Review of electric motor technologies for ESP applications

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Introduction

The aim of this presentation is to summarise the findings of an 8-week motor study commissioned by Aramco Europe’s Aberdeen Technology Office (ATO) with the University of Manchester.

The presentation is divided in 3 sections:

1. Electrical Machine Topologies and Drives
2. Proposed improvements in the design of the Induction Machine

Where are we now on ESP motor technology

- From the early days of commercial ESP applications (circa 1928), 2 pole inductions motors have been the work horse of the industry
- In the late 2000’s Permanent Magnet Motors (PMMs) started to gain popularity, owing to their high efficiency and power density
- With a growing focus on sustainability and recycling this presentation will take a high level look at possible alternative Electrical Machines, to meet the demands of the industry

Figure 3 – Permanent Magnet Machine [3]-[9]

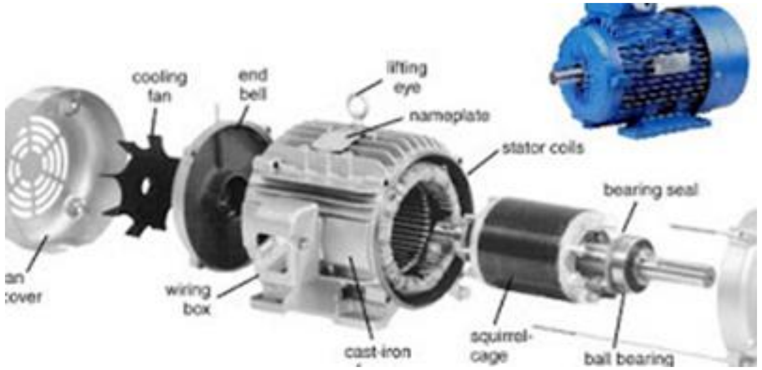

Figure 4–Induction Machine [3]-[9]

Electrical Machine Topologies and Drives

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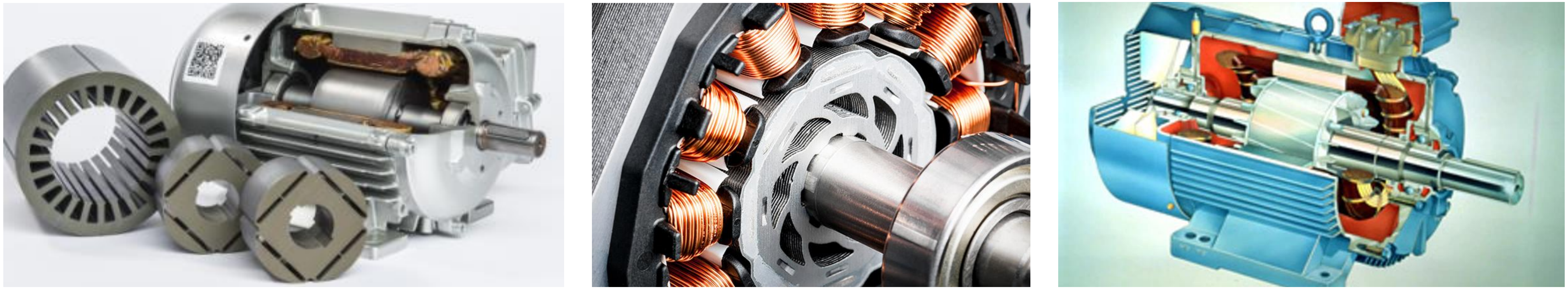
Motor technologies to interest



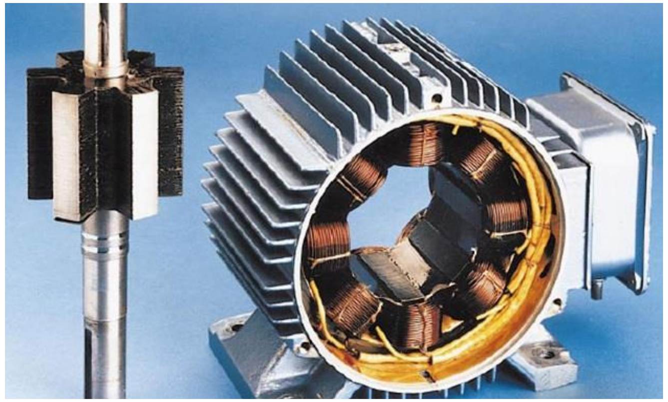
Permanent Magnet Motor (PMM)

Brushless DC Motor (BLDC)

Induction Motor (IM)

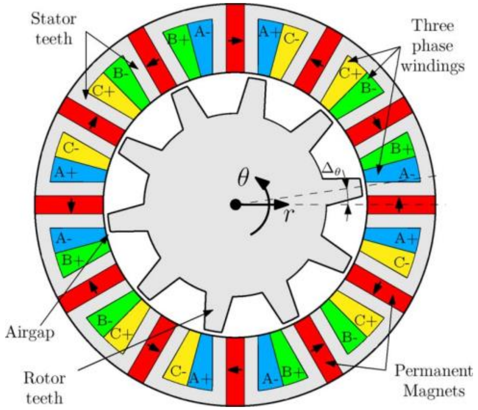
Figure 5–Machine Topologies [3]-[9]

Motor technologies of interest



Switched Reluctance Motor (SRM)

Synchronous Reluctance Motor (SynR)



Flux-switching Motor

Figure 6–Machine Topologies [3]-[9]

Motor Dimensions

- In essence the power generated by an electrical machine is determined by 4 factors: A , B_g , the mechanical speed and the volume of the rotor:

$$P_{mech} = \pi^2 \cdot \frac{rpm}{60} \cdot \frac{A \cdot B_g \cdot \cos\varphi}{\sqrt{2}} \cdot D^2 \cdot L$$

Where A and B_g are *linear RMS current density* and *peak magnetic flux density* in the airgap respectively, which are predefined from well-known ranges. "A" is effectively the amount of current in the motor (limited by heating) and "B_g" is the magnetic field in the stator (limited by saturation).

- With the outer diameter of the motor constrained by the well casing diameter, the active length of the machine is increased to provide the required output power
- The high aspect ratio L/D, of an ESP motor gives rise to some specific problems concerning the rotor-dynamics:
  1. Critical Speed
  2. Unbalanced Magnetic Pull (UMP)

Critical Speed

- Any shaft deflection due to out-of-balance forces increases as the rotor speed approaches the first critical speed and the rotor will start to “whirl”.
- The rotor must be operated either below the first critical speed (sub-critical) or between the first and second critical speed (super-critical).
- The critical speed will decrease for higher aspect-ratios L/D.

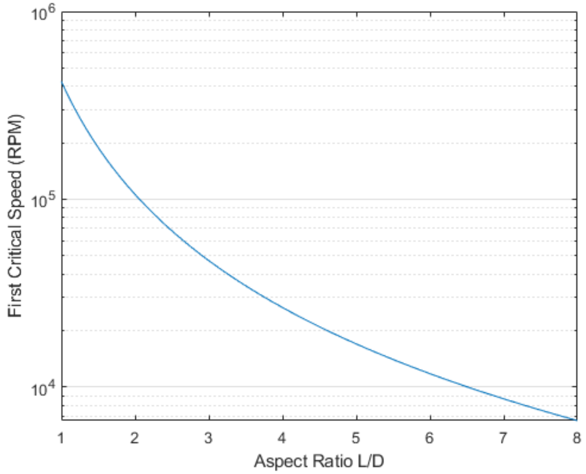


Figure 7 – Critical Speed vs Aspect Ratio

Unbalanced Magnetic Pull

- When the rotor is eccentric, one side will have its magnetic airgap reduced.
- The uneven distribution of the airgap produces a magnetic force (UMP) to reduce it further
- When UMP is large, the rotor is ‘pulled’ from its axis and the critical speed is reduced.
- UMP can cause permanent damage to the machine (rotor strikes the stator!)
- One method of reducing the UMP is to increase the air gap but with performance penalties.

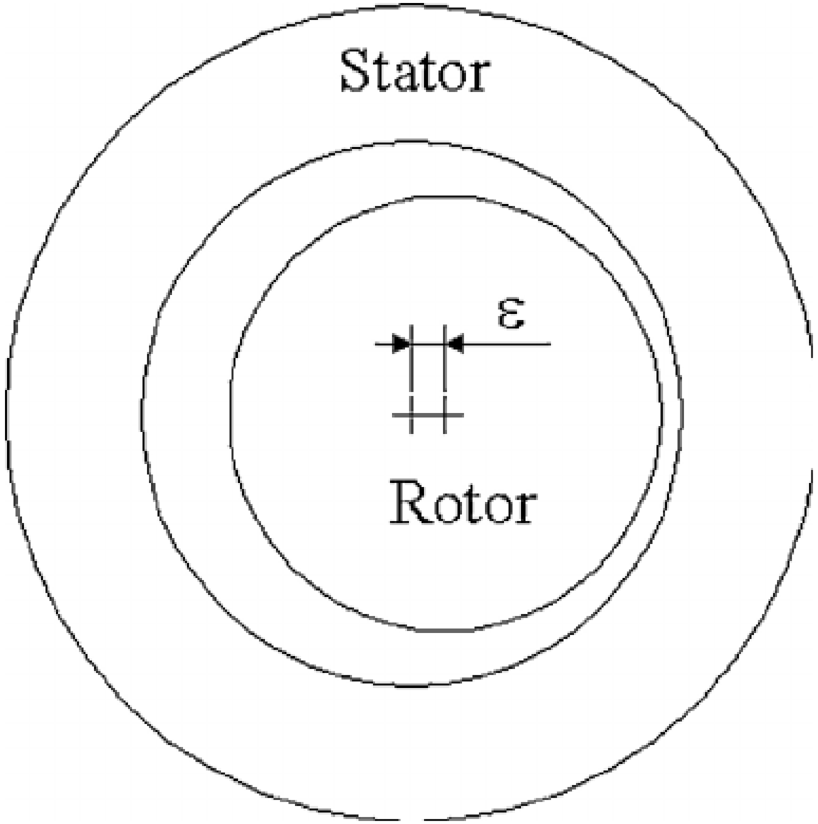


Figure 8 – UMP [10]

Permanent Magnets

- PMs are rare-earth materials that are able to retain a high magnetic field strength after being magnetized
- Demagnetization (partial or complete) due to high temperature exposure is an issue.
- Consider operation to an ambient well temperature of 135˚C.
- Neodymium Iron Boron (NdFeB) magnets have higher energy product compared to Samarium-Cobalt (SmCo) but above 150˚C SmCo has better performance.
- Current state of the art PMM in ESPs use SmCo for the rotor magnets.

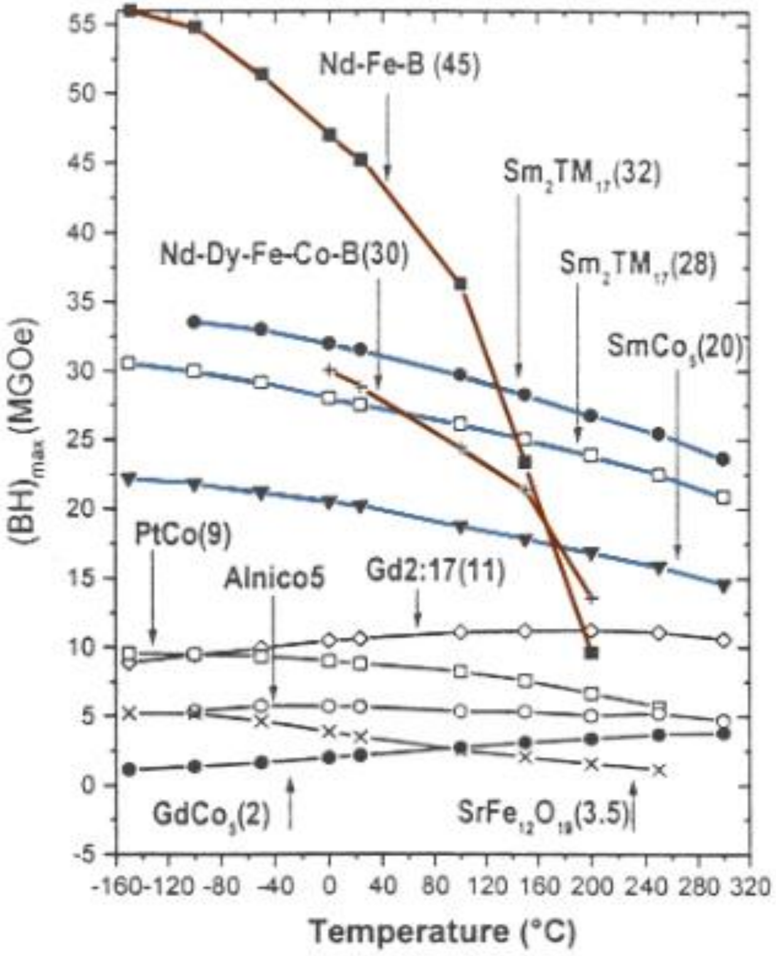


Figure 9 - (BH)max vs Temperature [11]

Airgap

- For “in-well” downhole the dielectric oil inside the airgap cools down and lubricates the rotor bearings.
- If the diameter of the airgap is too big, the magnetic performance is reduced.
- In induction motors if the airgap is increased the magnetizing current must also increase to provide same power and power factor reduces
- In PMM the increase in airgap is mitigated with the increase of the magnet thickness (more magnet!)
- In SyncR and SR machines, the air gap is required to be as small as possible to force the motor into a highly saturated mode to increase power density.

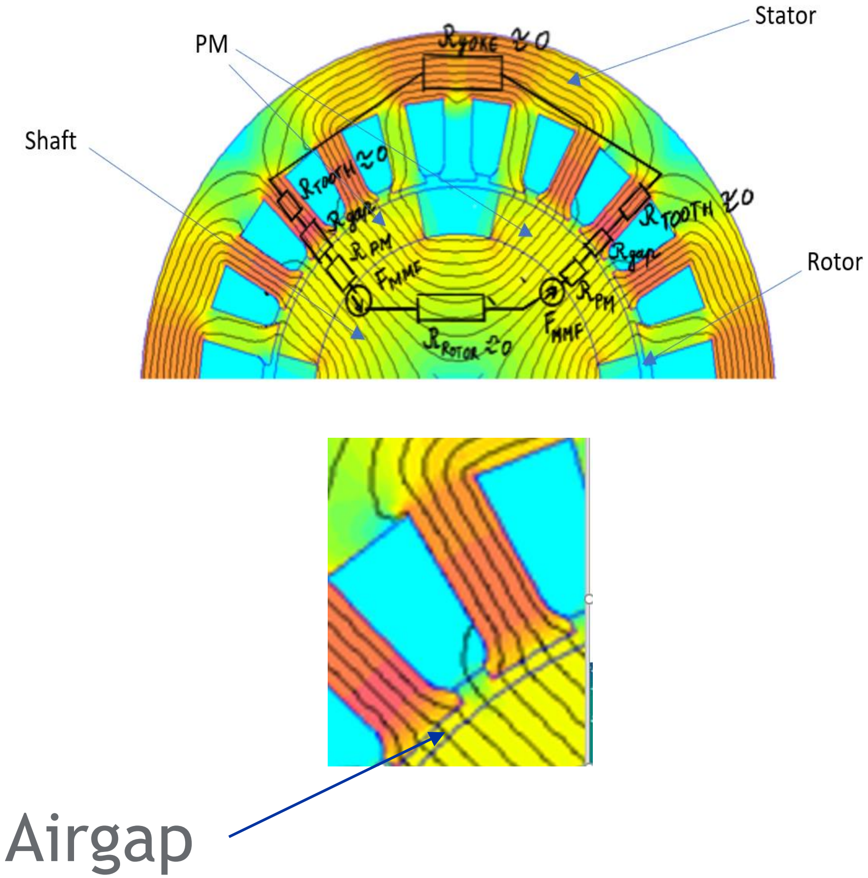


Figure 10 - Airgap

Windings

- The windings of a motor can be of 2 types:
  1. concentrated
  2. distributed
- Brushless DC (BLDC), Switched Reluctance and Stepper motors use concentrated windings.
- Concentrated windings provide less copper losses but have high eddy current losses in high speed applications for PMM.
- Induction and Synchronous Reluctance machines use distributed windings by design.
- Switched Reluctance Machines use concentrated windings. In conventional machines there are 6 wires used to drive the motor.

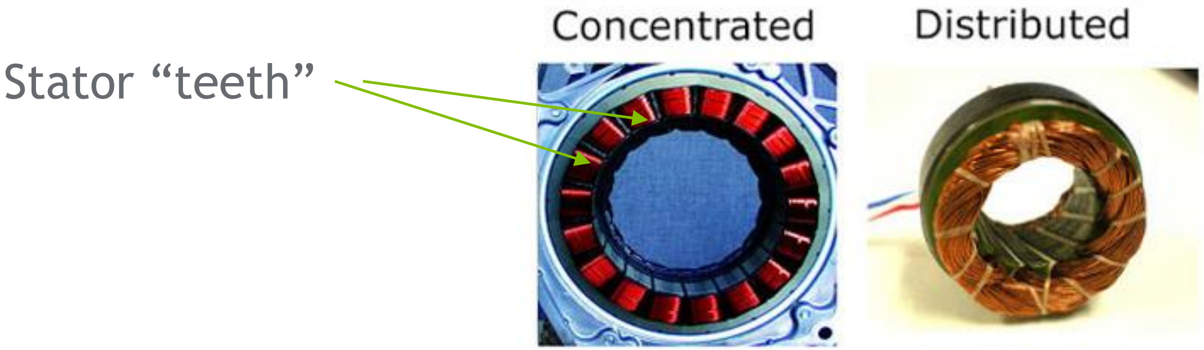


Figure 11 – Concentrated and Distributed windings [12] [13]

Table 1 – Number of wires required to drive the motor

Motor Technology	Power Wires	Control Wires
Induction Machine	3	0 - No sensor
PM Machine	3	0 - No sensor
BLDC	3	0 - No sensor
SyncRM	3	1
SRM	3	3
Flux-Switching	3	1

Machine Characteristics…Pros/Cons

- Compared to 2 pole IM:
  - PMM:
    - Power density and efficiency: higher => for the same volume, PMM provides more power
    - Length v Diameter: PMM shorter length and smaller diameter due to high power density=> good candidate for ESP applications
    - Demagnetization and fault current issues
  - BLDC motors:
    - Power density: higher => as the PMM, smaller package
    - Efficiency: higher efficiencies => no need for magnetizing current
    - Demagnetization issues and control over long distance

Machine Characteristics…Pros/Cons

- SRM:
  - Very good fault tolerance
  - More cables are required to drive the machine
- Flux-Switching:
  - Power density: higher => PMM still have better characteristics
  - Modular design (Stator made from segments) good for fault tolerance
  - Cogging torque is a big issue
  - Require double the PM amount compared to PMM (two airgap-crossings per PM)
- SynR:
  - Power density: SynR machine can produce more torque per volume than an IM
  - Power Factor: lower => better efficiency
  - Torque: SynR machine provide around 80% of a same size IM
  - Copper losses: 50% less => better thermal results => can push the design even further to achieve more power

Power Electronics

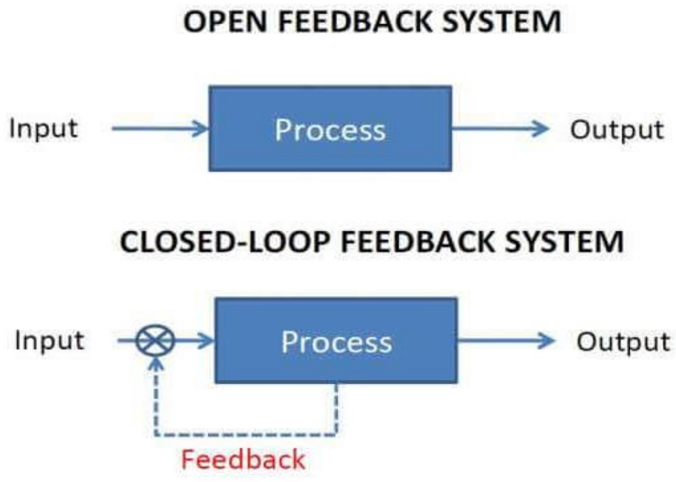


Figure 12 – Open and Closed Feedback system [14]

- Motor control, operations:
  1. open loop (no feedback)
  2. closed loop (feedback required)
- Constant-frequency IM efficiency falls off either side of nominal values => Variable Frequency IM or PMM better for variable loads or/and optimised design
- Open-loop simple & robust “V/Hz control” technique available for IM, more challenging for PMM (instability)
- Well-estabished closed-loop, high-dynamics control technique for IM & PMM (including sensorless, if accuracy at nearly-zero speed is not a requirement)
- Rotor position required for: SR, SynR and BLDC motors
  - Hall sensor not suitable in high temperature environments => Back-EMF is used to calculate rotor position.
- SRM and BLDC require square wave pulse to energize the stator coils

Sustainability

- Permanent Magnet Machine:
  - High efficiency compared to other topologies
  - Compatible with the equipment already installed
  - Mining for Neodymium and Dysprosium used in PMs, is very harmful for the environment
  - Recycling of Rare Earth Elements is not a well established procedure
- Induction Motor:
  - Compatible with the equipment already installed
  - Less efficient and power dense compared to PMM and SyncRM
- Synchronous Reluctance Machine:
  - Rotor does not contain any Rare Earth Elements or copper windings
  - Efficient Design
  - Needs an additional wire for control

Conclusion

- There is not a universal solution for electrical motors, and an in-depth analysis in respect to the specific application must be made.
- Although PMM have recently caught the attention of the oil industry for artificial lifting solutions, IM is still a valuable candidate in this application, and SynR may be worth assessing.
- BLDC and SRM control requires DC pulse switching which requires a complete redesign of the inverters.

Proposed improvements in the design of the Induction Machine

02

Induction Machine

- The rotational speed of the Induction Motor (IM) is given by: $RPM = \frac{120 \cdot Supply\ Frequency}{Nr\ of\ Poles}$
- Historically, two-pole IMs have been used for ESP owing to direct line start & run requirement (50/60 Hz) and high speed (3000 RPM/3600 RPM), ideal in the early days of ESPs before Variable Speed Drives (VSDs) were available/common place
- VSD allows the ESP to “run-up” slowly/gently to it’s operating speed, which maybe above synchronous speed, reducing shock and extending system live
- IM design can be improved by increasing the number of poles
- Higher pole number will reduce the core mass, although power factor will be reduced
- There is likely a trade-off IM design with pole number higher than two (...most industrial IM are 4-pole!)

Induction Machine

2-pole IM series 562 design

- Notice the discrepancy between stator and rotor back-iron depths
- The rotor back-iron is insufficient

2-pole IM series 562 (better rotor design…*but the shaft will not fit*)

- rotor back-iron depth just slightly less than stator
  - balanced saturation level
  - better performance

4-pole IM design (just concept…needs accurate analysis)

- stator and rotor back-iron thinner than in 2-pole
- airgap diameter a bit larger
- rotor ID constraint likely to work

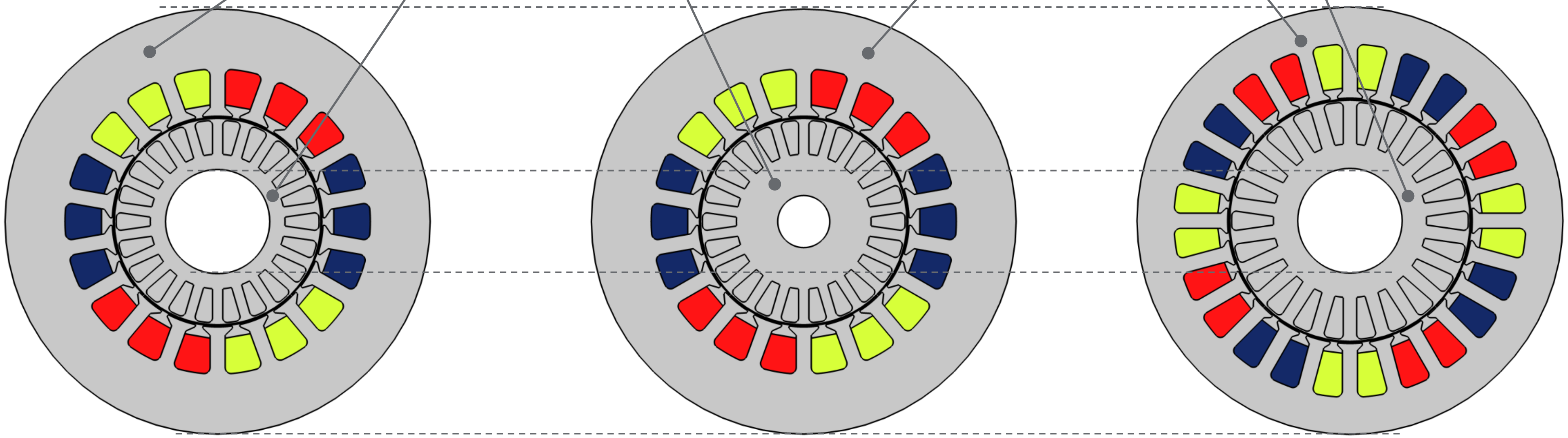


Figure 13 – Improved IM design

Summary of the investigation

- Induction Machine
  - The induction machine should not be completely overlooked. A redesign could improve the performance levels
  - Can use the already developed infrastructure (power electronics)
  - Because of the windings on the rotor, the machine is less efficient compared to PM and SyncR Machine
  - Redesign to take full advantage of the machine potential
  - No PM to recycle

- Permanent Magnet Machine
  - High efficiency and power density proven, in a smaller package
  - Can use the same infrastructure as the Induction Machine
  - Careful consideration of the demagnetisation due to high temperature of the down-hole environment
  - High manufacturing cost due to PM material, but the initial investment can be recovered overtime (High efficiency)
  - The infrastructure for recycling isn’t there yet

- Synchronous Reluctance Machine
  - Very cheap to manufacture (no winding or PM on the rotor)
  - Higher torque per volume compared to IM.
  - Needs 4 wires (3 x power + 1 x control)…IM and PMM use only 3!
  - Not field proven, needs a more in-depth investigation
  - Very easy to recycle

Thank you

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