SWITCHED RELUCTANCE MOTOR AND DRIVES FOR HIGH-PERFORMANCE EV – A REVIEW

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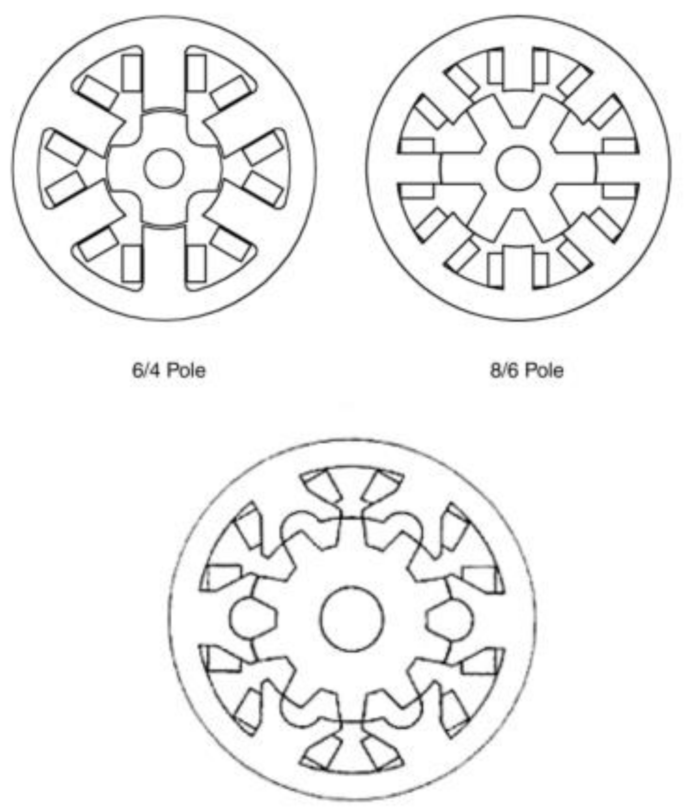
OUTLINE

- Introduction
- Design methodologies
- Converter circuits
- Control strategies
- Development in automotive applications
- Conclusion

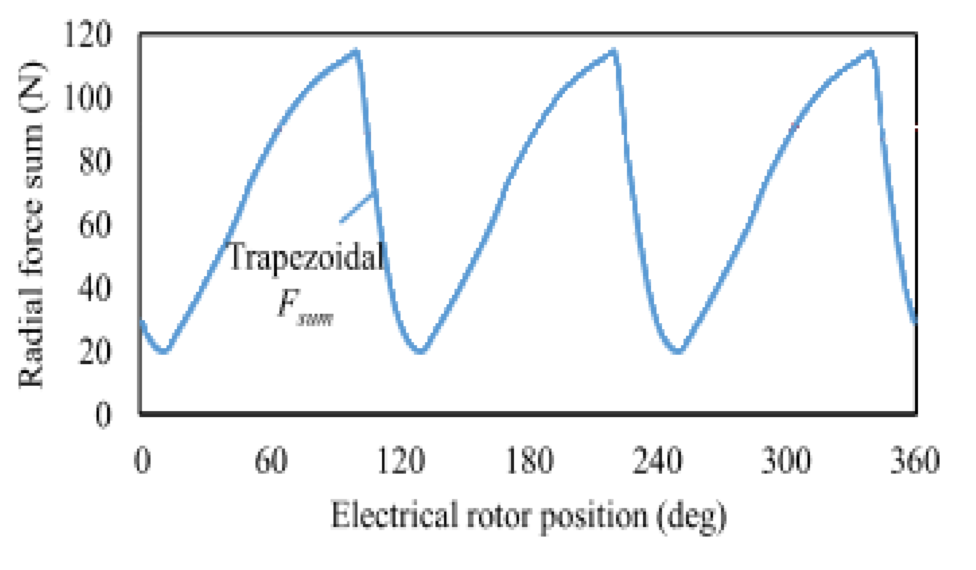
INTRODUCTION

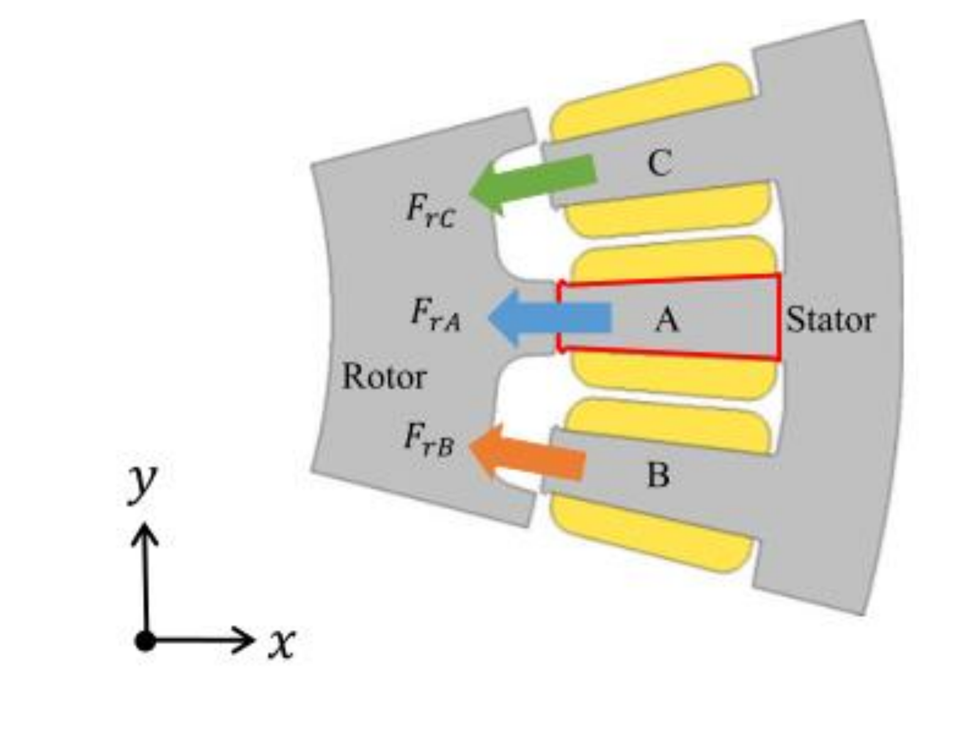
- The concept of SRMs were first developed in late-1830s.
- Did not succeed in capturing a market share due to lack of modern power electronics and CAD-based design tools.
- SRMs are doubly-salient and singly-excited.
  - Rotor is made of stacks of laminations.
- Simple, rugged structure without the need for permanent magnets make SRM cheap to manufacture.
- Majority of the copper lies in the stator i.e., in the periphery of the machine, thus cooling is easier.



INTRODUCTION (CONTD.)

- Current is unidirectional and is independent of the direction of current.
  - Drives can work with one switch per phase.
- Pulsating radial forces on rotor cause acoustic noise and vibrations.
- Pulsating stator excitation cause significant torque ripple.





DESIGN METHODOLOGIES

- First step is to develop accurate machine models and determine the operating parameters.
- Due to double saliency, non-linear current flows in the windings.
  - Design is therefore more difficult and complicated than conventional singly salient machines.
- Extreme care is required during the initial design process is to ensure high torque and power density, quick response, extensive speed range and high efficiency.
- Design methods can be classified as:
  - Analytical method
  - FEA
  - Optimisation method

DESIGN METHODOLOGIES (CONTD.) ANALYTICAL METHOD(1/3)

- Analytical methods involves solving implicit and explicit expressions involving machine dimensions and inputs to performance variables.
  - Can be subdivided into linear method and nonlinear method.
- Linear methods involve only the parameters which are current independent.
- Non-linear methods involve current dependent parameters like magnetic saturation.
- Most often these methods give the three-dimensional relationship between torque, flux linkage and rotor position.

DESIGN METHODOLOGIES (CONTD.) ANALYTICAL METHOD(2/3)

- Ray and Davis [1] presented a method to linearise the inductance to allow voltage switching at any point in a cycle.
  - This helped in development of control strategies.
  - Leading to accurate experimental examination of SRMs.
- Krishnan and Arumugam [2] presented output equations for SRM
  - Earlier no output equations were present
  - These equations helped engineers to make designs rapidly.
    - $P_d = k_e * k_d * k_1 * k_2 B * A_{sp} * D^2 * L * N_r$
    - $T = k_e * k_d * k_3 * k_2 * B * A_{sp} * D^2 * L$

DESIGN METHODOLOGIES (CONTD.) ANALYTICAL METHOD(3/3)

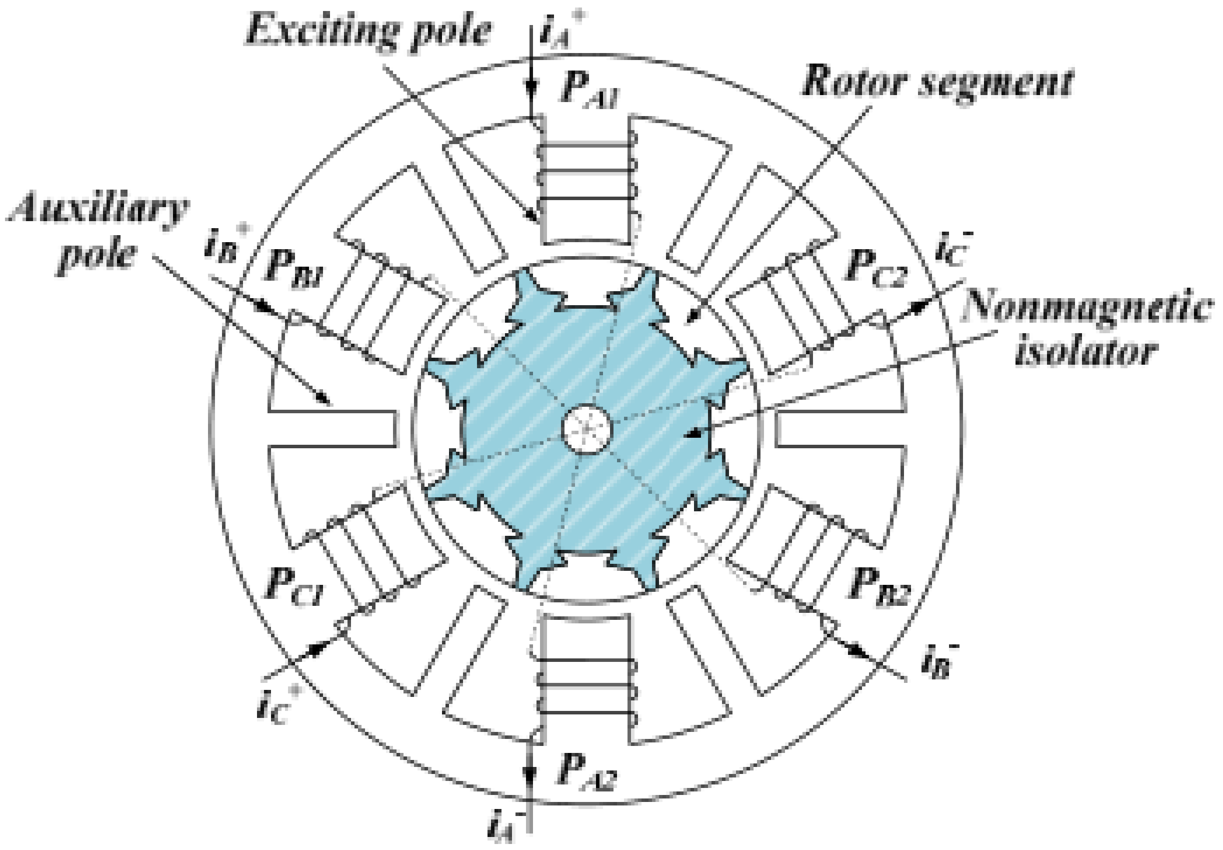
- During aligned position, rotor tends to saturate.
  - This introduces nonlinearities.
  - Modelling attempt through geometric studies considering stator/rotor geometries, multiple tooth per pole, etc.
- Radun [3], Finch [4] and Mao et al. [5] developed methods to determine air gap flux and phase inductances.
  - Radun and Mao papers approximate the rotor and stator poles into rectangular structures.
- Li et al. [6] developed on the works of Radun and Mao and generalised the method.
  - Assigned flexible boundary conditions and using on polar coordinates.

DESIGN METHODOLOGIES (CONTD.) FINITE ELEMENT ANALYSIS

- General, advantageous method to rapidly solve nonlinear differential equation.
- With improvements in computational power, FEA is a go-to tool for designers today.
- Dawson utilised two-dimensional FEM to analyse the torsion of an SRM drive system and made a comparison experimentally.
  - Experimentally measured torsion vs rotor angle closely match FEM results.
- A study done in [9][10] used FEM to develop a novel design with stator pole face with non-uniform air gap with a pole shoe attached to the rotor.

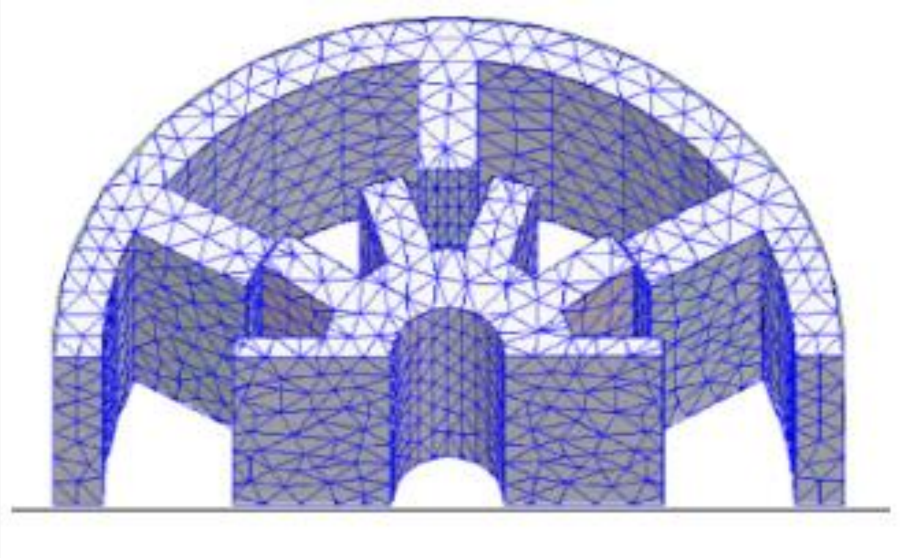
DESIGN METHODOLOGIES (CONTD.) RECENT DESIGN DEVELOPMENT (1/N)

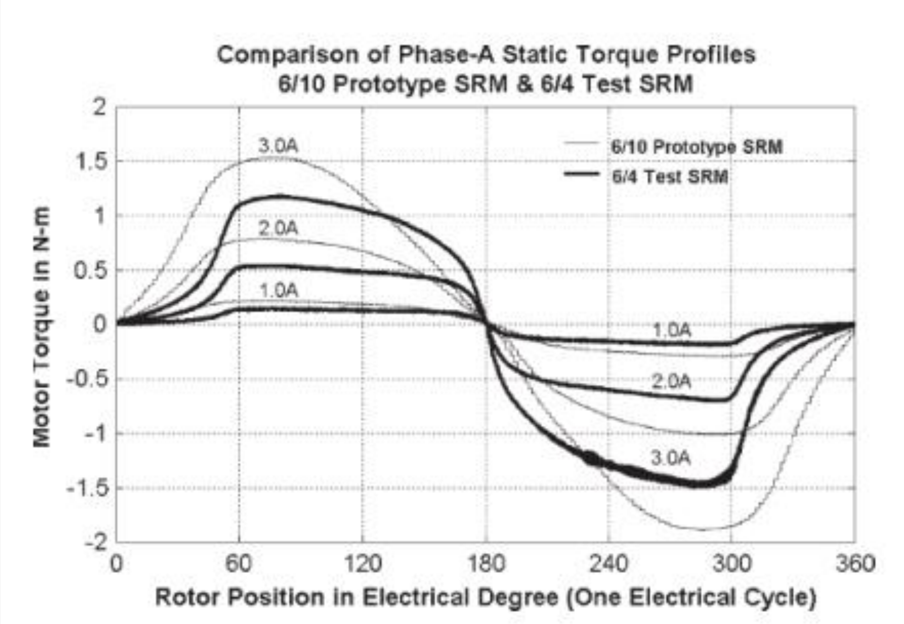
- Xu et al. [13] presented a 12/8 SRM with segmental rotor with hybrid stator.
- Shorter flux path and negligible flux reversal.
  - Hence, improved electrical utilization.
- Stator is comprised of main and auxiliary poles.
- Rotor is constructed on a non-magnetic isolator with series of discrete rotor segments.



DESIGN METHODOLOGIES (CONTD.)
RECENT DESIGN DEVELOPMENT (2/N)

- Desal et al. [14] developed a new pole design formula.
  - Results in more rotor poles than stator poles.
- In this study FEA is used to simulate conventional 6/4 SRM and compare with novel 6/10 SRM.
- The angular travel per stroke is lesser compared to conventional machine.
  - Higher average torque.
- The proposed machine has higher average torque and higher peak torque at all test currents and almost all rotor positions.
  - Torque ripple is comparable.

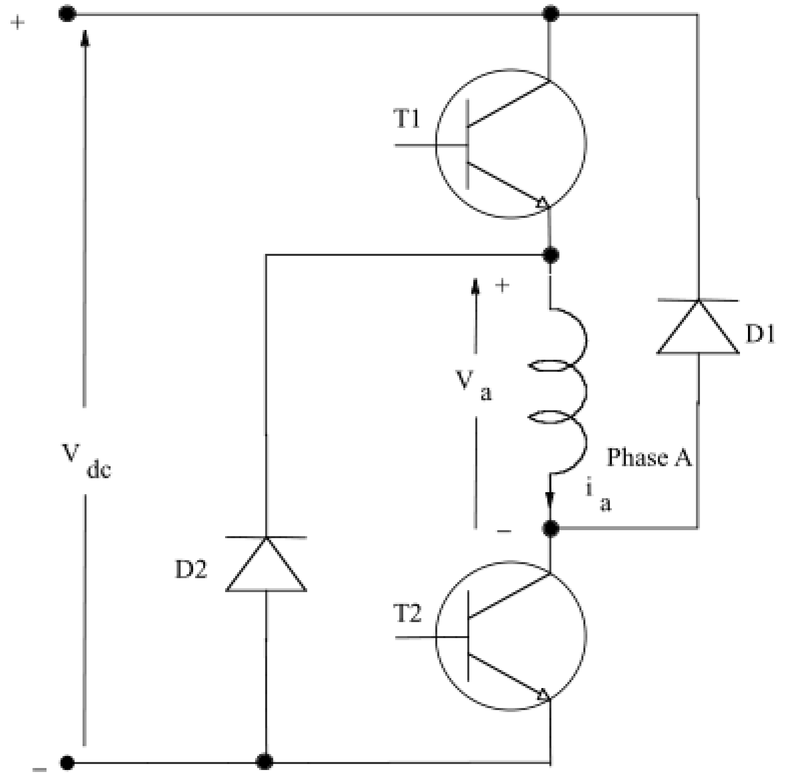


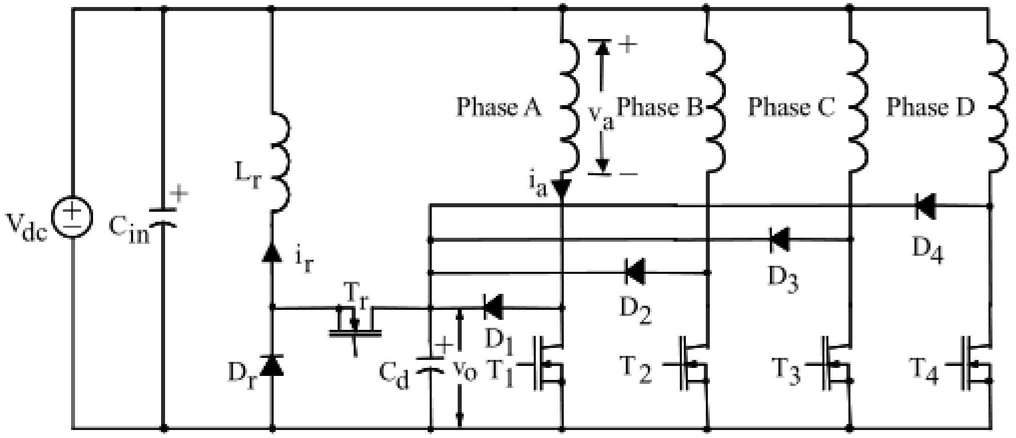


CONVERTER CIRCUITS

- Power converters form the heart of any drive.
- SRMs inherent issues of torque ripple and mutual coupling in high speeds can be addressed by accurate commutation and current control, and smooth switching.
- Unlike conventional motors, SRM have nonhomogeneous airgap flux
  - Hence nonconventional power converter are required.
- The key advantage of converters for SRM is that minimum switch required per phase is only one.

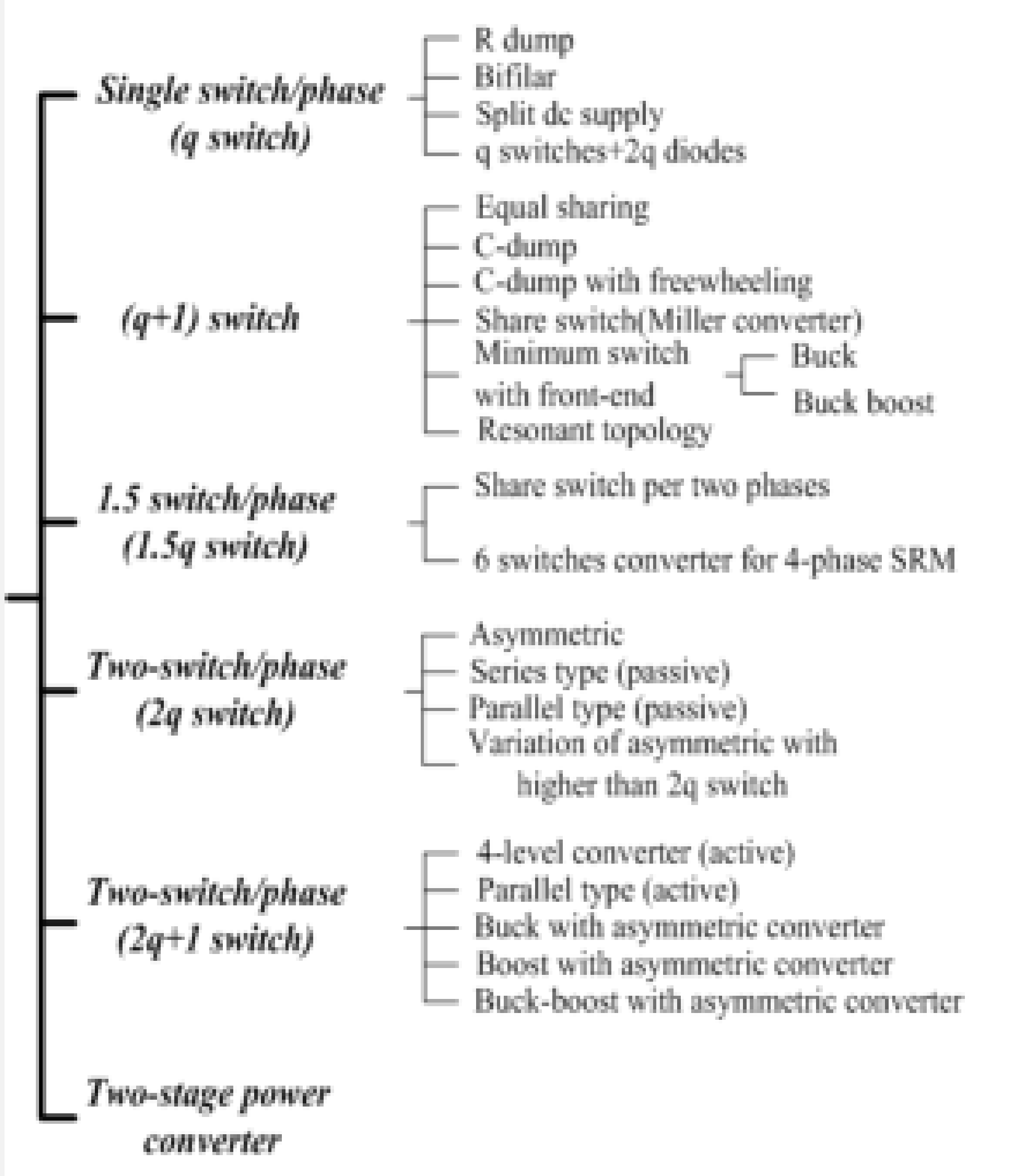
CONVERTER CIRCUITS (CONTD.)





CONVERTER CIRCUITS (CONTD.)

- Choice of converter topology depends on application for which the drive is used.
- Significant features of SRM drives:
  - Independent phase conduction.
  - Complete phase demagnetization before unalignment occurs.
  - Switches are always in series with phase and they are parallel to the source; high reliability.
  - Safe and continuous operation at reduced power in case of phase failure.

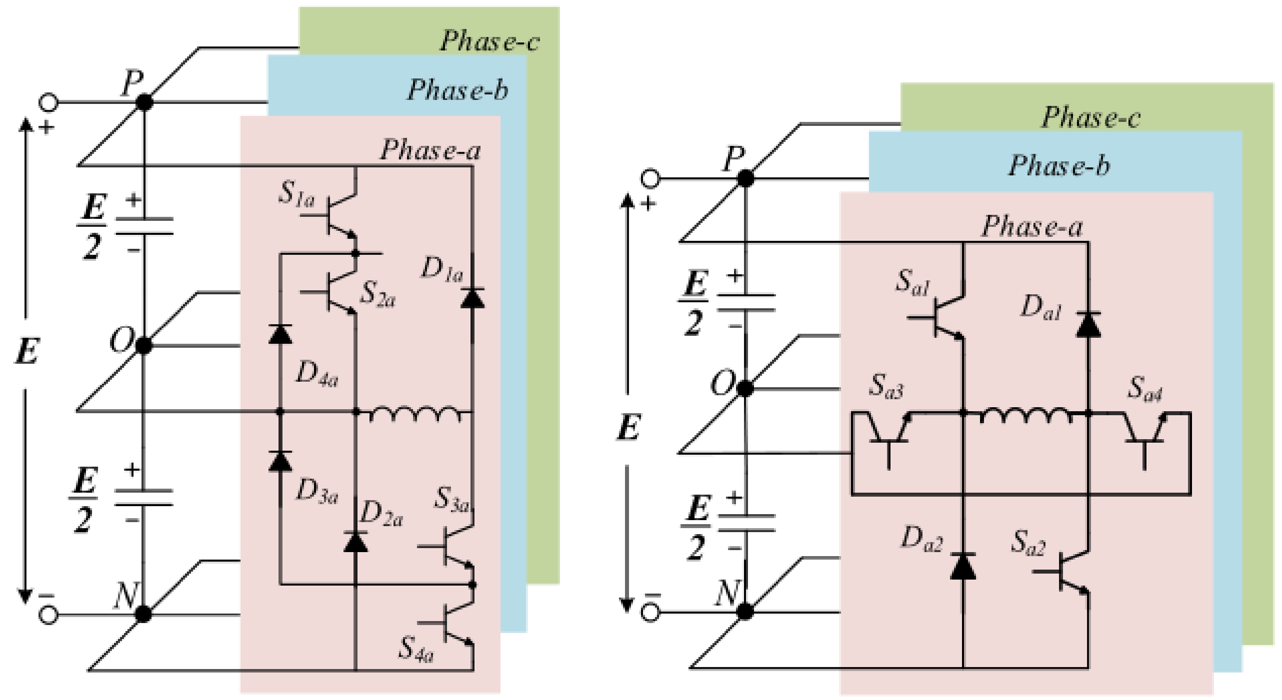


CONVERTER CIRCUITS (CONTD.)

Converter type	Benefits	Drawbacks	Applications
R-Dump Converter	Low Cost	Low efficacy	Low speed
C-Dump Converter	Independence phase control	Low efficiency	Low speed
C-Dump with Freewheeling	Low cost	Complex control	Motoring operation
Asymmetric, Series& Parallel	High efficiency, Simple control	High No. of devices	Low power
Bifilar	Regenerative operation	Low power density	Small motors
Split DC supply	Low cost	Motoring operation only.	Even phases No. motors
Minimum Switch with Variable DC- link	Low core losses, Reduce noise, Low switching	Low efficacy	Sensorless applications
Two- Stage Power Converter	High power density	High No. of devices	Wind energy
Resonant Converter	Low switching losses, High switching	Low power density EMI influence	High-frequency applications

CONVERTER CIRCUITS (CONTD.)
RECENT DEVELOPMENT

- Azer et al. [34] proposed a three-level T-type converters for HEV applications.
- Proposed converter is compared to conventional asymmetric NPC converters.
- Better efficiency and higher reliability against open-switch faults.
  - Cost is comparable to conventional NPC converter.
- Simulations of Chevrolet Spark EV on repeated UDDS cycles predict 10% farther drive compared to conventional converter on same battery energy depletion.



CONTROL STRATEGIES

- The key disadvantages of SRMs like, acoustic noise, vibration and torque ripple can be mitigated to a large extent by implementing complex control strategies.
- Control of high-performance EVs cannot be sufficed by using simple PID controllers.
  - Modern control strategies for machines have been presented, like model-referencing adaptive control, self-tuning control, fuzzy control, neural network control, AI-based control, etc.
  - For EV applications fuzzy control and AI-based control are most promising [15].

CONTROL STRATEGIES (CONTD.)

- Control is done using position sensor or using sensorless methods.
  - Sensorless methods require at least a current sensor.
- SRM control can be done based by:
  - Current control,
  - Speed control, and
  - Torque control.
- Control can also be done based on performance parameters such as, minimising torque ripple or acoustic noise and vibrations.

CONTROL STRATEGIES (CONTD.) CURRENT CONTROL

- Voltage control although cheaper, but is prone to supply fluctuations.
- Two types of current control:
  - Hysteresis Current Control (HCC),
  - PWM Control.
- HCC is a basic strategy; commonly used during starting to reduce the current overshoot.
  - Also used in low speed control.
- HCC requires high switching frequency to reduce current ripple.

CONTROL STRATEGIES (CONTD.) CURRENT CONTROL

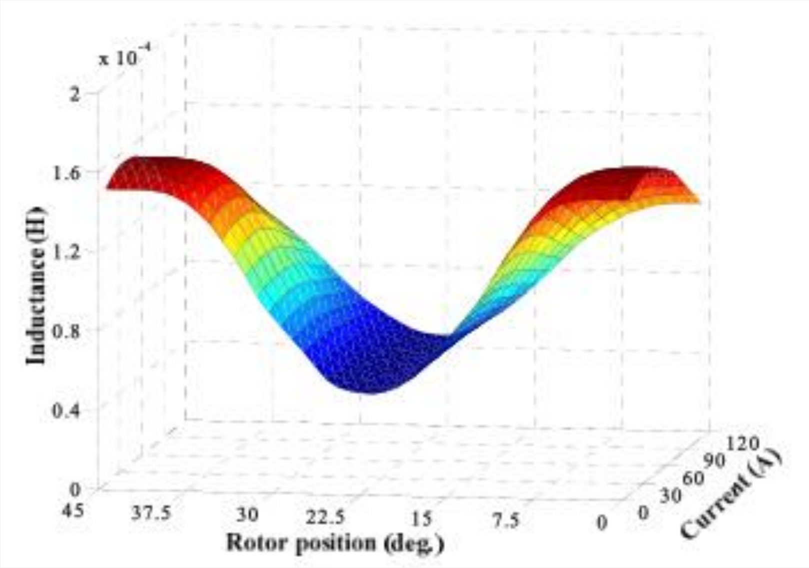
- In PWM control simpler controllers like P, PI and PID can be easily implemented.
  - Common choice for lower-end drives.
- Difference between reference and control input is fed to controller, its output modulates the width of the pulse to gate drivers.
- At conditions that cannot be tracked, the switches are kept ON till commutation occurs.
  - This is called Single Pulse Control (SPC).

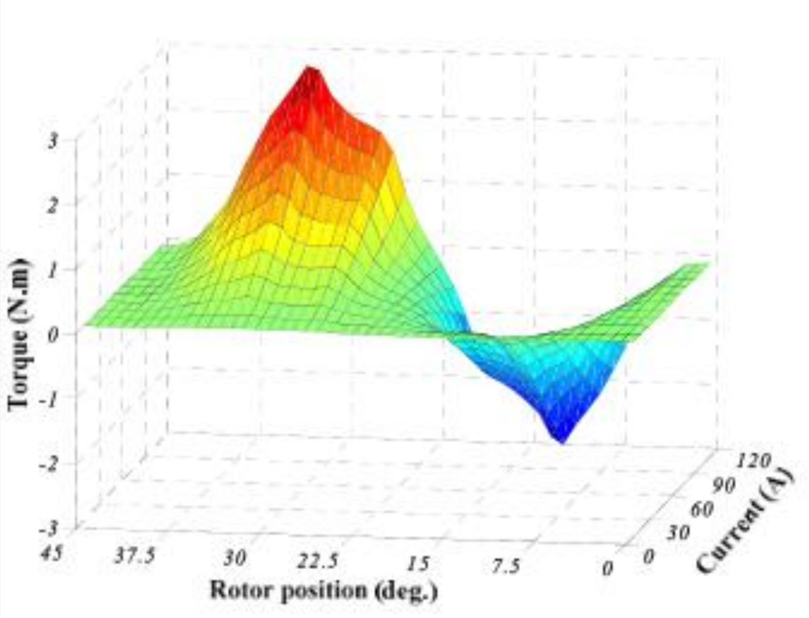
CONTROL STRATEGIES (CONTD.)
SPEED CONTROL

- Speed is measured using speed sensor or estimated using rotor position and compared to reference speed.
  - Reference is set using throttle.
  - Very commonly used in automotive applications.
- High-performance, high-efficiency drives use double loop.
  - Inner loop is speed control and outer loop is current control.
- Parasivam et al. [20] proposed advanced DSP based controller.
  - Experimentally shown to accurately control speed over a wide range and at various conditions.

CONTROL STRATEGIES (CONTD.) TORQUE CONTROL

- Three dimensional relationship exists between flux linkage, phase current and rotor position
  - Resulting in nonlinear relationship between torque and excitation current.
- Types of torque control:
  - Indirect torque control; uses complex algorithm to determine reference current.
  - Direct torque control; uses simpler methods like hysteresis control





CONTROL STRATEGIES (CONTD.)
TORQUE CONTROL

- Torque Sharing Function control is a simple and powerful control strategy.
- Sensed rotor position determines the torque requirement.
  - Lookup tables are used to determine torque reference.
- Reference torque is split for each phase and reference current for each phase is determined.
  - Nonlinear controllers are used to generate gating pulses.
- Indirect control are simple to implement but require several predetermined values such as command current and switching angle.
  - These values must be determined experimentally which tends to increase the cost, especially for high-end drives.

CONTROL STRATEGIES (CONTD.) TORQUE CONTROL

- Drawbacks of indirect control can be overcome using direct control strategies.
  - Motor torque itself is the control variable.
- Instantaneous torque is estimated using either functions of phase currents and rotor position, or flux linkage and phase currents.
  - Functions can be determined accurately using FEA.
- Measured rotor position and phase currents are compared with FEA plots to determine the torque reference.
  - This is called Direct Instantaneous Torque Control (DITC).
- DITC is considered most promising strategy for high-performance EV drives.

CONTROL STRATEGIES (CONTD.) RECENT DEVELOPMENT

- DITC performance can be improved by using PWM generator control the duty cycle of the power switches.
  - The phase voltages can be regulated to control the currents in single sampling time.
- Another method is to predict future machine states to obtain optimum switching commands
  - Current is used to determine only the flux linkage and no current loop is required.
- Pulsating radial forces on rotors due to excited stator pole its neighbours are the main cause of noise and vibrations.
- Research led by Akira Chiba at Tokyo Tech proposed to reduce noise and vibration by flattening radial forces by using novel current waveforms [22]-[26].

DEVELOPMENT IN AUTOMOBILE APPLICATIONS

- While designing SRMs for EVs special attention must be given to vehicle dynamics.
  - Speed-torque profile for propulsion is dictated by VD.
- Studies show that drives must work in constant power region entirely.
  - Required to meet operational characteristics [28].
- Most of the research is targeted towards SRM drives is to develop powertrains comparable to Nissan Leaf and Toyota Prius [30].
- In a study done by Kasprzak et al. [31] and Jiang et al. [32] proposed a 24/16 SRM with speed-torque profile similar to Prius.

DEVELOPMENT IN AUTOMOBILE APPLICATIONS (CONTD.)

Affiliation	Peak power	Peak torque	Maximum Speed	Maximum speed at peak torque	Maximum power-to-weight ratio	Efficiency over 85% region portion	Machine topology	Cooling method	Validation method
University Manchester	26 kW	120 Nm	4,500 rpm	1,200 rpm	N/A	N/A	24/16	Liquid/Coolant	Experiment
Fukuoka Inst of Tech	30 kW	594 Nm	2,200 rpm	482 rpm	N/A	N/A	6/4	Liquid/Water	Simulation
Meiji University	40 kW	100 Nm	6,400 rpm	3,000 rpm	N/A	N/A	12/8	N/A	Experiment
University of Akron	50 kW	122 Nm	12,000 rpm	8,000 rpm (48 Nm)	N/A	60%	12/8	Liquid/Water	Experiment
Illinois Inst of Tech	50 kW	300 Nm	6,000 rpm	1,600 rpm	1.18 kW/kg	85%	12/8	N/A	Simulation
General Motors	56 kW	710 Nm	N/A	750 rpm	N/A	70%	24/16	Liquid/Coolant	Experiment
McMaster University	60 kW	210 Nm	13,500 rpm	2,750 rpm	2.64 kW/kg	92%	24/16	N/A	Simulation
Newcastle University	82 kW	285.8 Nm	10,500 rpm	2,750 rpm	2.52 kW/kg	N/A	12/8	N/A	Experiment
Toyota Industries	100 kW	164.7 Nm	10,000 rpm	5,800 rpm	2.22 kW/kg	N/A	6/4	Liquid/Oil	Simulation
HUST	101 kW	377.3 Nm	4,500 rpm	2,556 rpm	0.94 kW/kg	80%	8/6	Liquid/Coolant	Experiment
Tokyo Inst of Tech	109 kW	209 Nm	13,900 rpm	5,400 rpm (185 Nm)	4.32 kW/kg	88%	18/12	Natural Air	Experiment

DEVELOPMENT IN AUTOMOBILE APPLICATIONS (CONTD.)

- For EVs, a large maximum peak torque is a preferred advantage.
  - This indicates the maximum acceleration motor can provide while running at moderate speed.
- Conventional ICEs have significant torque ripple [33].
  - Since EVs work in dynamic states, torque ripple may not pose significant problem.
- Pulsed stator excitation results in considerable torque ripple; hence most SRMs are 3-phase or 4-phase.
- In addition, torque ripple can be reduced by using advanced control strategies.

CONCLUSION

- A brief review of switched reluctance motors as an emerging technology is presented.
- Focus is given to automotive applications of SRM, especially EVs/HEVs.
- Existing and novel methods for designing SRM, converter topologies and control strategies are discussed.
- A brief overview of current research on SRM for EV/HEV is presented.
- Most often the research focuses on one particular aspect of SRM drive.
- This often leads to compromise on some other parameters of the drive.
- A multi-objective design research is necessary to push the SRM towards commercial viability.

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