Advances on Control Approaches for Salient Rotor Motors (SRM)

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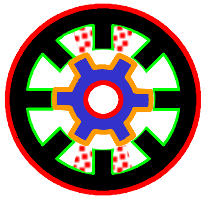
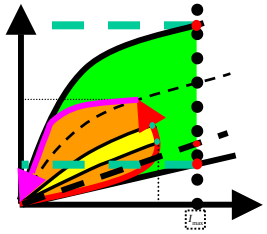
Presentation Outline

- **Brief Introduction to SRMs**
  - **General characteristics**

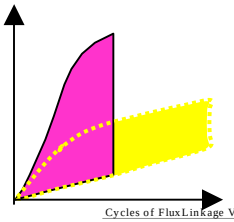


  - **Fundamental principles of operation**

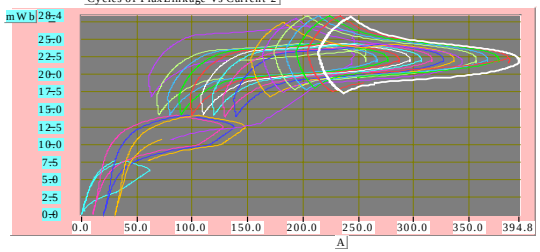


  - **Magnetic map and trajectories.**

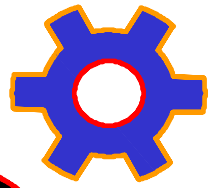
- **Control Strategies**
  - **Current Vs. Dwell Control**



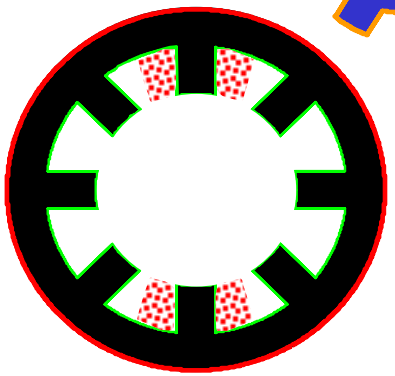
  - **Continuous Current Operation**



SR Motors Are Simple and Rugged



- **Rotor: a chunk of ferromagnetic material with teeth**
  - **cheap, reliable and low heat production**

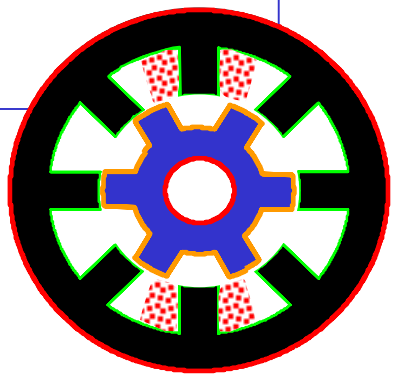


- **Stator: similar to other electric motors**
  - **slotted ring**
  - **slots filled with electrical conductors**

- **Number of rotor and stator teeth must be different**

- **Operating Principles: similar to stepping motors**
  - **magnetized stator tooth attracts nearest rotor tooth (independently of magnetic polarity)**

Drives for SR Motors Are NTS
(Not that simple)



- **Ideally: Magnetic fields build up and die out instantly.**
- **In reality:**
  - **Rate of change in magnetic field strength driven by an electric field is limited by the electric circuit inductance (which in an SRM varies with rotor position and speed.)**
  - **Ferromagnetic materials Saturate.**
  - **When a rotor tooth begins to emerge from under a stator tooth any remaining field produces negative torque.**

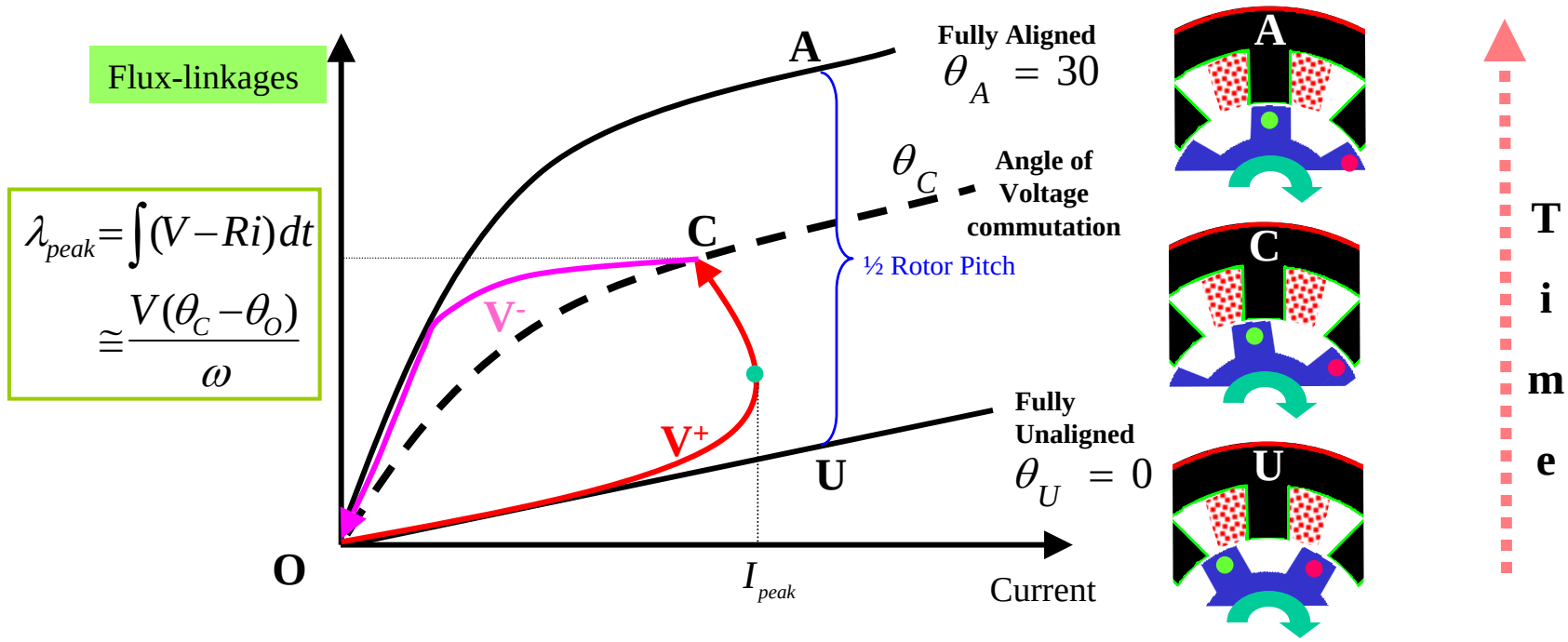
SRM Operating Principles

- Fundamental equation of electromagnetic machinery: $V = Ri + \frac{d\lambda_\phi}{dt}$

  In terms of magnetic flux-linkages: $d\lambda_\phi = (V - Ri)\,dt$

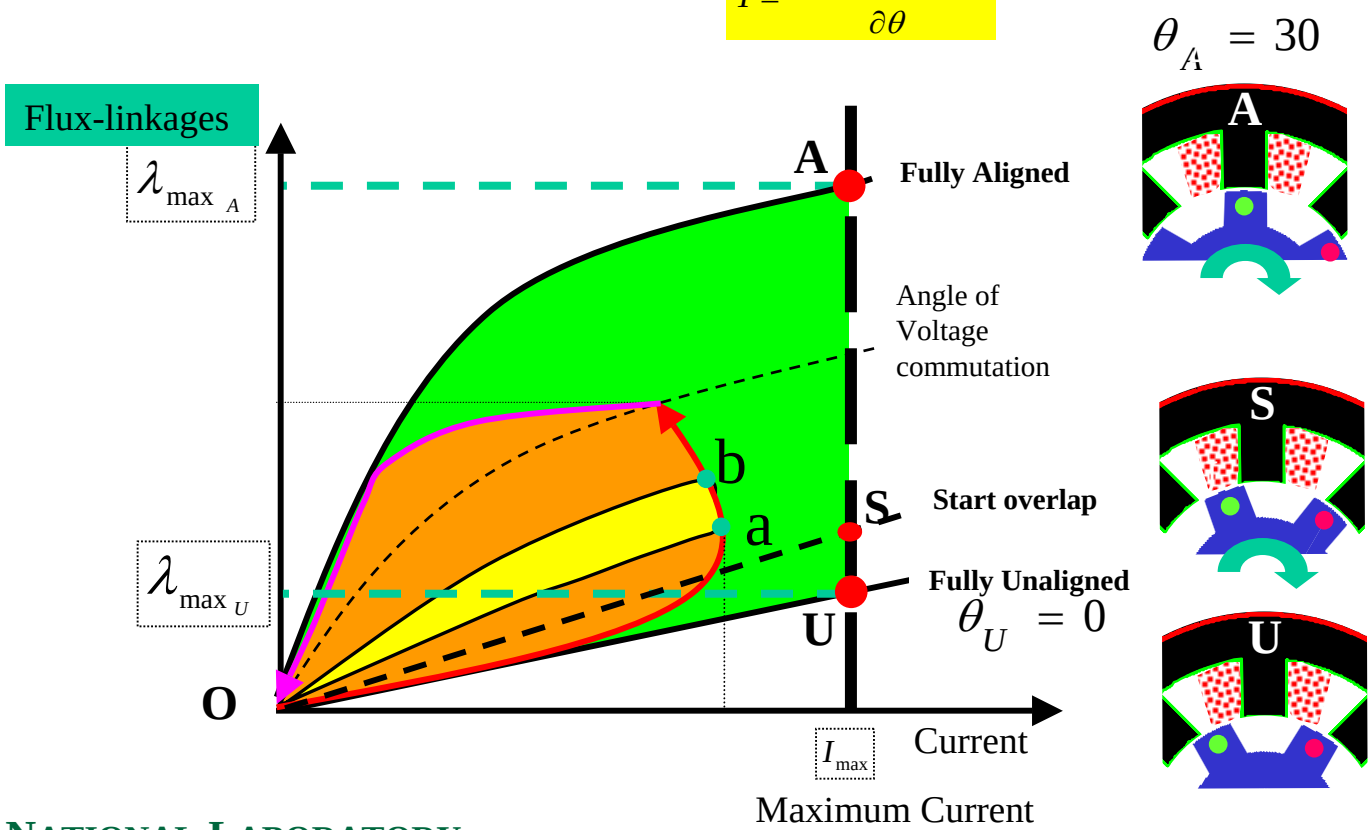
  In terms of power flows: $id\lambda_\phi = (iV - Ri^2)dt = (Power_{in} - Power_{loss})dt$

- Magnetic Map and trajectory: flux-linkages Vs. stator current as a function of rotor position



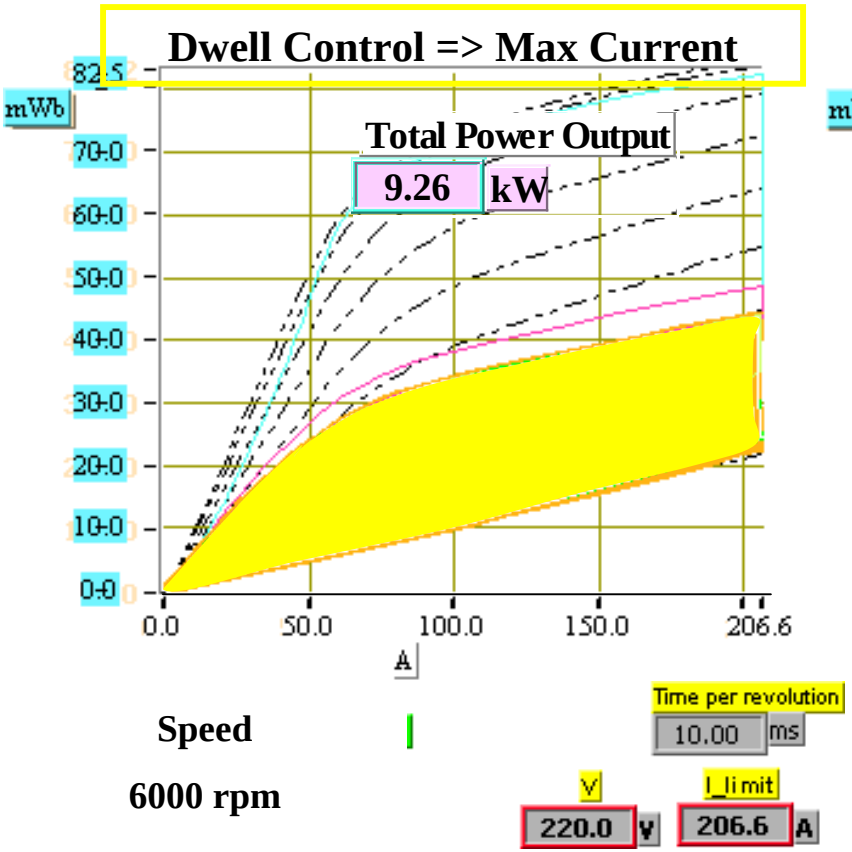
The Magnetic Map Characterizes an SRM's Performance Potential

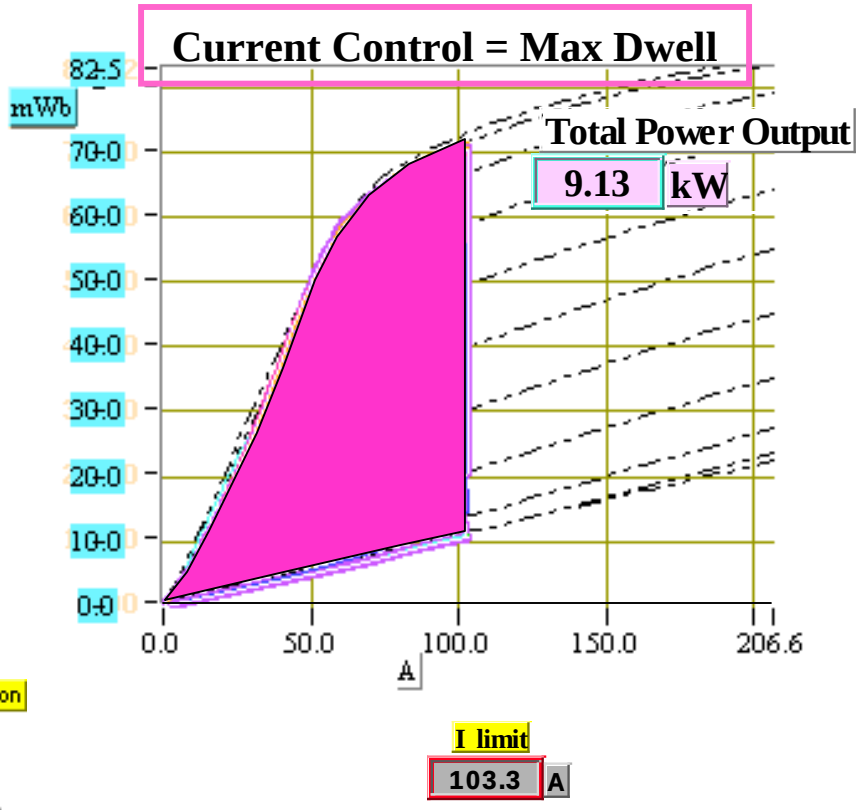
For Max Torque: Need to encompass as much of the available area (green) as possible!!! Torque: $T = \frac{\partial\left(\int_{i_o}^{i_a} \lambda(i,\theta)\big|_{\theta} di\right)}{\partial\theta}$



SRM's Control Choices
Current or Flux-Link (dwell) Control?

For Any Torque: Need to encompass the appropriate area.



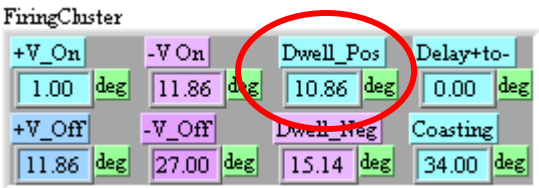


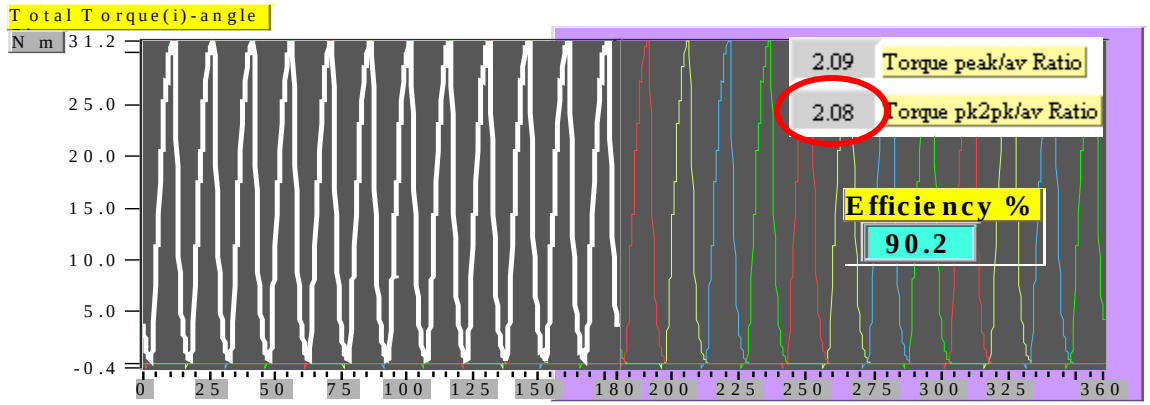
Current Control

Less Torque Ripple + Better Efficiency

I limit

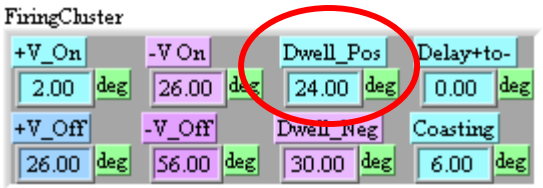
206.6 A

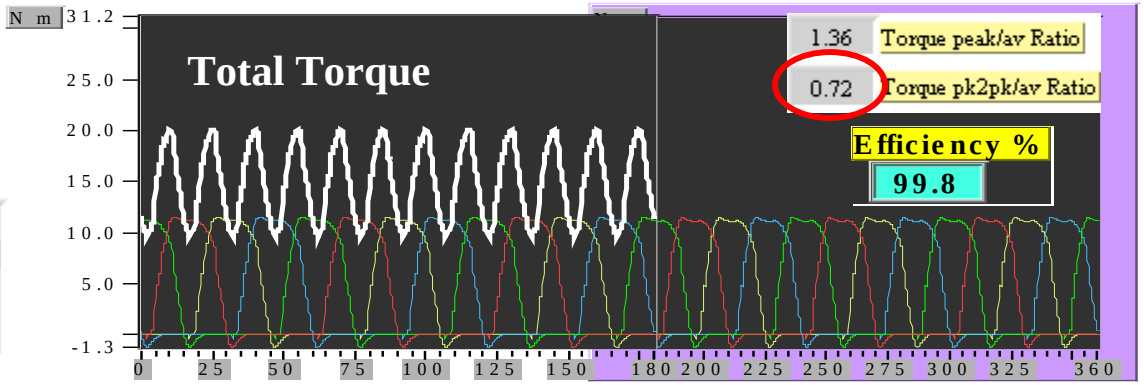




I limit

103.3 A

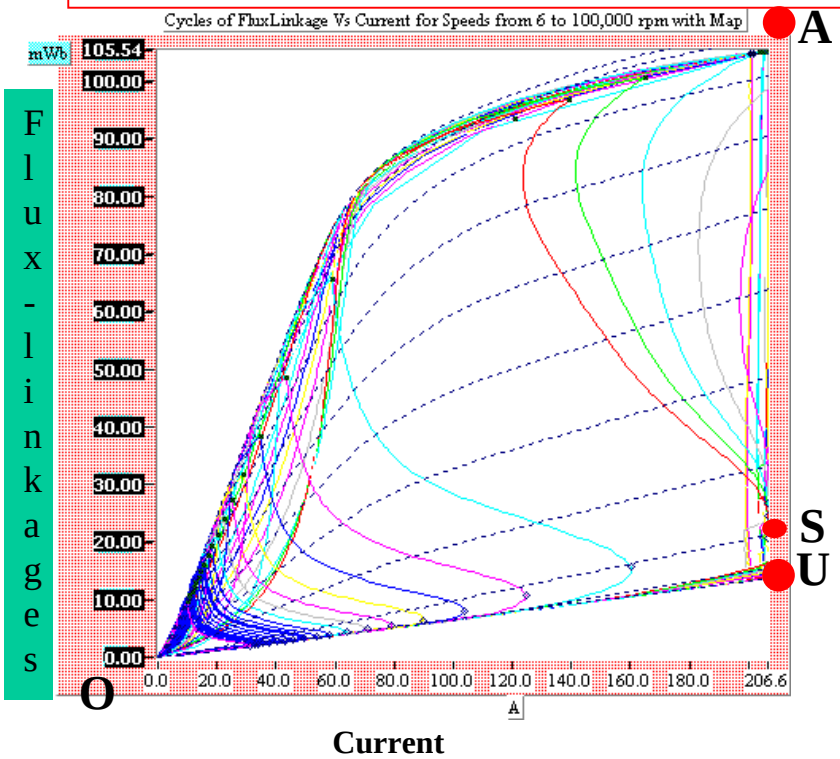


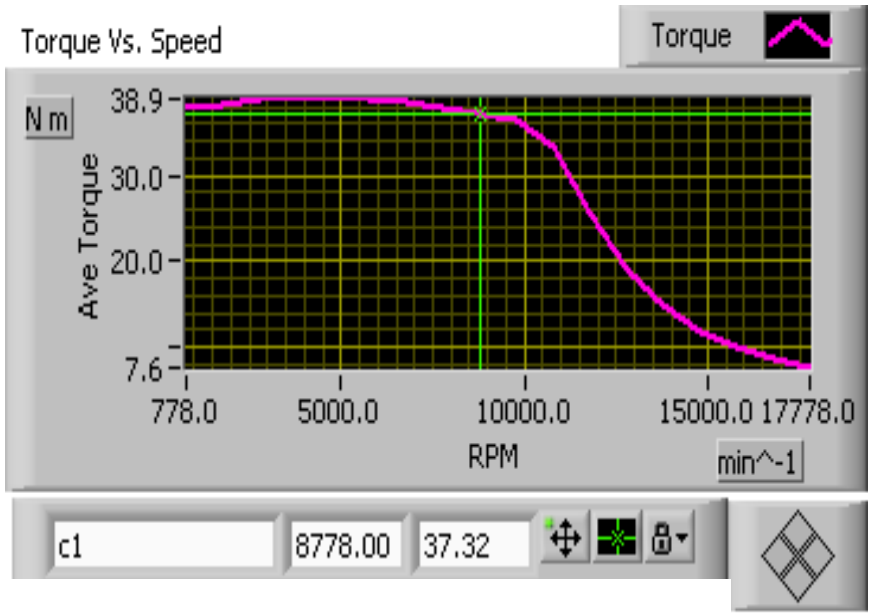


SRM MaxTorque Vs. Speed

Standard λ_o= 0.0 , Zero Flux Links Base

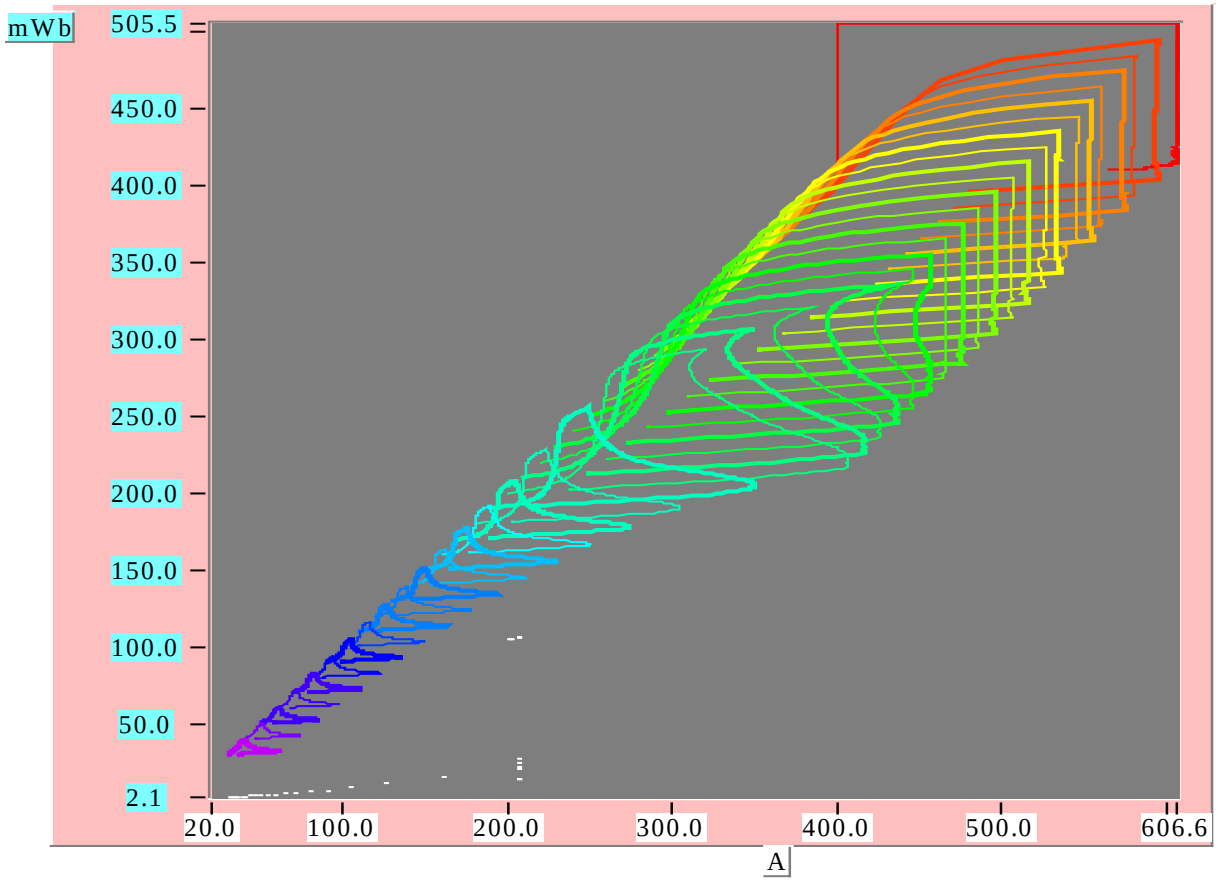
- Approximately constant torque for as long as I_{max} can be reached and sustained, lower torque for higher speeds.





SRM Performance Reduction with Speed

Trajectories for classic control from 6 to 100,000 rpm

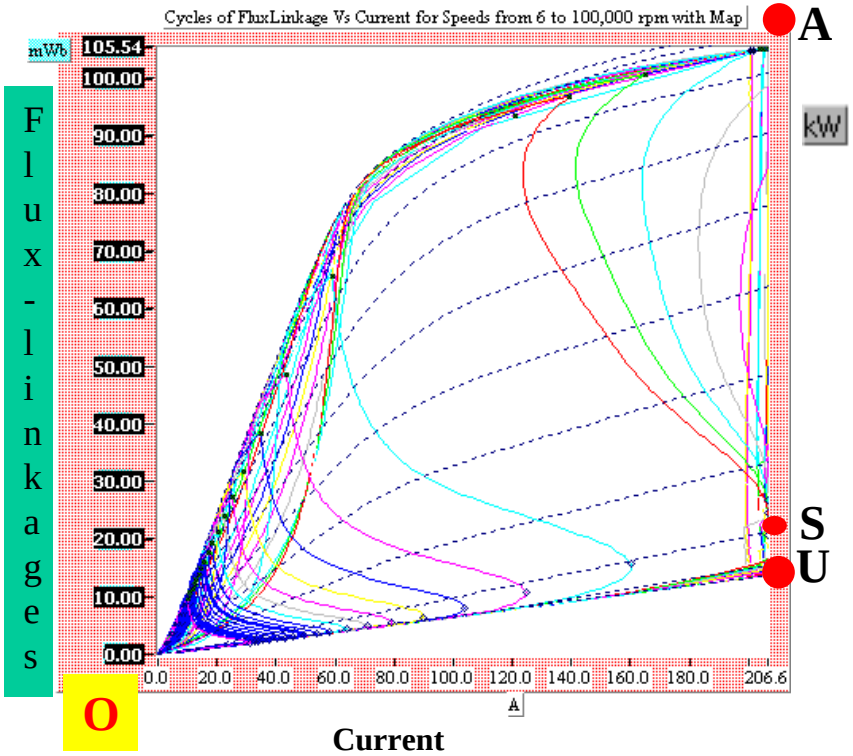


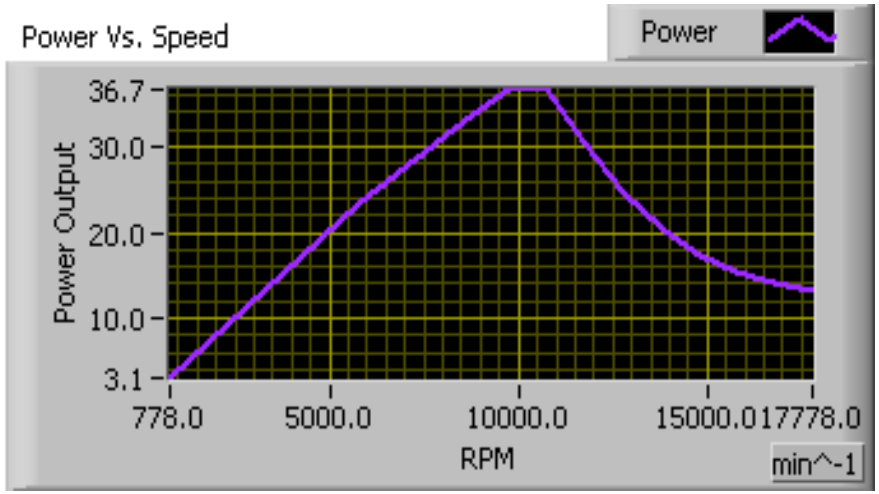
Current

Standard SRM MaxPower Vs. Speed

λ_O= 0.0 , i.e. Zero Flux Links Base

- Approximately linear power for as long as Imax can be reached and sustained, diminishing power for higher speeds.





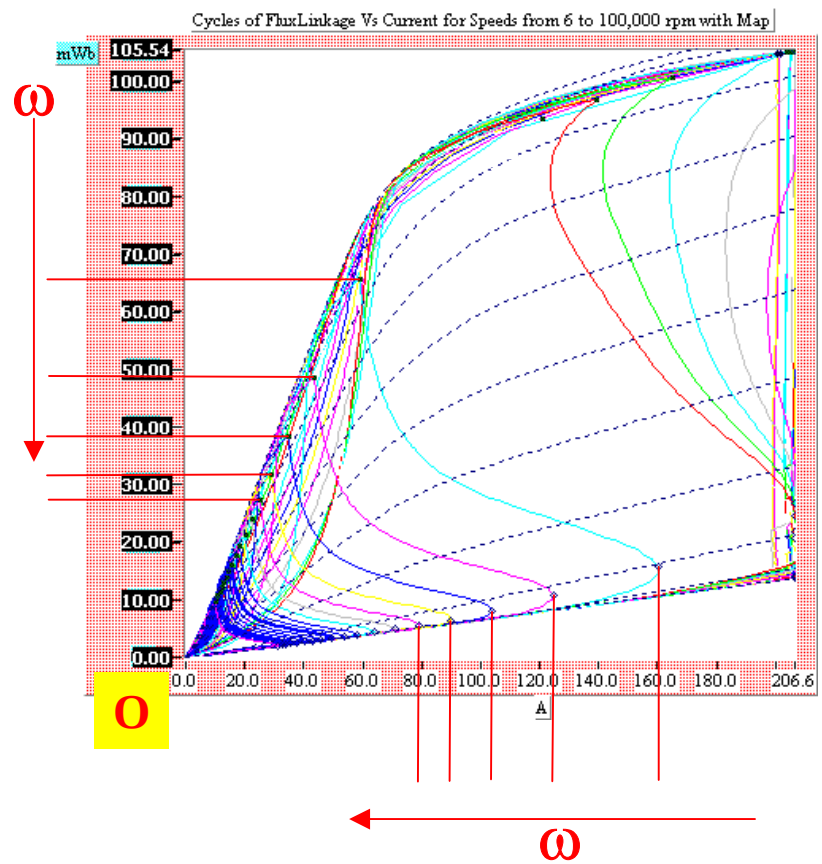
SRM Performance Reduction with Speed
Main Reasons

- **Both: Flux-link injection and Peak Current depend on the inverse of speed:**

$$\lambda_{OC} \Rightarrow V\,\Delta t_{O\text{->}C} = V\,\Delta\theta_{O\text{->}C}/\omega$$

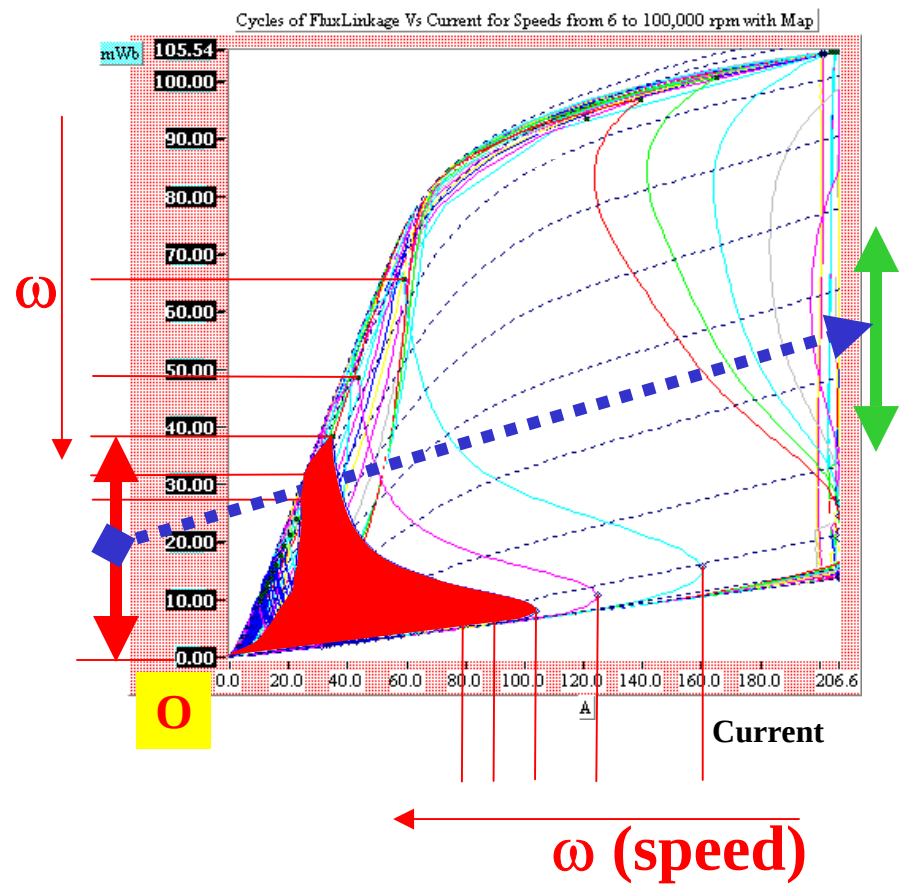
$$I_{peak} \Rightarrow V/|R+\omega L j|$$

- **As speed increases operation is confined to the narrow non-saturating region.**



SRM Performance Reduction with Speed
What Can We Do About It

- **Increasing the Voltage will help Both: Flux-link injection and Peak Current (seldom an option)**
- **Move the operating cycle to a higher magnetic energy region.**
- **Make I_{peak} independent of speed!!!**



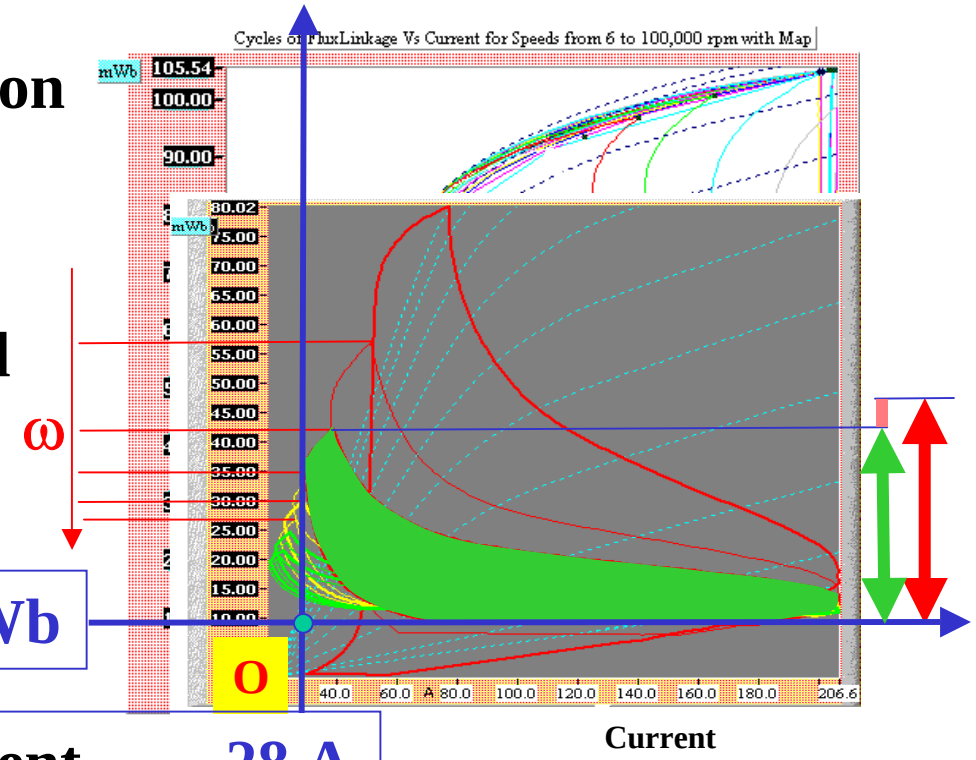
Current

SRM Performance Reduction with Speed
The Fix: Continuous Conduction

- **Achieve Continuous conduction with a non-zero origin base!!!**

By not draining all flux-links until enough have accumulated to supply the power needed reaching the appropriate I_{limit}

New base: **flux-links 8.5 mWb**



Continuous current **28 A**

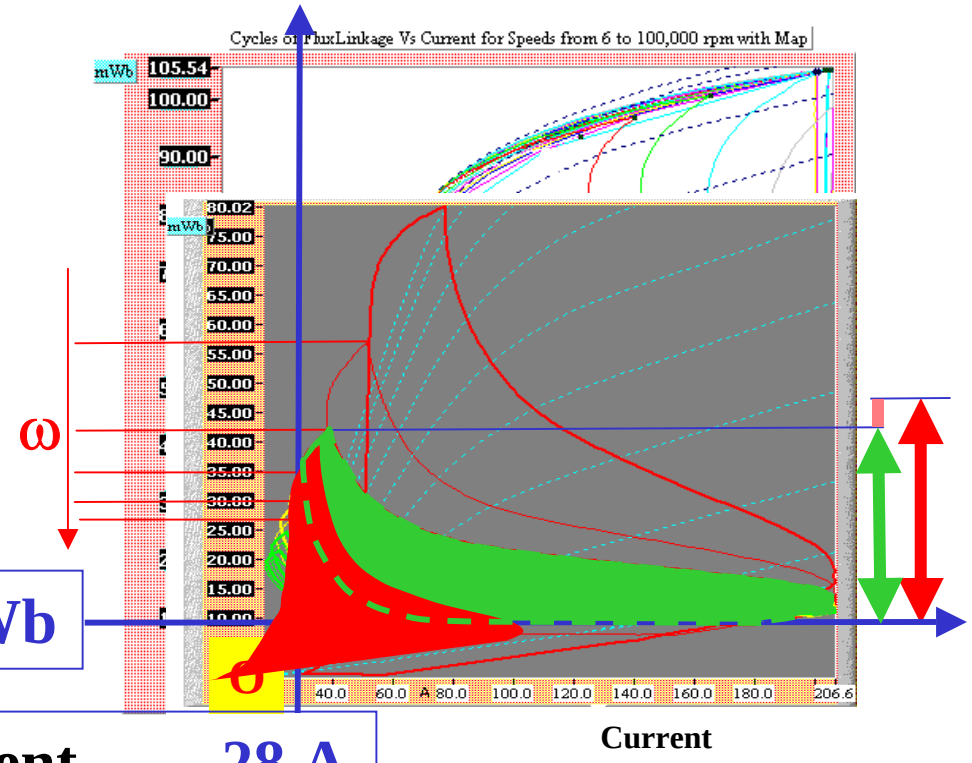
I_{peak} independent of ω (speed)

Additional ohmic loss

Current

SRM Performance Reduction with Speed
The Fix: Continuous Conduction

- **For the same speed the area of the continuous conduction loop is significantly larger.**



flux-links 8.5 mWb

Continuous current 28 A

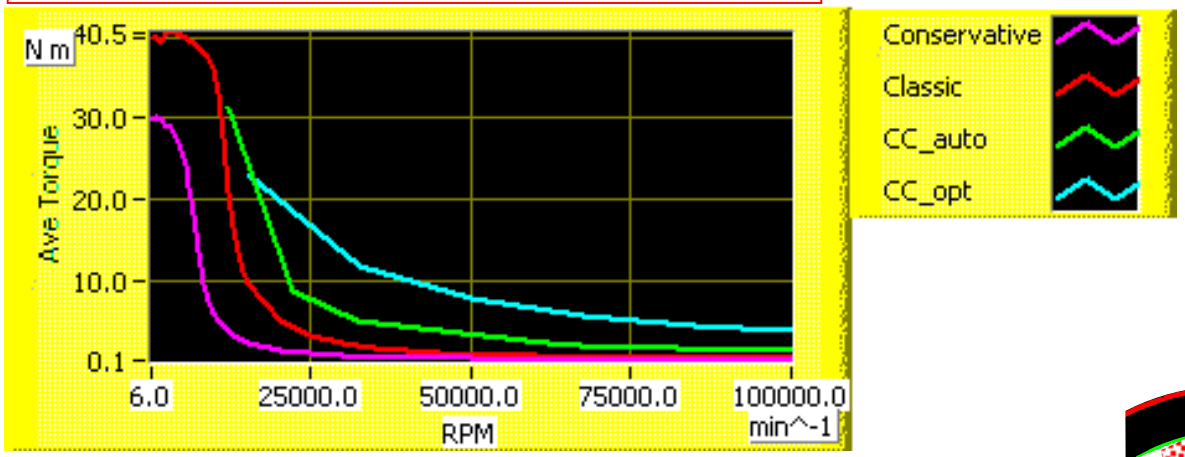
Additional ohmic loss

SRM Performance as a function of Speed

Comparison of Control Strategies

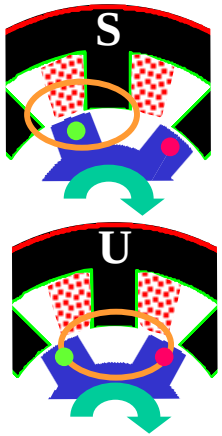
8/6 SRM, 12.5 kW nominal power and 6,000 rpm base speed

Output Torque Vs. Speed from 6 to 100,000 rpm



Conservative control: Firing at the moment the teeth start to overlap (zero angle reference for some experts in the field) + Full flux-link drainage)

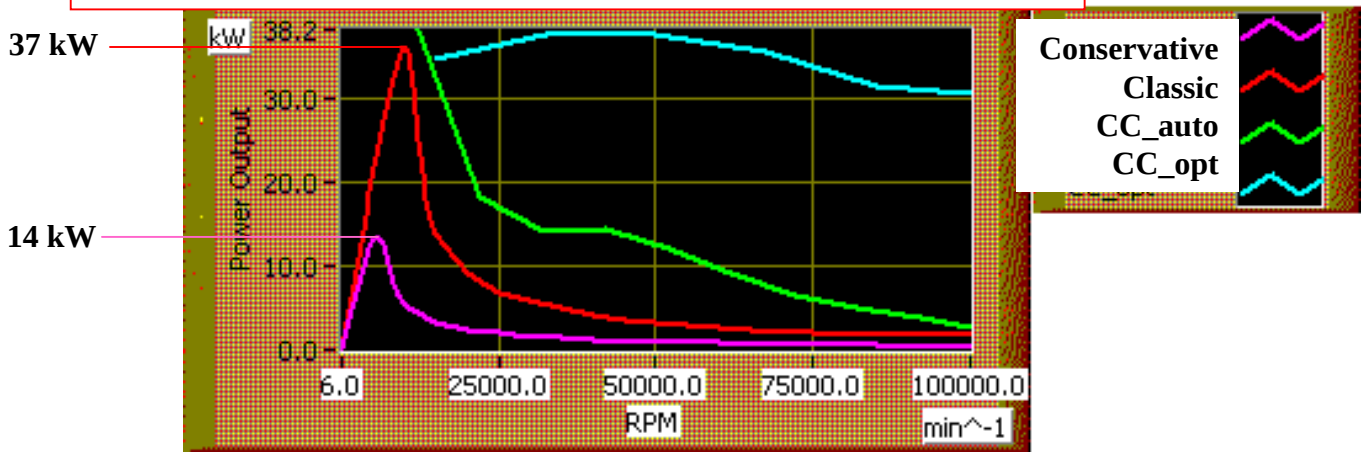
Classic control: Firing at the fully unaligned position (zero angle referei for some people at ORNL) + Full flux-link drainage)



Comparison of SRM Control Strategies

8/6 SRM, 12.5 kW nominal power and 6,000 rpm base speed

Output Power Vs. Speed from 6 to 100,000 rpm



Continuous conduction automatic control: Firing angle advances with speed. Starts at zero angle or earlier.

Do not overlap previous tooth.

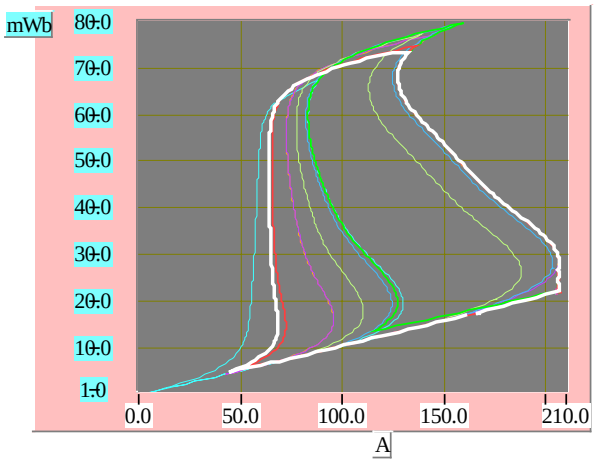
Accumulation of flux-links until the I_{max} is reached (shortening of the negative dwell initially)

Continuous conduction optimal control: Like automatic mode but the Firing angle can overlap the previous rotor tooth. Try to maximize the $^{+}$Dwell. (Used flux-link injection to accumulate links)

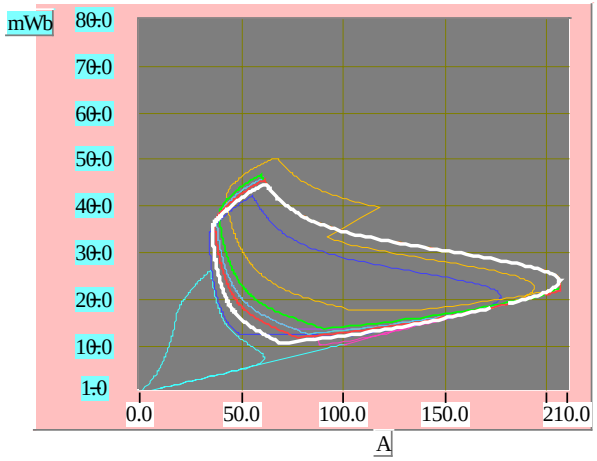
Automatic Trajectory Development

8/6 SRM, 12.5 kW nominal power and 6,000 rpm base speed

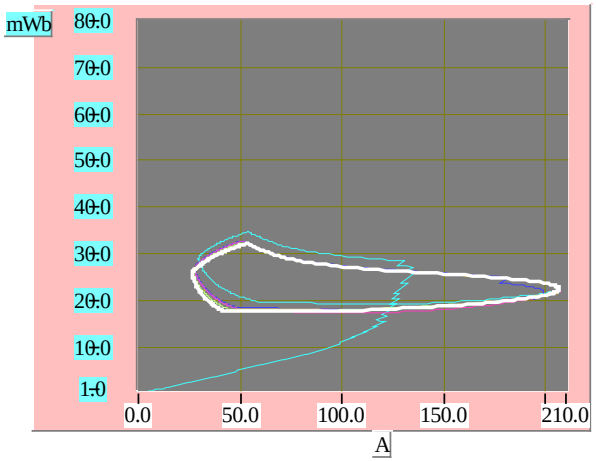
Continuous Conduction at 15,000, 32,500, 67,500 and 100,000 rpm:



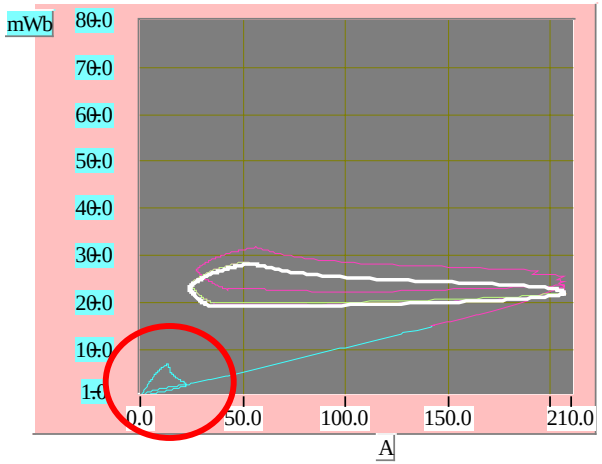
15,000 rpm



32,500 rpm



67,500 rpm

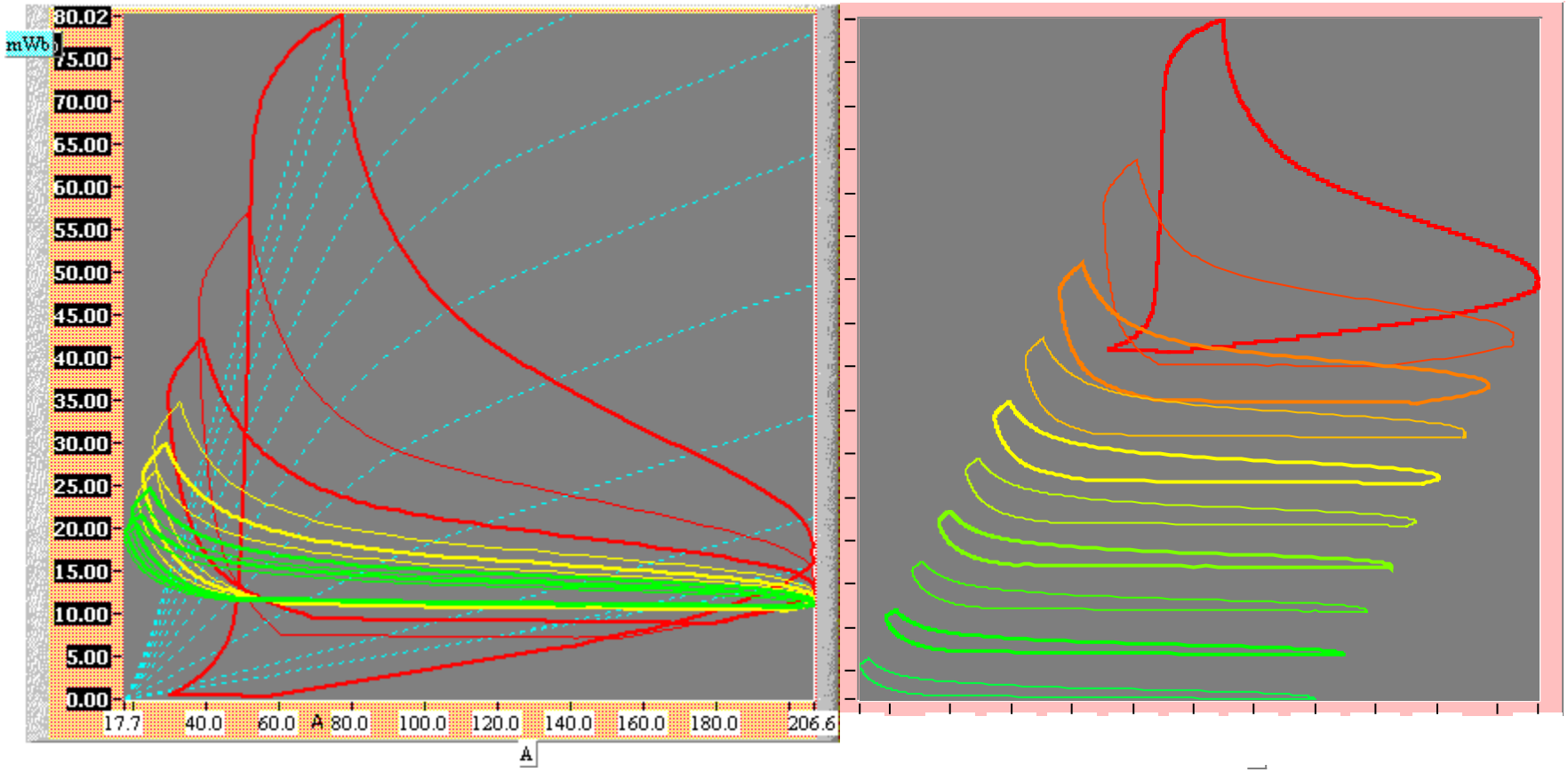


100,000 rpm

Final Trajectories

8/6 SRM, 12.5 kW nominal power and 6,000 rpm base speed

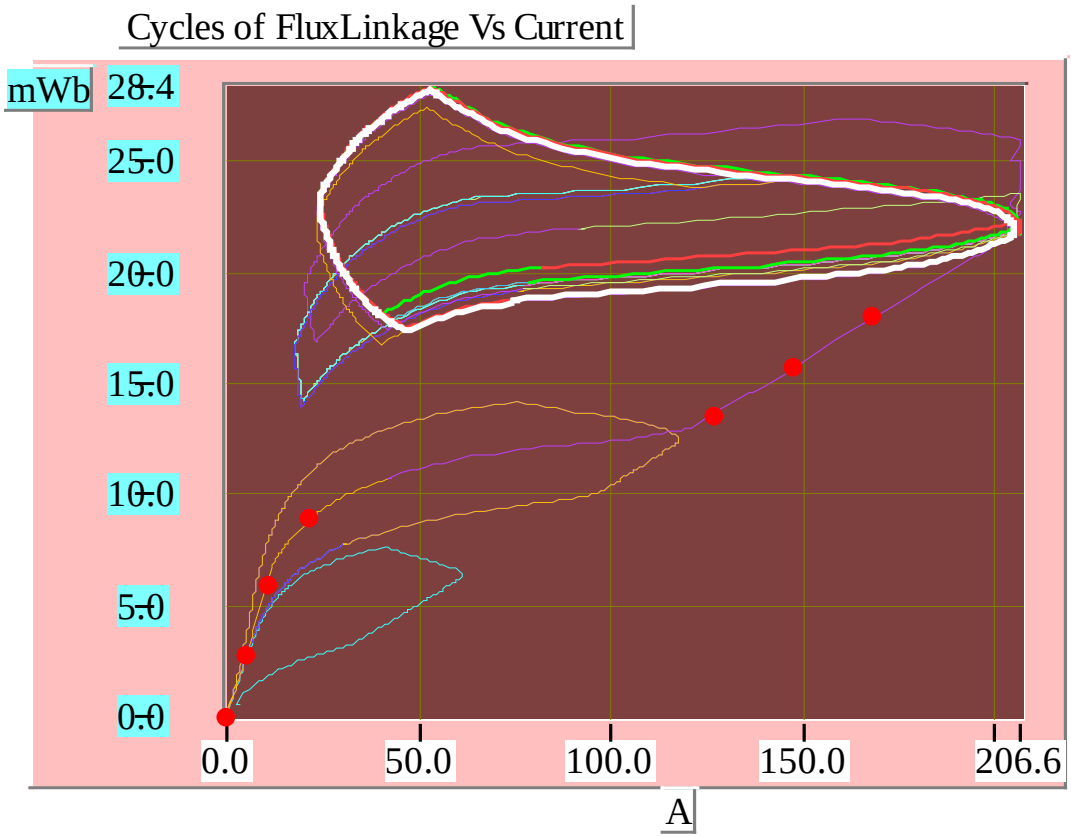
Automatic Continuous Conduction from 12,000 to 100,000 rpm:

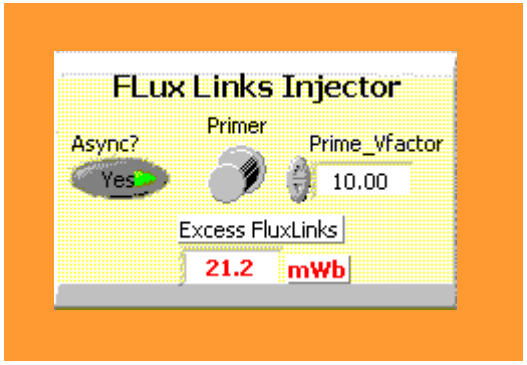


Manual Trajectory Development

8/6 SRM, 12.5 kW nominal power and 6,000 rpm base speed

Trajectories at 100,000 rpm: 20 cycles with various control choices



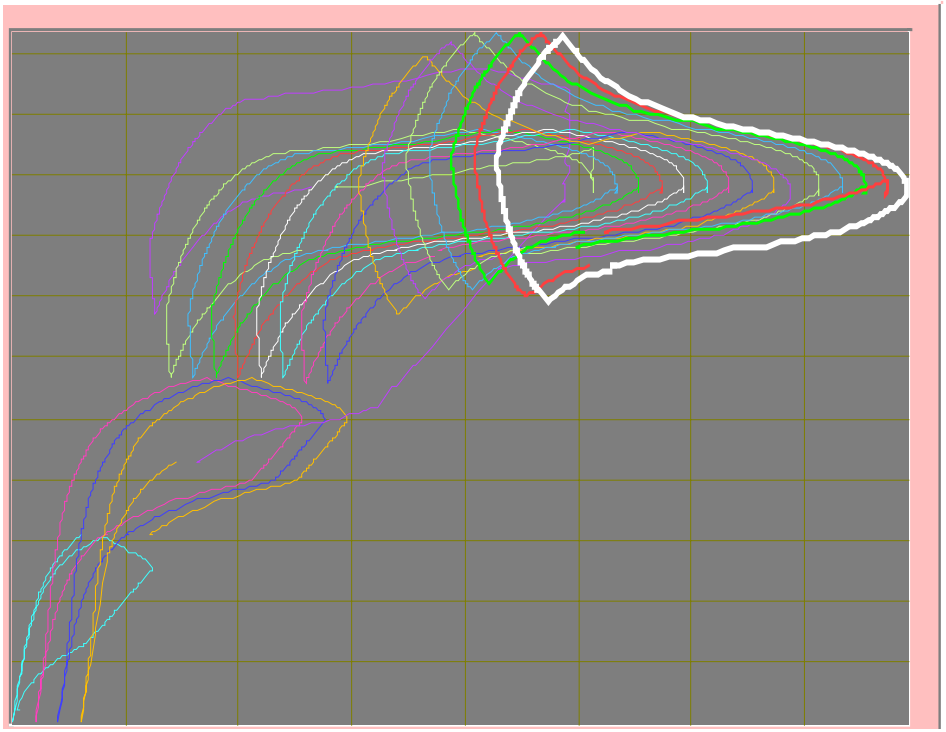


● Flux-Link Injection

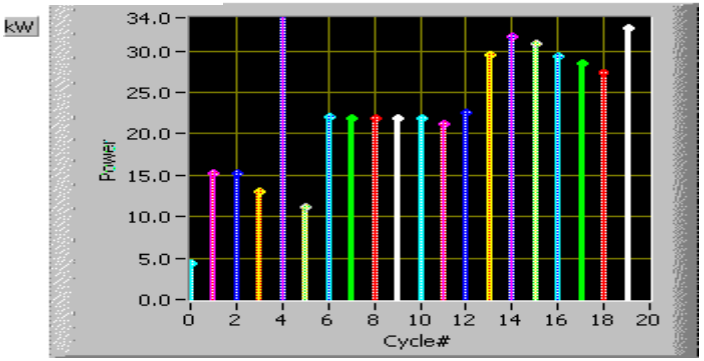
Manual Trajectory Development

8/6 SRM, 12.5 kW nominal power and 6,000 rpm base speed

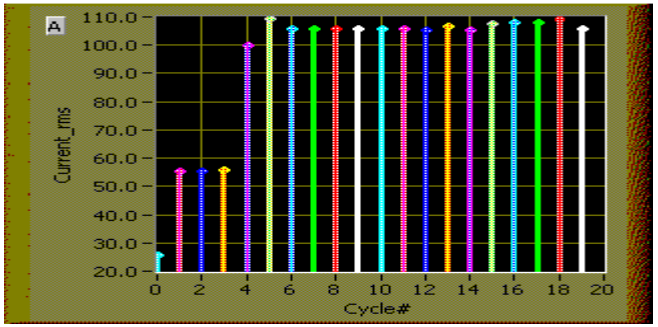
Trajectories and Output Power at 100,000 rpm: 20 cycles with various control choices



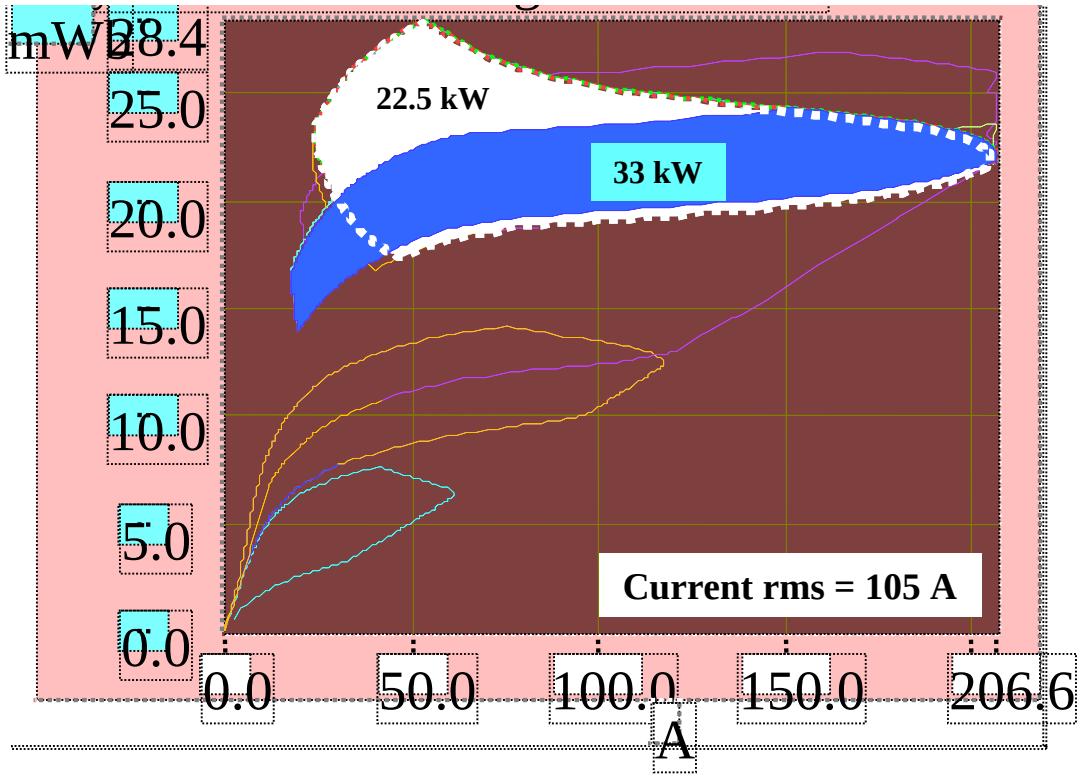
Power



Current (rms)



Manual Trajectory Types at 100,000 rpm

8/6 SRM, 12.5 kW nominal power and 6,000 rpm base speed

Two main trajectory types: Same current rms but different power output.