SR Motor Design with Reduced Torque Ripple

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Overview

- Motivation
- Review of SRM Theory of Operation
  - Theory of Operation
  - Mathematical Analysis
  - Definition of the SRM's "Base Speed"
  - SRM's Torque Ripple and Performance
- Optimization of the Conventional SRM
- New SRM Geometry
  - Torque Ripple and Performance
  - Physical Airgap and Acoustic Noise
- Outlook

Theory of Operation

SRM - Theory of Operation

- Characteristics of the SRM:
  - the SRM is a “constant power” machine
    - similar to a series wound motor
  - it is well suited to operate efficiently over a wide speed range and at very high speeds
    - does not require sinusoidal waveforms
    - requires excitation with high harmonic contents for efficient operation

SRM - Theory of Operation

- The torque output of the SRM can be controlled by regulating the current:
  - current limit
  - phase angle control (natural commutation)

SRM - Theory of Operation

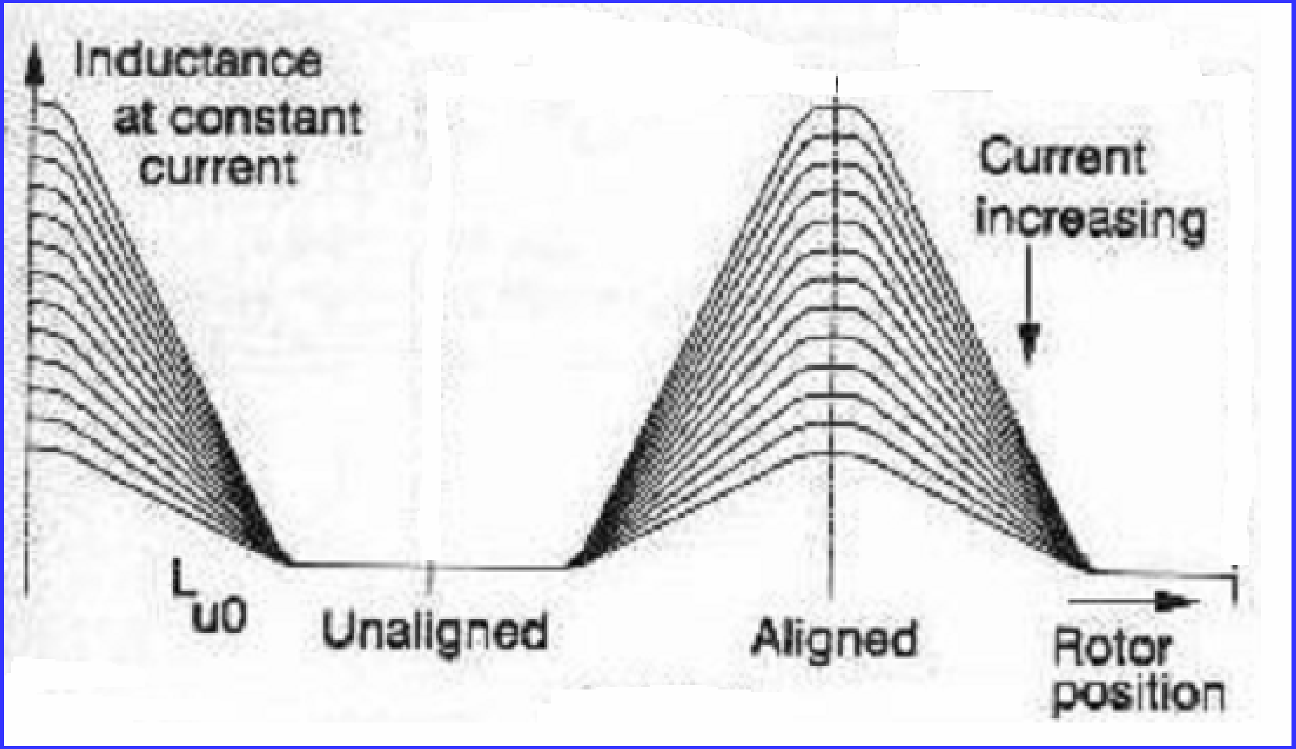
- The SRM generates torque in all regions where

$$\frac{dL(i,\Theta)}{d\Theta} \neq 0$$

- The inductance L is a function of the current i (saturation) and the angle of rotation Θ:

$$L = L(i,\Theta)$$

SRM - Theory of Operation



Inductance distribution of a typical SRM

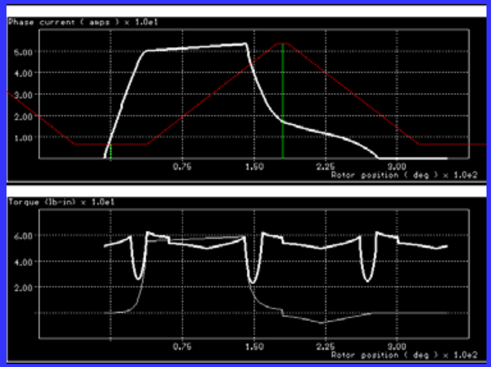
Picture courtesy Prof. T.J.E. Miller

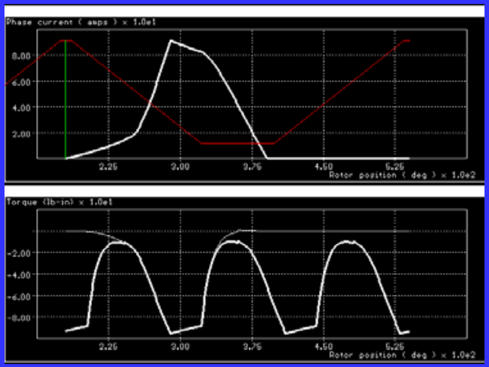
SRM - Theory of Operation

Inductance and torque distribution of a typical SRM

SRM - Theory of Operation

- Characteristics of the SRM:
  - can operate both as a motor and a generator





  - the SR Generator is a current source
    - generation process needs energy to be excited
    - once the phase is exited it is difficult to control

Mathematical Analysis

SRM - Mathematical Analysis

- The mathematical analysis of the SR motor is challenging due to:
  - non-linear airgap
  - non-linear saturation
- Closed form models do exist for the SRM
  - linear case: $T = f(i^2)$

SRM - Mathematical Analysis

- Simulations are typically used to analyze the SRM:
  - FEA (finite element analysis)
  - PC-SRD (SRM Analysis software)
    - Prof. Tim Miller, Glasgow, Speed Consortium
    - Motorsoft Inc. is US distributor
  - custom software

Definition of “Base Speed”

SRM - Definition of “Base Speed”

- The SRM allows the designer great flexibility when selecting a suitable motor winding

- To better compare machines we need to
  - define a specific operating point
  - define a specific winding

SRM - Definition of “Base Speed”

- When a single winding of the SRM is energized we can determine the winding current as:

$$V = R \cdot i + L(i, \Theta) \cdot \frac{di}{dt} + \omega \cdot \frac{d\Phi}{d\Theta}$$

where

– V is the applied bus voltage

SRM - Definition of “Base Speed”

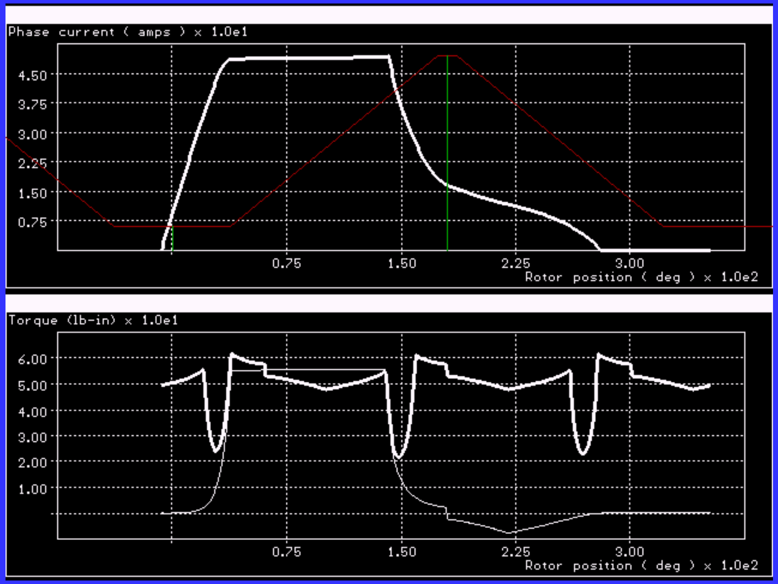
- We now define the base as the speed, where

$$L(i,\Theta)\cdot\frac{di}{dt}+\omega\cdot\frac{d\Phi}{d\Theta}=0$$

thus the current i is constant throughout the region of the inductance change

SRM - Definition of "Base Speed"

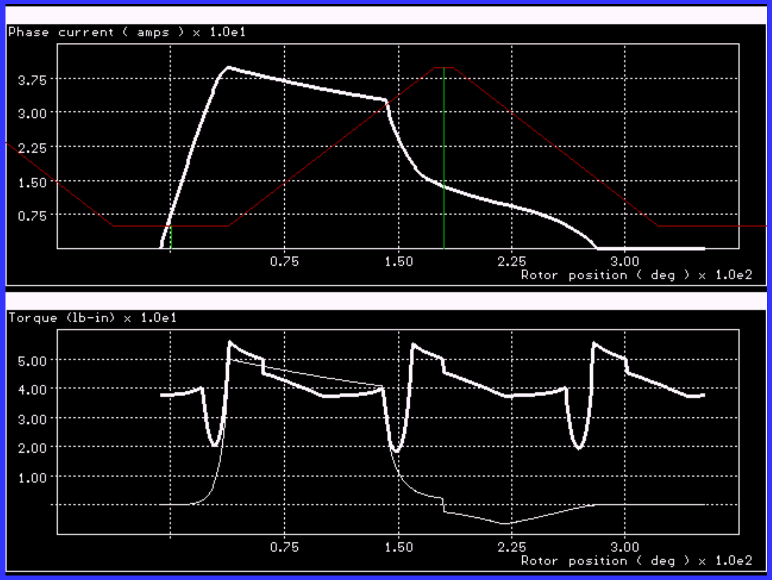
- Motor operating at base speed



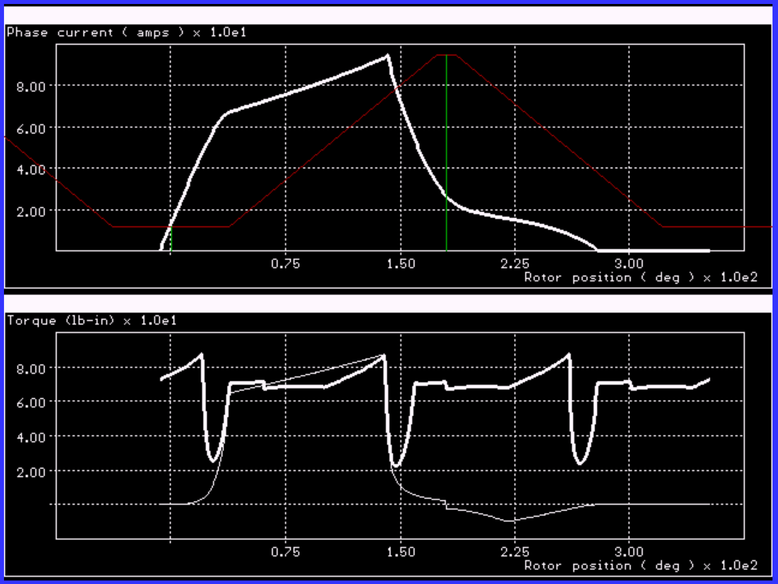
efficiency 89.6%

SRM - Definition of "Base Speed"

- Motor operating above/below base speed



efficiency 90.4% (above)



efficiency 87.6% (below)

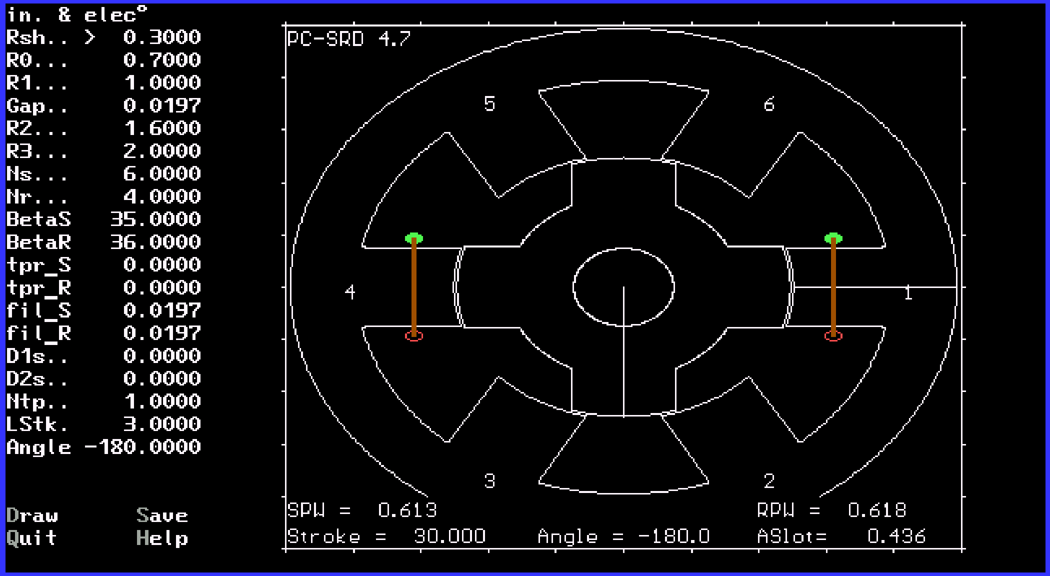
SRM - Definition of "Base Speed"

- The "base speed" is a point of comparison
  - it is a good point of reference
  - it is an efficient operating point
  - allows better comparisons between different motor designs
  - simulations do show that the efficiency of the SRM drops a speeds greater than 2x"base speed"

Torque Ripple and Performance

SRM - Torque Ripple and Performance

- Design of a typical SRM



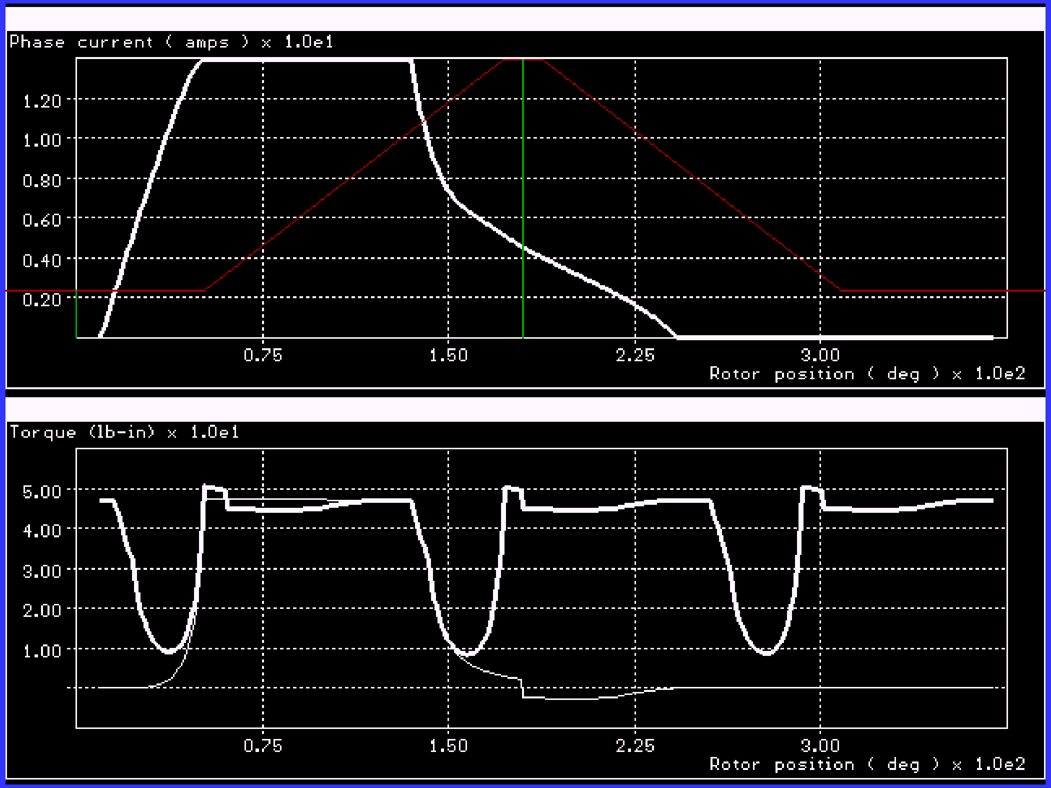
6/4 design

3 phase

matched pole geometry

SRM - Torque Ripple and Performance

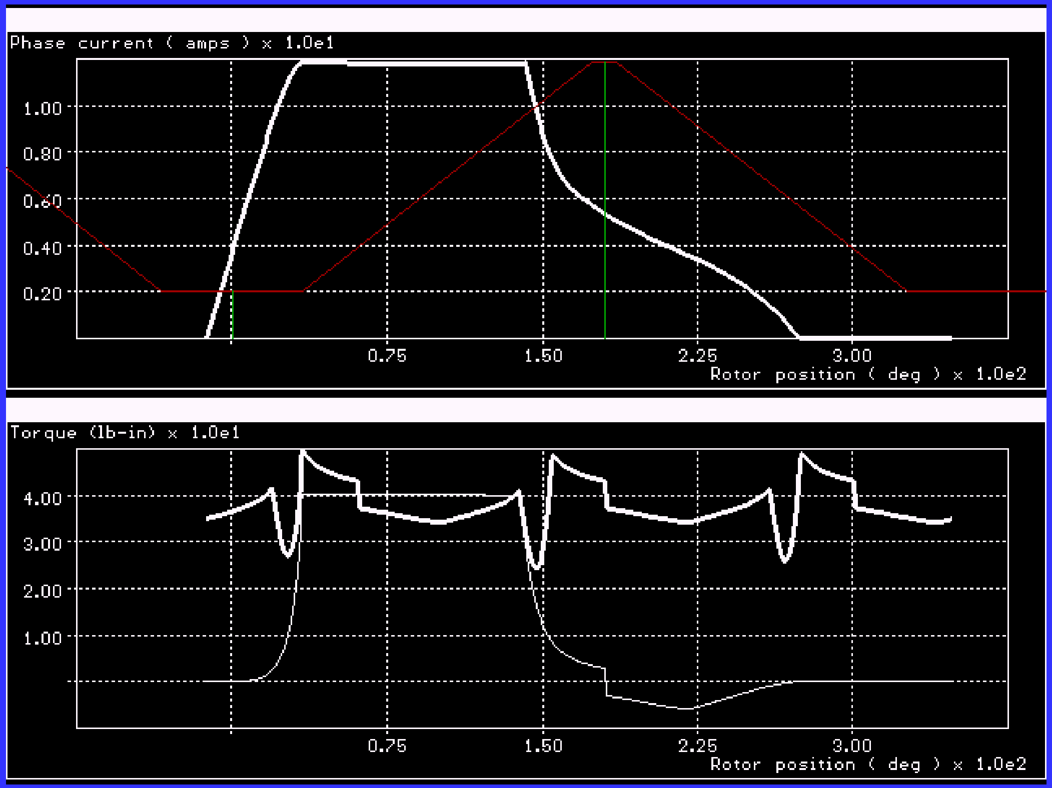
- Design of a typical SRM



shaft power:	1.0 kW
efficiency:	85.1 %
min/ave torque:	32%

SRM - Torque Ripple and Performance

- Improved Commutation of a typical SRM



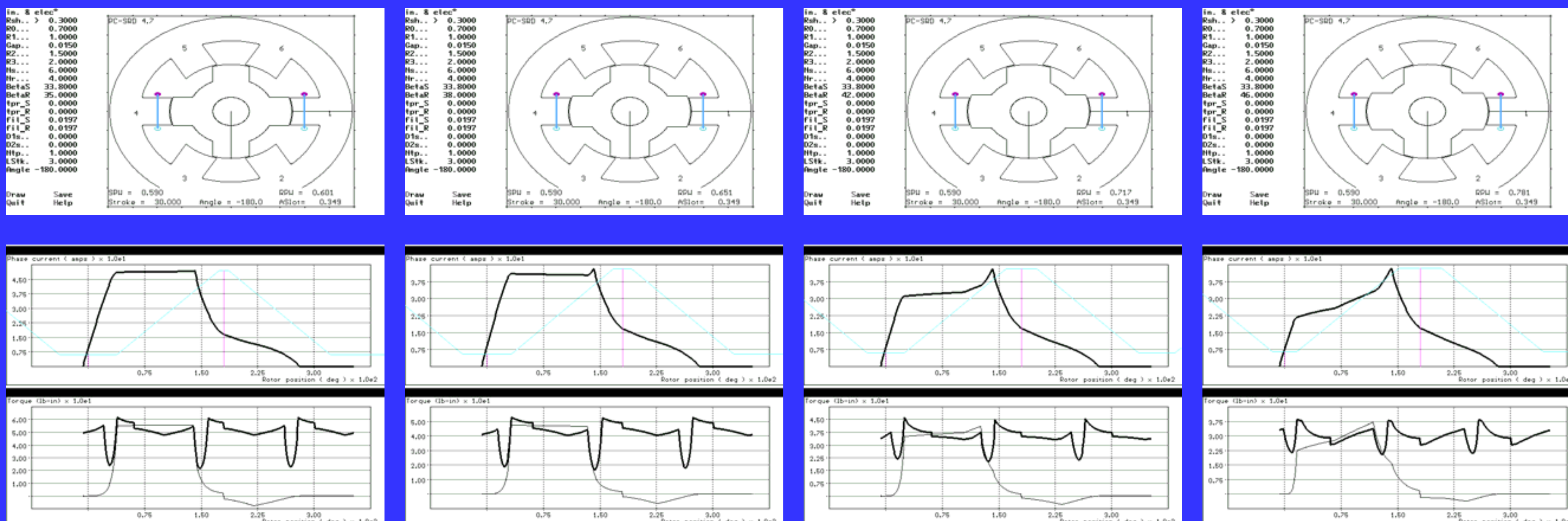
shaft power: 1.0 kW

efficiency: 82.7 %

min/ave torque: 71 %

SRM - Torque Ripple and Performance

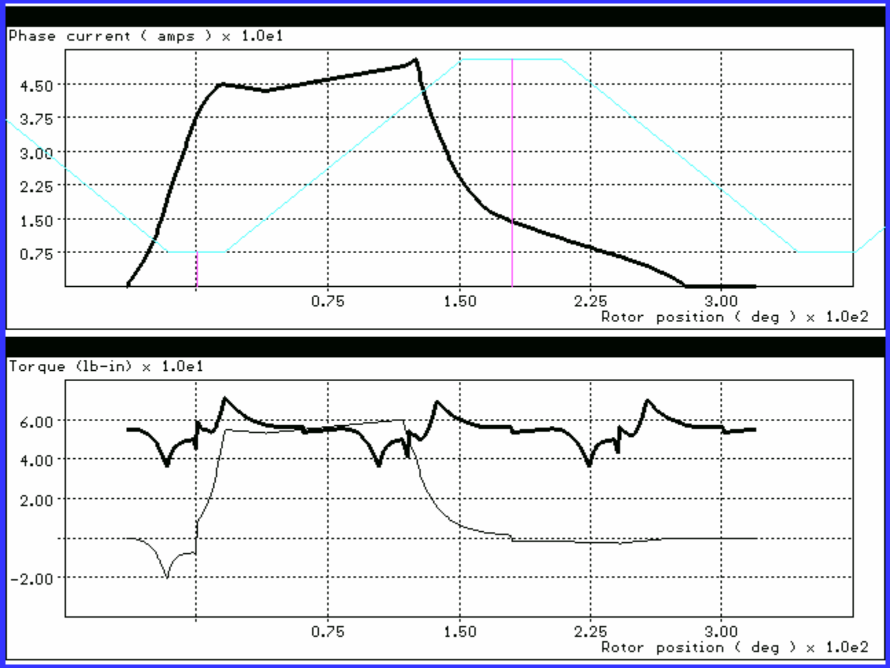
- Torque ripple appears to be reduced as the rotor tooth is widened



Power:	3.1 kW	2.5 kW	1.8 kW	1.3 kW
eff.:	89.6%	89.6%	90.2%	89.3%
min/max	39%	48%	54%	67%

SRM - Torque Ripple and Performance

- as the rotor angle widens, the power output drops
  - some correction can be made in the winding



Power:	3.0 kW
eff.:	88.6%
min/max	92%

The n/n+2 SRM

The n/n+2 SRM

- Design of a 6/8 SRM

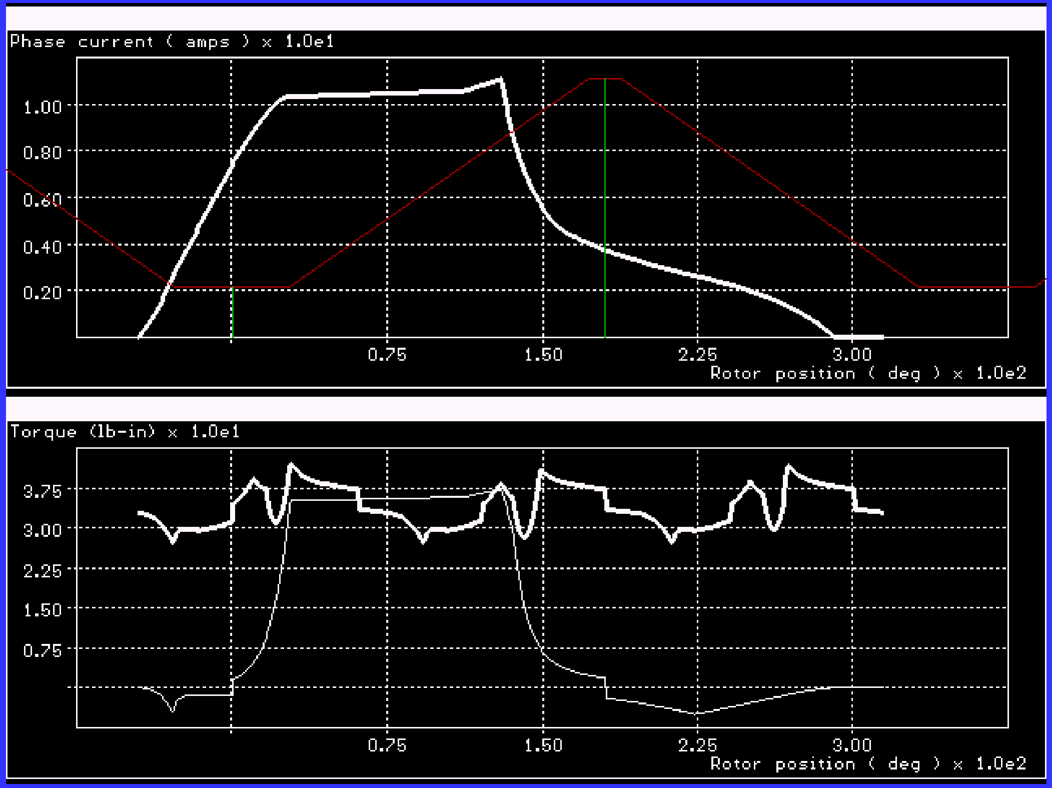
6/8 design

3 phase

mismatched pole geometry

The n/n+2 SRM

- Design of a 6/8 SRM



shaft power: 1.0 kW

efficiency: 86.7 %

min/ave torque: 88%

The n/n+2 SRM

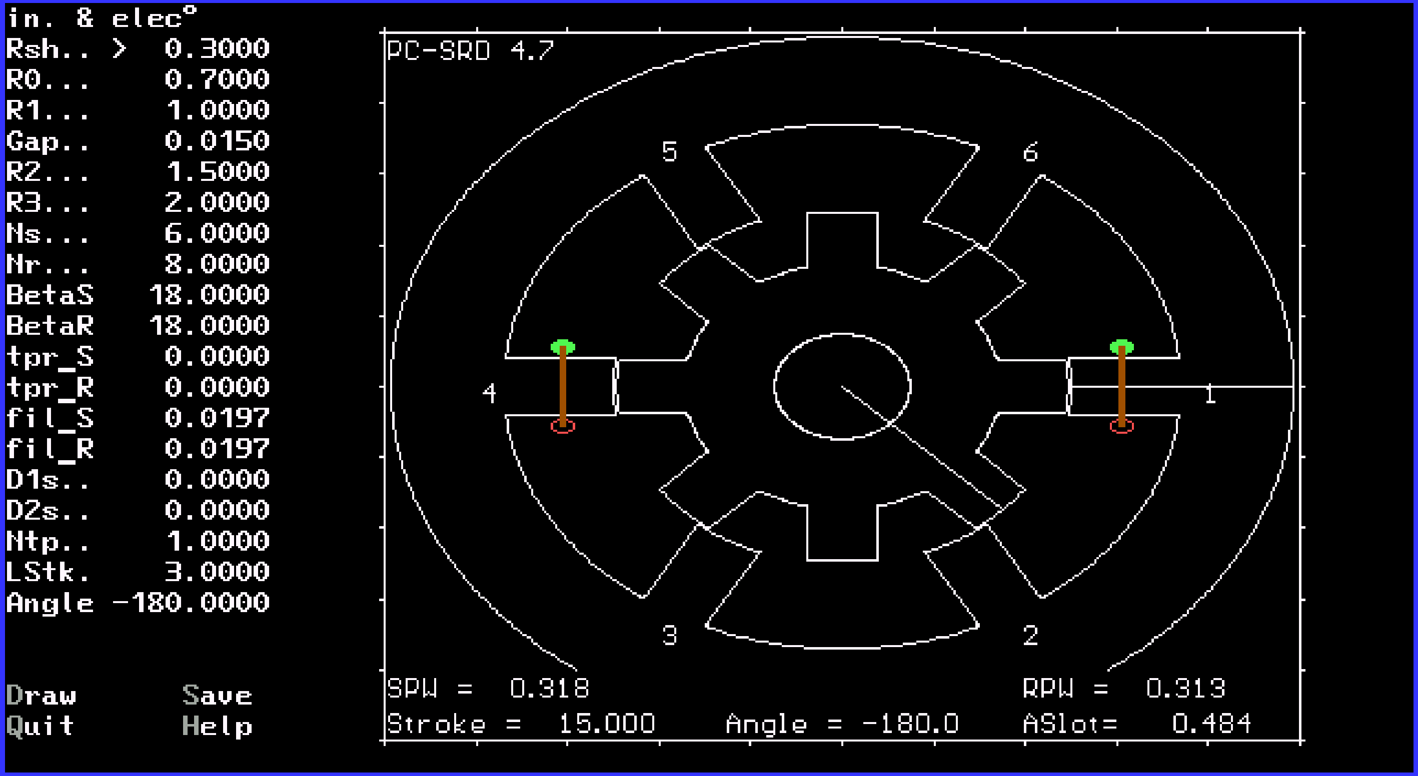
- Theory of Operation of the n/n+2 design
  - the n/n+2 design results in a physically smaller airgap (tangential direction) and a more rapid saturation of the rotor tooth
  - the n/n+2 design requires mismatched poles to achieve a wide enough zero torque zone to assist the commutation

The n/n+2 SRM

- Advantages of the n/n+2 design
  - reduced torque ripple
  - improved efficiency
  - potentially lower noise
  - advantageous flux distribution 12/10

The n/n+2 SRM

- advantageous flux distribution



The n/n+2 SRM

- Disadvantages of the 6/8 design
  - requires mismatched poles
  - commutation angles become more critical
  - variable commutation angles are required for efficient operation

The n/n+2 SRM - Test Results

The n/n+2 SRM - Test Results

- The n/n+2 design offers advantages in some applications where low torque ripple is required
- The 4/6 motor is a 2 phase motor with improved starting torque
- We have built a 4/6 motor and its performance matches the simulations
- The motor has been tested up to 24 kRPM

The n/n+2 SRM - Test Results

- No comparative measurements of the acoustic noise between a 4/2 and a 4/6 motor have been performed to date
- Worldwide patent applications have been filed to protect the n/n+2 SRM geometry

The n/n+2 SRM - Future Work

The n/n+2 SRM - Future Work

- A more detailed analysis of the motor's acoustic noise will be performed
- Several other n/n+2 motors are under construction to further validate the concept

The n/n+2 SRM - Future Work

- Potential Applications:
  - Automotive fuel and water pumps (2 phase)
  - Refrigeration compressors (2 phase)
  - Small appliances (3 phase)