

Analytical modelling of air-cored partially HTS motor with permanent magnet rotor

Zhishu Qiu¹, Min Zhang¹, Alexandre Colle²

1. University of Strathclyde, Glasgow, UK
2. Airbus UpNext Airbus ExO Zero Emissions Blagnac, France

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Contents

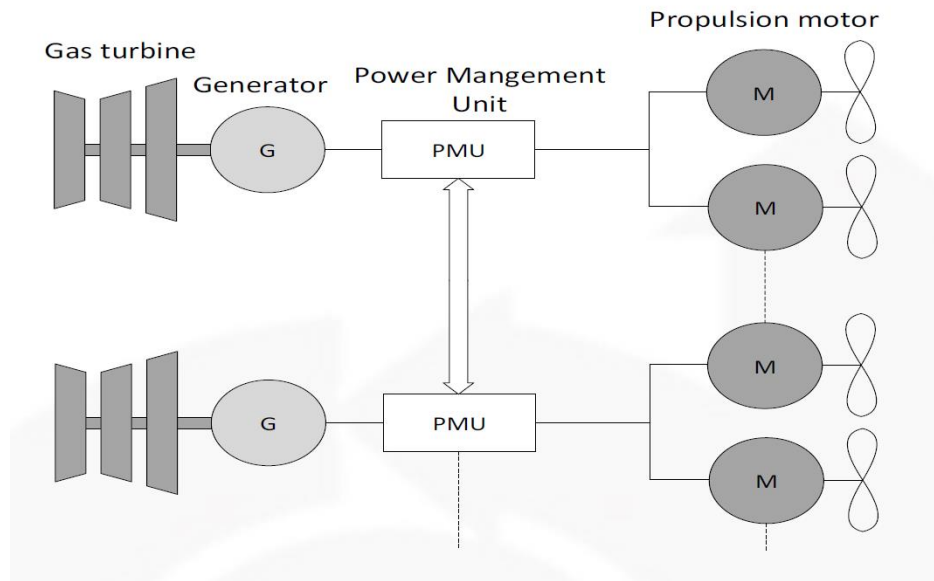
1. Background
2. Structure of air-cored radial flux PM-HTS (permanent magnet rotor and HTS stator) motor
3. Motor equivalent circuit and analytical modelling method
4. 450kW motor modelling results and analysis
5. Conclusions

1. Background

Regulation of aviation emissions (e.g. flight path 2050 by the European aviation industry)



Hybrid/full electric aircraft propulsion systems



Superconducting machines(high power density)



image source: Rolls-Royce

Hybrid electric propulsion system:
Low (zero) emissions and low noise;
Decouple power generation and propulsion.

1. Background

Partially HTS machine

This study:

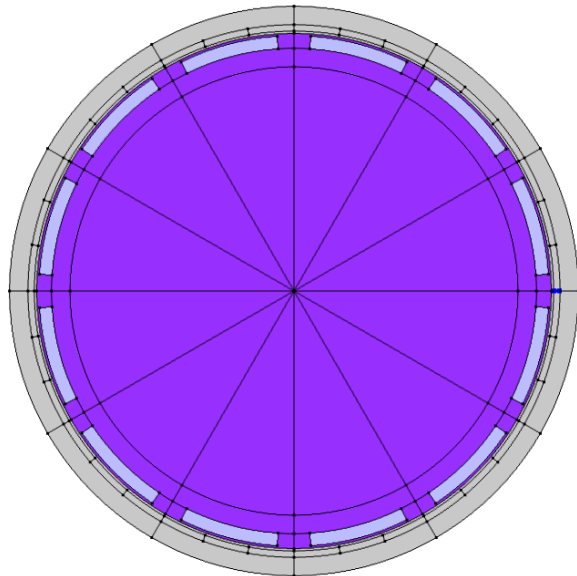
- Permanent magnet rotor
 - Achieve $B \sim 1\text{T}$ with relatively small amount of magnet materials comparing to conventional magnetic field coil.
- HTS armature winding
 - Achieve high electrical loading, thus higher efficiency

Other choice:

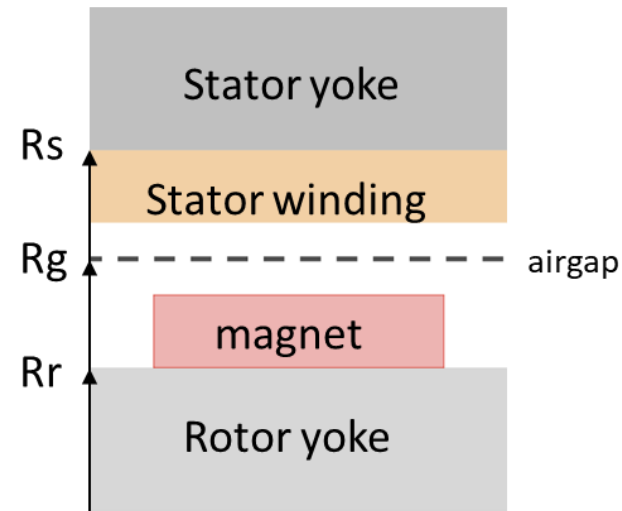
- HTS field winding (rotor)
 - Achieve magnetic loading up to 14T
- Normal copper armature winding

2. Air-cored radial flux PM-HTS (permanent magnet rotor and HTS stator) motor

- Structure



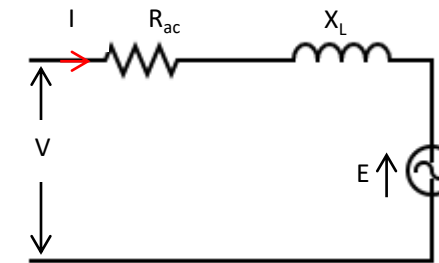
cross-section schematic of motor



Simplified linear one pole section

R_s stator outer radius
 R_g mean airgap radius
 R_r rotor inner radius

- Equivalent circuit



Stator single phase equivalent circuit

V phase voltage

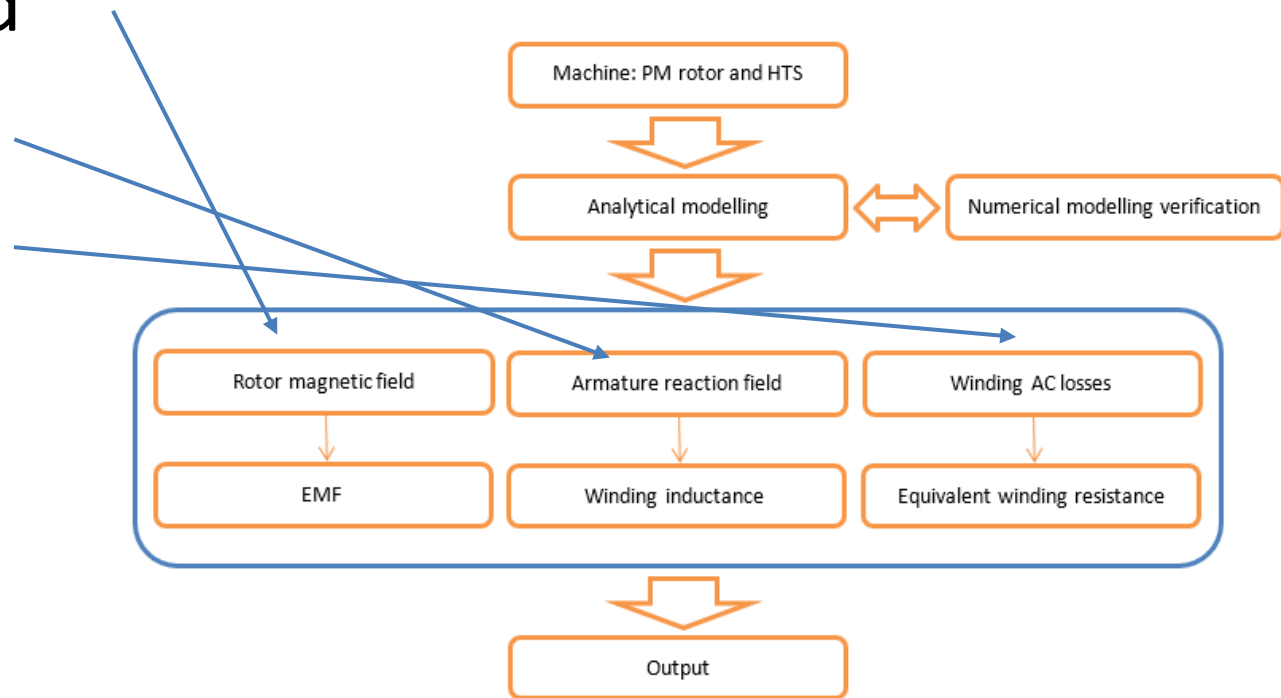
R_{ac} armature winding ac resistance

X_L armature reactance

E induced emf

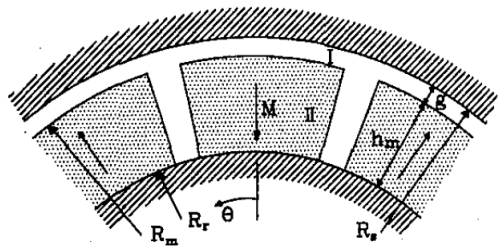
3. Motor analytical modelling method

- Input: machine output power, input phase voltage etc.
- Function magnetic field
- Function inductance
- Function resistance
- Output



3. Motor analytical modelling method

- Airgap magnetic field distribution



$$\text{In general } B_r(r, \theta) = \sum_{n=1,3,5,\dots}^{\infty} \frac{\mu_0 M_n}{\mu_r} \frac{np}{(np)^2 - 1} \cdot \left\{ \frac{(np-1) + 2\left(\frac{R_r}{R_m}\right)^{np+1} - (np+1)\left(\frac{R_r}{R_m}\right)^{2np}}{\frac{\mu_r+1}{\mu_r} \left[1 - \left(\frac{R_r}{R_s}\right)^{2np}\right] - \frac{\mu_r-1}{\mu_r} \left[\left(\frac{R_m}{R_s}\right)^{2np} - \left(\frac{R_r}{R_m}\right)^{2np}\right]} \right\} \cdot \left[\left(\frac{r}{R_s}\right)^{np-1} \left(\frac{R_m}{R_s}\right)^{np+1} + \left(\frac{R_m}{r}\right)^{np+1} \right] \cos np\theta$$

Where p is the pole pair number, residual magnetization vector,

$$M_n = 2(B_r/\mu_0) \frac{\sin \frac{n\pi\alpha_p}{2}}{\frac{n\pi\alpha_p}{2}} \text{ and } \alpha_p \text{ is the magnet pole-arc to pole-pitch ratio}$$

3. Motor analytical modelling method

- Induced emf

$$e(t) = BLv = -N \frac{d\varphi}{dt}$$

Assume airgap flux, $\varphi_g = \varphi \sin 2\pi f t$

$$E_{ph} = N_{ph} 2\pi f \varphi \cos 2\pi f t$$

$$E_{ph, rms} = \frac{N_{ph} 2\pi f \varphi}{\sqrt{2}} = \sqrt{2} \pi N_{ph} f \varphi$$

Where N_{ph} is the armature coil turns per phase

3. Motor analytical modelling method

- Inductance

Calculate through induced emf:

$$\text{emf} = N \frac{d\varphi}{dt} = L \frac{di}{dt}$$

Where N is the winding turn/phase and L is the inductance per phase

According to [1], there is a factor that can transfer inductance per phase to three phase inductance

3. Motor analytical modelling method



- Equivalent resistance
- R_{ac} and R_{dc} relationship

Low frequency range case $R_{ac} \approx R_{dc}$

High frequency range, should consider skin effect, not common for machines

For copper windings,

$$R_{dc} = \rho \frac{l}{A_{cu}}$$

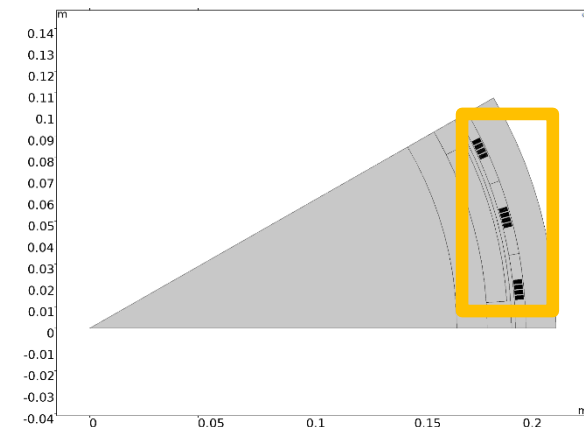
For HTS tapes at low frequency range, we consider calculating equivalent ac resistance from ac losses

$$P_{loss} = I^2 R_{ac}$$

4. 450kW motor modelling results and analysis

- 450 kW motor specifications

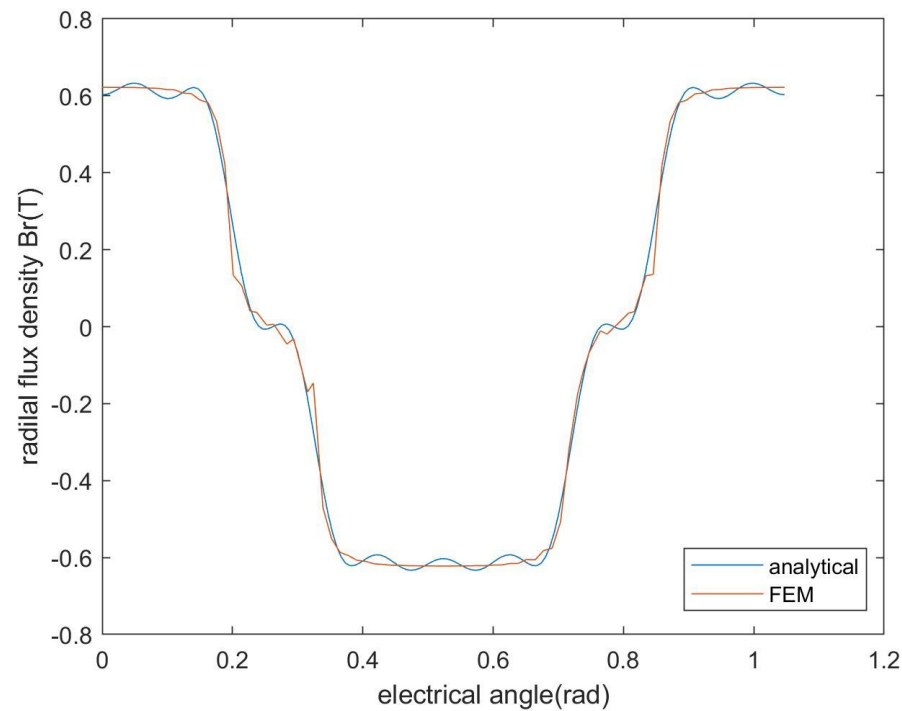
Parameter	symbol		unit
output power	P	450	kW
Input phase voltage	V _{ph}	170	V _{rms}
rated speed	n _s	5000	rpm
Input frequency	f	500	Hz
Airgap magnetic loading	B _g	0.6	T
Winding type			
distribution		distributed	
No.coils per phase		12	



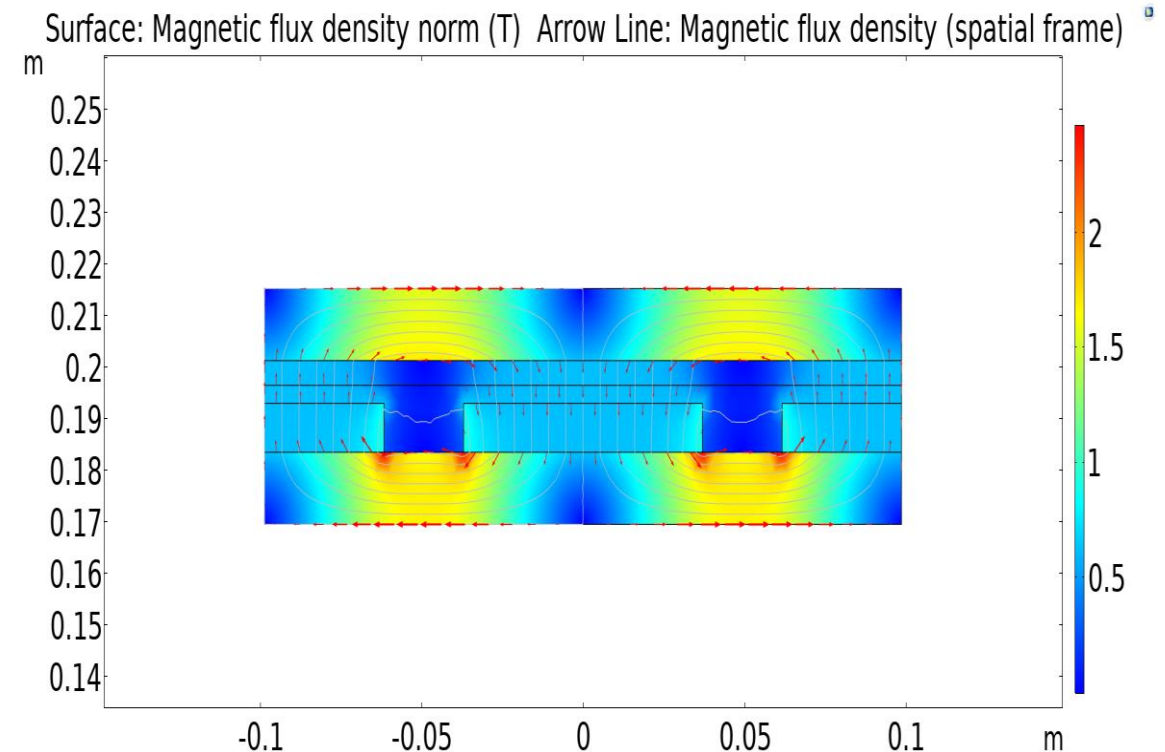
2D geometry, treat HTS tapes as 1d lines
4mm superOx tapes

4. 450kW motor modelling results and analysis

- Rotor field distribution and induced emf



Analytical modelling validation of rotor radial flux density



4. 450kW motor modelling results and analysis

- Inductance

Check through COMSOL FEM model

Calculate through magnetic energy $E_{p,m} = \frac{1}{2}LI^2$

Inductance	Analytical	FEM	Unit
1 phase	49.5	50.08	uH
3 phase	66.9	-	uH

4. 450kW motor modelling results and analysis

- COMSOL model and AC loss calculation using T-A formulation

T formulation (superconducting domain)

$$\mathbf{J} = \nabla \times \mathbf{T}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

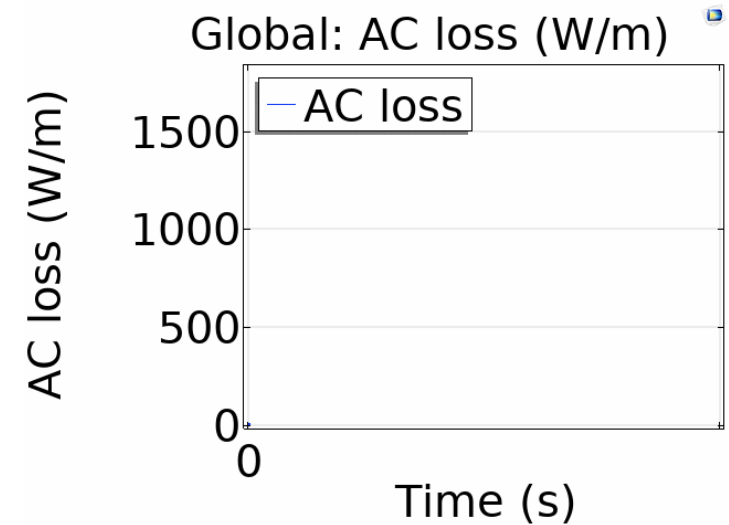
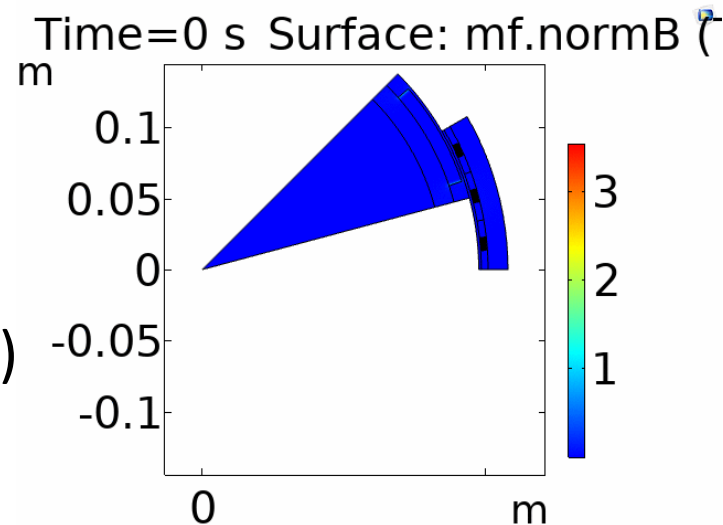
E-J power law

$$\mathbf{E} = E_0 \left(\frac{|\mathbf{J}|}{J_c(B, T)} \right)^n \frac{\mathbf{J}}{J_c(B, T)}$$

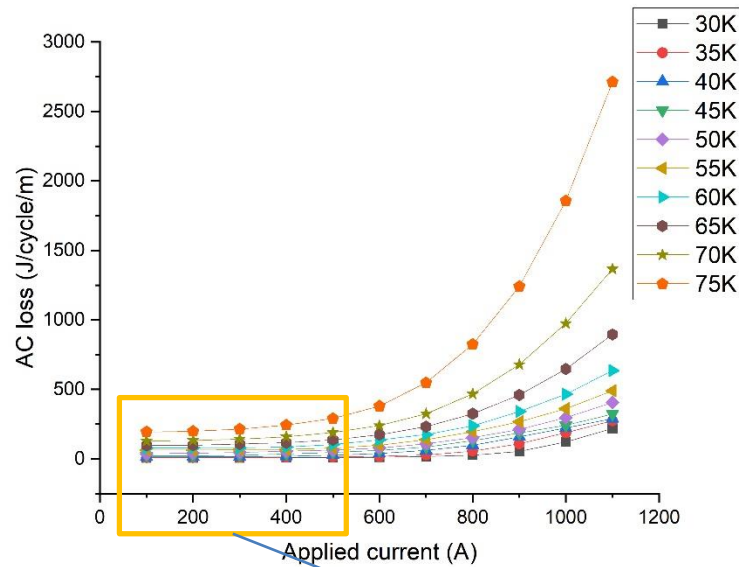
A-formulation(whole domain)

$$\mathbf{B} = \nabla \times \mathbf{A}$$

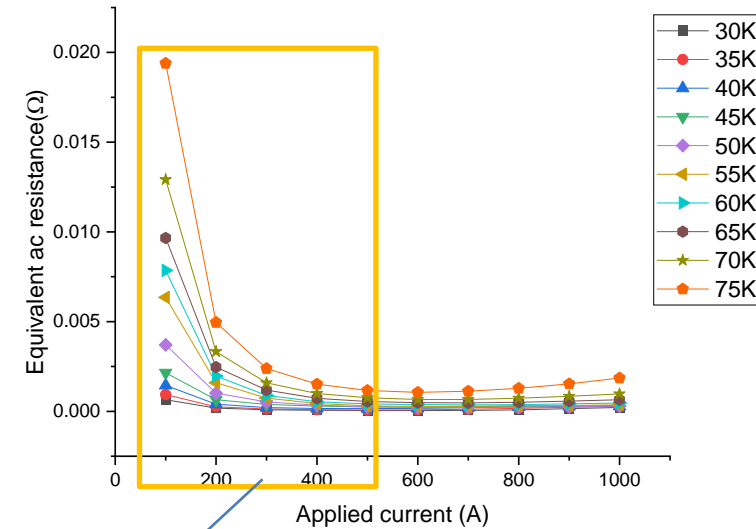
$$\nabla \times \nabla \times \mathbf{A} = \mu \mathbf{J}$$



4. 450kW motor modelling results and analysis



AC loss

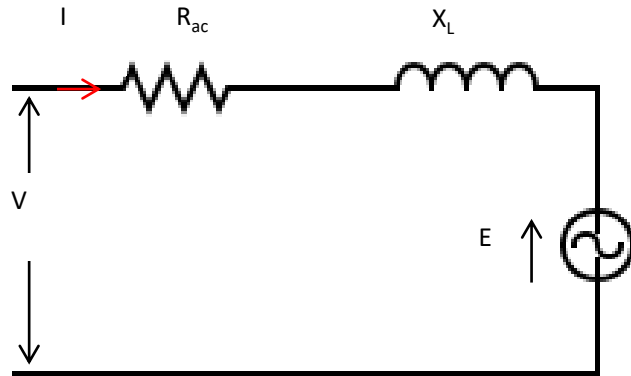


Equivalent ac resistance

AC loss increases very small amount;
Applied current increases linearly (from
10% to 100% rated current);

$$R \propto \frac{1}{I^2}$$

4. 450kW motor modelling results and analysis



Final result for phase equivalent circuit @35K

V 170Vrms

I 1000Arms

R_{ac} 274.2m Ω

X_L 49.5 μ H

E 155.6V

5. Summary and future plan

Summary

- An analytical technique for finding machine equivalent circuit variables of air-cored radial flux partially HTS motor is developed.
- Equivalent AC resistance for HTS windings at low frequency range is calculated with the help of FE modelling in COMSOL

Future plan

This study only considers the steady state mode, transient fault conditions such as short circuits are worth analyzing in the future.