Theory of SR Motor Operation

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About the instructor

- Companies worked for include:
  - Honeywell
  - Pacific Scientific
  - General Electric
  - AMC

- Currently
  - Dean Computer Science and Engineering at UVSC
  - consulting under Rocky Mountain Technologies Inc.

About the instructor

- has worked with SR motors since 1992
- has designed and built SR motors/generators and controllers
  - 0.5 kW to 80 kW
  - up to 120,000 RPM
  - 2, 3, 4 and 5 phase motors/controllers
  - military, industrial, consumer products
  - some designs are in the production cycle

Overview

- The history of the SR motor
- SR motor physics
- The design of SR motors
- Controller design for SR motors
- Sensorless control SR motors
- Application considerations

Overview

- The SR motor is an old technology
- The SR motor was invented by Davidson in Scottland in 1838
  - there were no suitable electronics to make the SR feasible at the time
- In 1920 Walker invented the variable reluctance (VR) stepper motor, which shares many features of the modern SR Motor

Overview

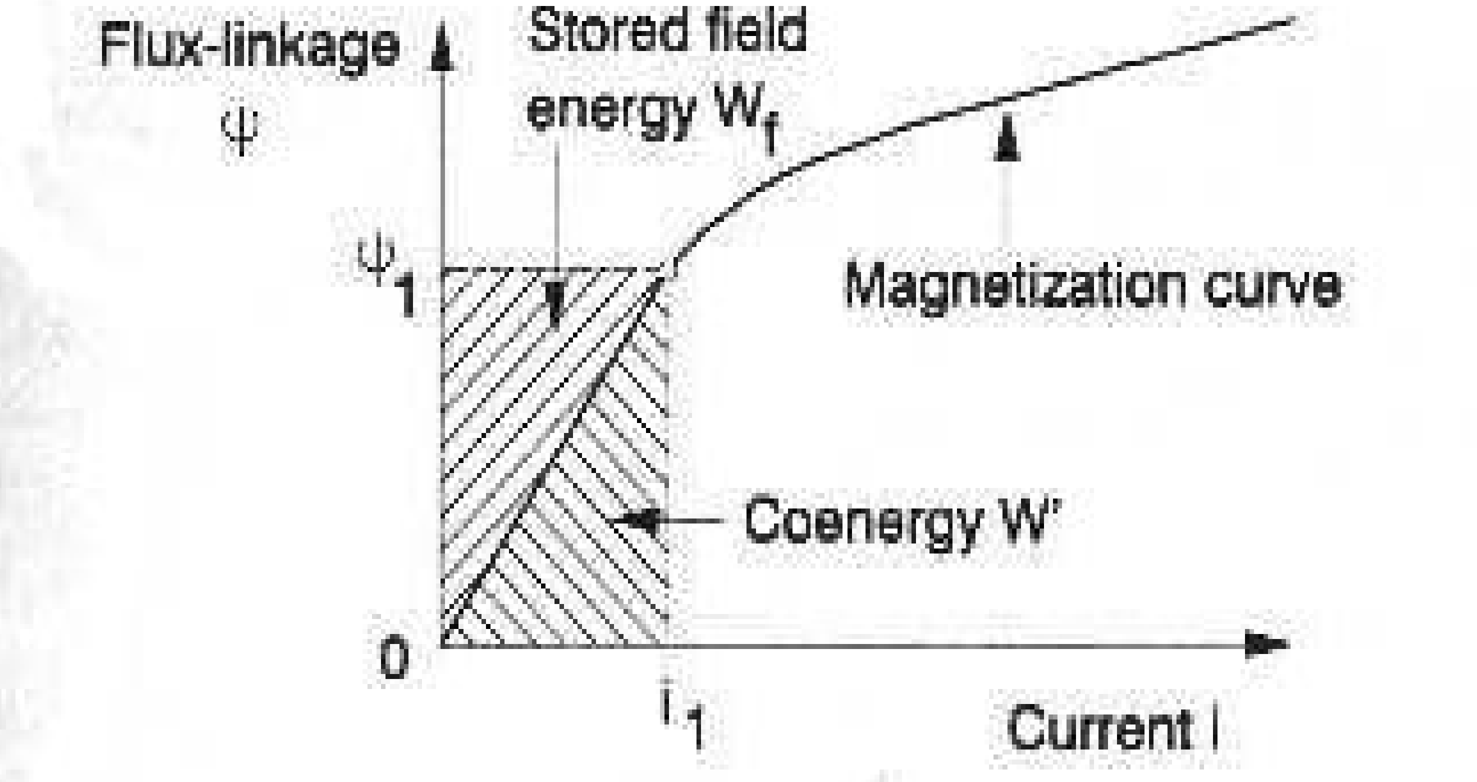
- In 1971 Bedford and Hoft filed US patents on the modern Switched Reluctance Motor
- Hewlett Packard used the first Switched Reluctance Motor in a volume application for the DraftMaster plotter
- Today several manufacturers have introduced successful SR products

SR motor physics

SR motor physics

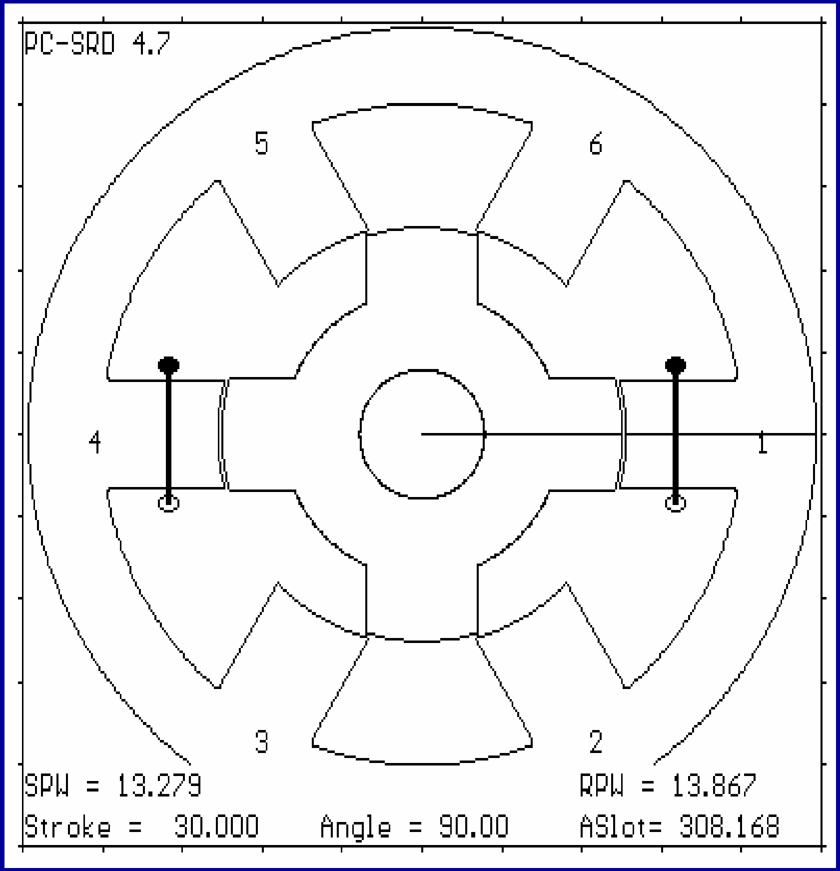
- The physical principle on which the VSR motor operates is that every magnetic circuit tries to maximize its stored energy

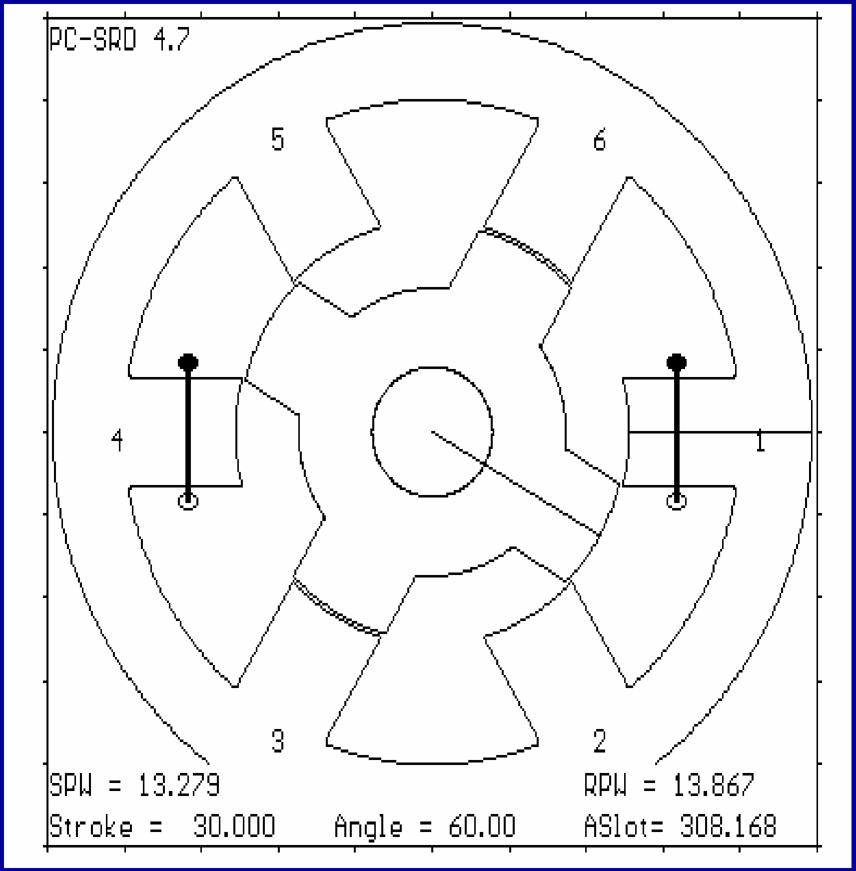
SR motor physics



Definition of *coenergy W'* and *stored field energy W_f*

SR motor physics

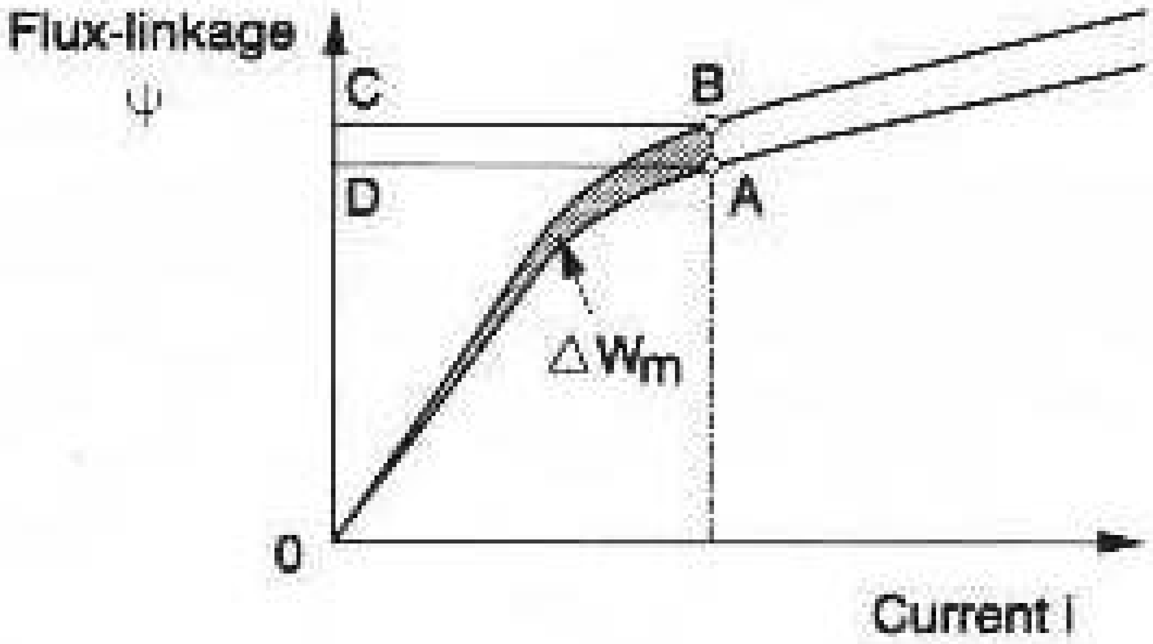




SR motor physics

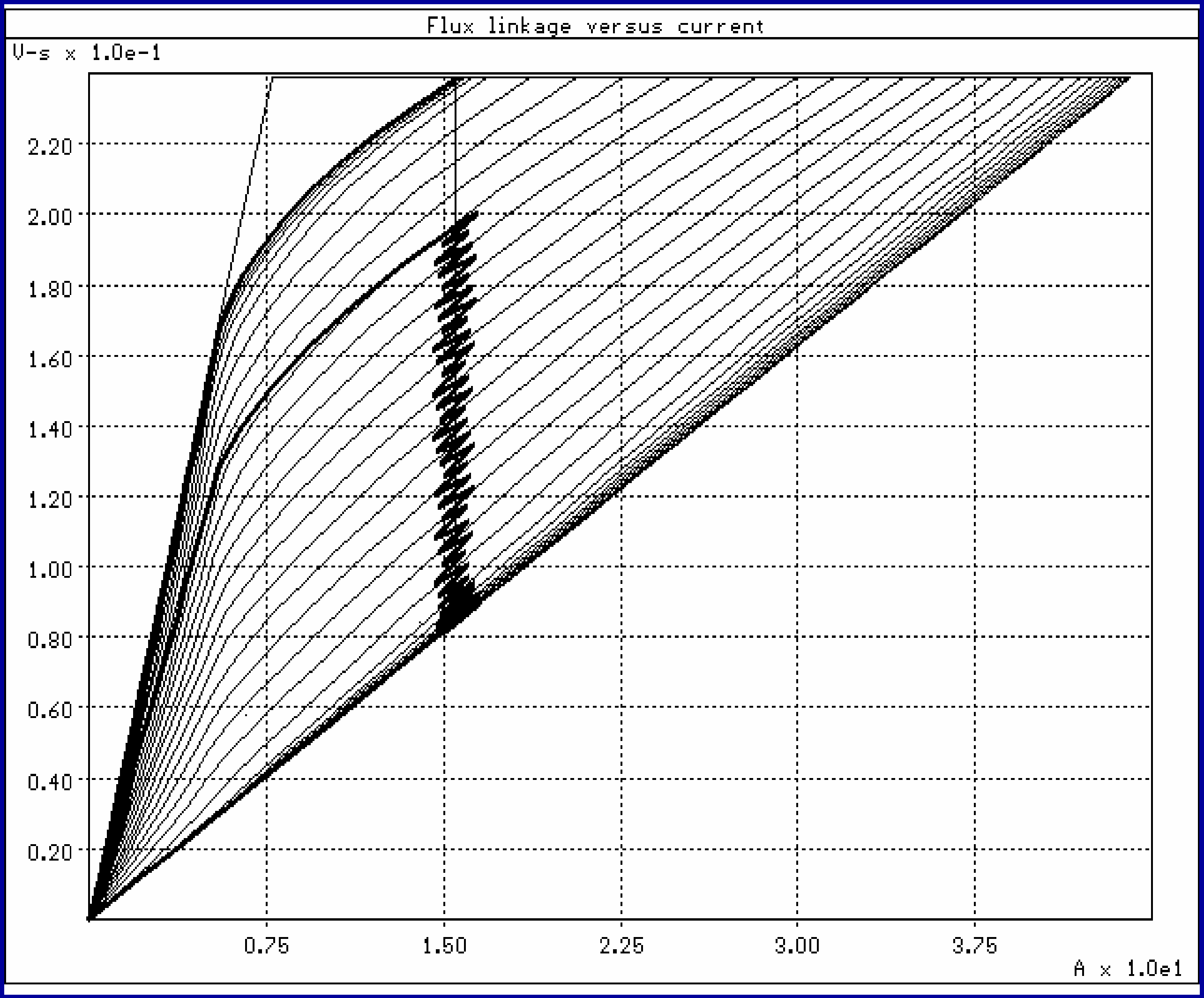
- Terminology
  - aligned position: rotor and stator tooth are aligned
  - un-aligned position: rotor and stator tooth are most unaligned between two neighboring phases
  - absolute torque zone: phase produces non-zero torque
  - effective torque zone: phase produces positive torque
  - regular SR motor: rotor and stator poles are equally spaced

SR motor physics



Calculation of instantaneous torque from the rate of change of coenergy at constant current

SR motor physics



SR motor physics

- 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:

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

SR motor physics

- It is possible to build an SR motor without saturation in the motor's steel
  - the power density will be low

$$T = \frac{1}{2} \cdot i^2 \frac{dL}{d\Theta}$$

SR motor physics

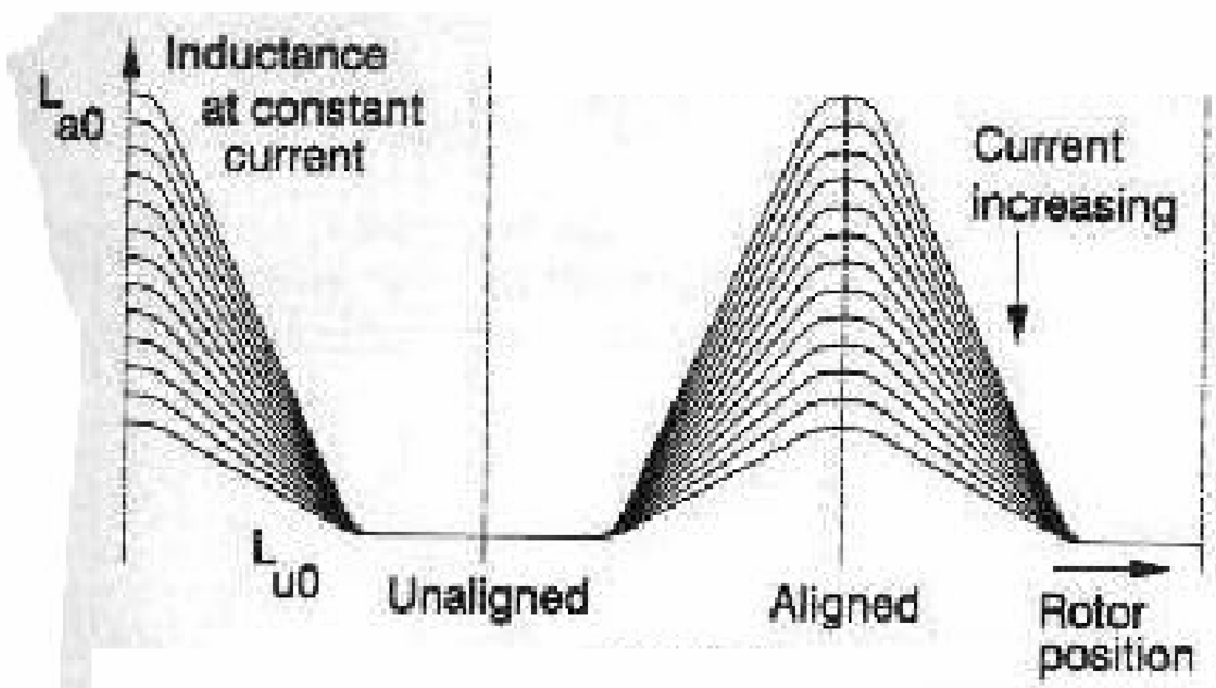
- Typically a SR motor will operate with heavily saturated steel
  - efficient SR motors require high saturation in the motor’s steel
  - high quality steels must be used to limit the magnetization and eddy current losses in the steel
  - the ratio of the inductance in the aligned vs. the unaligned position yields information about the performance of the SR motor

SR motor physics

- The torque generated by the SR motor is a function of its rotor angle and the current

$$T = f(i, \Theta) = \frac{\partial W}{\partial \Theta}$$

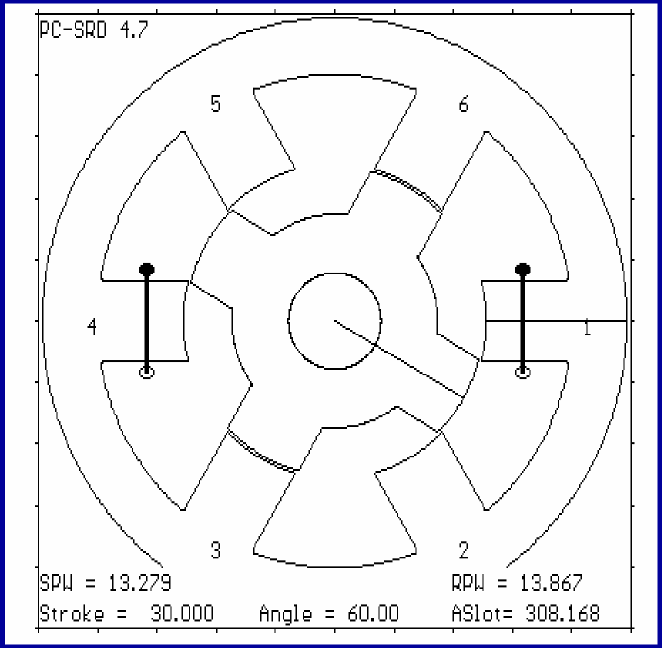
SR motor physics

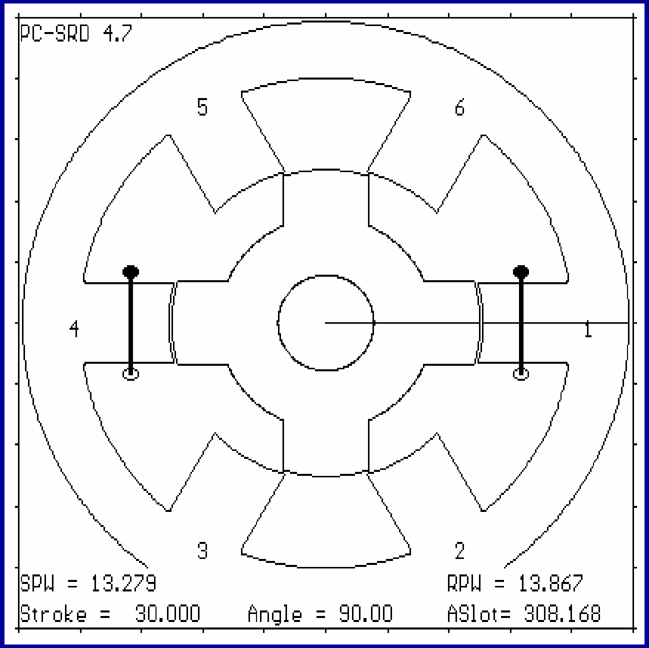


Inductance vs. rotor position, showing the effect of saturation as the current increases.

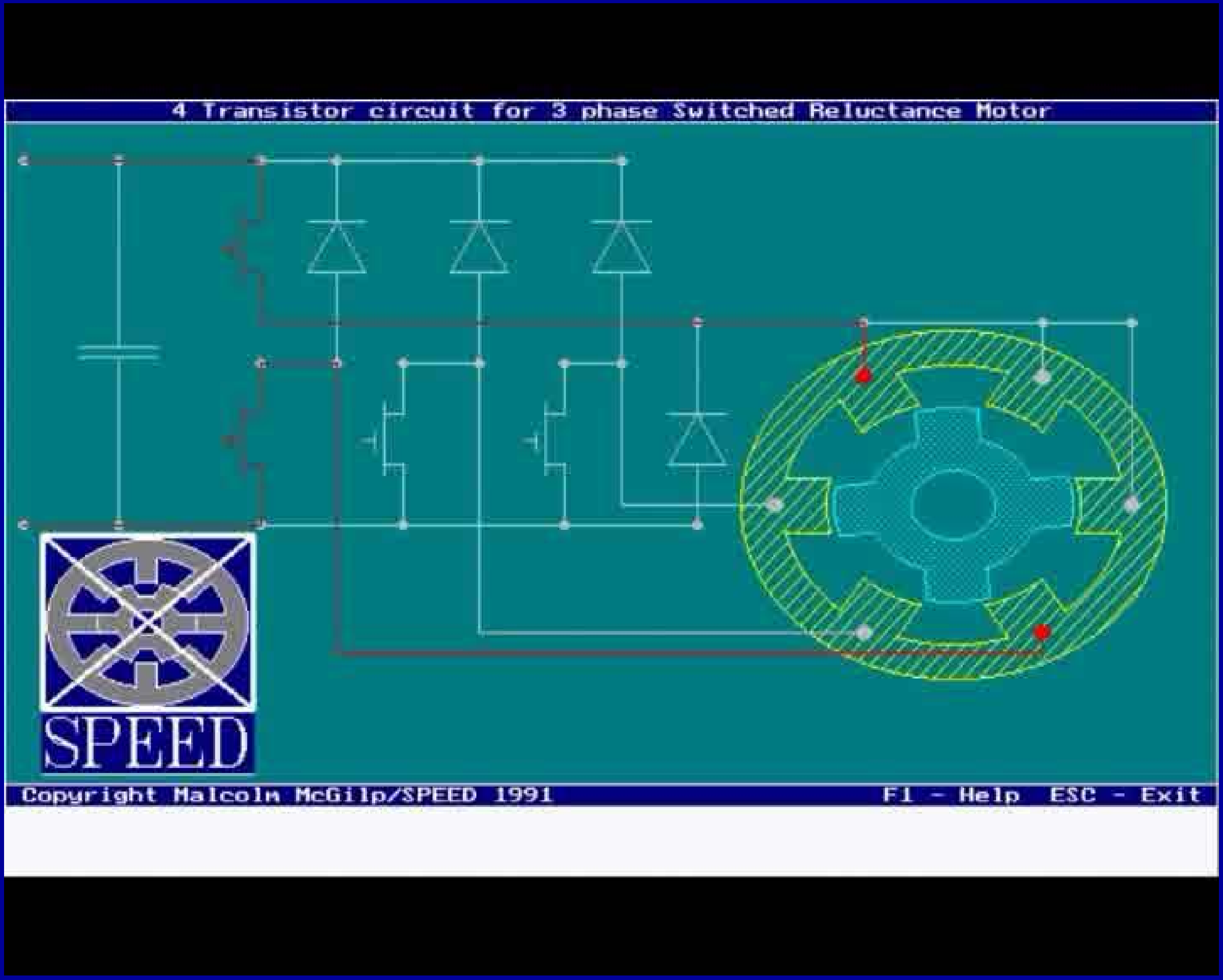
SR motor physics

- The rotation of the SR motor is achieved by sequentially energizing and de-energizing the phases of the motor

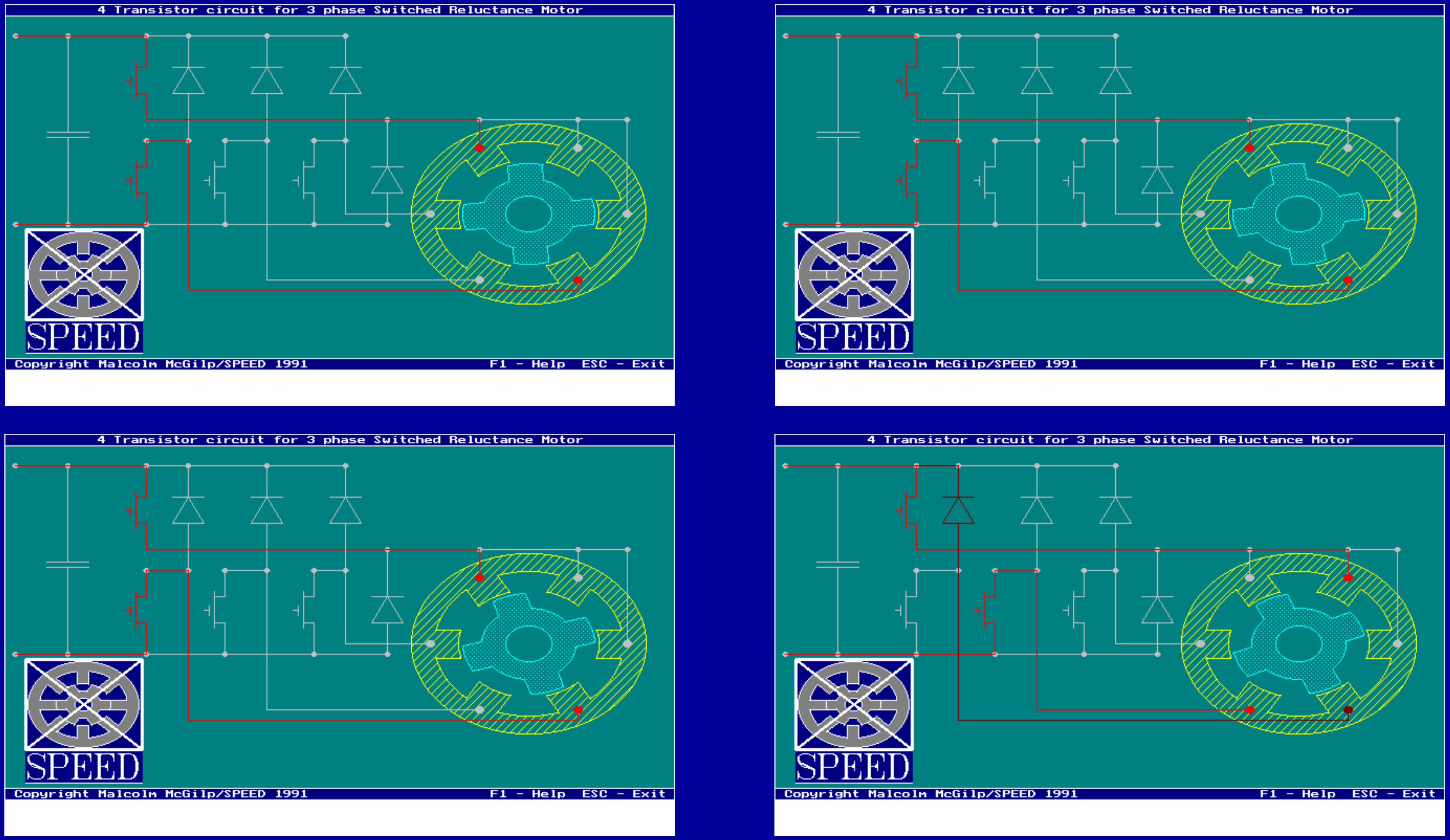




SR motor physics



SR motor physics

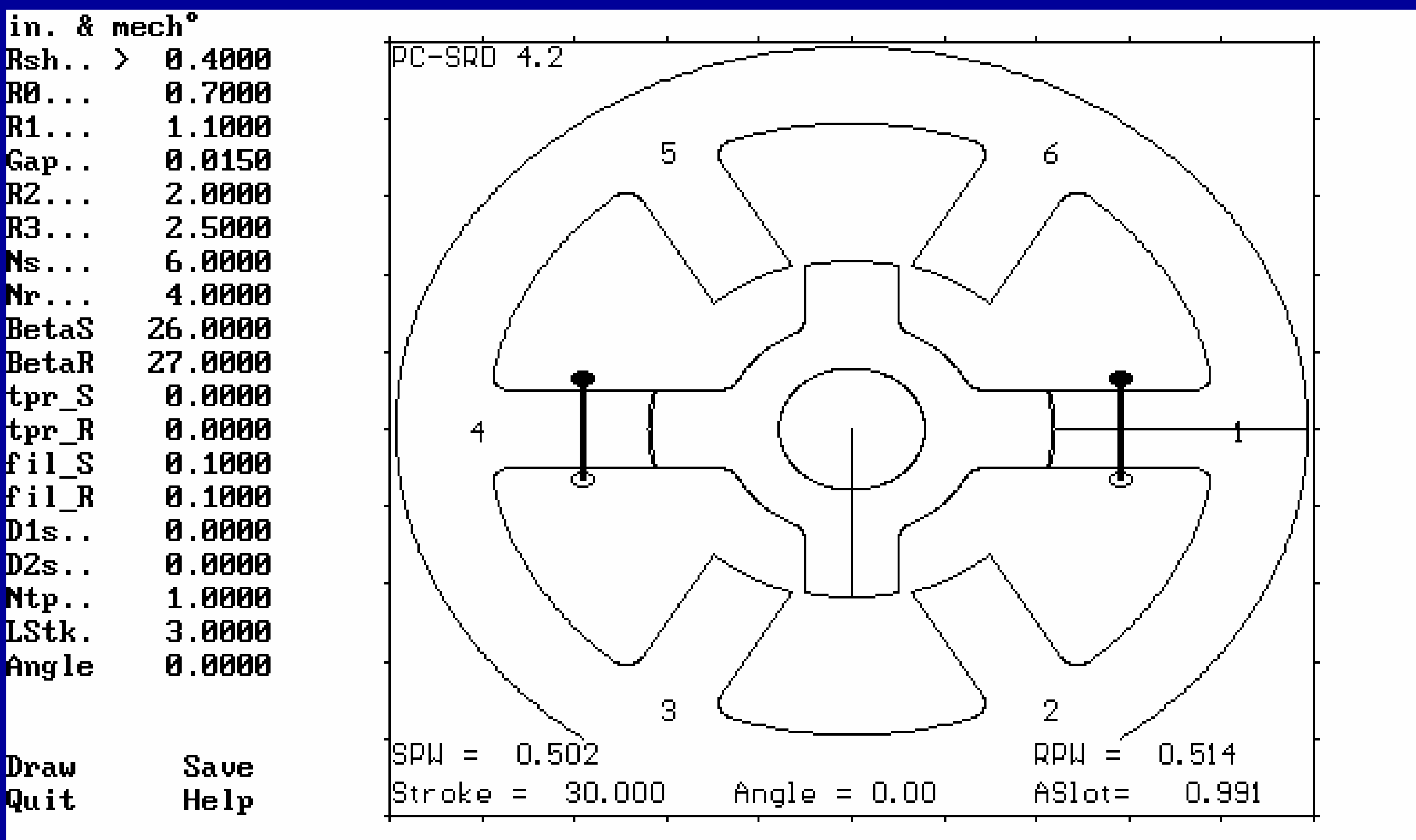


SR motor physics

- A clockwise sequential excitation of the phases results in a counter clockwise rotation of the SR motor

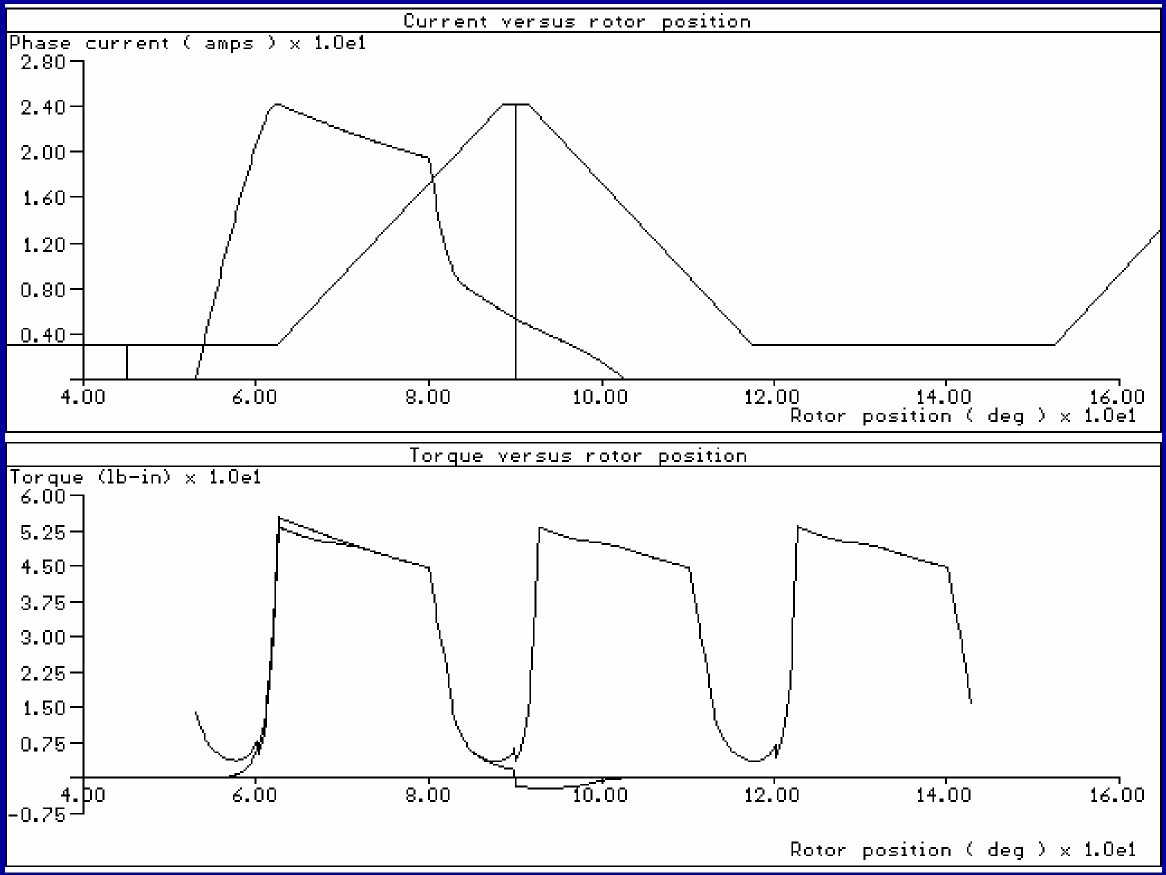
SR motor physics

- Example of a typical 3 phase SR motor



SR motor physics

- The torque profile



SR motor physics

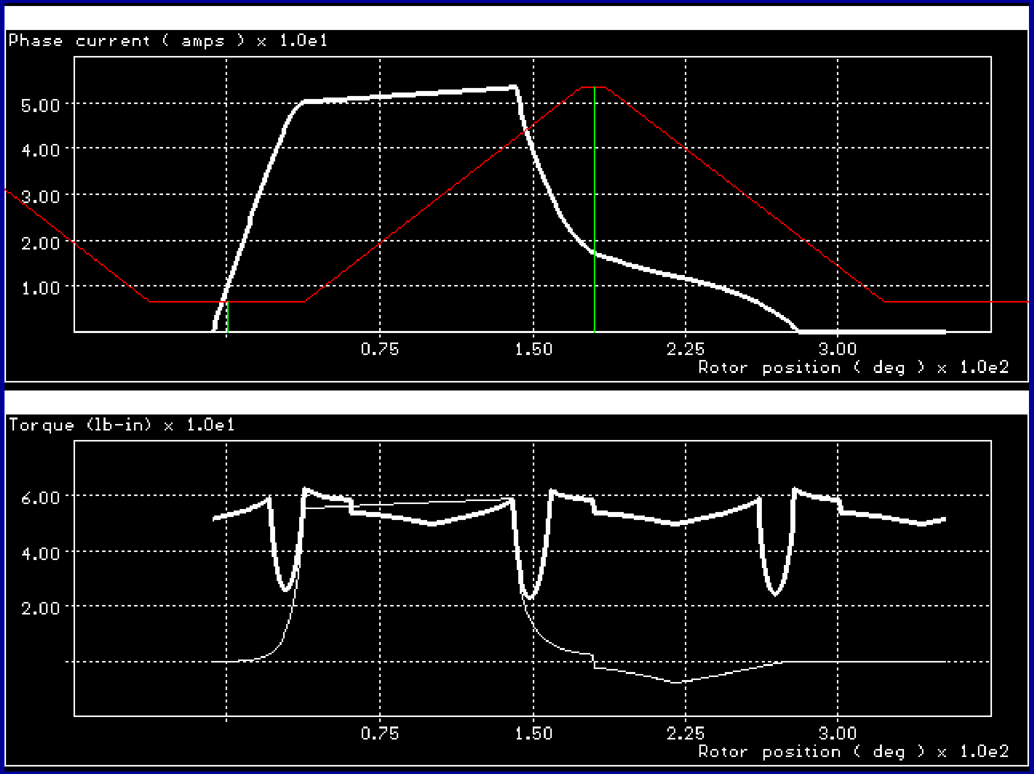
- All of this sounds just like a VR stepper, what is so special about the SR motor ???
  - answer: the SR motor is a self commutated motor
    - in the SR motor the field follows the rotor. T
    - the rotor position determines which phase will be energized.
    - this is called: closed loop commutation
  - in contrast operation of the stepper motor assumes that
    - in the stepper motor the rotor follows the field
    - stability problems result
    - the rotor may lose steps and/or stall

SR motor physics

- closed loop commutation requires that:
  - rotor position feedback must be provided
  - rotor position feedback must be used for commutation
  - commutation angles may not be fixed and constant
  - technology is available to determine the rotor position of the SR motor without adding physical position sensors: sensorless control

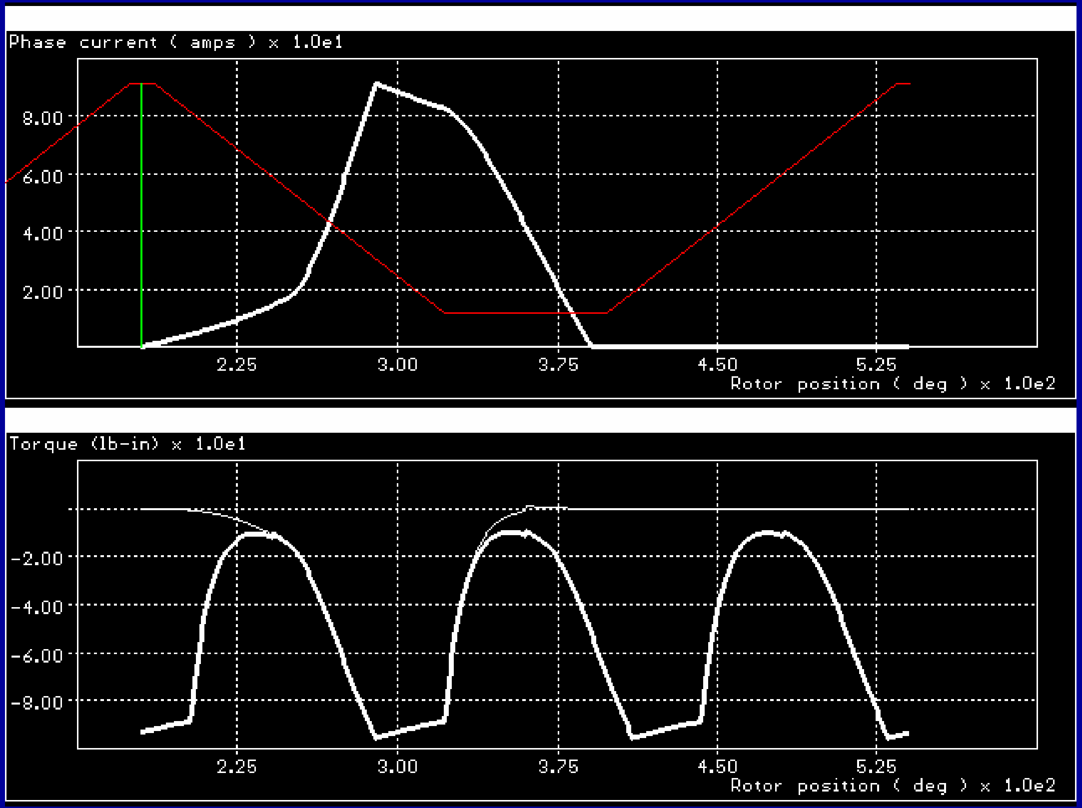
SR motor physics

- The SR motor can operate both as a motor



SR motor physics

- and a generator



SR motor physics

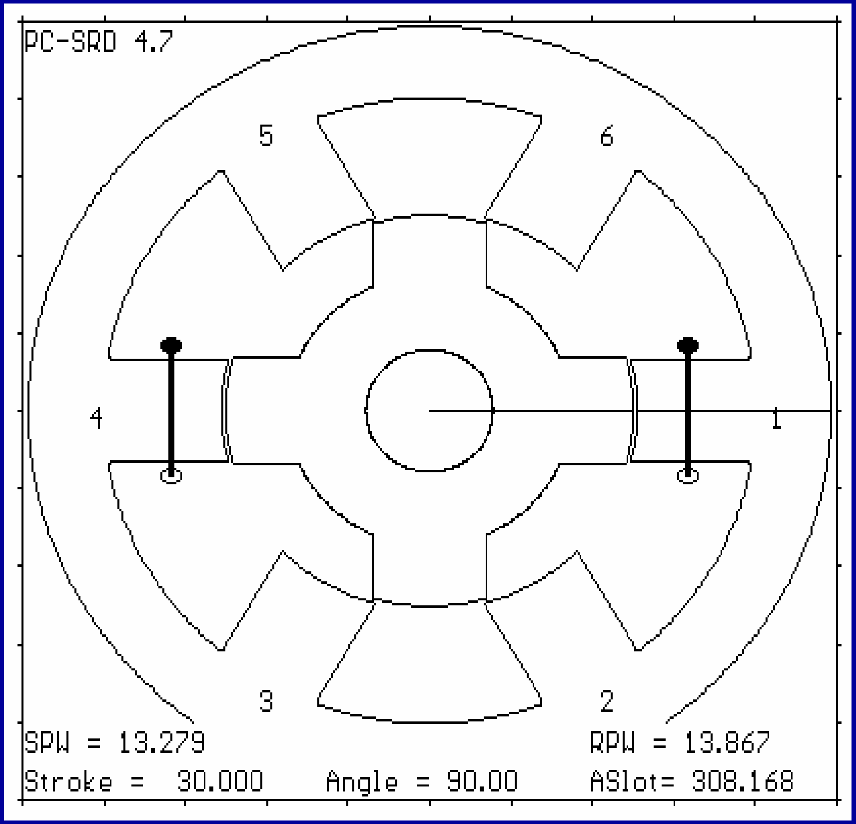
- the SR Generator is a current source
  - generation process needs energy to be excited
  - once the phase is exited it is difficult to control the generation process
  - unlike other technologies a well designed SR motor is not necessarily a good generator

SR motor physics

- the phase/pole combinations in the SR motor
  - a typical SR motor is referenced as an x/y n-phase
    - x = number of rotor poles
    - y = number of stator poles
    - n = number of phases
  - the number of rotor and stator poles must be different to allow a motor to generate torque at stall
    - x = y is possible for a generator or a specialized application
    - typically y = x – 2 but other combinations are possible
  - the number of stator poles is an integral multiple of the number of phases
    - x = n * m; m = 2, 4, 6 …

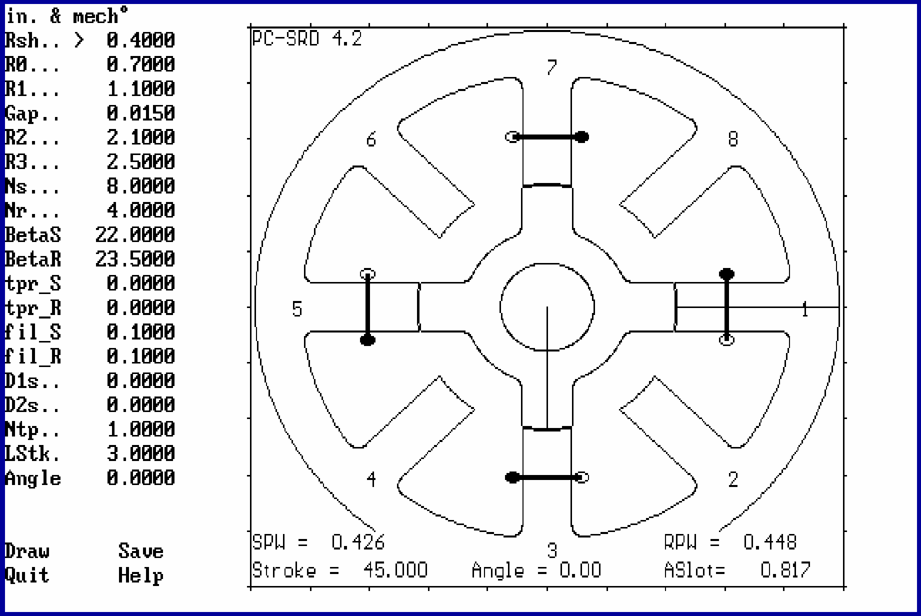
SR motor physics

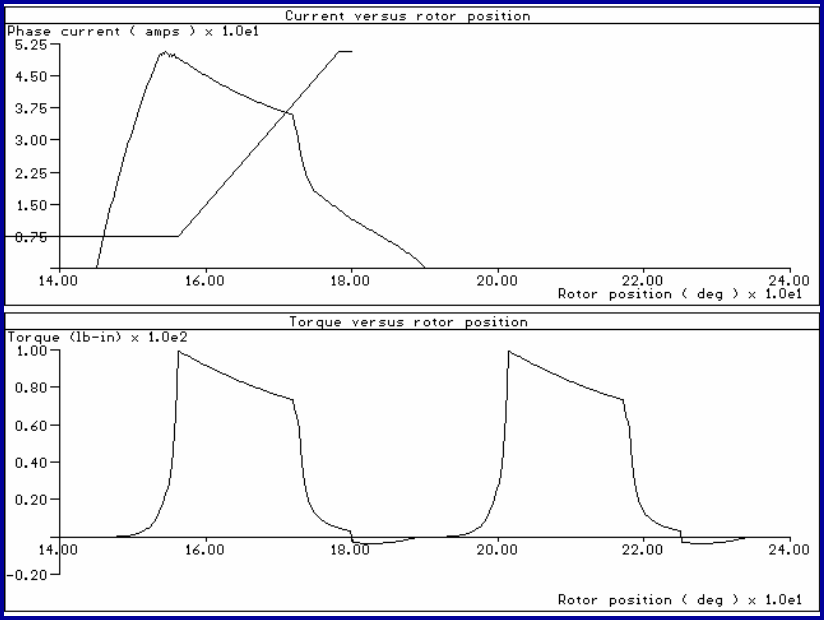
- example of a 6/4 3 phase motor



SR motor physics

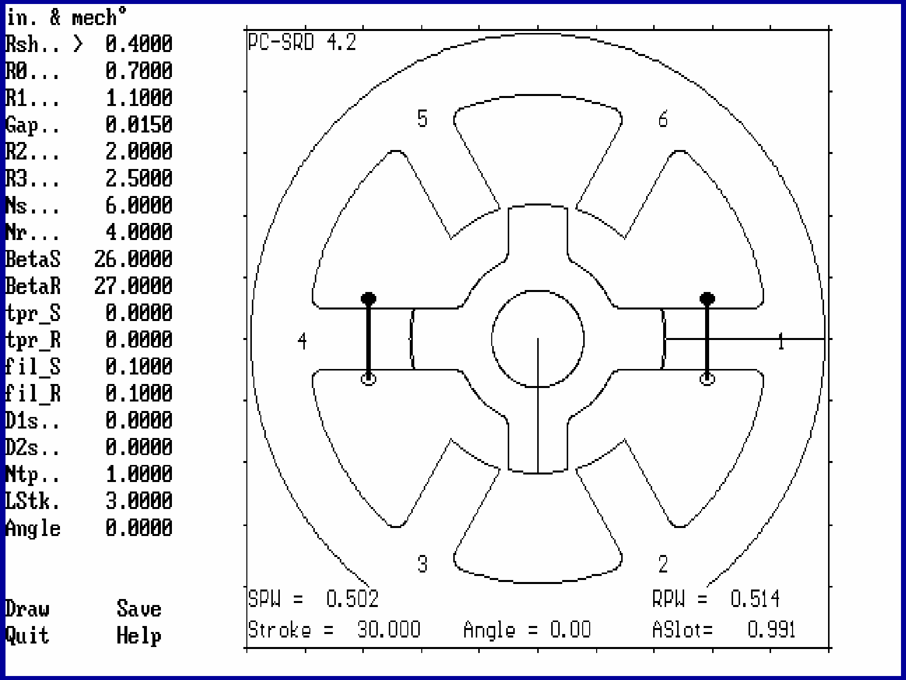
- the 8/6 2 phase motor

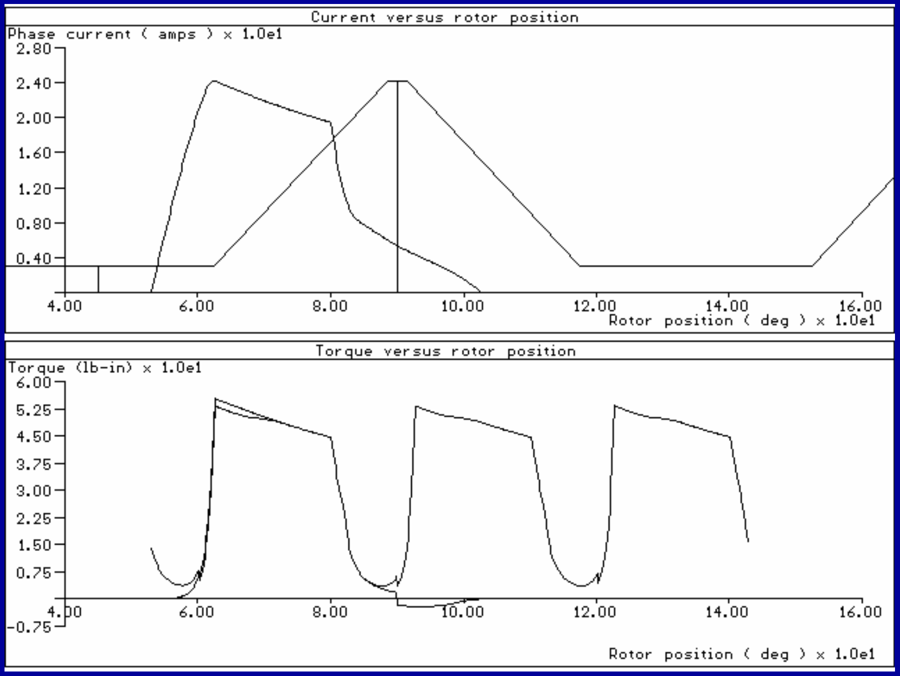




SR motor physics

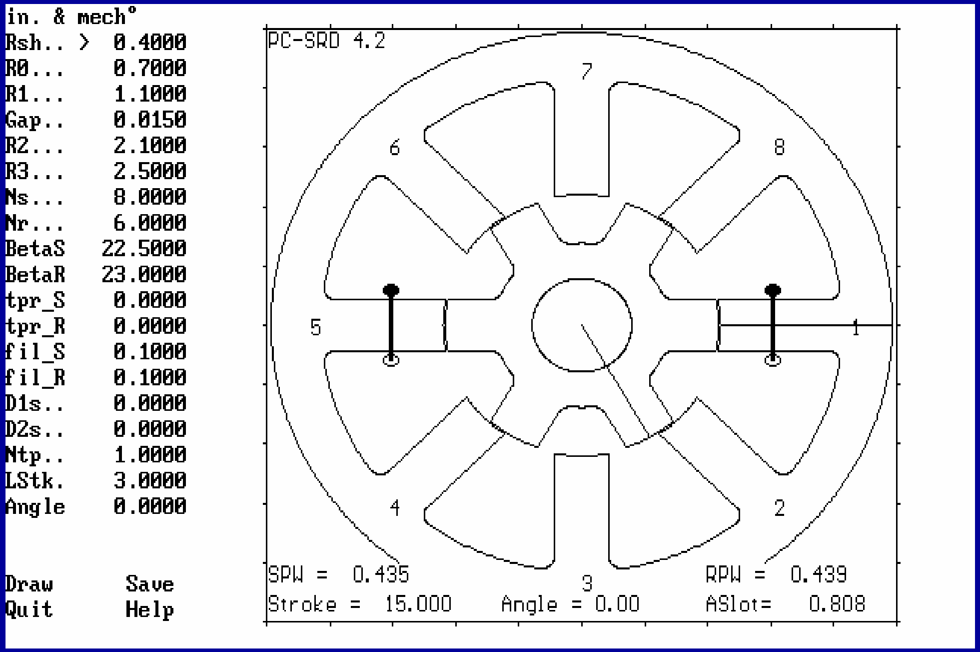
- the 6/4 3 phase motor

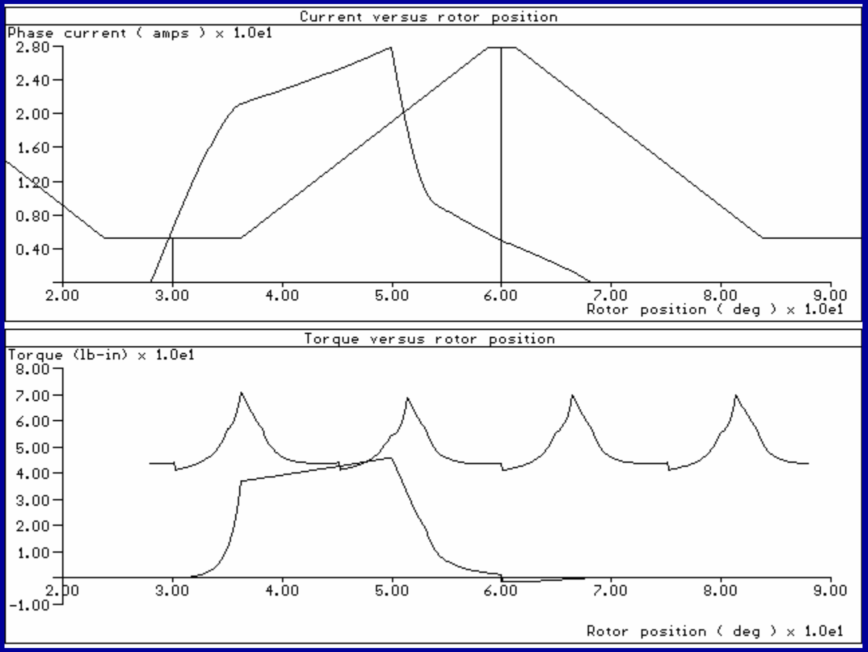




SR motor physics

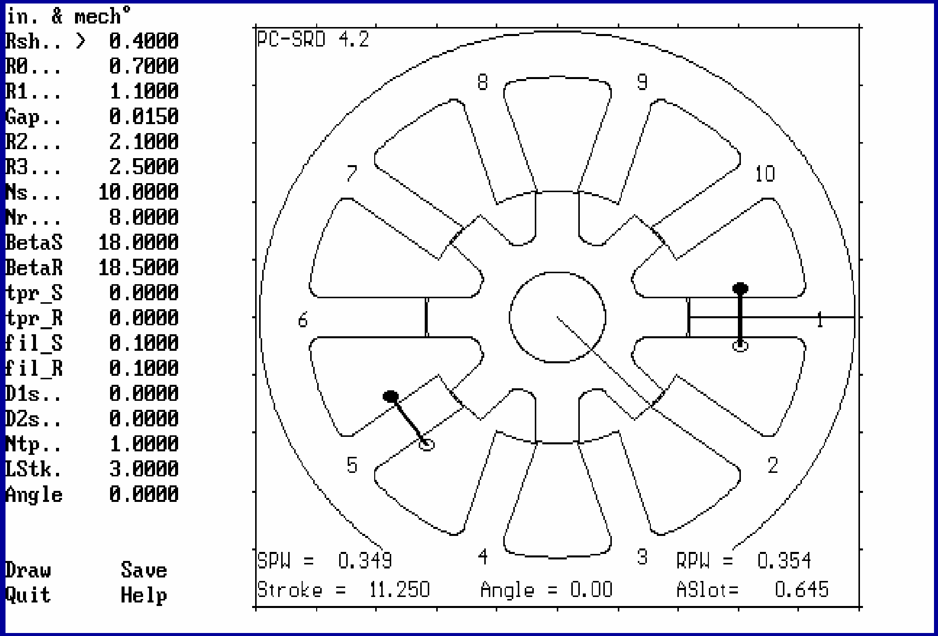
- the 8/6 4 phase motor

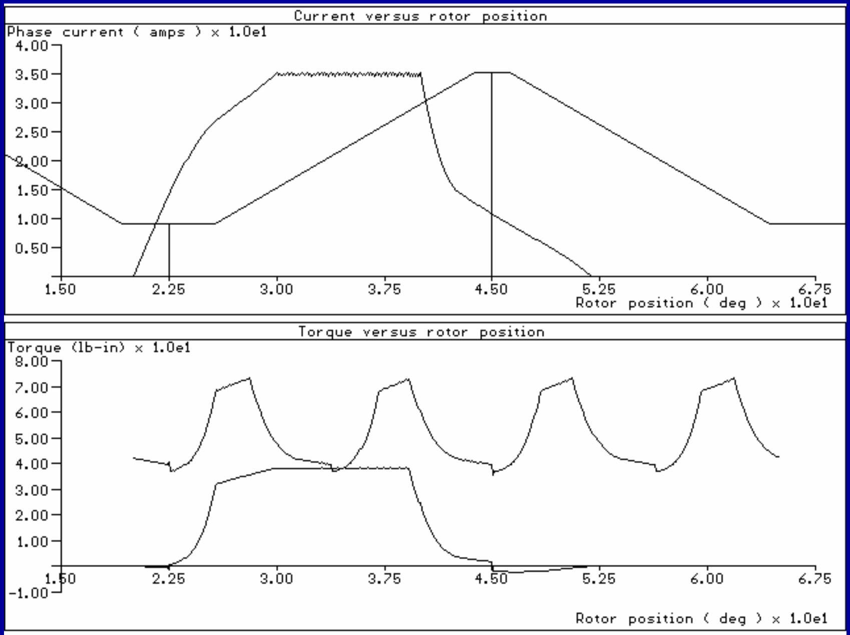




SR motor physics

- the 10/8 5 phase motor





SR motor physics

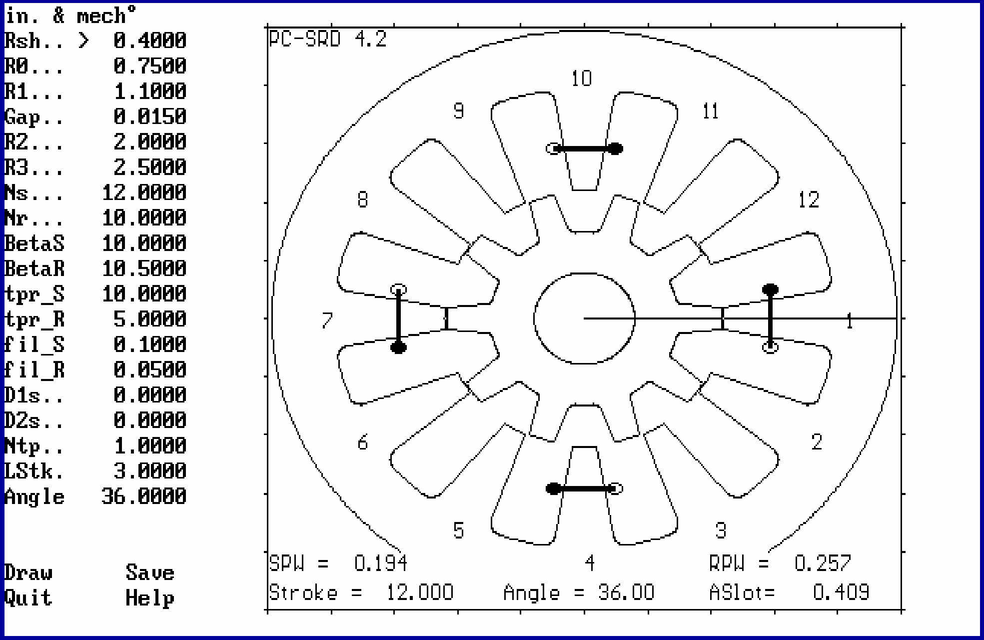
- acoustic noise in SR motors
  - the magnetic forces are strong enough to force the teeth to elongate and to distort the stator yoke
  - the radial forces are significantly higher than the tangential forces (torque) by a factor of 10:1 or more
  - a small airgap can aggregate the problem due to mechanic tolerances

SR motor physics

- acoustic noise in SR motors
  - the rate of change in the magnetic field has an impact on the acoustic noise
  - geometry, mechanical construction and electronic control schemes can be used to reduce acoustic noise

SR motor physics

- acoustic noise in SR motors
  - the 12/10 3 phase SR motor
    - short flux path
    - good force distribution
    - patented design



SR motor physics

- acoustic noise in SR motors
  - tooth design can help to reduce the acoustic noise
  - strong backiron in the stator can help to reduce the acoustic noise
  - a large airgap can help to reduce the acoustic noise

SR motor physics

- acoustic noise in SR motors
  - commutation is critical: turn on early, turn off late when the inductance is highest (if possible)
    - tradeoff: efficiency vs. quiet operation
  - Polluck has described and patented a scheme to turn the phase off in 2 steps
    - must be tuned to the motor's natural frequency
    - mixed results have been reported

SR motor physics

- acoustic noise in SR motors
  - measurements in actual systems show that BLDC and SR are similar in audible noise (within 3 dB)
  - the emitted audible spectra are different between a BLDC and an SR motor
    - SR has a more defined spectrum
    - can be used as an advantage
    - can be mechanically supressed

SR motor physics

- acoustic noise in SR motors
  - measurements in actual systems show that BLDC and SR are similar in audible noise (within 3 dB)
  - the emitted audible spectra are different between a BLDC and an SR motor
    - SR has a more defined spectrum
    - can be used as an advantage
    - can be mechanically supressed

SR motor physics

- acoustic noise in SR motors
  - measurements in actual systems show that BLDC and SR are similar in audible noise (within 3 dB)
  - the emitted audible spectra are different between a BLDC and an SR motor
    - SR has a more defined spectrum
    - can be used as an advantage
    - can be mechanically supressed

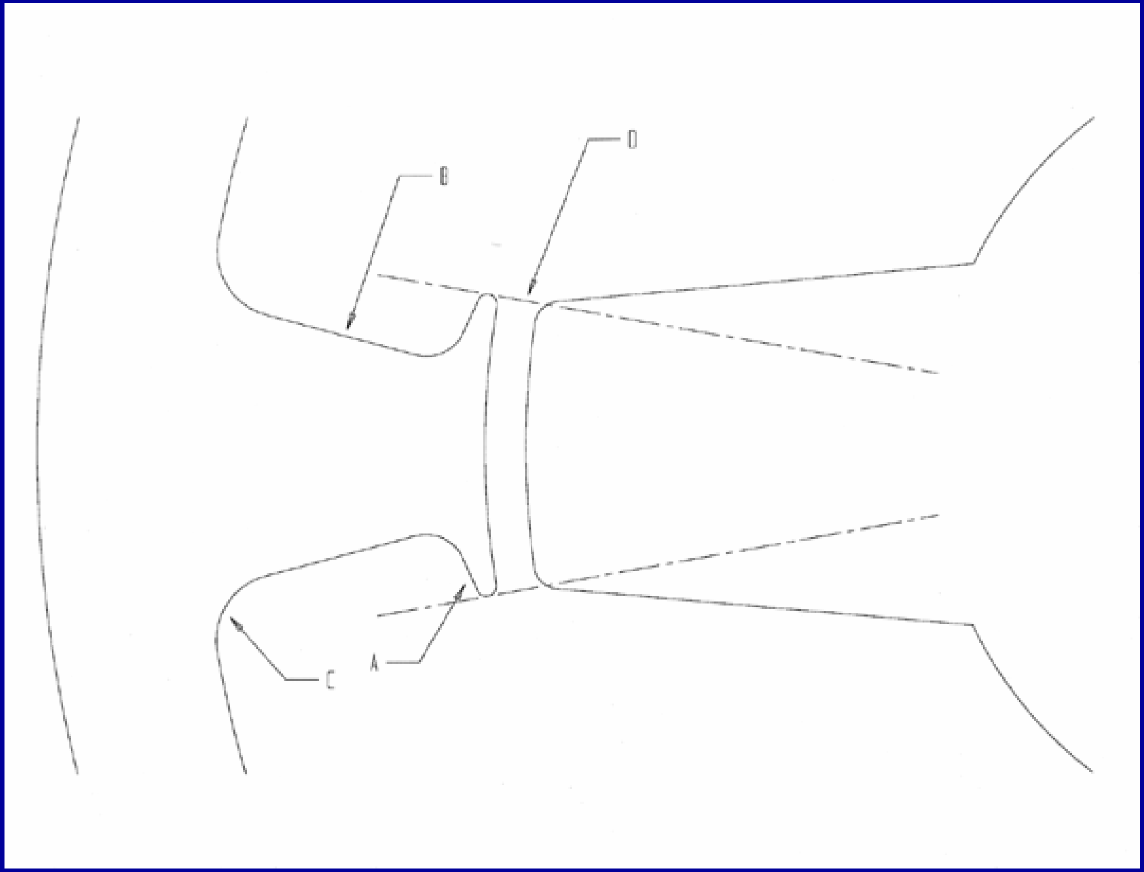
The design of SR motors

The design of SR motors

- the mechanical and magnetic design of the SR motor is of extreme importance

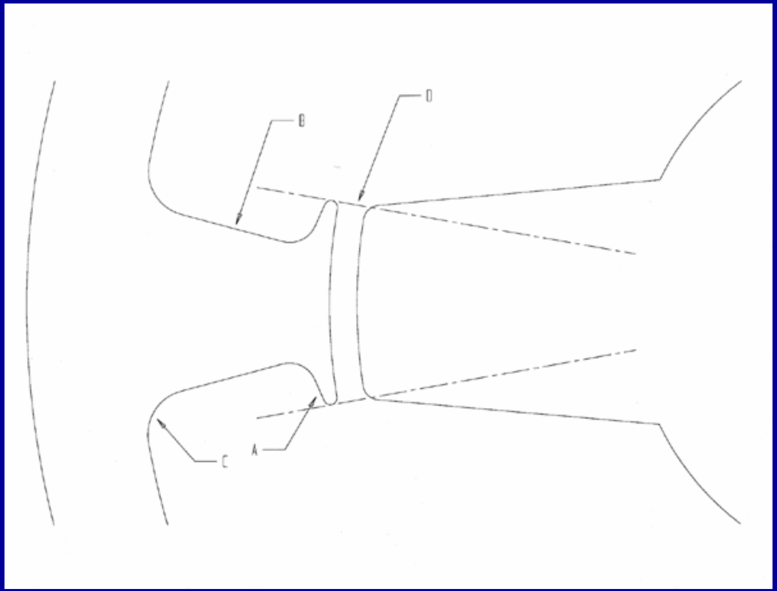
The design of SR motors

- geometric considerations



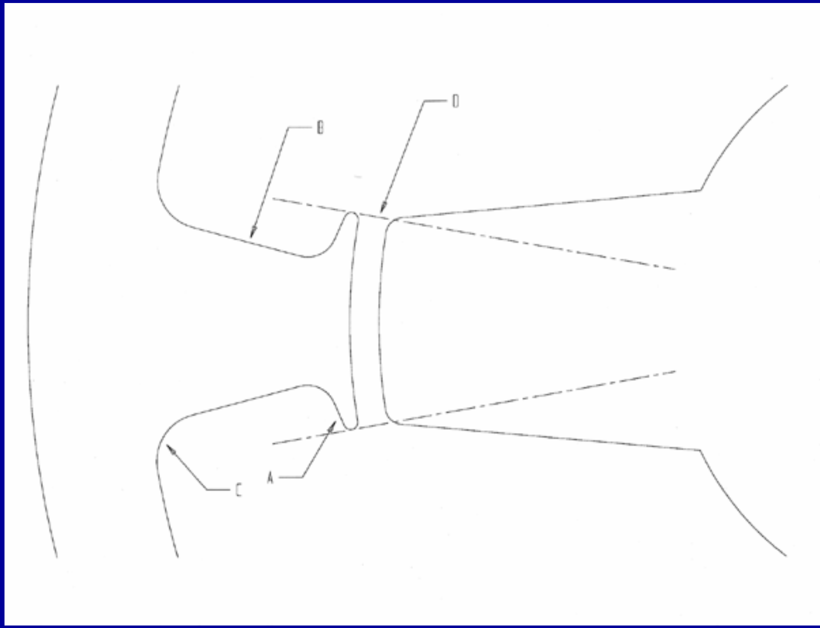
The design of SR motors

- geometric considerations
  - wide rotor tooth tip
    - improved saturation pattern
    - more winding space



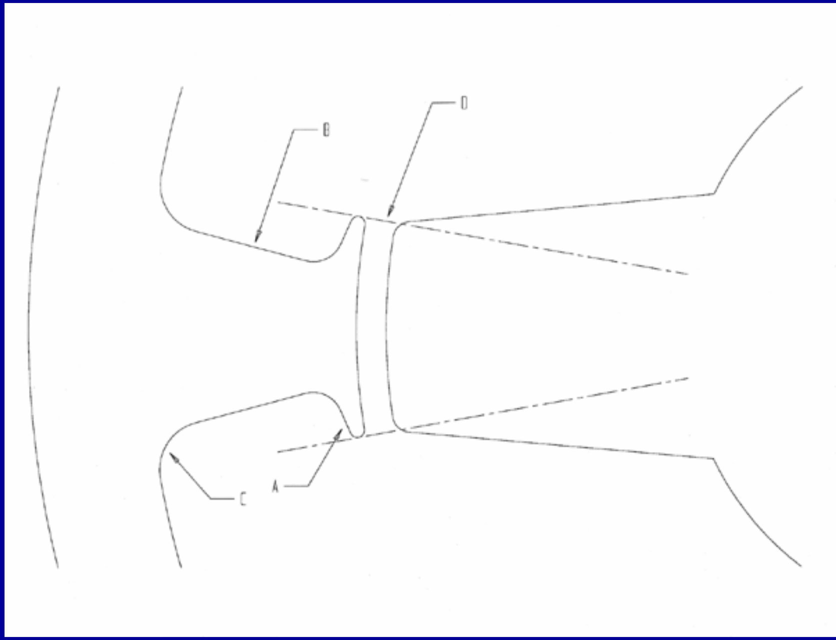
The design of SR motors

- geometric considerations
  - angled stator tooth
    - improved magnetics
    - Improved mechanic integrity
    - improved acoustic noise



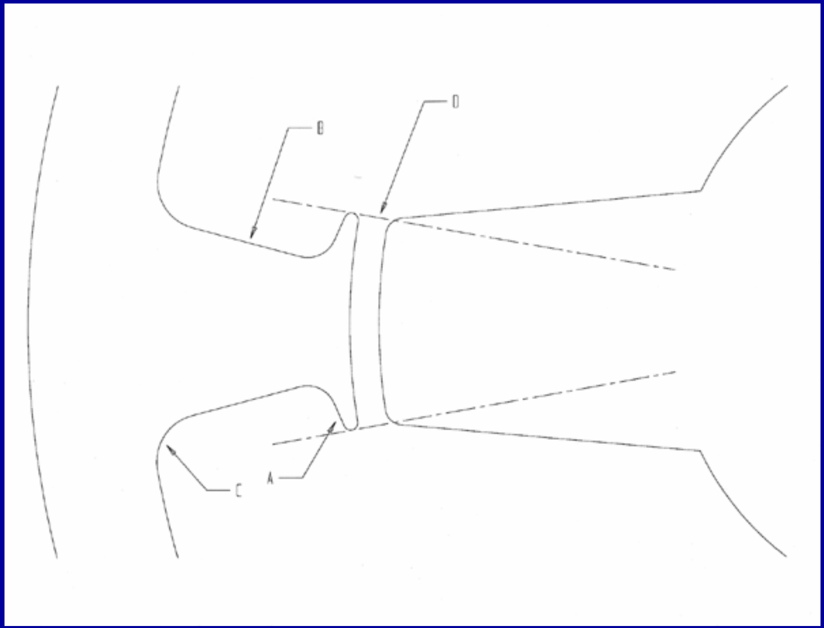
The design of SR motors

- geometric considerations
  - chamfered transitions
    - reduced mechanical stress



The design of SR motors

- geometric considerations
  - angled rotor tooth
    - reduced inertia
    - improved magnetics
    - Improved mechanical integrity



The design of SR motors

- the airgap
  - an airgap of 0.01” is typical for most SR motors
  - many designers believe that an SR motor can not be designed with a large airgap
  - SR motors with 0.025” – 0.04” have been successfully build and demonstrated
    - loss in efficiency is as low as 0.5% increasing the airgap from 0.01” to 0.03”

The design of SR motors

- the airgap
  - SR motors with large airgaps reduce some manufacturing problems
    - mechanical tolerances
    - contamination
    - shaft vibration
  - SR motors with large airgaps are more cost effective
    - cost of bearings
    - tolerances

The design of SR motors

- no good mathematical models exist to design or describe the SR motor
- the use of simulation tools and magnetic design software are required for the design of SR motors and systems
- PC-SRD is commonly used for SR motor design
  - developed by the SPEED Consortium
  - software is distributed by Motorsoft in the US

The design of SR motors

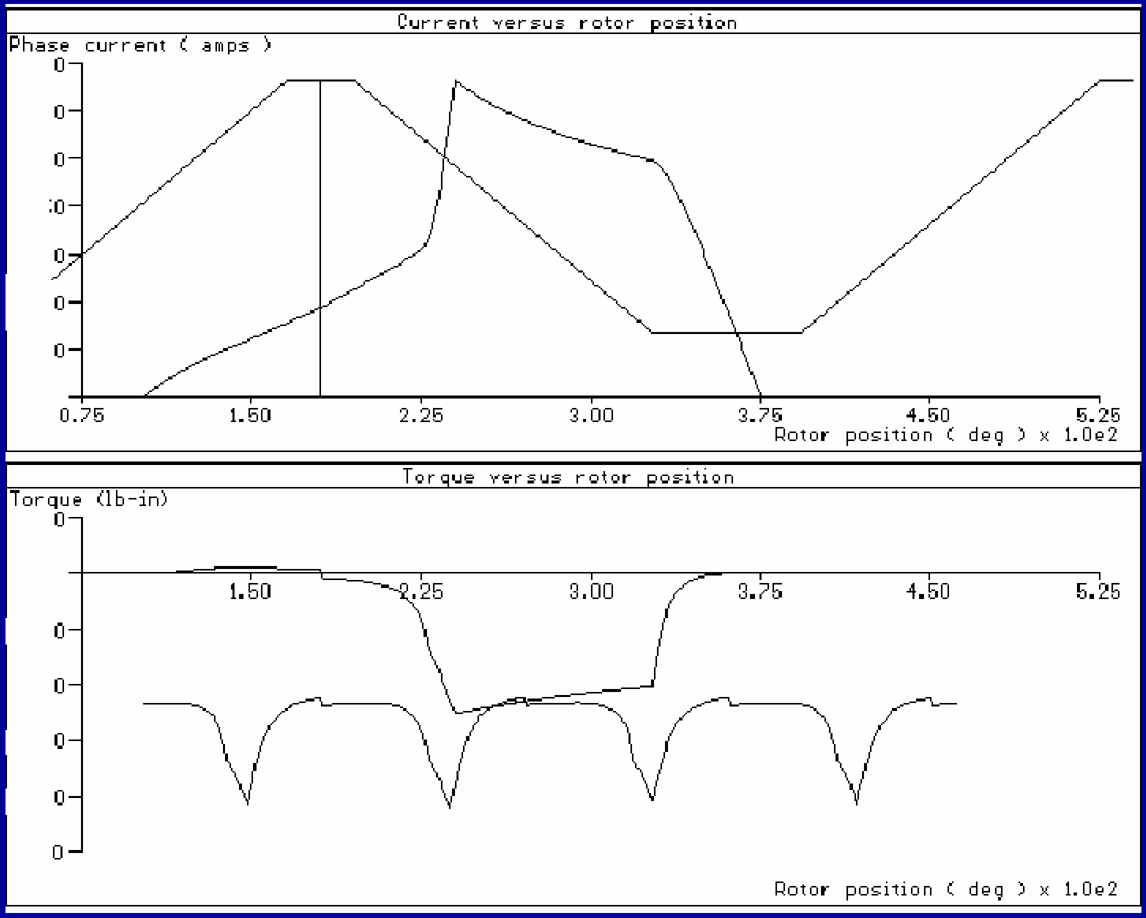
- finite element magnetic (FEM) software can also be used to design and analyze SR motors
  - PC-SRD is a better tool for the initial sizing
  - FEM yields more valid results

The design of SR motors

- both tools were used simultaneously in one instance to design an 80kW generator
  - initial sizing was done using PC-SRD
  - due to the cost of the prototypes (~ $100k) additional performance assurance was desired
  - MAGSOFT FEM software was used to validate the result
  - the FEM confirmed the general performance but indicated some minor, favorable differences in the torque distribution
  - measurements performed on the actual generator confirmed both the overall performance as well as the torque distribution closer to the one predicted by FEM

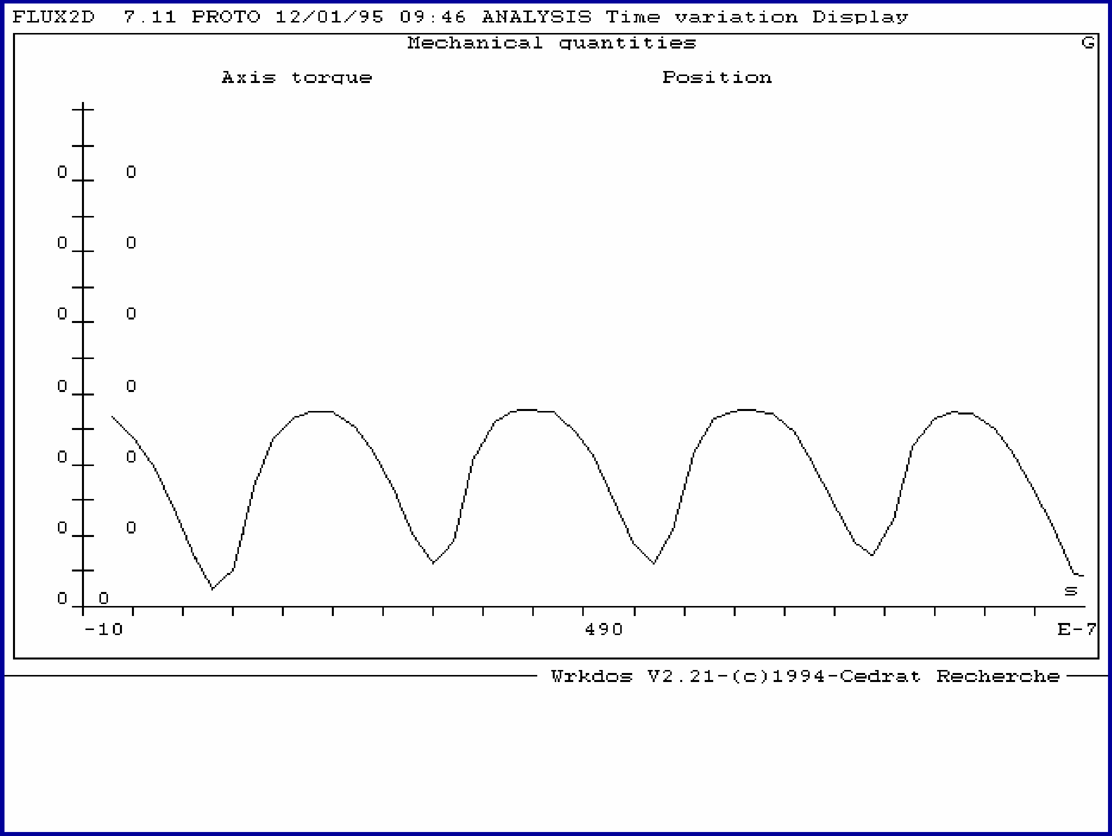
The design of SR motors

- the design as predicted by PC-SRD



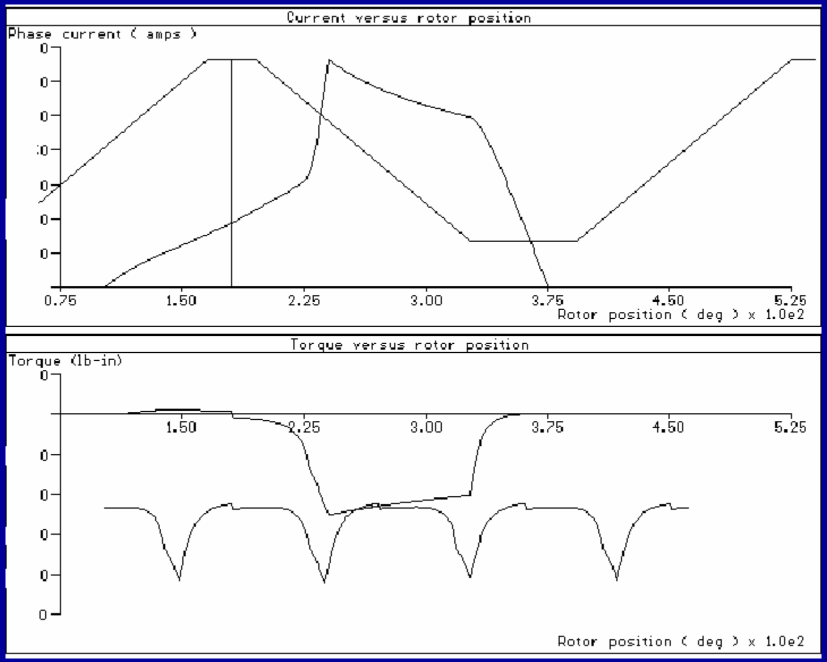
The design of SR motors

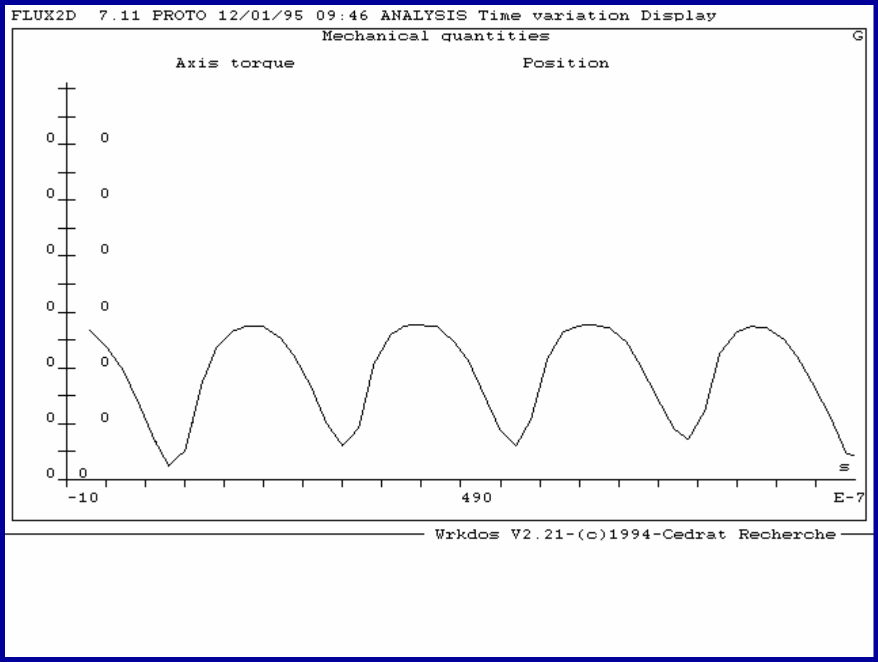
- the design as predicted by MAGSOFT's FLUX2D



The design of SR motors

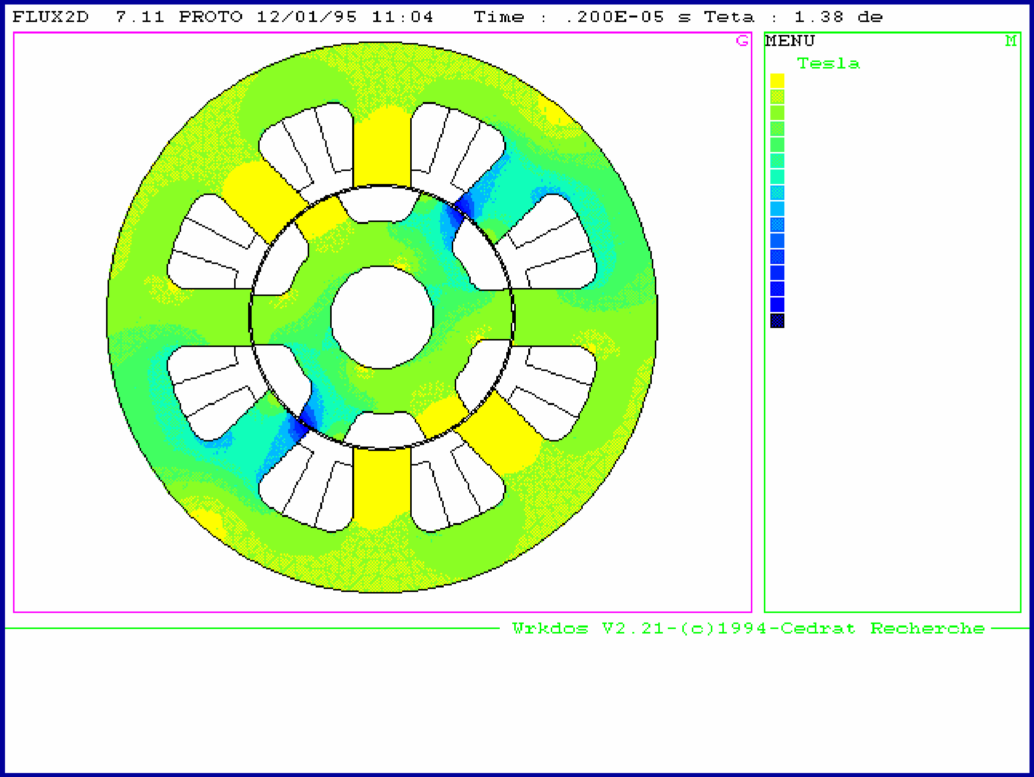
- comparison of the results

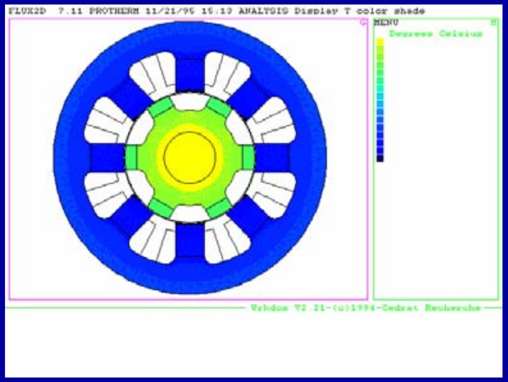


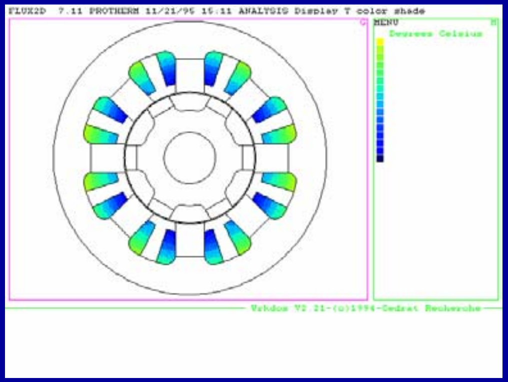


The design of SR motors

- magnetic saturation and operating temperature as predicted by FLUX2D







The design of SR motors

- SR motors require high quality steel
- Asian manufacturers often have problems providing quality steel with consistency
- M-17 and M-19 are typically used, M-15 is a good steel for high speed motors
- very high performance motors use Hyperco and Vanadium Permendur steels

The design of SR motors

AISI Designation	Allegheny Ludlum Designation	General Use
M-6	Silectron 66	Lowest core loss at high induction for use in power & distribution transformers and large turbogenerators.
M-14	Transformer AA	Low core loss transformer steel for high efficiency rotating machines and transformers
M-15	Transformer A	Higher core loss than M-14 Used for distribution transformers & rotary machines
M-17	Transformer B	Used occasionally for power transformers
M-19	Transformer C	Most suitable for high performance servo motors
M-22	Dynamo Special	Most suitable for high performance induction motors
M-27	Dynamo	Popular grade for servo motors
M-36	Electrical	Used especially for rotary machines. Popular grade for permanent magnet motors.
M-43	Armature	Used for fractional horsepower motors and relays
M-50	Field	Used for pole pieces and intermittent electric devices

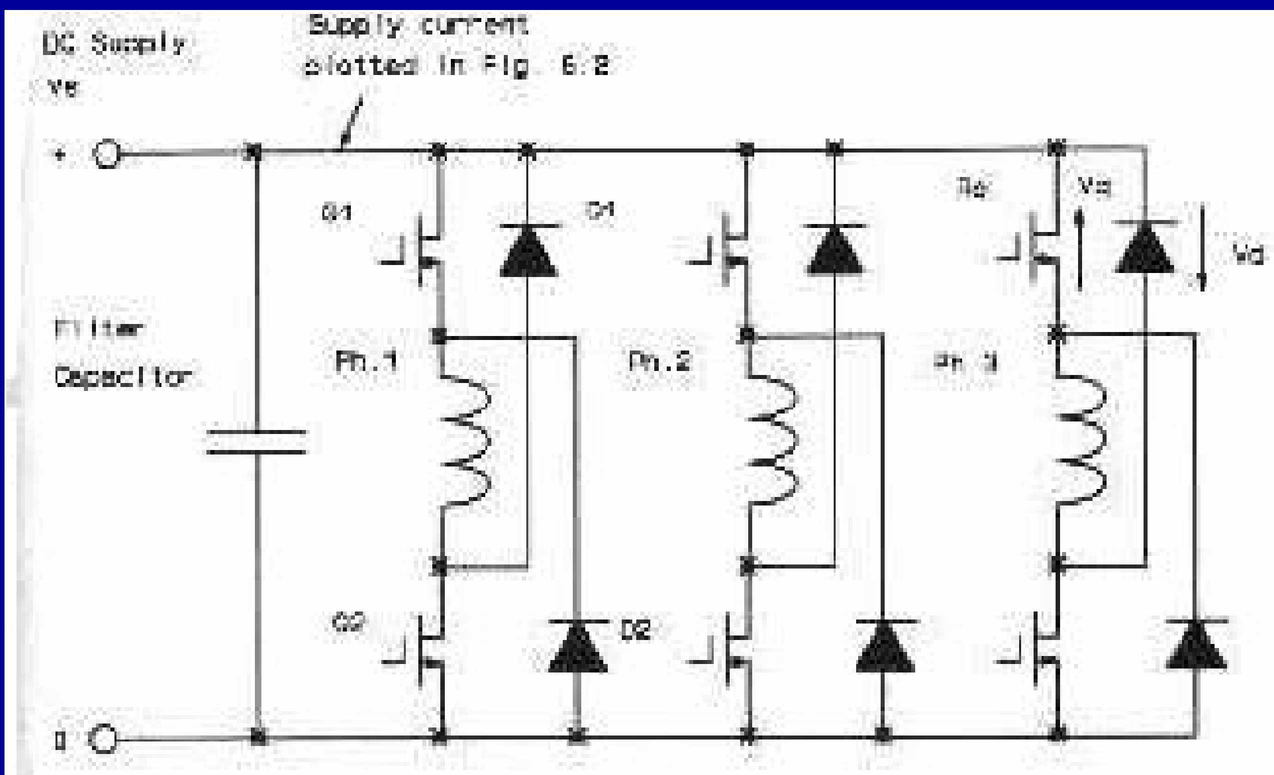
The design of SR motors

- “inside out” and linear SR motor designs are possible although more difficult than in PMBL motors
- pancake motors are typically inefficient
- best results are obtained when the stacklength equals the diameter although motors from ½ to 2 times this “ideal” stacklength perform well

Controller design for SR motors

Controller design for SR motors

- the typical power stage configuration for a 3 phase SR motor controller is shown here

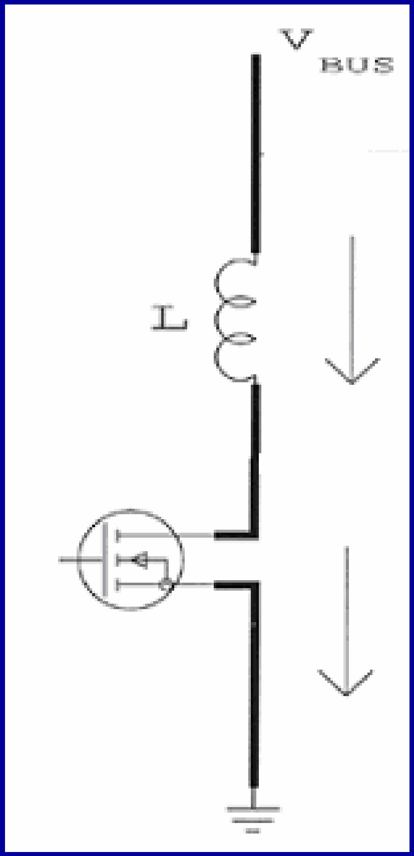


Controller design for SR motors

- the phases in the SR motor are typically independently controlled
  - methods have been introduced that allow to use a "standard" 3 phase inverter to control an SR motor
  - a controller (inverter) designed to drive an SR motor can be used to drive BLDC motors

Controller design for SR motors

- why not use a single switch ???



Controller design for SR motors

- a mathematical analysis will quickly show the reason

$$V_{bus} = L \cdot \frac{di}{dt} + i \cdot \frac{dL}{d\vartheta} + R \cdot i$$

V_{bus} : supply voltage

L : armature (phase) inductance

R : armature (phase) resistance

ϑ : the angular position of the rotor

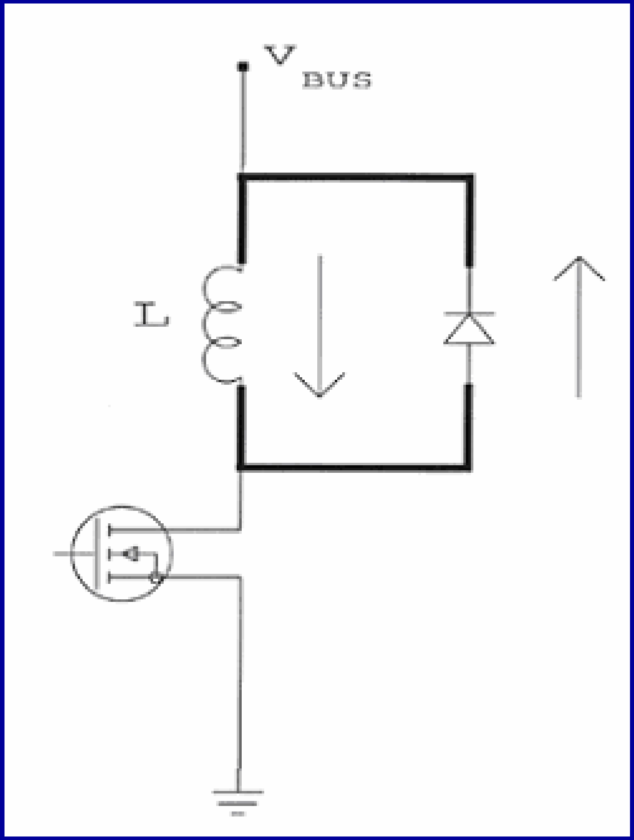
Controller design for SR motors

- solving this when the phase is turned on yields:

$$i(t) = \frac{V_{bus}}{R} \cdot \left(1 - e^{-\frac{t}{L/R}}\right) + i(t=0) \cdot e^{-\frac{t}{L/R}}$$

Controller design for SR motors

- what happens when the phase current turns off ???



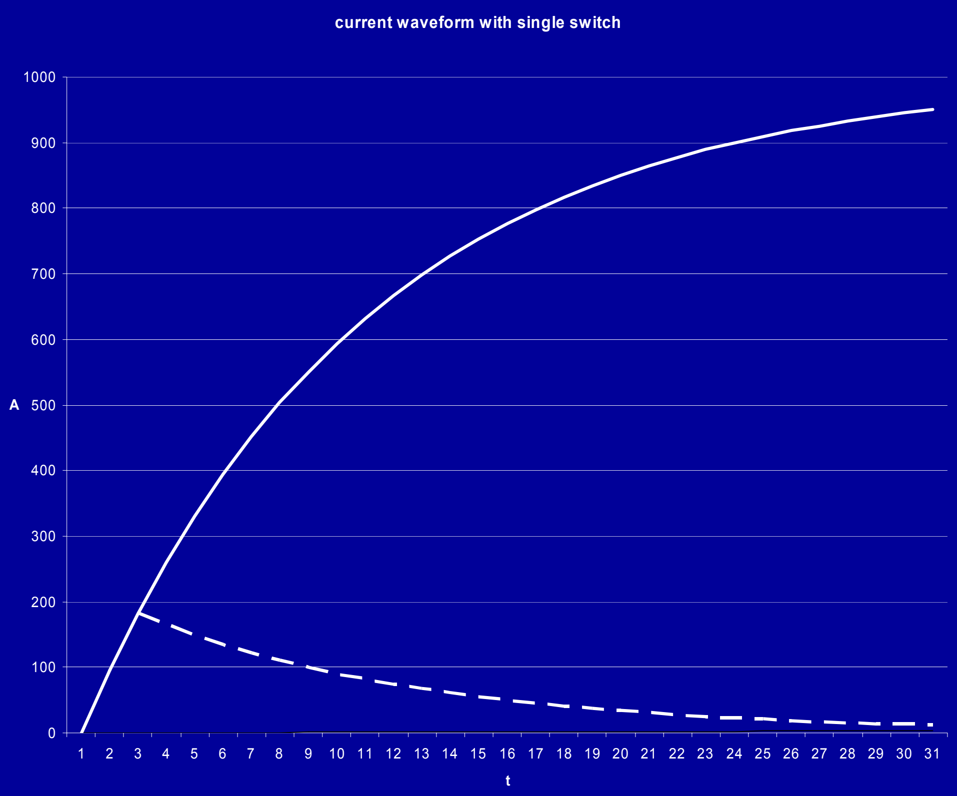
Controller design for SR motors

- solving the equations yields yields:

$$i(t) = -\frac{V_{diode}}{R} \cdot \left(1 - e^{-\frac{t}{L/R}} \right) + i(t=0) \cdot e^{-\frac{t}{L/R}}$$

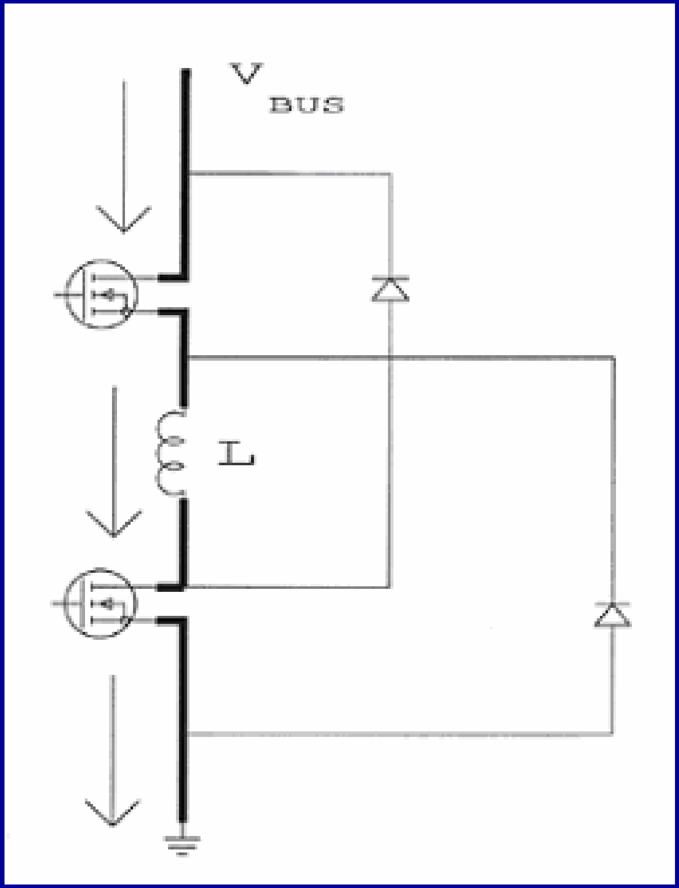
Controller design for SR motors

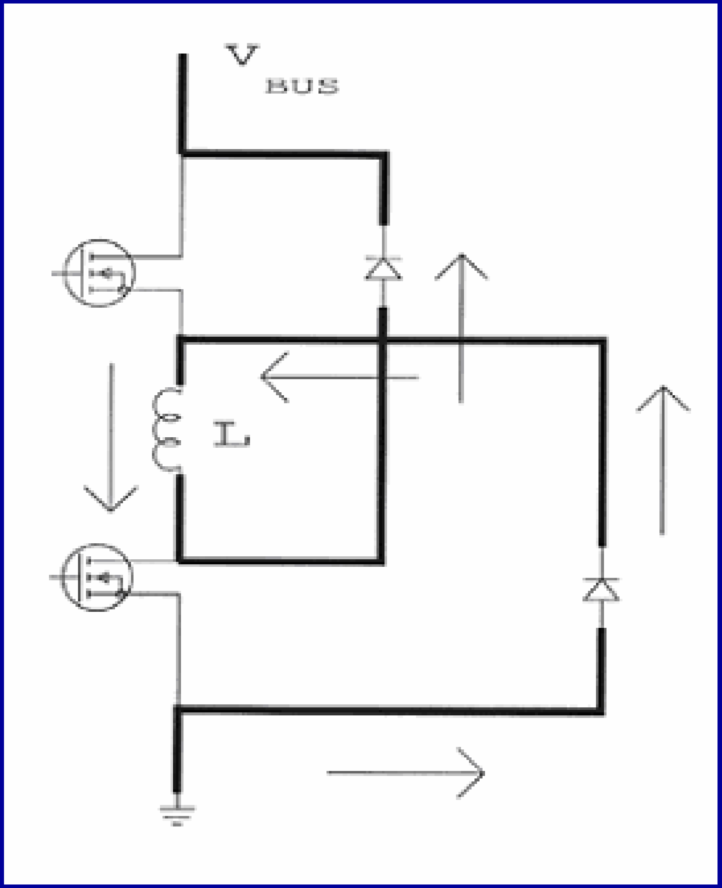
- solving the equations yields yields:



Controller design for SR motors

- what happens with 2 switches ???





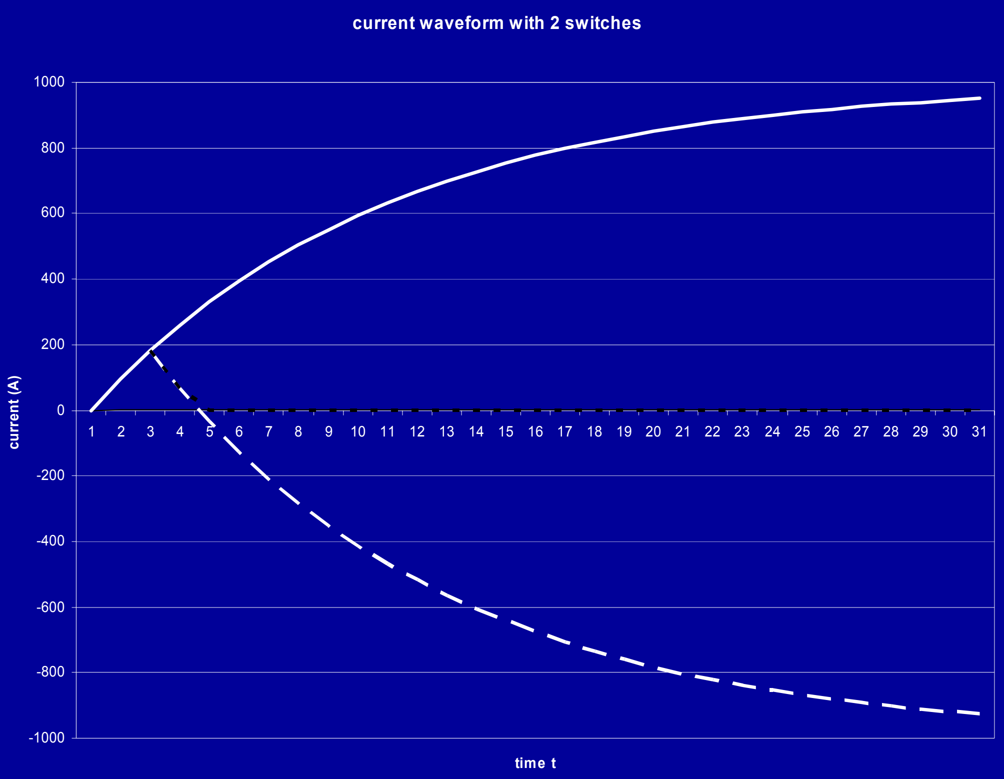
Controller design for SR motors

- the turn on does not change significantly
- solving the turn off yields:

$$\begin{cases} i(t) = -\frac{V_{bus}}{R} \cdot \left(1 - e^{-\frac{t}{L/R}}\right) + i(t=0) \cdot e^{-\frac{t}{L/R}} & i > 0 \\ 0 & else \end{cases}$$

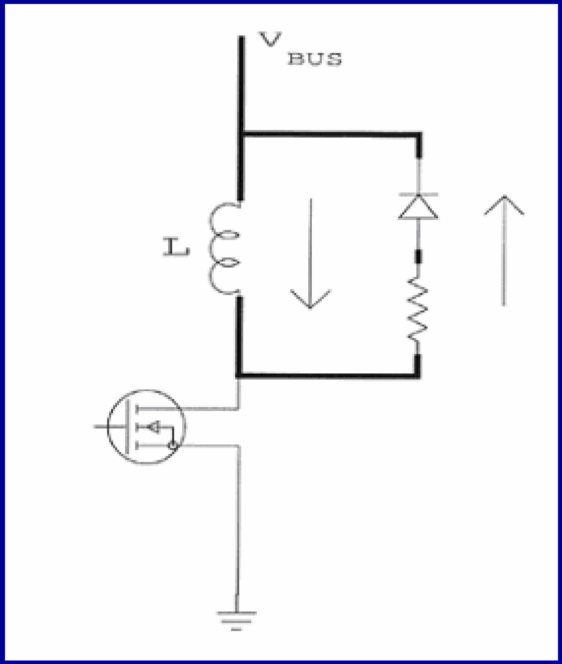
Controller design for SR motors

- solving the equations yields yields:



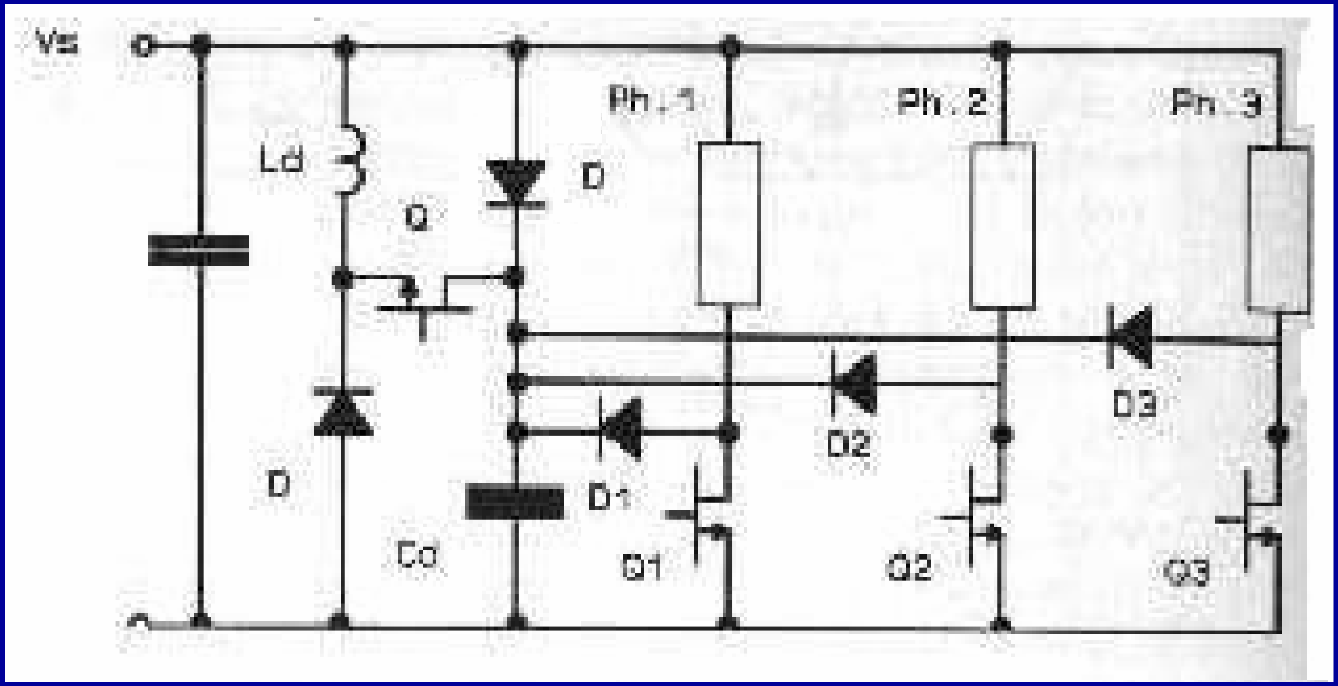
Controller design for SR motors

- what else can be done ???
  - add a series resistor



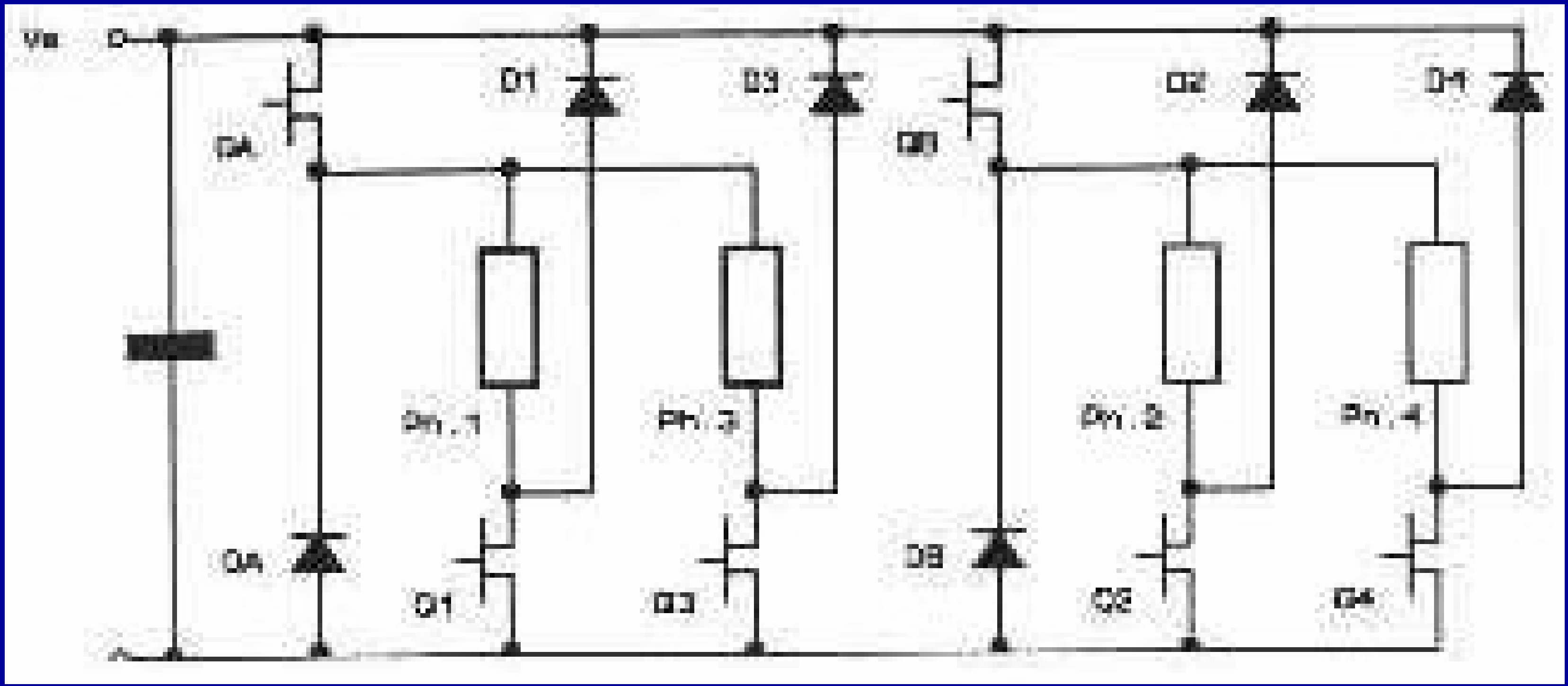
Controller design for SR motors

- what else can be done ???
  - use a C-dump circuit



Controller design for SR motors

- controller for a 4 phase SR motor

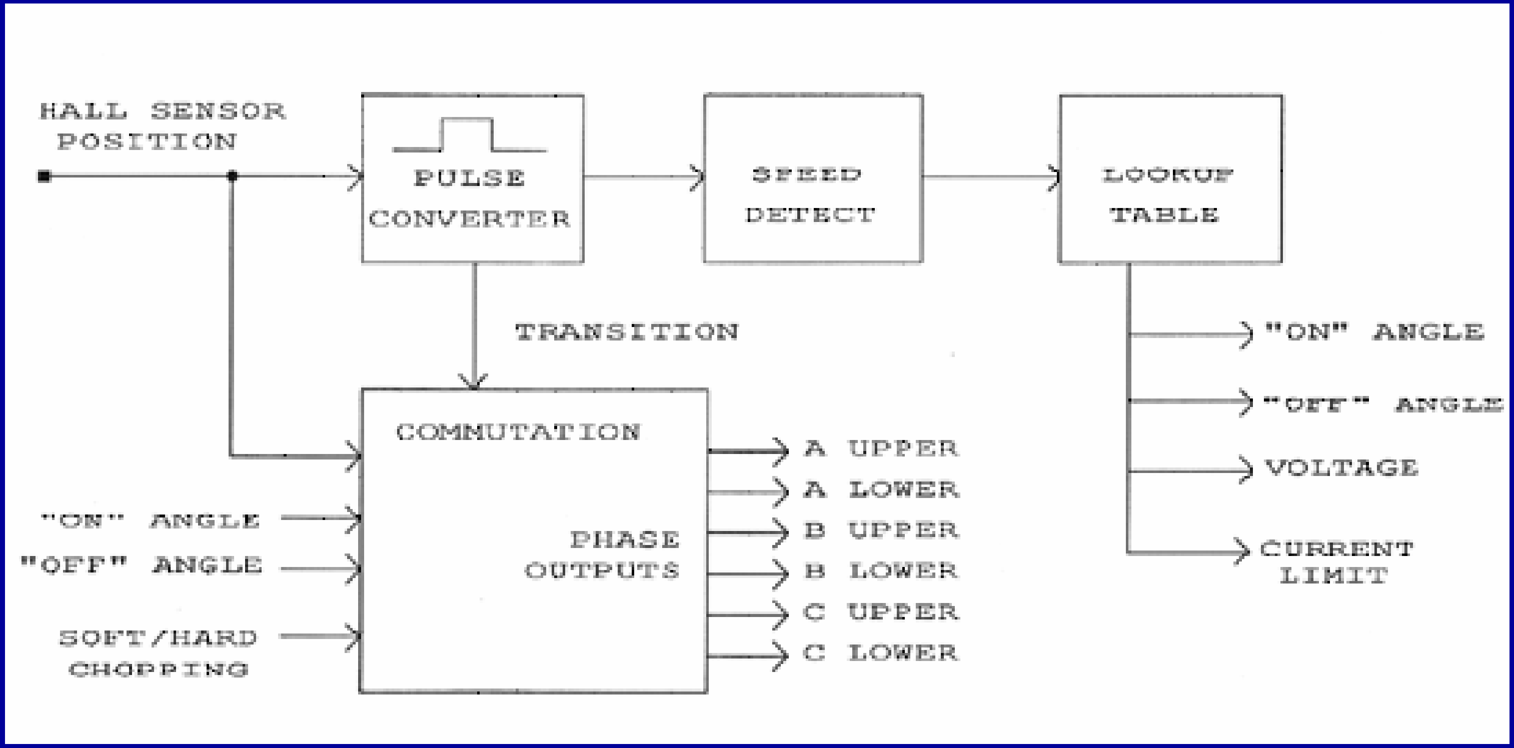


Controller design for SR motors

- drawbacks of the 2*(n-1) power topology
  - phases can not be controlled independently
  - upper switches must be sized for a higher load
  - the system loses its fault tolerant characteristics

Controller design for SR motors

- features of the SR control logic



Sensorless control SR motors

Sensorless control SR motors

- sensors are undesirable in any motor but especially in the SR motor
  - added cost
  - contamination
  - temperature limitation
  - interconnects

Sensorless control SR motors

- multiple schemes are available for sensorless control of the SR motor
  - observer models
  - inductance measurement through active probing
  - inherent inductance measurements during normal operation

Sensorless control SR motors

- observer models
  - construct mathematical model of the motor and match the model to the motor
  - difficulties at startup, when no operating history is available
  - have only been demonstrated at low speed, variable speed operation of up to 2000 RPM

Sensorless control SR motors

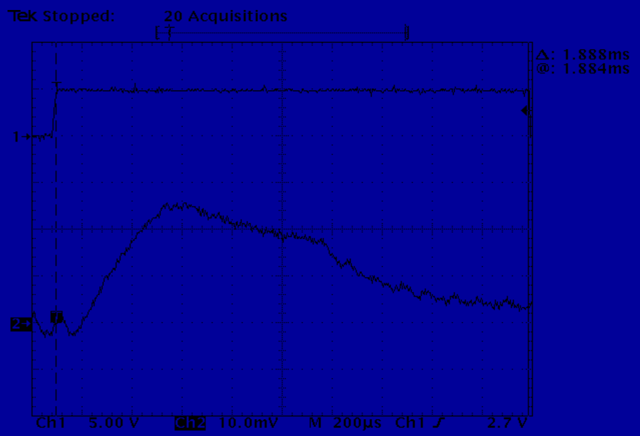
- inductance measurements through active probing
  - injects a signal (i.e. HF) into a phase (active or inactive) and measures the response
  - additional hardware is required, which increases cost
  - may be sensitive to noise pickup from switching

Sensorless control SR motors

- inherent inductance measurements during normal operation
  - comparison of the current waveform
  - measurement of the current level
  - current rise time
  - these methods will be discussed in greater detail

Sensorless control SR motors

- inherent inductance measurements during normal operation
  - comparison of the current waveform
    - typical VSR motor current waveform shows a hump in the motor current
    - determine the slope of the current and detect the peak or the shoulder
    - Problems with this approach:
      - can not be used to start the motor
      - different motors may have different waveforms
      - different loads may have different waveforms



Sensorless control SR motors

- inherent inductance measurements during normal operation
  - measurement of the current level
    - at low speeds compare the motor current to an absolute value
    - commutate at a preset level
    - Problems with this approach:
      - may not work for all motors
      - does not work at startup or

Sensorless control SR motors

- inherent inductance measurements during normal operation
  - current rise time
    - measure the time it take the current to rise by a given delta
    - compare the result to a preset level to determine the motor’s inductance and thus the position
    - Problems with this approach:
      - requires that a PWM signal is present
      - does not work with firing (phase) angle control

Sensorless control SR motors

- inherent inductance measurements during normal operation
  - differential derivative current measurement (patented)
    - measure the derivative of the motor current
    - compare the result to a preset level to determine the motor’s inductance and thus the position

Application considerations

Application considerations

- Advantages of the SR motor
  - VSR motors are of low cost construction
  - VSR motors exhibit very high efficiencies
  - VSR motors are very efficient at very high speeds
  - VSR motor power density is equal or better than high energy product magnets
  - VSR motors are tolerant to single point failure in winding and driver power stage
  - lack of magnets makes it suited for use in hostile (corrosion), extreme (temperature), or sensitive (clean, sealed) environments

Application considerations

- Drawbacks of the SR motor
  - SR motors are often noisy
  - SR motors require more complex control and commutation than BLDC
  - most VSR motors exhibit inherent torque ripple

Application considerations

- other issues with SR motors
  - maximum efficiency is achieved at rated (full) load
    - external excitation must be provided
    - the excitation becomes part of the power equation
  - suitable for efficient very high speed operation
    - waveforms contain high harmonic content
    - requires no special shaping of the current waveform
      - turn on and turn off of the phases
      - does not require sinusoidal waveforms

Application considerations

- the cost of the SR motor
  - studies show that the VSR motor is less costly than BLDC or AC induction motors for a given framesize and power rating
  - the bearing system is more expensive than those of comparable alternatives
  - mechanical tolerances and airgaps have tighter tolerances than those of comparable alternatives

Application considerations

- the cost of the SR controller
  - the commutation for best efficiency is a function of speed, desired torque, and efficiency
  - the commutation will be different for each motor geometry and operating point
  - the discrete implementation of the VSR control section will be complex
  - the cost of the integrated (IC) implementation of the VSR control section will be comparable to that of the BLDC or AC induction motor
  - speed and torque control can often be accomplished by controlling the firing (phase) angles, rather than pulse width modulation (PWM)

Application considerations

- the cost of the SR power driver
  - Unipolar phase currents require fewer power switches
  - Firing (phase) angle control results in reduced switching losses
  - Firing (phase) angle control reduces the cost of the power stages

Application considerations

- the cost of the SR system
  - the motor costs less than BLDC or AC induction
  - the power section costs less than BLDC or AC induction
  - the control section cost equals that of BLDC and AC induction

Application considerations

- typical applications for SR motors
  - pumps (cost, size, weight, fail safe)
  - high speed compressors / fuel cells (high speed, cost)
  - traction drives (cost, fault tolerance)
  - appliances (weight, performance, cost, ruggedness)