



Interior Permanent Magnet Machine For Use In The XM1124 Hybrid Electric HMMWV

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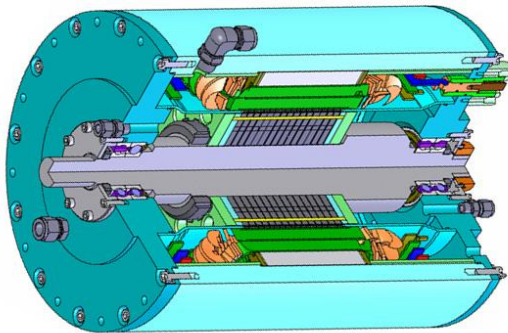
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- DRS-TEM was tasked in the Control Development, Testing, and Validation of a Prototype IPM suitable for use in the XM1124 HMMWV
 - IPM chosen due to special characteristics that make it desirable when compared to other ac machines (Specifically, SPM Machines)
 - Rotor design topology produces increased saliency ratio (Armature Axis Inductance is larger than the Field Inductance)
 - Saliency makes the reluctance torque component available, in addition to the permanent magnet torque, for low speed torque boost as well as extended-speed operation under FW Control
 - Trajectory Control implemented in order to utilize unique machine characteristics and optimize performance

IPM Machine Modeling

Table 1 : XM1124 Prototype IPM Motor Parameters

Number of pole pairs – P	4
Stator resistance – R	9.9e-3 Ω
Magnet flux linkage – λ _f	0.098 Wb
d-axis inductance – L _d	400e-6 H
q-axis inductance – L _q	800e-6 H
Maximum phase voltage – V _{sm}	230 V _{pk}
Maximum dc-link voltage – V _{dc-link}	400 V _{dc}
Maximum phase current – I _{sm}	600 A _{pk}
Base Speed – ω _b	1500 RPM
Crossover Speed – ω _c	5600 RPM
Rated Power – P _R	100 kW



IPM Governing Equations: Voltage in the d-q rotating reference frame

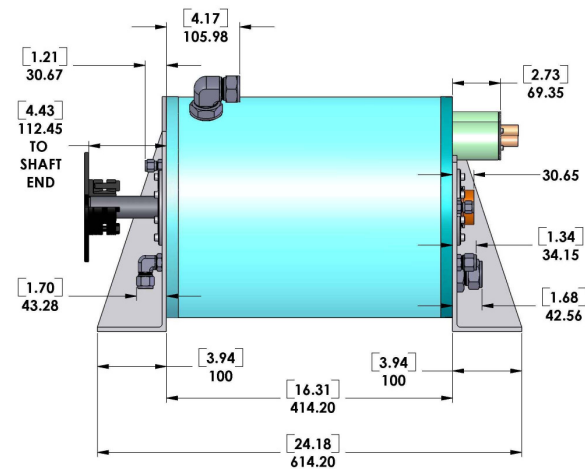
$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R + pL_d & -\omega_e L_q \\ \omega_e L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_e \lambda_f \end{bmatrix}$$

Torque Developed

$$T = \frac{3}{2} P \left[\lambda_f i_q + (L_d - L_q) i_d i_q \right]$$

Permanent Magnet Component

Synchronous Reluctance Component



IPM Machine Modeling



- For successful control implementation, operating limits and stability criteria must be effectively defined and observed
- Current and voltage restraints are used in order to define the operating region for the Maximum Torque Per Amp (MTPA) Trajectory

Current Limit Circle

$$X^2 + Y^2 = r^2$$

Center Point Lying at zero with a radius of I_{sm}

Voltage Limit Ellipses

$$\frac{(X - h)^2}{a^2} + \frac{(Y - k)^2}{b^2} = 1$$

Center Point Lying at

$$(h, k) = \left(0, \frac{-\lambda_f}{L_d} \right)$$

Half Length of Major Axis

$$a = \left(\frac{V_{om}}{\omega_e * L_d} \right)$$

Half Length of Minor Axis

$$b = \left(\frac{V_{om}}{\omega_e * L_q} \right)$$

Where $V_{om} = V_{sm} - I_{sm} * R$ and $V_{sm} = \frac{V_{dc-link}}{\sqrt{3}}$

IPM Machine Modeling



- The MTPA Trajectory utilizes machine characteristics and system limitations in such a way as to maximize the torque/amp ratio while maintaining optimum efficiency.
- Intersecting point of MTPA Trajectory and current limit circle yields maximum operating point at base speed
 - Base Speed is defined as the speed at which the load generated CEMF reaches the inverter bus voltage

MTPA Trajectory Maximum Operating Point At Base Speed

$$i_{dA} = \frac{\lambda_f}{4(L_q - L_d)} - \sqrt{\frac{\lambda_f^2}{16(L_q - L_d)^2} + \frac{I_{sm}^2}{2}}$$

$$i_{qA} = \sqrt{I_{sm}^2 - i_{dA}^2}$$

Analytical Maximum Operating Point $(i_{dA}, i_{qA}) = (-367 A, 474 A)$

Operational MTPA Trajectory d-axis current calculation

$$i_d^* = \frac{\lambda_f}{2(L_q - L_d)} - \sqrt{\frac{\lambda_f^2}{4(L_q - L_d)^2} + (i_q^*)^2}$$

d-axis Current command calculated based on q-axis current command (Indirect Torque Control, Speed Control Error)

Modeling and Simulation between Base Speed and Crossover Speed



- In order to safely operate the IPM beyond base speed and up to crossover speed, the controlling algorithm must be transitioned to MTPA + FW Control
 - Crossover speed is defined as the speed at which the no load PM generated EMF reaches the bus voltage
 - Beyond base speed, MTPA or FW control is selected based on the load condition
 - Required d-axis current is calculated using q-axis current command and FW equation
 - Great care must be taken to avoid stability criteria due to a non-real i_d calculation

FW Control d-axis Current Calculation

$$i_d^* = \frac{-\lambda_f}{L_d} + \frac{1}{L_d} \sqrt{\frac{V_{om}^2}{\omega_e^2} - (L_q i_q^*)^2}$$

Only Real while

$$|i_q^*| \leq \frac{V_{om}}{\omega_e L_q}$$



If non-real solution

$$i_d^* = \frac{-\lambda_f}{L_d}$$

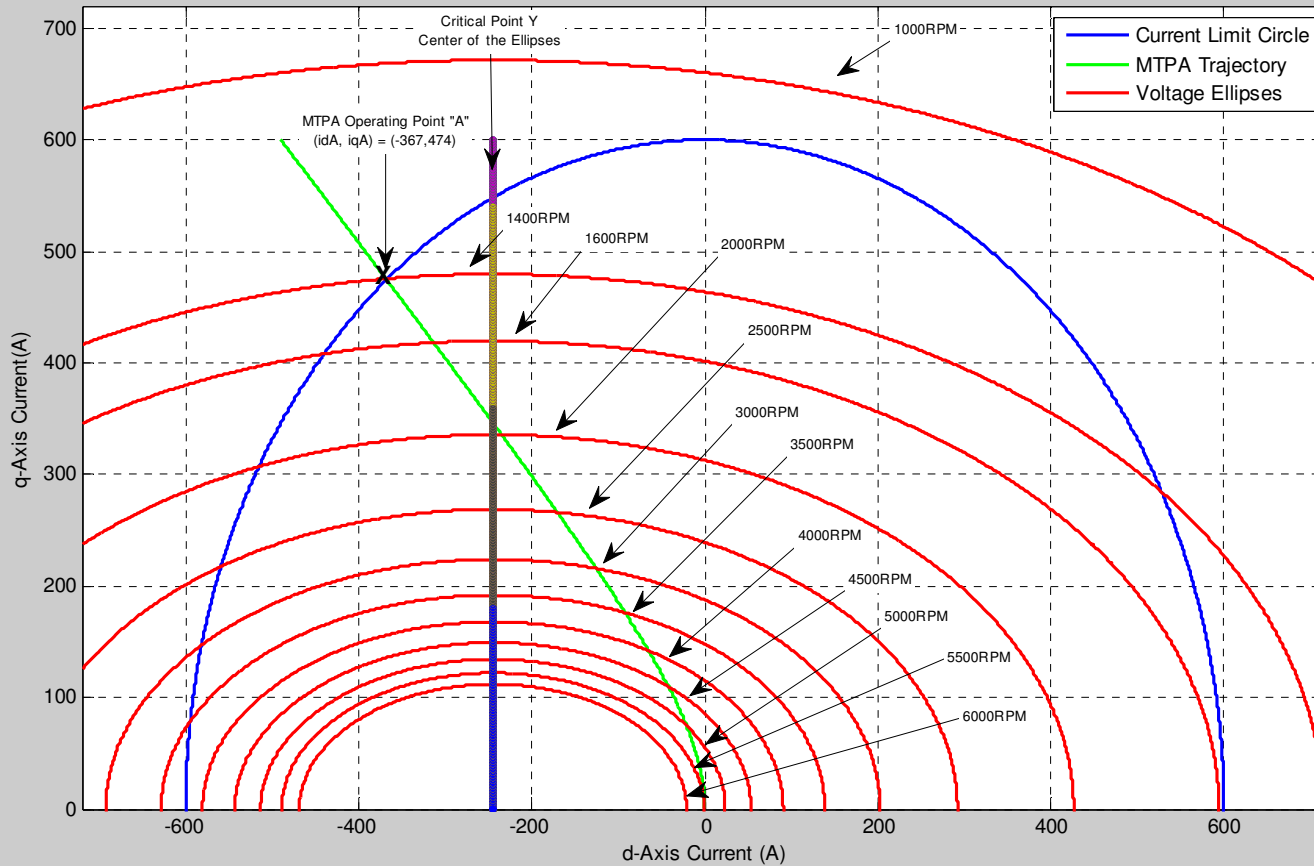
MTPA Trajectory

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Current Limit Circle, Voltage Limit Ellipses, and MTPA Trajectory for The XM1124 Prototype IPM in the i_d - i_q Plane

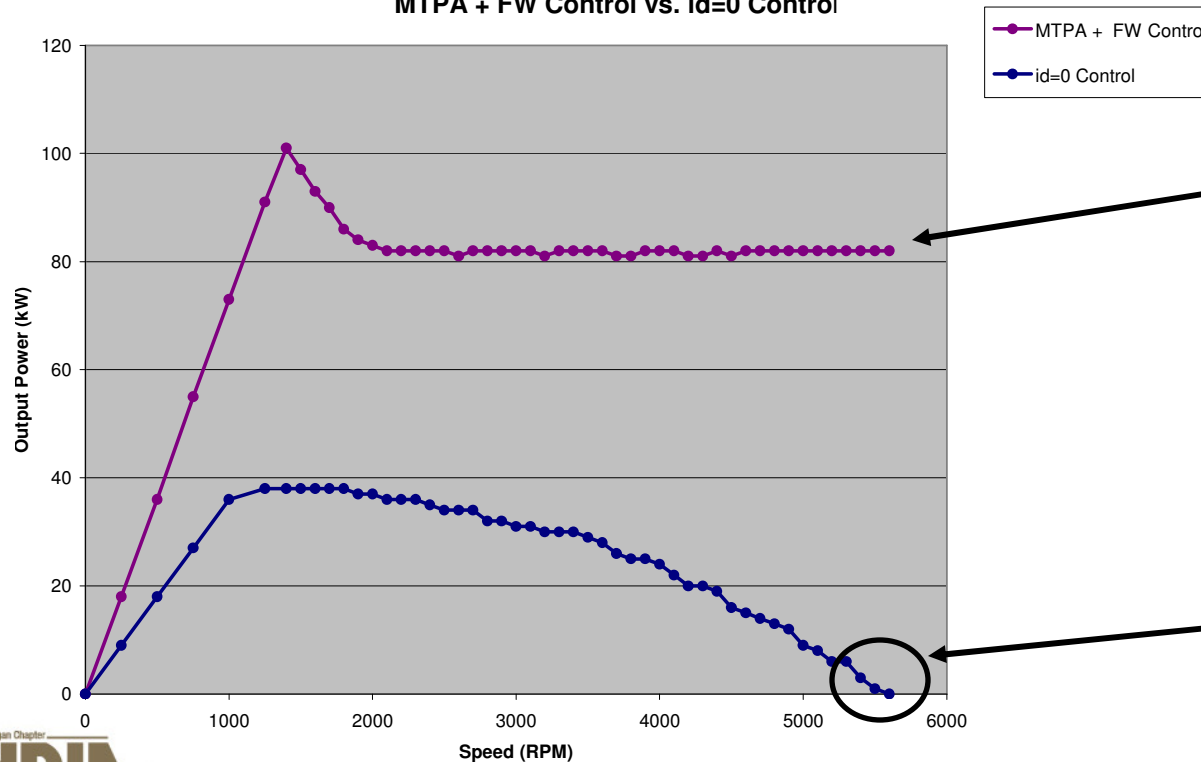


Simulated Results



- Simulated Comparison of SPM machine and Id=0 Control

Simulated XM1124 Prototype IPM Output Power vs. Speed
MTPA + FW Control vs. id=0 Control



MTPA is stable below base speed and FW Control performs well in the CPR

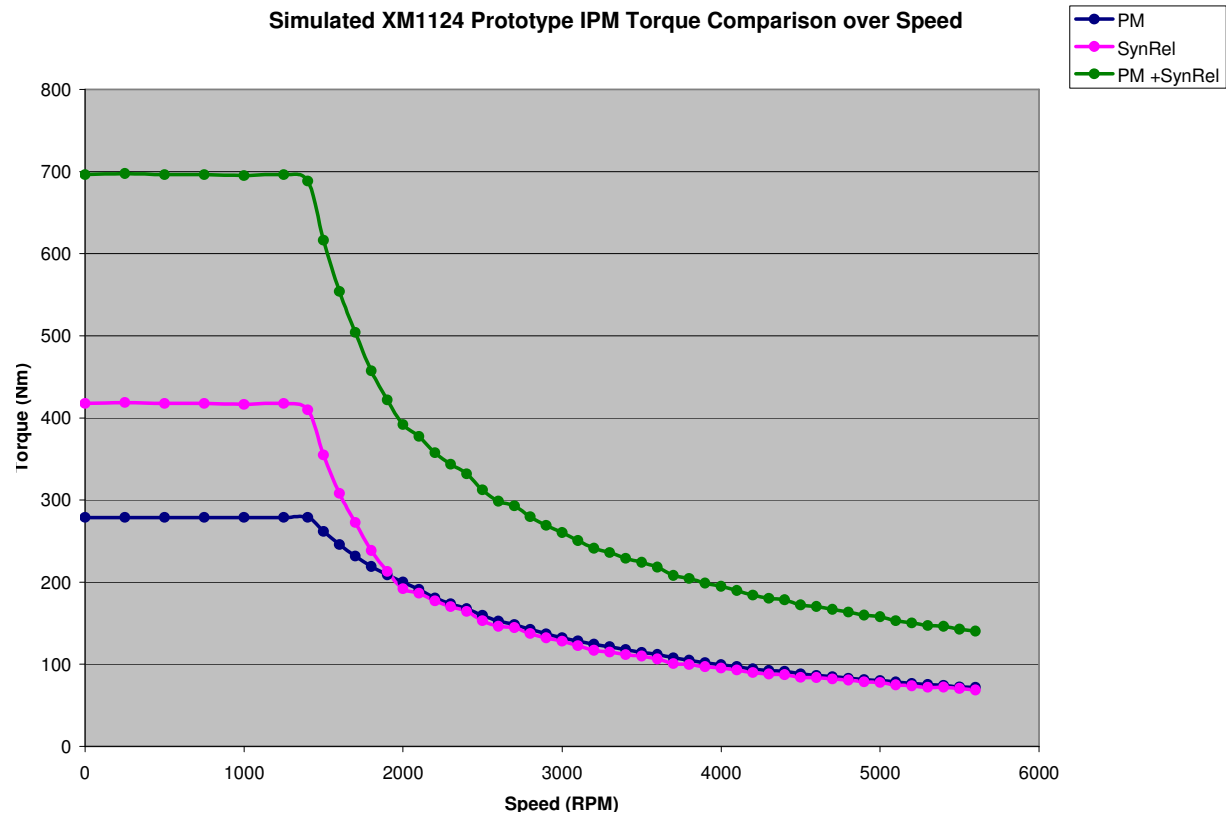
Crossover Speed Observed

Simulated IPM Torque Comparison

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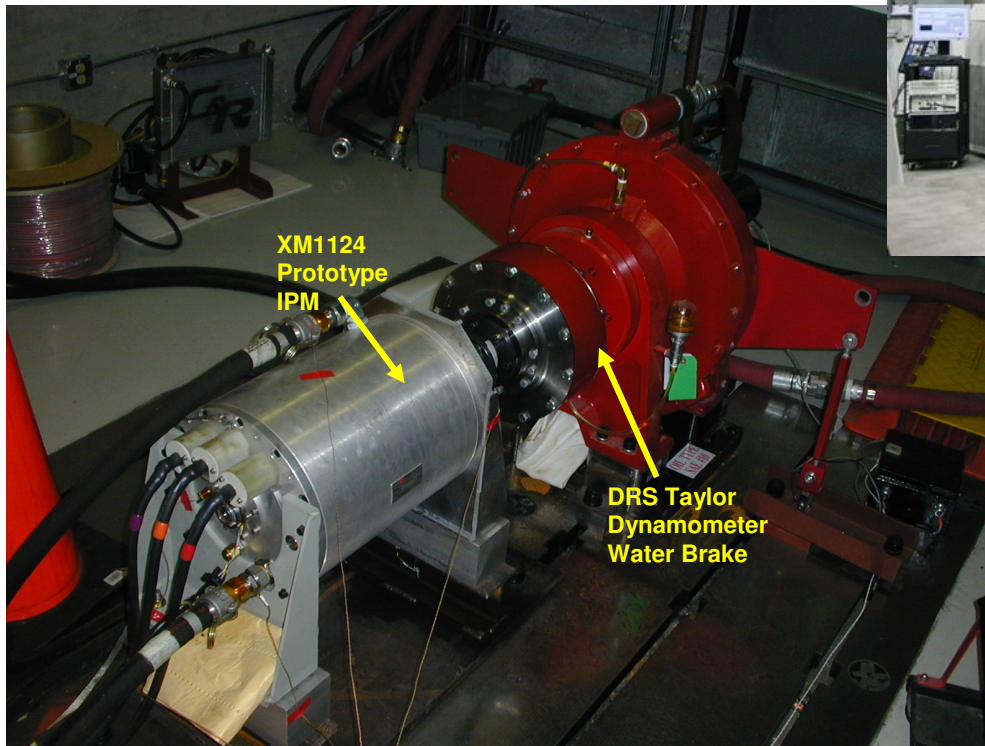
- Extraction of individual torque components is very beneficial
- Sum of torque components is greater than either alone



Experimental Validation

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- DRS System Integration Lab (SIL) used to test machine and controlling algorithm

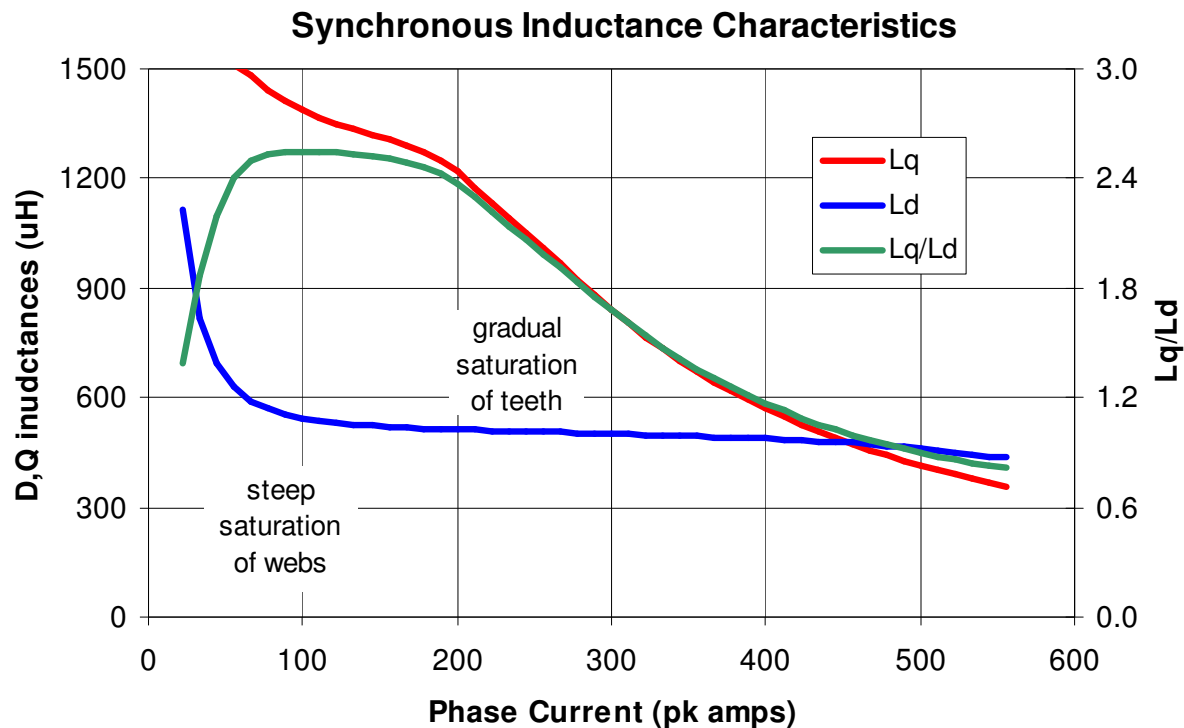


- XM1124 Prototype IPM coupled directly to DRS Taylor Dynamometer Water Brake for load testing

Saturation Effects



- Significant saturation of the armature axis inductance observed at start of experimental testing
- Results in reduction of saliency ratio and limits overall output torque by reduction of synchronous reluctance torque component





Experimental Results with Saturation Effects

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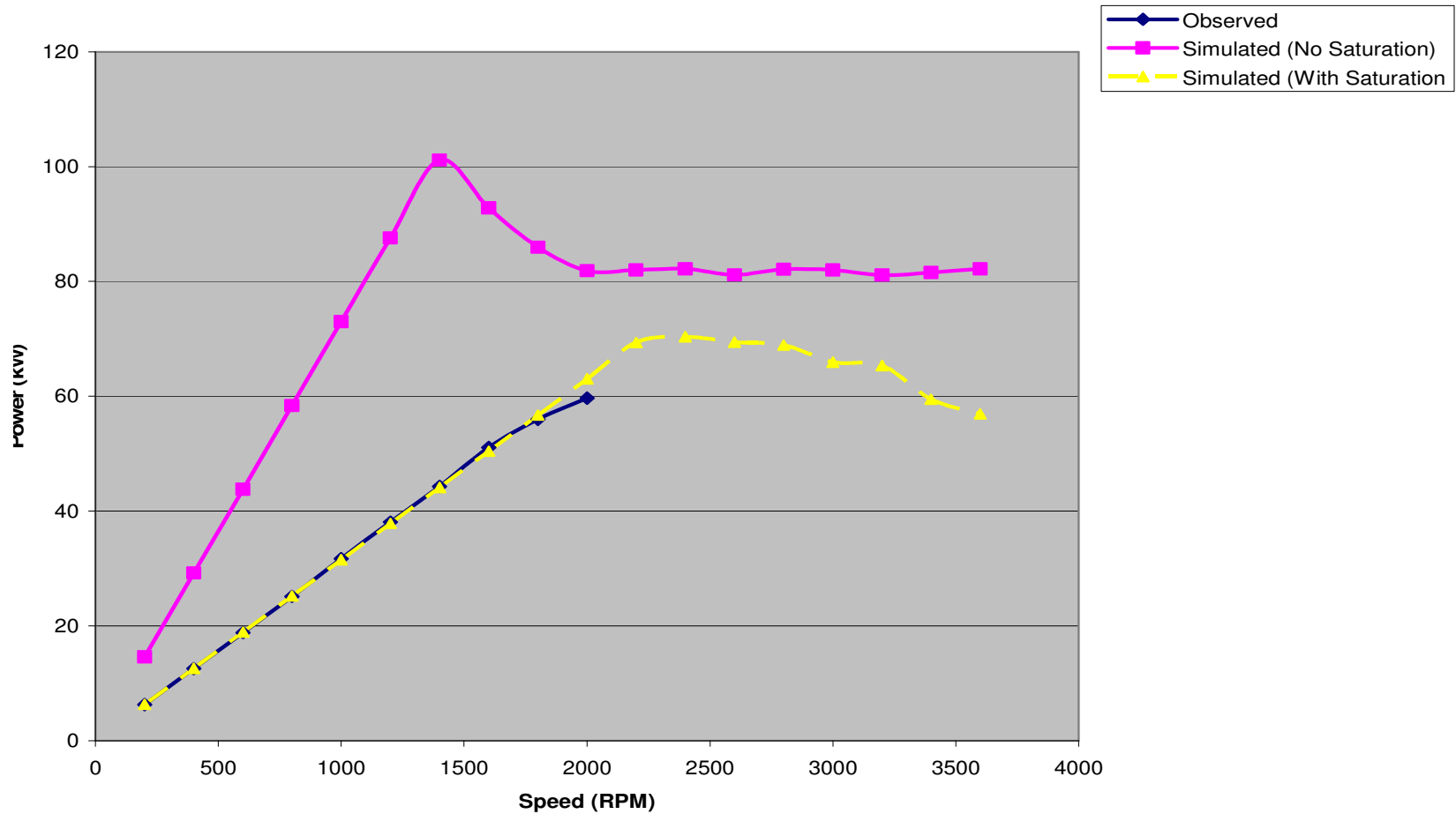
- Prototype IPM tested and controlled by DRS MCU using Trajectory Control
 - MCU introduces safety limitations not observed in initial simulation
 - Reduced DC-Link Voltage
 - Current Safety Margin for IGBT's
- Water Brake provided desired torque load while MCU controlled IPM in speed control mode
- Approximately 300 Nm of torque observed while using MTPA below base speed.
 - Torque reduction attributed to quadrature axis saturation at higher currents negating benefits of synchronous reluctance component

Experimental Results with Saturation Effects

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Prototype IPM Testing: Simulated Output Power vs. Actual





Conclusions

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- Modeling and Simulation of XM1124 Prototype IPM show the distinct advantages of this new technology
- Unique motor characteristics produce advantages not seen in other ac machines (SPM in general)
- Actual testing revealed IPM torque output heavily dependent on quadrature axis inductance saturation
- Torque boost at lower current levels due to additional synchronous reluctance component is apparent
- Testing is ongoing
 - Motor power efficiency mapping
 - FW Control
 - Comparison with similar SPM traction machines

Acknowledgements/Contact

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