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Inductance Determination for Air-Cored Permanent Magnet Axial Flux Machine

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Outlines

- Overview
- PMAF Machines Applications
- Machine Description
- Objective of the research
  - Mathematical Model
  - FEA Model
  - Simulink/Matlab Model
  - Experimental Tests
- Conclusions & Recommendations

Overview

PM machines:

- Efficiency
- Maintainability
- Reliability
- Manufacturability
- Adaptability

AF machines:

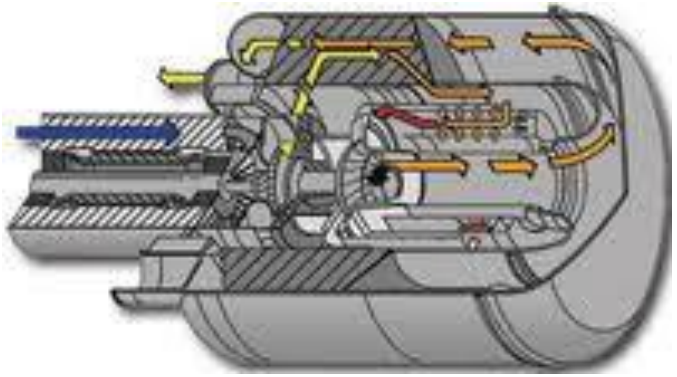
- Compact and Robust
- Short axial length/can be over hanged on the shaft

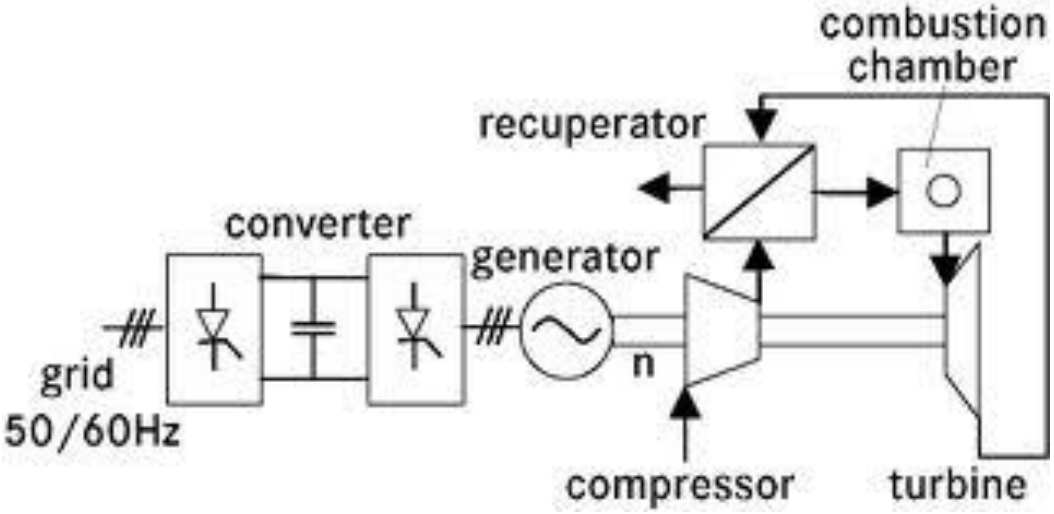
Air-cored windings:

- Zero cogging torque
- Sinusoidal flux distribution/ less output harmonics
- Less manufacturing complexity / Low cost
- Lower core losses / higher efficiency

PMAF Machines Applications (1 of 2)

- Small scale electrical power generating sets





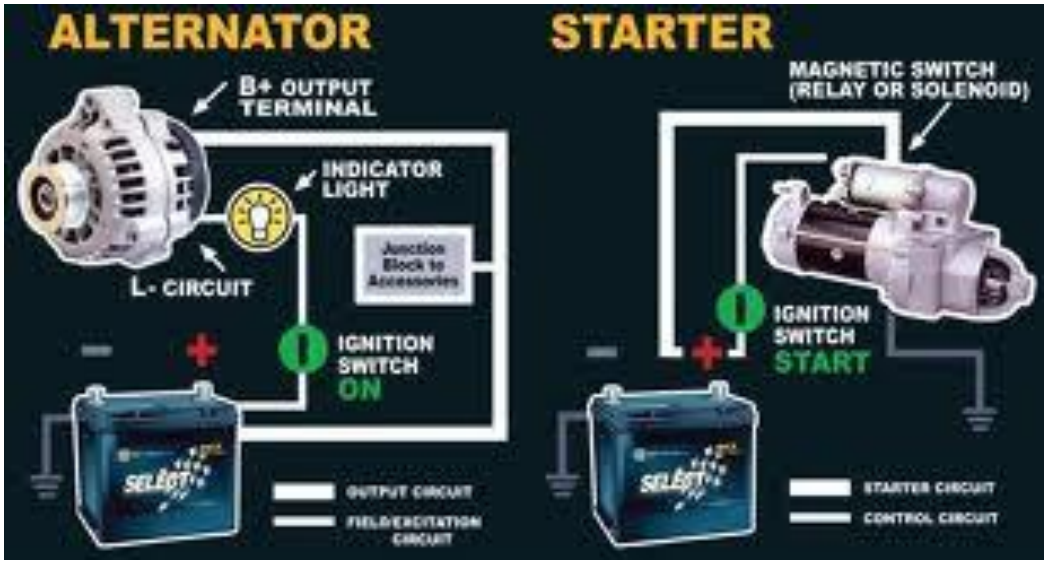
- Electrical Supercharger for Automotive





PMAF Machines Applications (2 of 2)

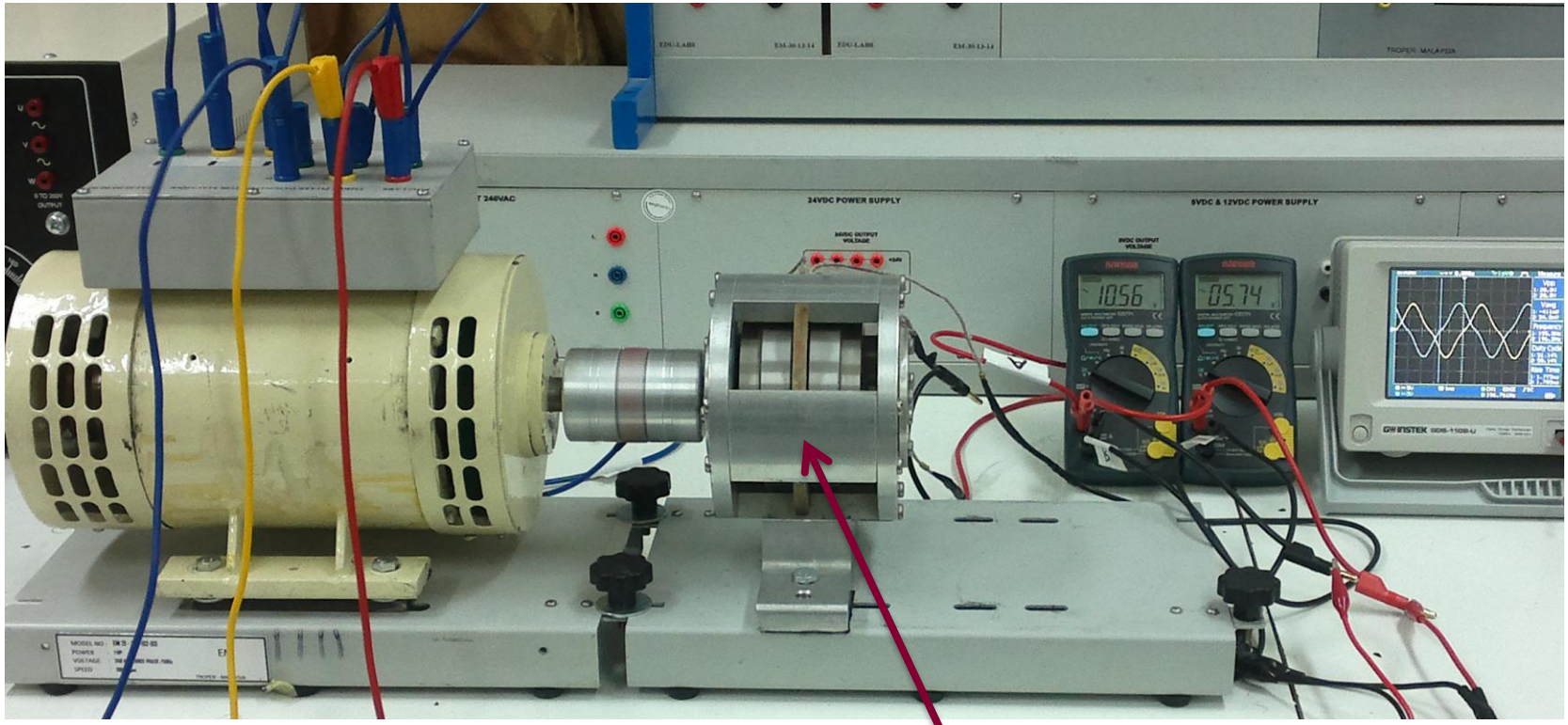
- Automotive alternator sets





Machine Description (1 of 3)

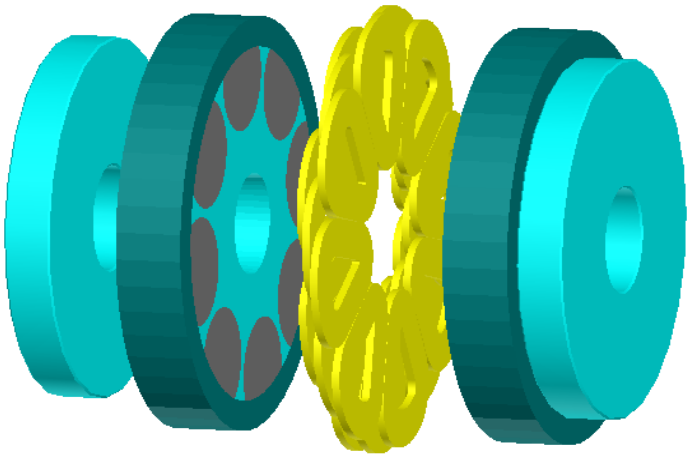
- The **PMAF** machine under consideration is proposed as an alternative to the **claw-pole** automotive alternator



Air-cored AFPM Alternator

Machine Description (2 of 3)

- 3-Phase Single stage **Air-cored** stator with double PM rotor
- Semi circular Axially magnetized PMs
- Rotor integrated back iron
- Shaft integrated fan



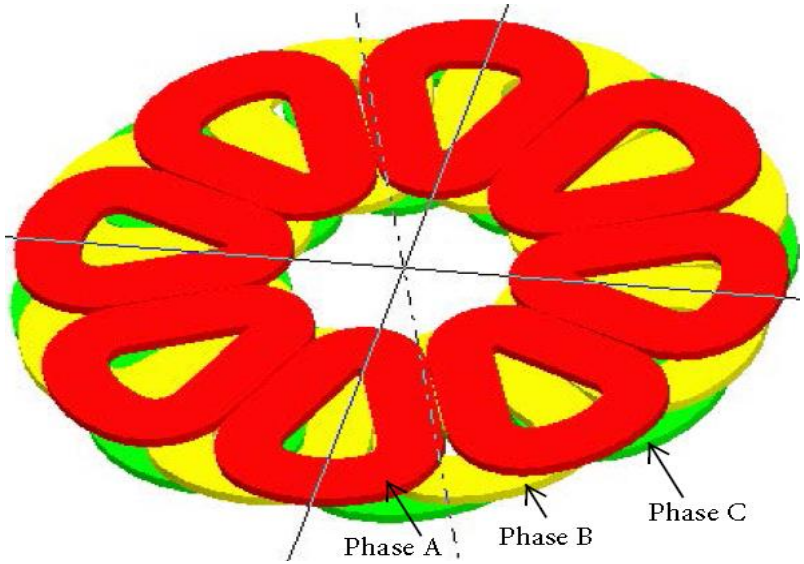
Rated Power (KVA)	Rated Current (A)	Rated Voltage (V_{L-L})	Rated Speed (RPM)
2	65	18	5000

Machine Description (3 of 3)

- Per phase windings ccs

Winding Length (m)	Copper cross area (mm^2)	Resistance (mΩ) @ 25 C°
12.6	**3.0**	**72.5**





Objective of the research

To determine the Inductance of the of the Machine by:

- Developing Mathematical Model
- Developing FEA Model
- Developing Simulink/Matlab Model
- Conducting Experimental Tests

The goal is to use the obtained results to assist in predicting the performance of such machine

Mathematical Model

Inductance is separated into two parts

- Leakage Inductance:

$$L_L = \mu_o \frac{pN_{CT}^2 C_l W_{ie}}{12 W_{ax}}$$

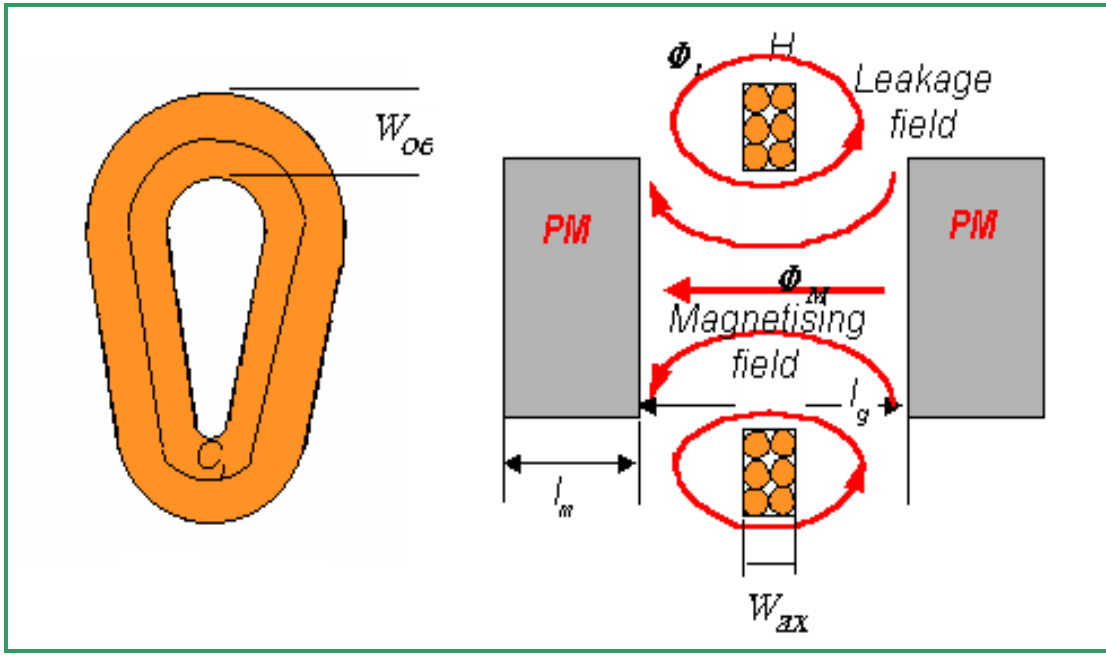
where

p Number of poles.

$N_{CT} = N_t N_l$ Number of coil turns.

$W_{oe} = W_{ie}$ are the outer and inner end windings respectively

W_{ax} winding axial thickness

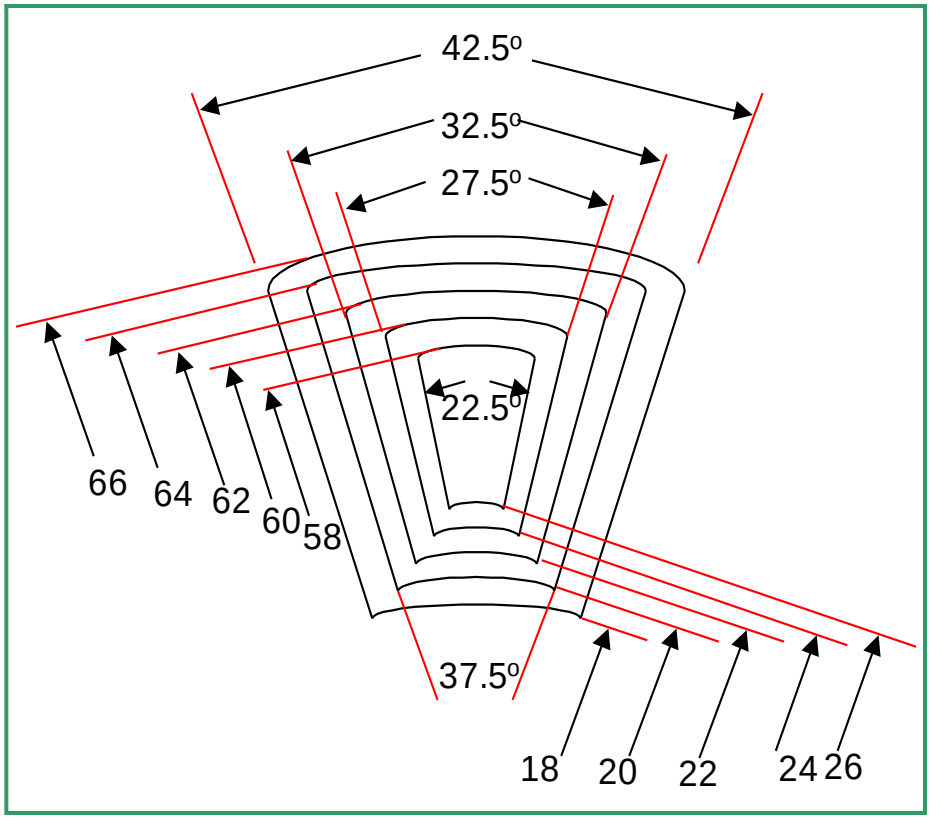


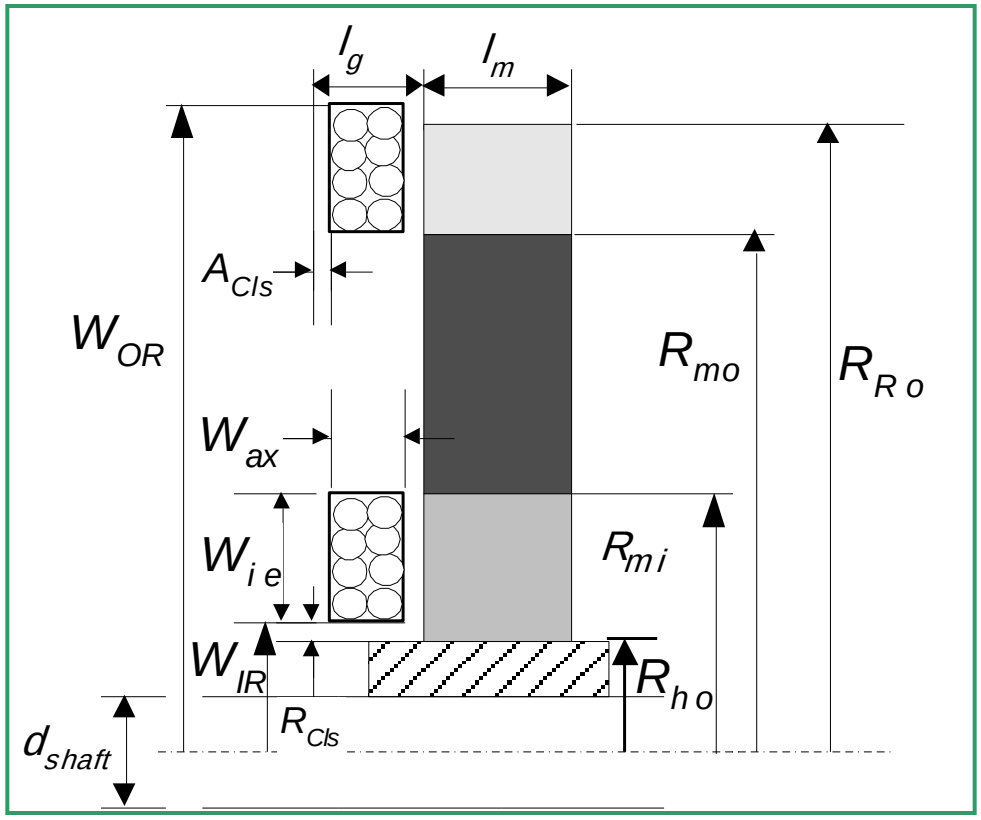
$$C_l = 2R_{mo}\left(\frac{\pi}{p}+1\right) + 2R_{mi}\left(\frac{\pi}{p}-1\right) + 2W_{ie}$$

C_l is the coil mean path.

Mathematical Model

Windings with respect to rotor illustrative diagrams





Mathematical Model

- Magnetizing Inductance:

$$L_M = \frac{pN_{CT}^2}{R_{eq}}$$

where R_{eq} is total reluctance of the path of the magnetising flux and can be calculated as

$$R_{eq} = \frac{l_{mg}}{\mu_o A_{mg}}$$

$$l_{mg} = 2l_m + l_g$$

$$A_{mg} = \pi \frac{\left(R_{outer}^2 - R_{inner}^2\right)}{p}$$

l_{mg} is the total magnet air gap length,

A_{mg} is the air gap/magnet interface area,

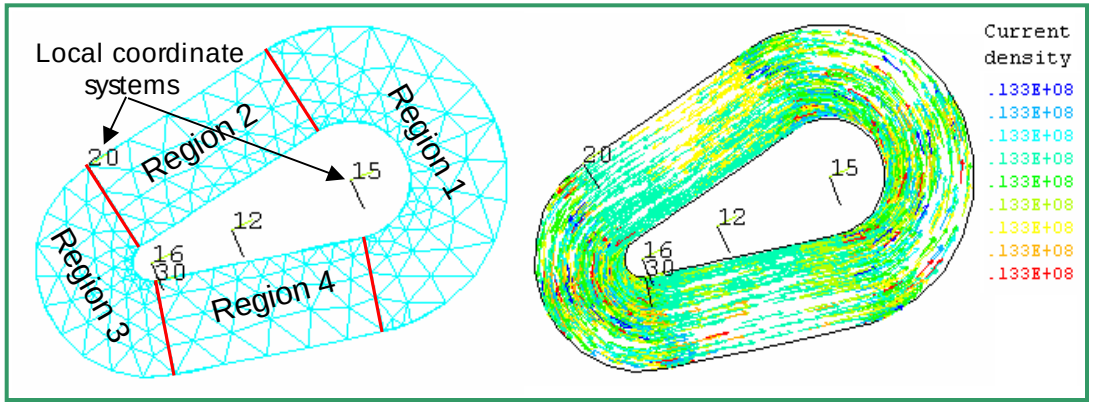
R_{inner} the rotor inner radius

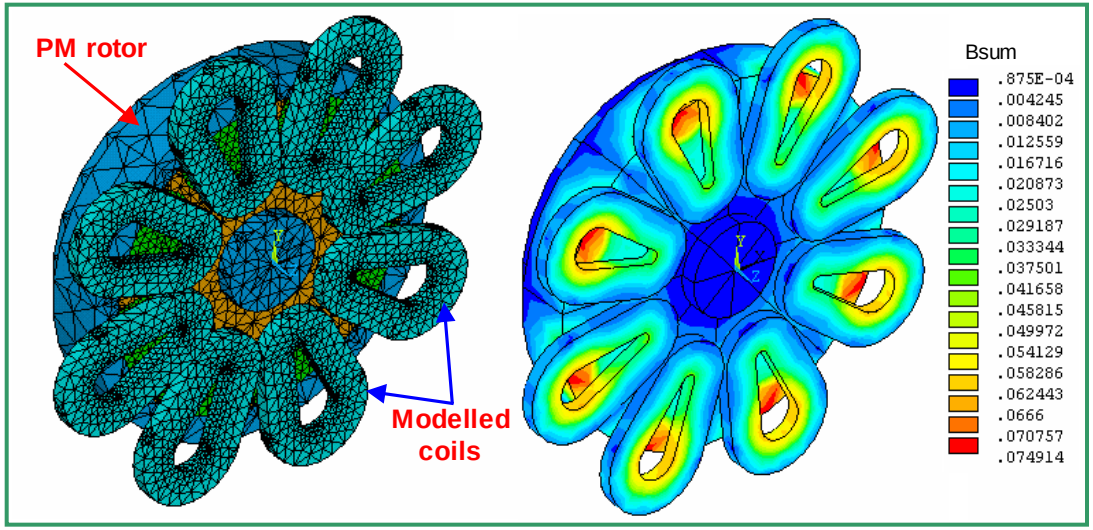
R_{outer} the rotor outer radius

Parameters	Values
N_t, turns	5
p, poles	8
R_{mi}, mm	27
R_{mo}, mm	47
R_{Ro}, mm	55
l_m, mm	17
L_{Tw}, m	12.6
R_{sc}, Ω	0.0725
L_L, μH	13.2
L_M, μH	25.12
Total Inductance, μH	38.32

FEA Model

- Complete **3D FE** Model of the machine is developed using ***ANSYS***.
- The inductance is computed from the stored energy in the machine due to the magnetic field generated from the armature current
- The total elements in the model are selected then the energy stored in these elements is calculated by invoking the built-in macro provided through the ***ANSYS*** postprocessor.





FEA Model

- The leakage and magnetising inductances are calculated as follows:

$$L_l = \frac{2W}{i^2}$$

where

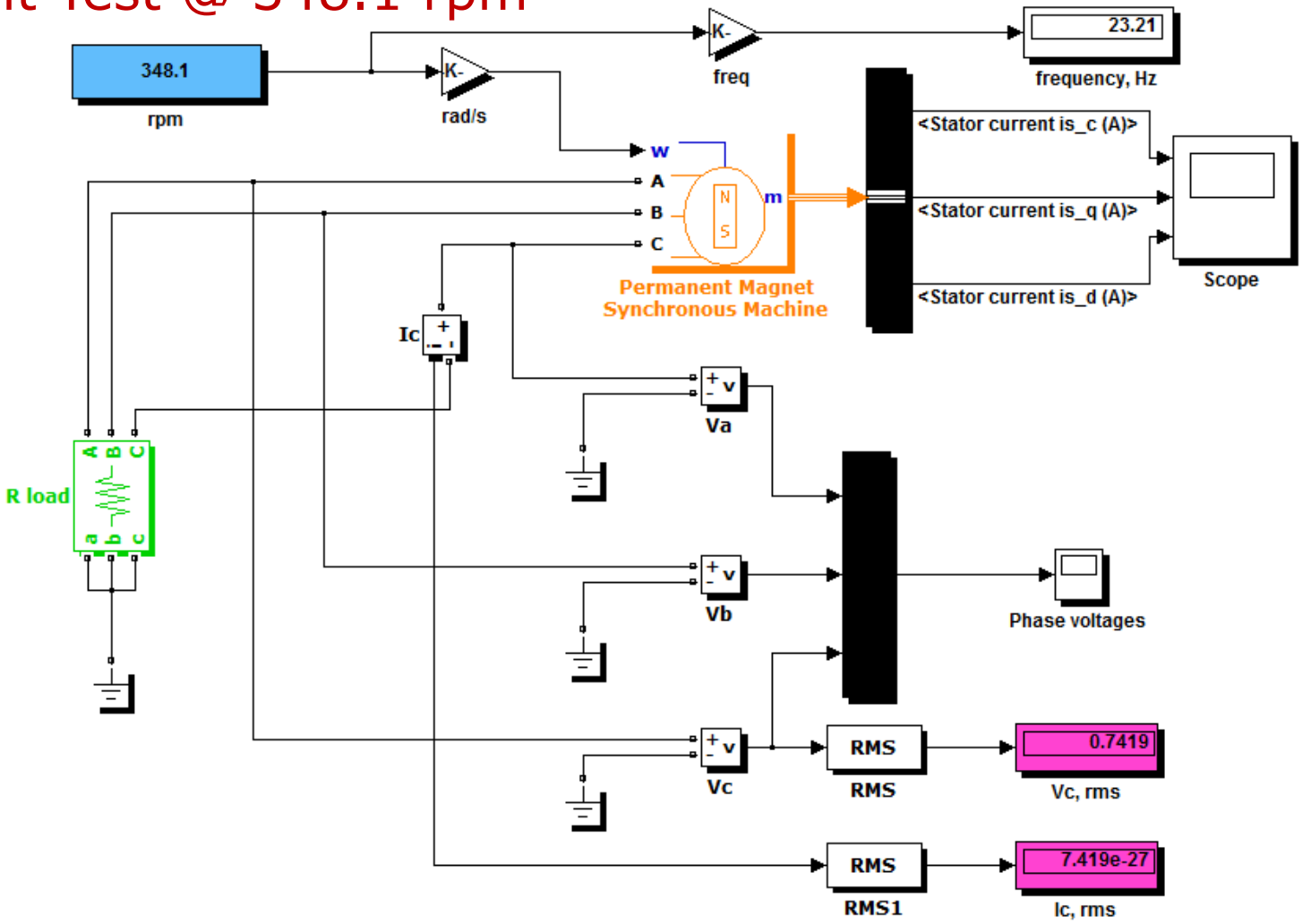
W is the energy stored in the selected elements in the model (Joule) and

i is the peak current per turn of the coil

	Leakage	Magnetising	Total
Energy, J	0.08219	0.14467	0.22686
Inductance, μH	14.630	25.752	40.382

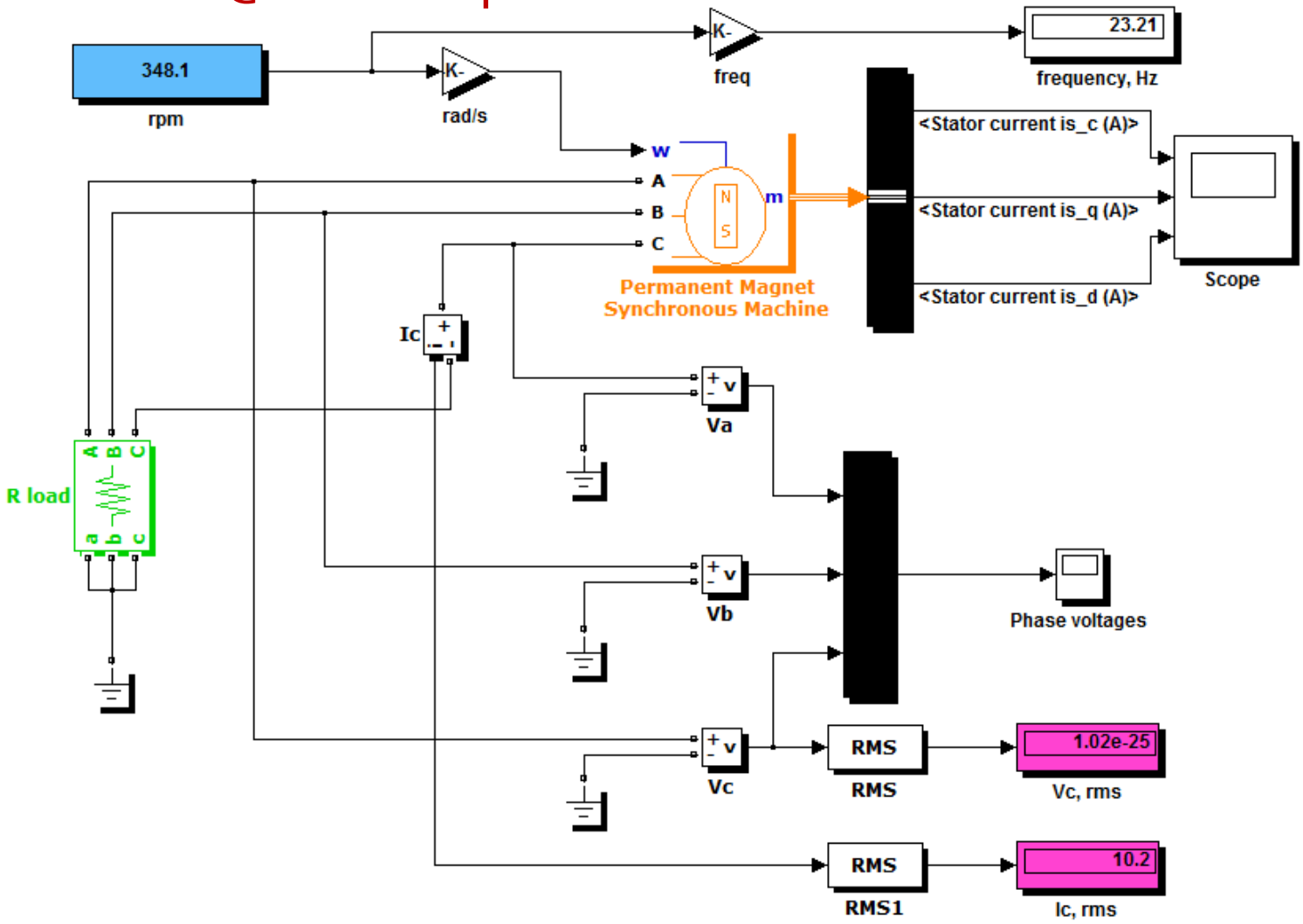
Simulink / Matlab Model

- Open Circuit Test @ 348.1 rpm



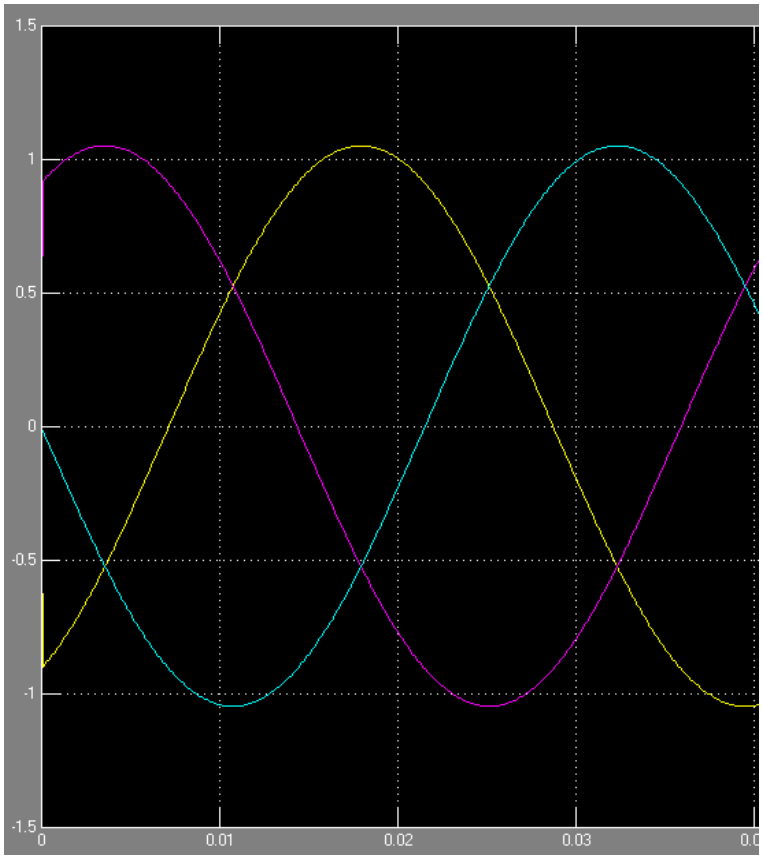
Simulink / Matlab Model

- Short Circuit Test @ 348.1 rpm

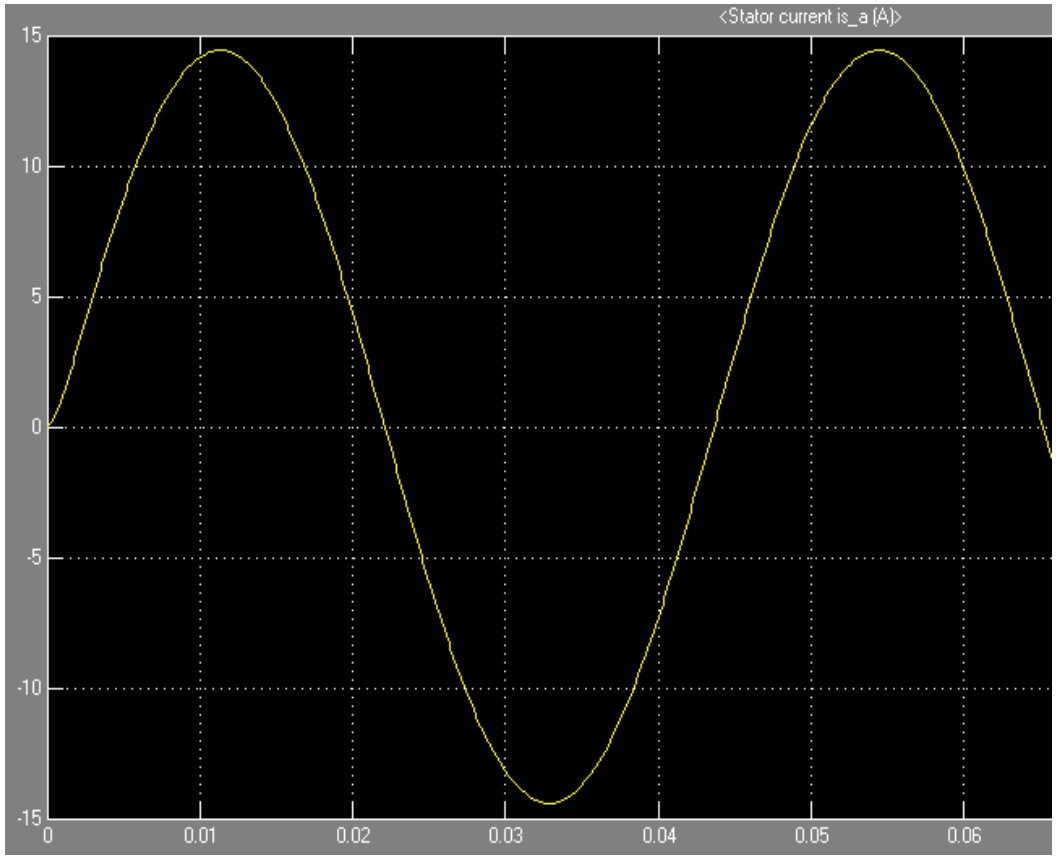


Simulink / Matlab Model

- Open Circuit Voltage @ 348.1 rpm



- Short Circuit Current @ 348.1 rpm



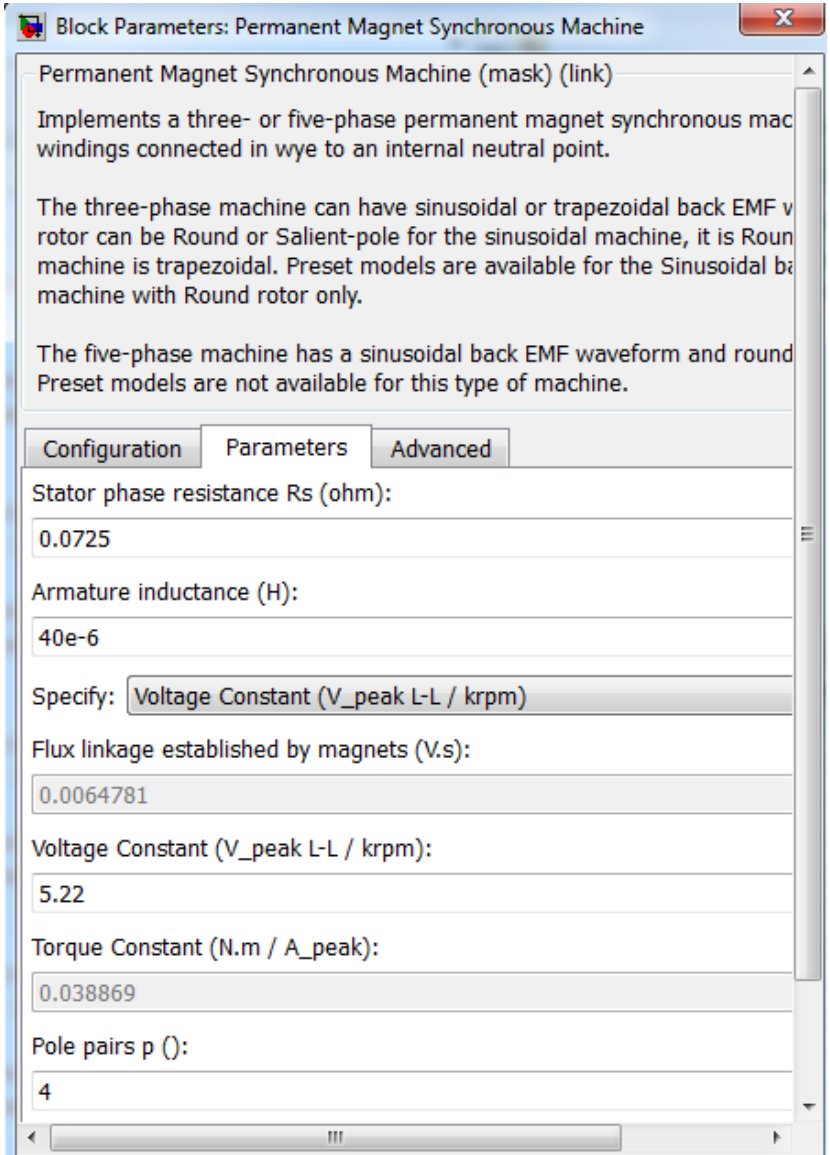
Simulink / Matlab Model

- Open Circuit Test @ 348.1 rpm

  $V_{L\text{-}N(rms)} = 0.7419$ V

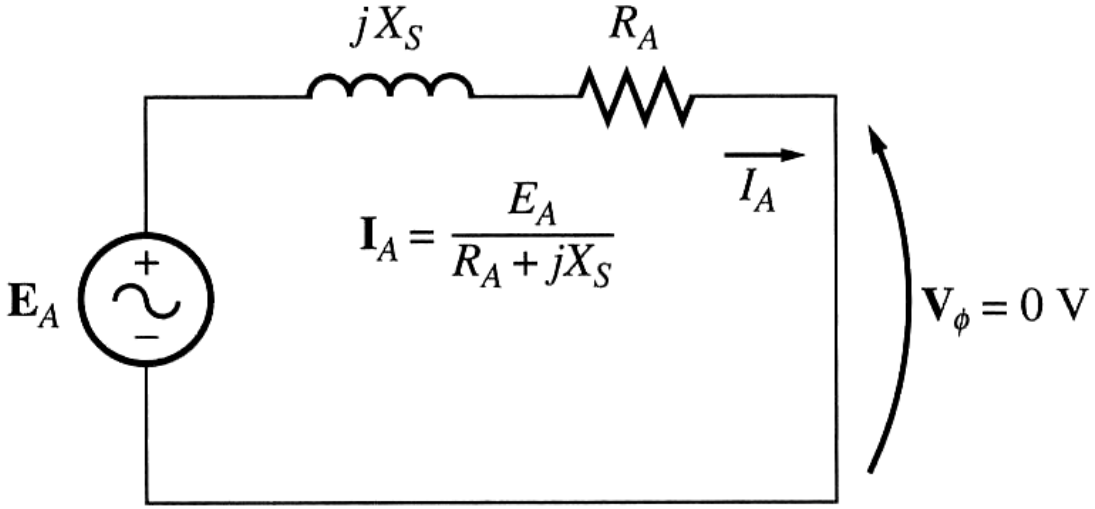
- Short Circuit Test @ 348.1 rpm

  $I_{L(rms)} = 10.2$ A



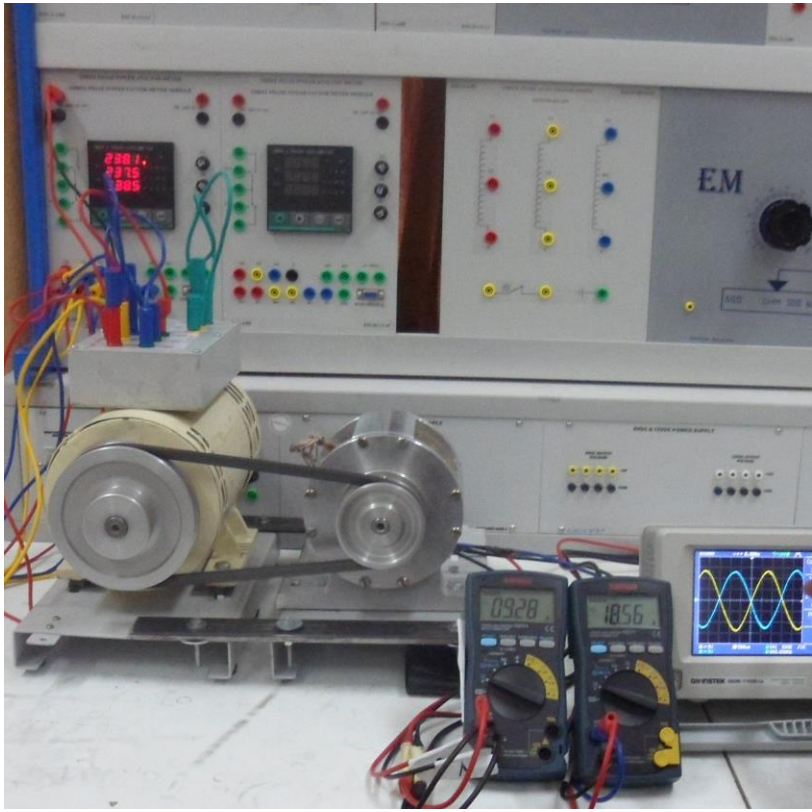
Experimental Test

- Machine parameters can be determined using simple equivalent circuit model
- The machine is runt at low speed (350 rpm) to minimize short circuit current
- Short circuit current and open circuit voltage are obtained



Experimental Test





Vo.c (rms)	Is.c(rms)	L (μH) calculated
0.7418	10.2	39.26

Conclusions & Recommendations

- Air-cored PMAF machine Inductance was successfully determined using several techniques
- Results obtained showed a good match between results of the proposed techniques

Method	Mathematical	FEA	Simulink	Experiment
Inductance, μH	**38.32**	**40.38**	**40**	**39.26**

- More tests on the and performance analysis of the machine is required at several conditions.

Questions?