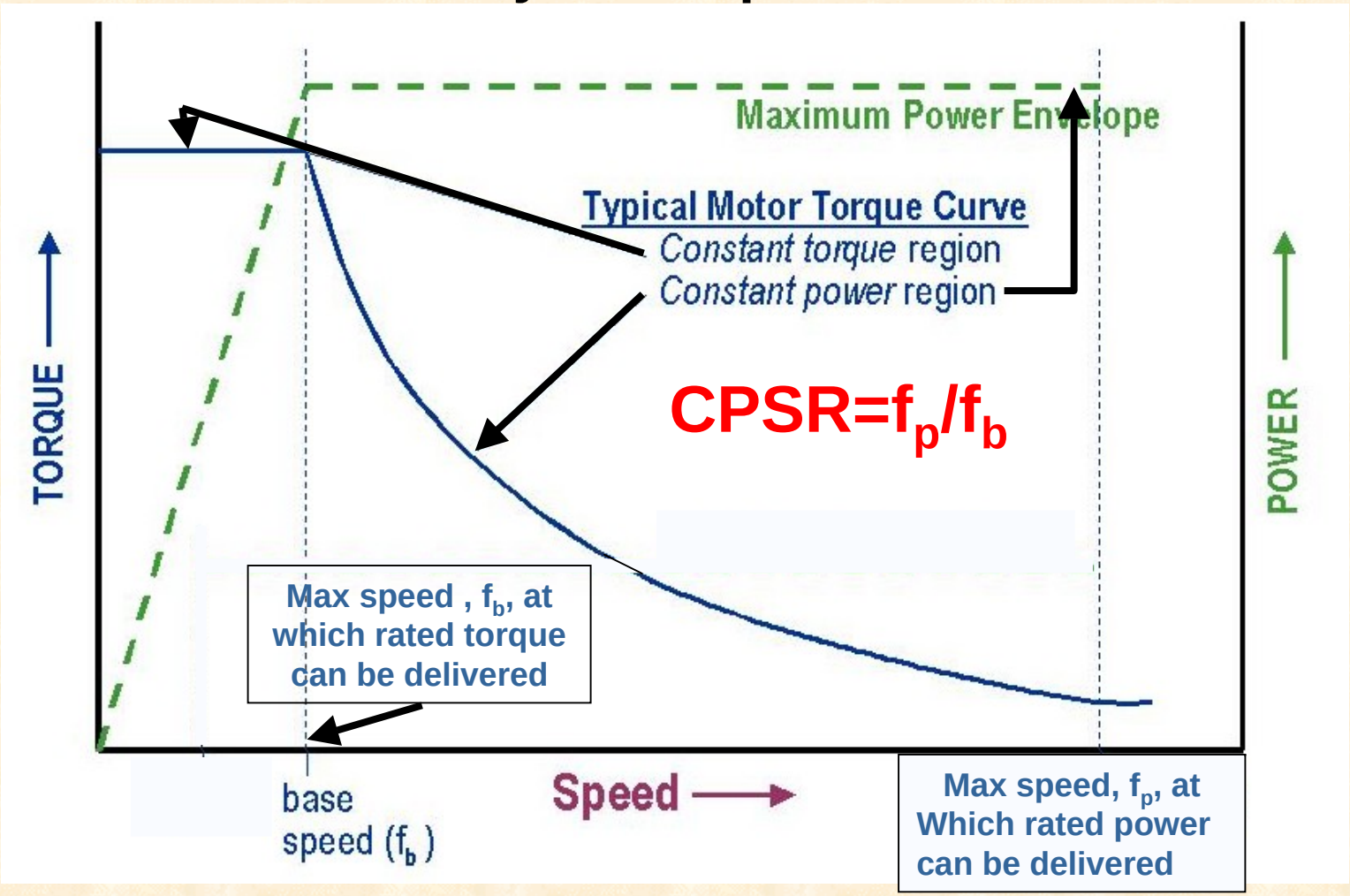
OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

Project Summary - Background

What is constant power speed ratio (CPSR), and why is it important?



Project Summary – (cont'd)

Background (Cont'd)

- **1998 – Began investigations of techniques to enhance CPSR of PM motors.**
- **1999 – Discovered a deficiency with benchmark control, which is conventional phase advance (CPA), leading to the birth of the dual mode inverter control (DMIC) to drive PM motors at high CPSR.**
- **2000 – Lab demo of CPSR = 6 using DMIC.**
- **2001 – Built HEV size BDCM to test DMIC. Patent awarded to ORNL for DMIC.**
- **2002 – Completed analysis leading to a better understanding of DMIC behavior, especially inductance bounds for machines with sinusoidal back-emfs as well as those with trapezoidal back- emfs.**
- **2003 – Developed linear magnetics model of switched reluctance motor showing it too is a high CPSR motor in continuous conduction mode. Demonstrated continuous conduction operation in the lab.**
- **2004 – Lab demo of CPSR = 11.6 using DMIC driving BDCM. Conceptualized simple model for DMIC control of a permanent magnet synchronous motor (PMSM).**

Project Summary – (cont'd)

- **Expected Outcomes**
  - Traction drive technologies that exhibit the minimum CPSR = 4
  - Improved drive system performance without increasing drive system cost
- **Approach**
  - Choose new technology with potential for improvement
  - Identify benchmark
  - Compare new technology and benchmark with respect to performance and cost
- **Timeframe**
  - Two yr (IC HEV) to seven yrs (fuel cell HEV)
- **Funding**
  - $670 K

Project Summary – (cont'd)

- **Related Projects**
  - Prius TH2 motor (benchmark)
  - Reluctance motor research at ORNL (HSUB)
  - Inverter development and control
  - Motor request for proposal
  - Automotive integrated power module (Semikron)
  - Z-source inverter
  - Collaborative interaction with UQM, John Deere
  - Collaborative interaction with:
    - Michigan State University
    - University of Tennessee
    - University of Wisconsin at Madison through the Wisconsin Electric Machine and Power electronics Consortium (WEMPEC)

Objective

- **Objective –** Simulate alternate field weakening techniques and determine the pros and cons of each with respect to FreedomCAR targets.
- **Goal –** Increase traction drive system performance without increasing cost.
- **Constraint –** All CPSR enhancement technology costs.
- **Challenge –** Determine benefit and decide if cost justifies using technology to obtain that benefit.
  - CPSR control must address all FreedomCAR and Vehicle Technology targets (cost, efficiency, peak power, continuous power, life, specific power, and power density).
  - Target penalties arise for each CPSR control (voltage, flux, inverter, inductance, and reluctance) may be overcome by system integration.

FY 2004 Progress

Task 3.3 CPSR Enhancement began in October 2004

Work Leading up to the Task

- Completed DMIC test on BDCM demonstrating CPSR = 11.6.
- Completed DMIC cost study
  - Off-the-shelf components in volumes of 10,000
  - Inverter-to-motor cost ratio is 7:1 (detailed study values 10:1)
  - There are cases where increased cost of DMIC SCRs can be compensated by lower inverter device costs
  - The minimum current control provided by DMIC may be used to calculate the life-cycle cost benefit if the duty cycle for a particular application is known

FY 2005 Plan

- **Description**
  - Investigate voltage control with dc/dc boosted PWM inverter and compare with Z-source inverter
  - Explore alternate flux weakening techniques such as coil switching
  - Compare CPA and DMIC under minimum current control
  - Collaborate with WEMPEC on motors that use their concentrated winding technology
    - ORNL will investigate design and performance benefits
    - ORNL will develop simplified motor driver controls
  - Model the PM/Reluctance motor and explore optimization potential
  - Explore possible combinations of the CPSR enhancement controls and identify research areas not being addressed

FY 2005 Plan (cont'd)

- **Expected progress/results this year**
  - Acquire or develop analytical or software models that may be used to draw conclusions and guide future technical decisions for efficiency calculations of boost converters
  - Define a topology and analysis of coil switching for flux control
  - Define a minimum current control scheme for motors with concentrated windings
  - Identify or develop a model of a surface mounted PM/Reluctance motor
  - Obtain a 6 kW motor with concentrated windings for testing
- **Milestones**

  09/30/05 – Simulation results from analytical or software models that may be used to draw conclusions.

FY 2005 Plan (cont'd)

- **Schedule**
  - 03/30/05: Report entitled, *Boost Converters for HEV and Fuel Cell Traction Drives*
  - 03/30/05: Report entitled, *The Role of Reluctance in PM Motors*
  - 05/30/05: Report entitled, *Status of Direct Flux Control Research*
  - 09/30/05: Report entitled, *Comparison of Minimum Current PM Motor Control for Concentrated Windings with Benchmark d, q Control*
  - 09/30/05: Report entitled, *Potential of PM Motors with Concentrated Windings*
  - 09/30/05: Report entitled, *Modeling of Reluctance Assisted PM Motors*

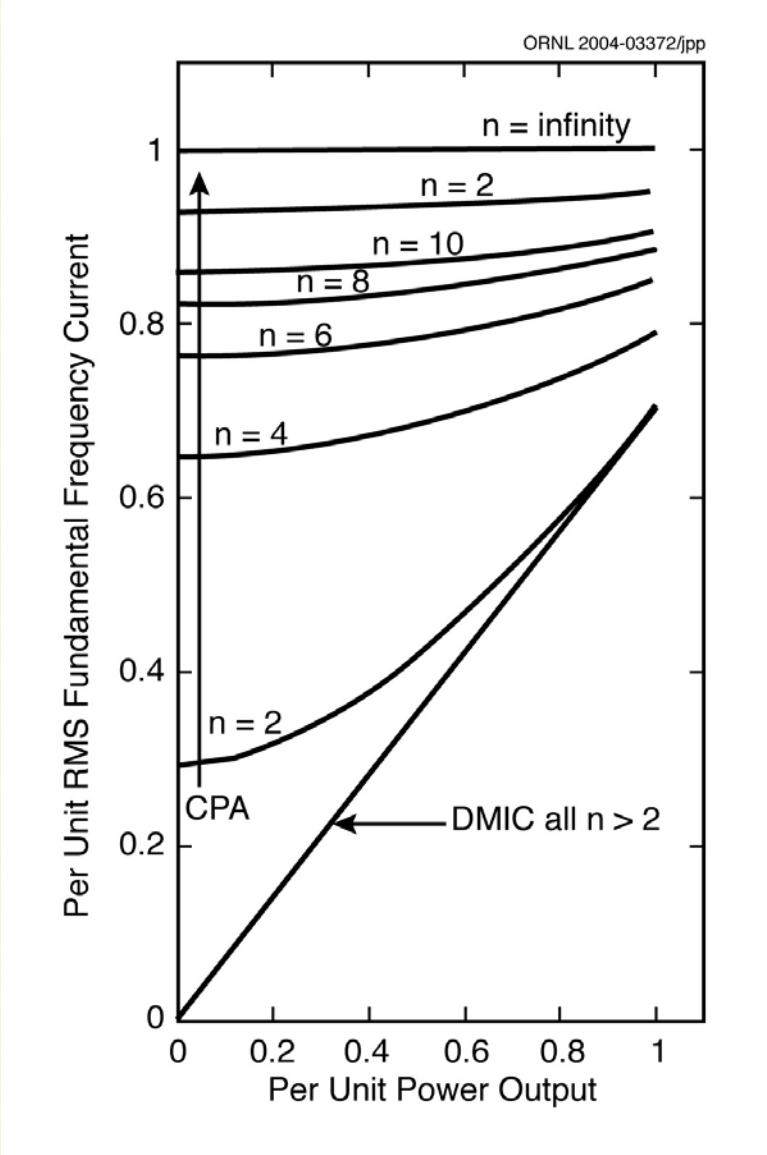
FY 2005 Progress to Date

- **October 2004 through December 2004**
  - Compared CPA with DMIC using new PMSM model showing that an inductive reactance (and therefore an inductance) exists that will minimize the current needed to produce a rated power
  - Completed simulations of a PM/Reluctance motor and created plots of reluctance torque and PM torque versus % magnet, which exhibited a maximum at 50%
  - Began study of standard boost converter and Z-source converter
  - Began collaboration with WEMPEC
- **Change**
  - The foundational technology selected for emphasis in flux control is stator coil switching
  - Footprint study will be delayed until FY 2006 to focus more research effort on flux control and reluctance control
  - The inverter control report will compare the new control system for concentrated windings with the benchmark d,q control (not with CPA and DMIC control)

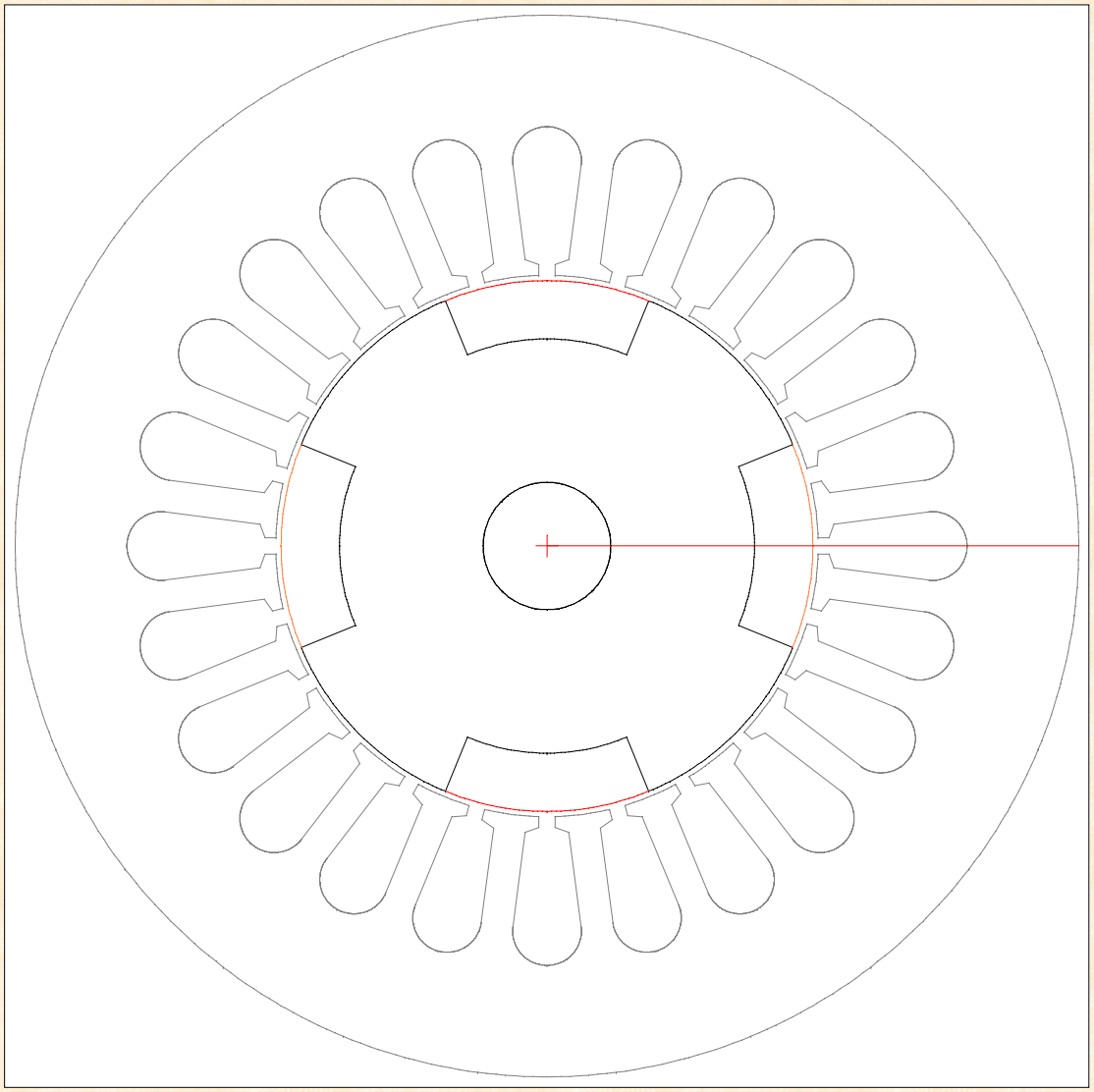
FY 2005 Progress to Date (cont'd)

- **Major technical accomplishments**
  - Submitted a foundational paper for minimum current control entitled, *Minimum Current Magnitude Control of Surface Mounted PM Synchronous Machines During Constant Power Operation,* to IEEE Power Electronics Letters
  - Developed equations to calculate eddy current power losses in the magnets of a PM motor with high pole count
- **Milestone**
  - Developed an analytical model of a synchronous PM motor showing how the DMIC provides minimum current control

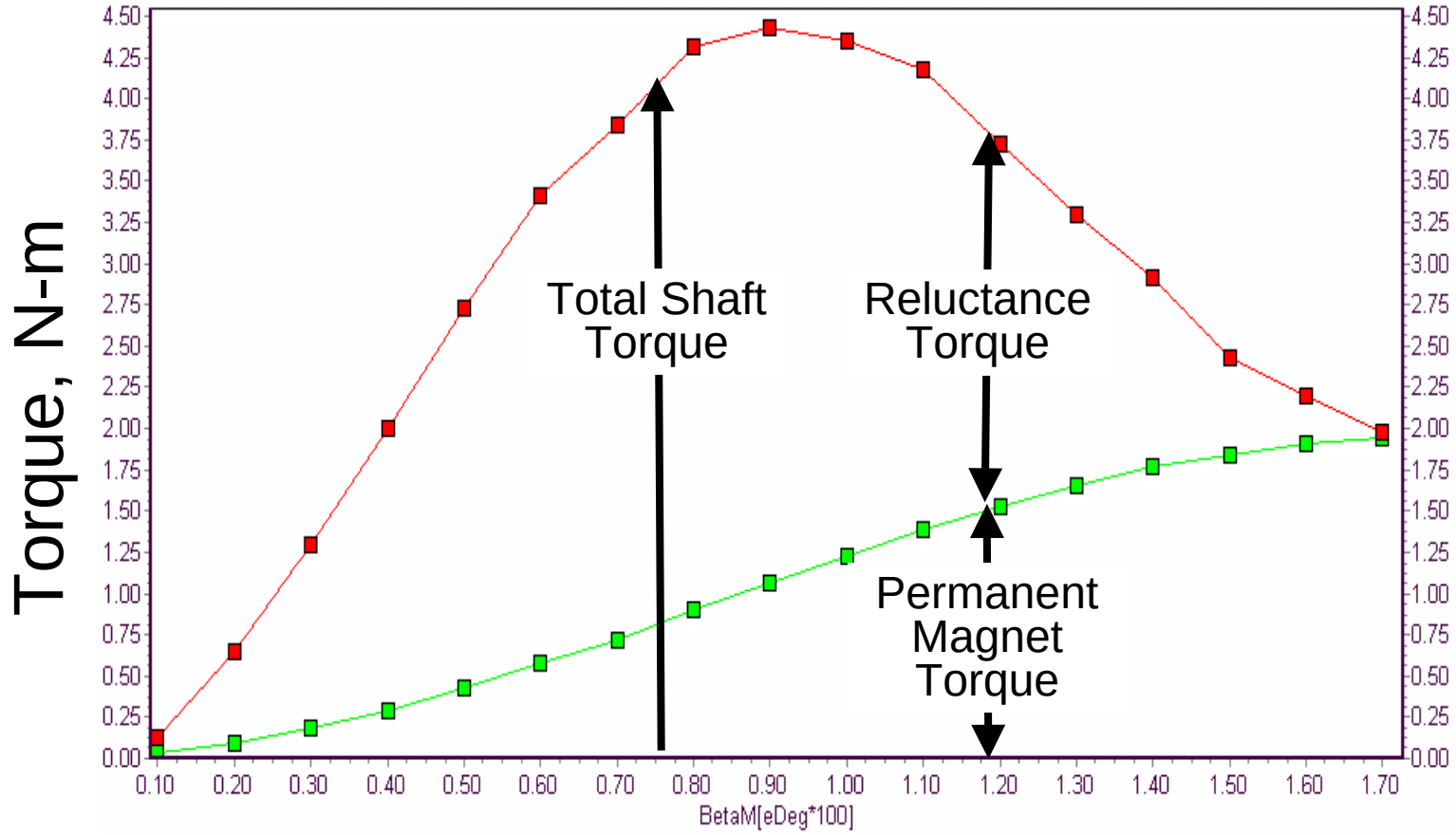
DMIC Controls to Provide Minimum Current



A PM/Reluctance Motor



Reluctance Contribution to Torque for a Surface Mounted PM/Reluctance Motor



Magnet Fraction is BetaM/180

Future Plans and Expectations

- Collaborate with WEMPEC to drive a motor with concentrated windings using ORNL's simplified control scheme and determine value added.
- Examine the fuel cell HEV system footprint and identify problems anticipated in the transition from IC HEV to fuel cell HEV.
- Modify an existing motor to employ the stator coil switching flux control method and test using a standard PWM inverter.
- Look for systems with combinations of components that can reduce size and cost. (e.g., to reduce the traction drive size, use a generator as a motor to assist the traction drive when high torque is required and return to use as a generator when torque requirements are reduced).
- Use the information generated by the radial-gap PM/Reluctance motor to explore the potential of a similar axial-gap motor to function as a traction motor (ORNL applied for patent).
- Examine the use of magnet temperature control for field weakening and mechanical flux control methods.
- Renew research on continuous conduction in reluctance motors.
- Pursue multi-national collaboration with the Korean Electro-Technology Research Institute on PM motors and reluctance motors.