Design of Low Speed Axial Flux Permanent Magnet Generators for Marine Current Application

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Presentation at a glance

- **Objective**
- **Background**
- **Design challenges**
- **First prototype**
    - **Minimization of Cogging Torque TORUS Configuration**
        - TORUS configuration
        - Alternating Pole Arc
        - Magnet Shifting
        - Fractional Number of Slots Per Pole
    - **Generator design**
        - Rotor
        - Stator
        - Stator winding
    - **Prototyped Generator**
    - **Test Result**
        - Mechanical Parameter test
        - Electrical parameter test
        - System model

Cont….

- **Second prototype**
  - **Generator Design**
    - Rotor
    - Stator
    - Stator winding
  - **Prototyped Generator**
  - **Test Result**
    - Mechanical Parameter test
    - Electrical parameter test
    - System model
- **Comparison between two prototype**
- **Conclusion**
- **Future work**
- **Acknowledgement**

Objective

- To extract few watts electrical power from the sea-floor ocean current.
- To design a generator suitable for under water application.
- To design a direct driven generator by eliminating step-up gearbox.
- To design permanent magnet generators as a low speed energy converter.

Background

- Permanent Magnet Generator (PMG)

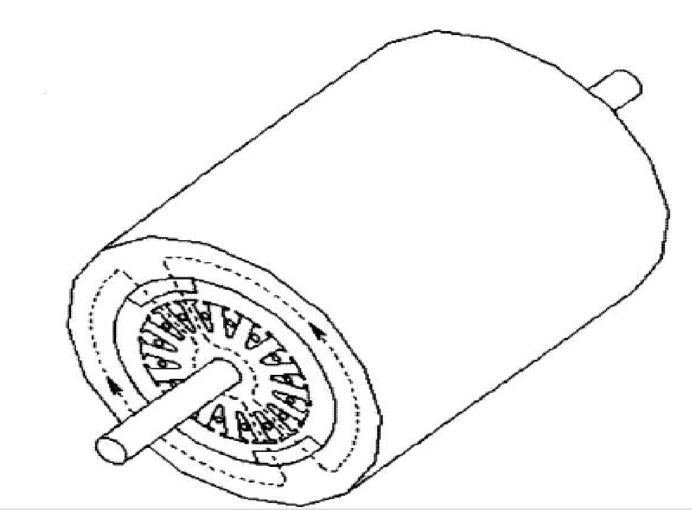


Figure 1(a): Radial Flux PMG

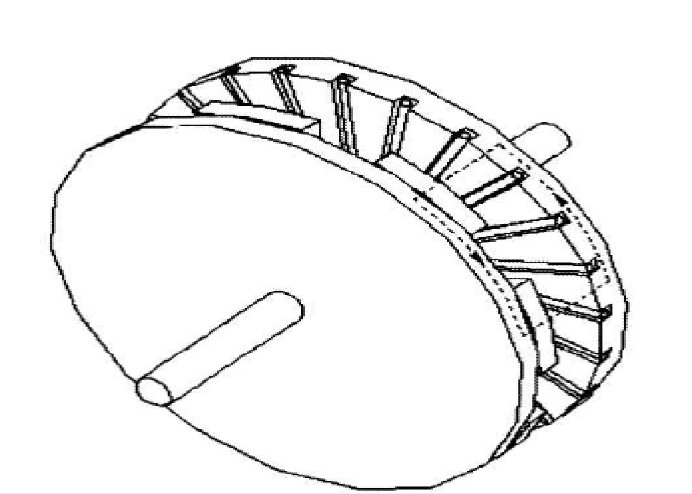


Figure 1(b):Axial Flux PMG

Background (Cont….)

- Axial Flux PMG

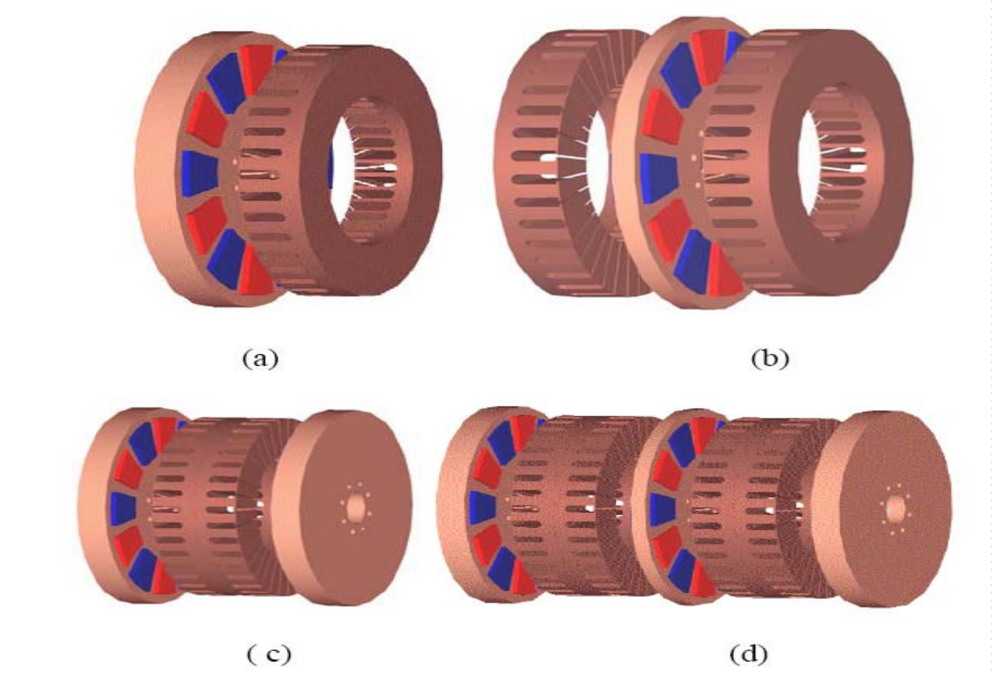


Figure 2:Different types of AFPMG

Background (Cont….)

- AFPM disc-type motor structures

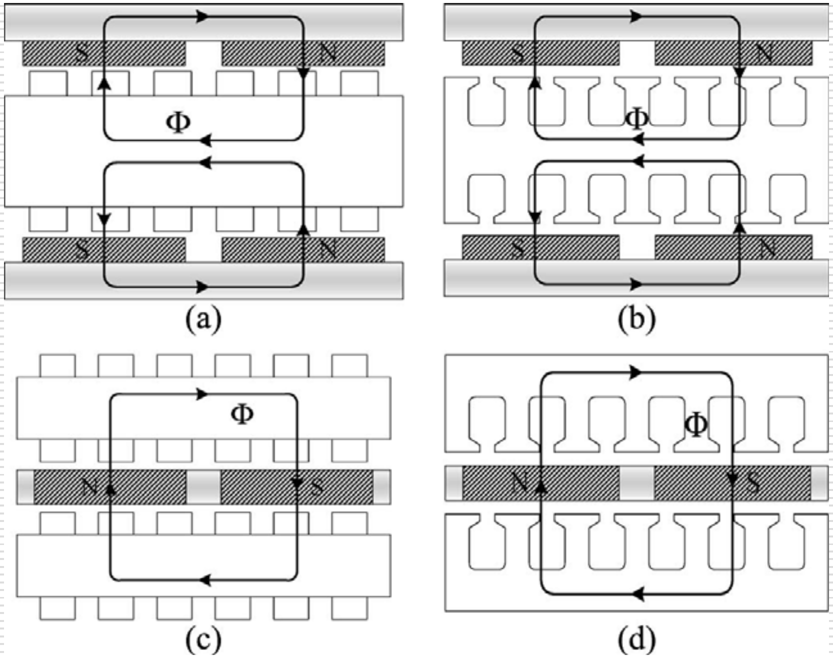


Figure 3: (a) slotless TORUS, (b) slottedTORUS, (c) slotless AFIR, and (d) slotted AFIR machines.

Design Challenges

- No of pole

$$T_{\max} \approx \frac{1}{L_s} \qquad L_s = L_m + L_\sigma$$

$$L_m \approx \frac{1}{p^2} \qquad n = \frac{120 \bullet f}{p}$$

- Size
- Material
- Air gap

First Prototype

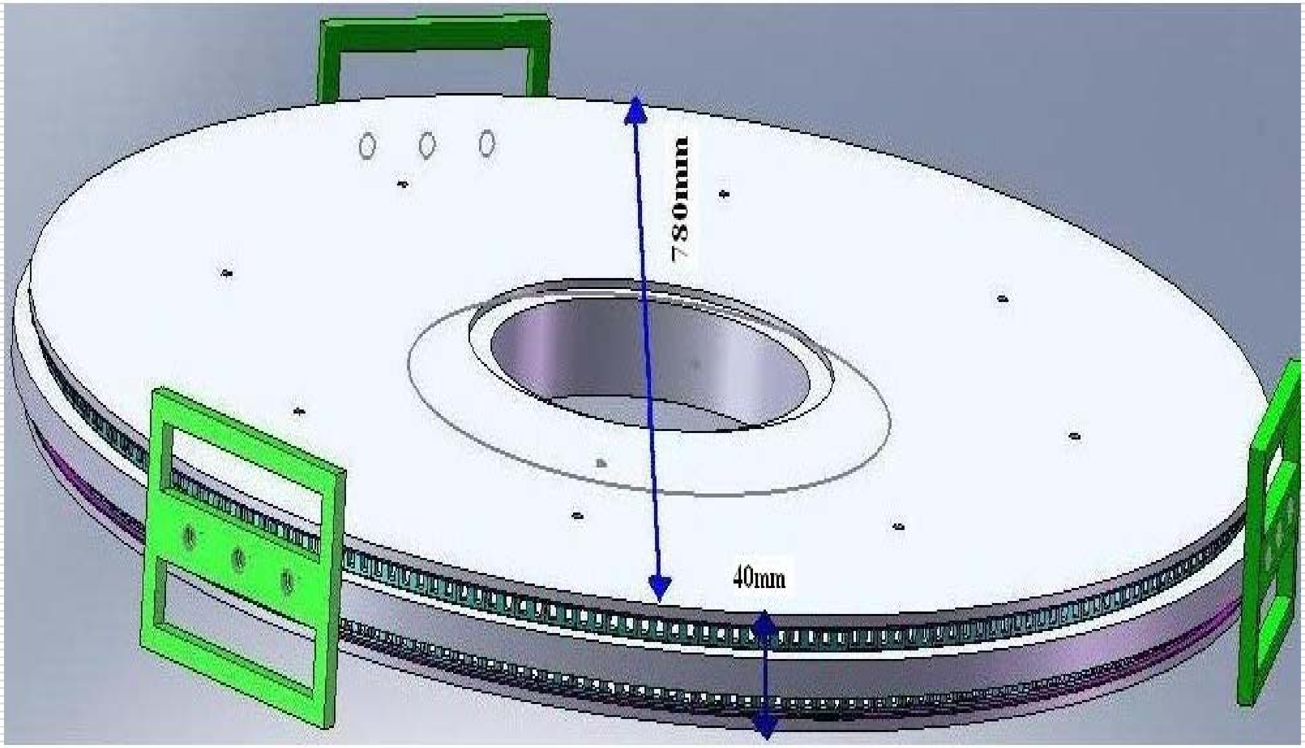


Figure 4: Designed generator

Minimization of Cogging Torque

- Torque Components

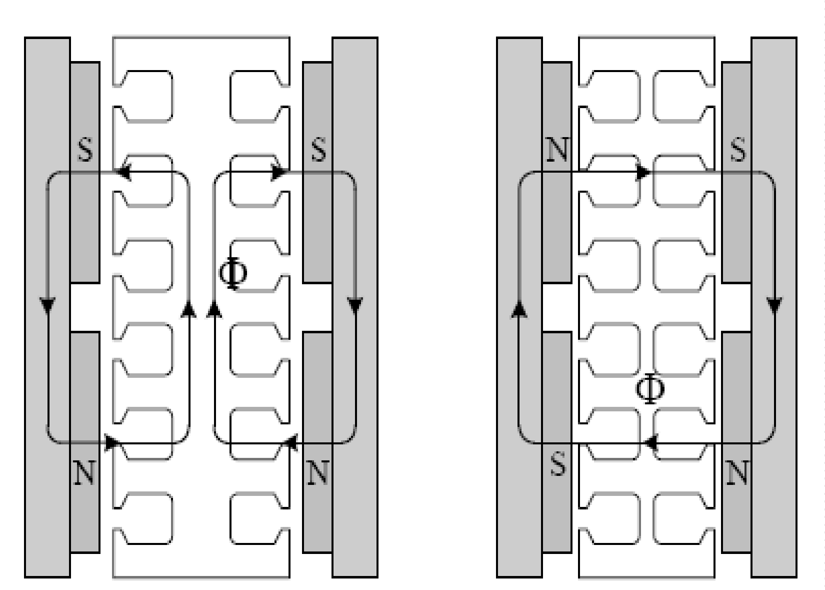
1. Torque Ripple
2. Cogging Torque
3. Pulsating Torque

- Minimization technique

1. Reducing the amplitude of each portion
2. Shifting the relative phase of the different components

Minimization of Cogging Torque (Cont….)

- TORUS Configuration



(a) (b)

Figure 5: TORUS Topology (a) NN type and (b) NS type

Minimization of Cogging Torque (Cont….)

- Alternating Pole Arc

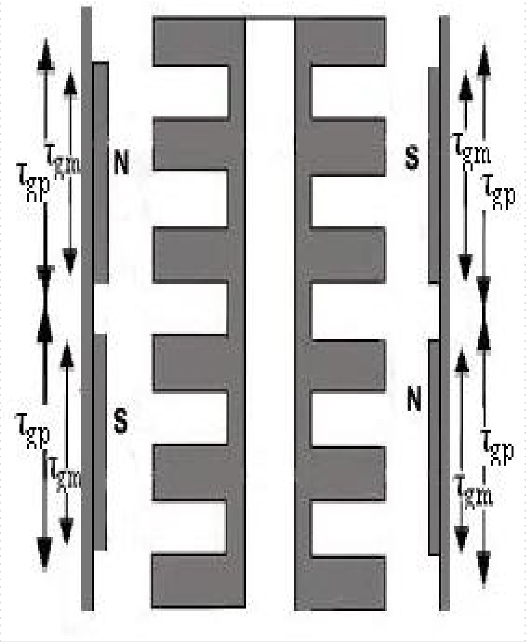


Figure 6(a): Same magnet pole arc

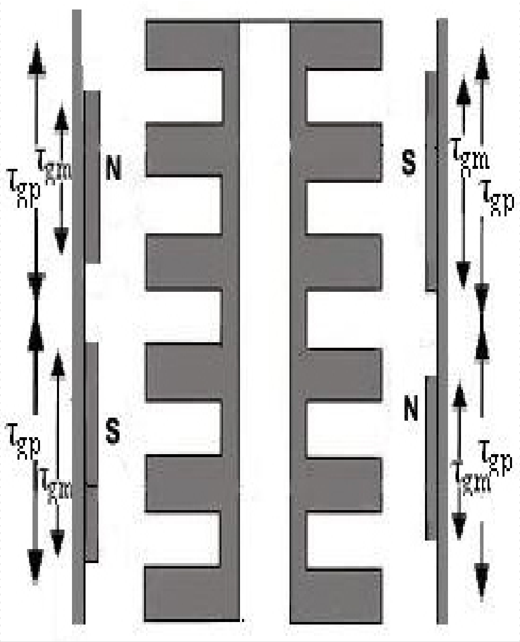


Figure 6(b): Different magnet Pole arc

Minimization of Cogging Torque (Cont….)

- Magnet Shifting
- Fractional Number of Slots Per Pole

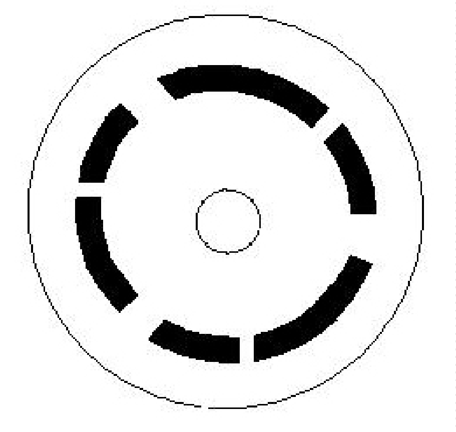


Figure 7: Axial view of Rotor With Shifted magnet

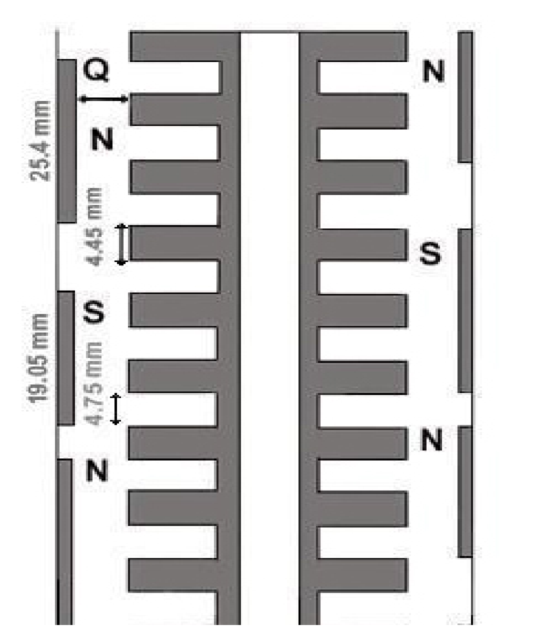
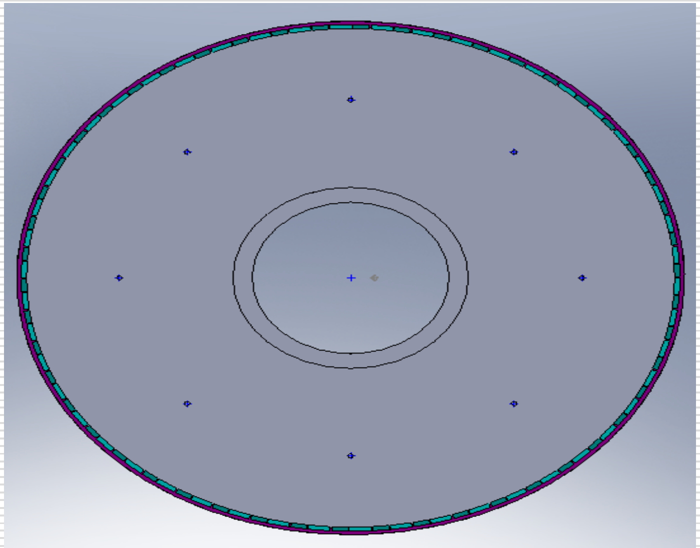


Figure 8: Two dimensional view of shifted magnet

Generator Design

- Rotor
  - Magnetic material- NdFeB
  - Number of pole- 100



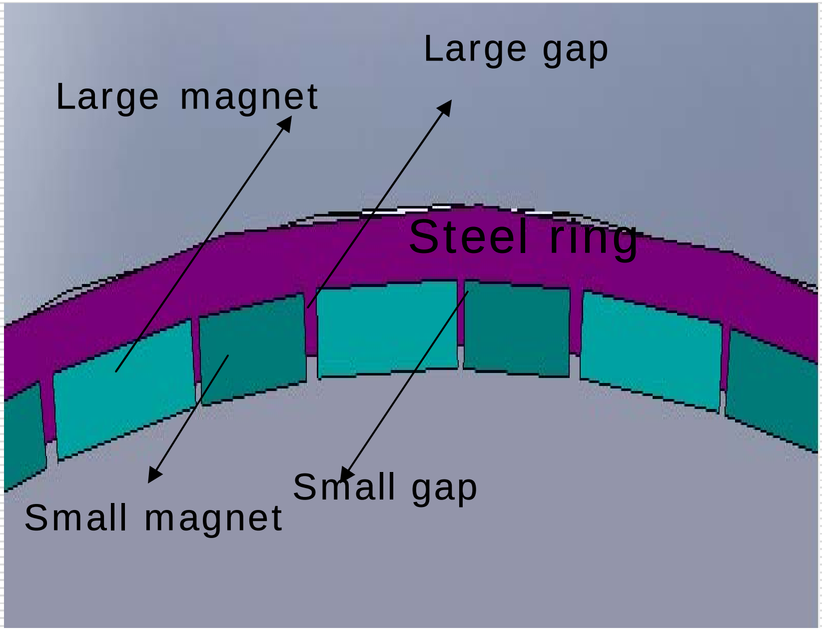
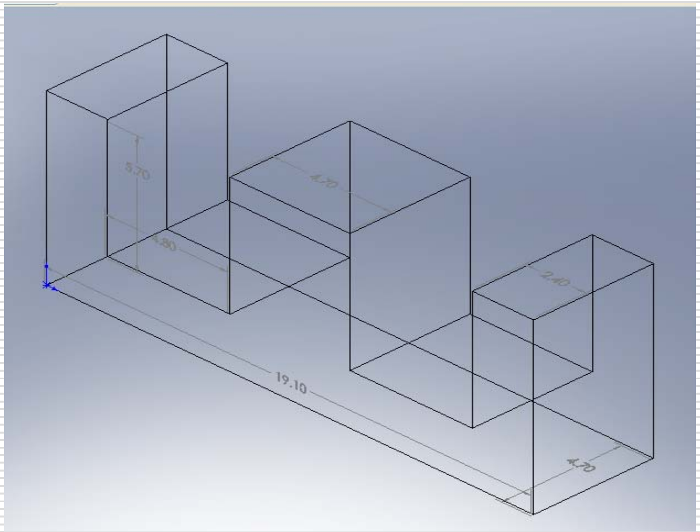


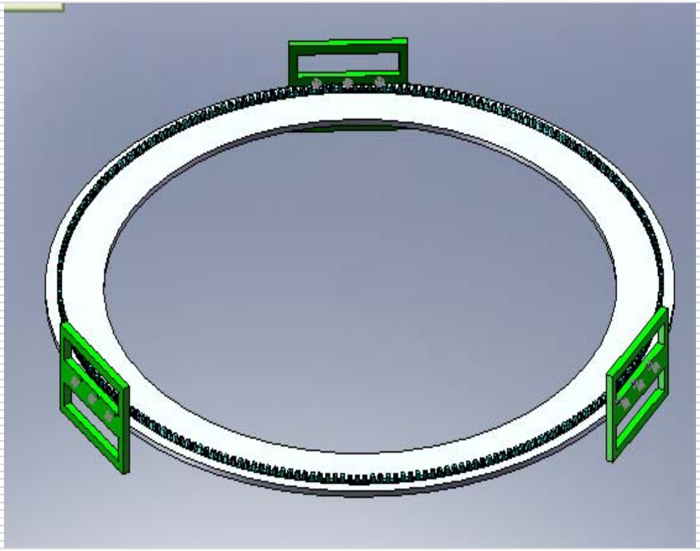
Figure 9: Full and sectional view of Rotor

Generator Design (Cont….)

- Stator
  - Slotted stator is build with ferrite E-cores.



(a)



(b)

Figure 10: (a) E-core (b) Stator

Generator Design (Cont….)

- Stator Winding
  - Number of turns

$$E_{rms} = \frac{E_{\max}}{\sqrt{2}} = \frac{2\pi}{\sqrt{2}} \times N \times f \times \varphi_{\max} \times \frac{N_s}{N_{ph}}$$

$$\varphi_{\max} = A_{magn} \cdot B_{\max}$$

$$B_{\max} = B_r \cdot \frac{l_m}{(l_m + \delta)}$$

Generator Design (Stator Winding) Cont…

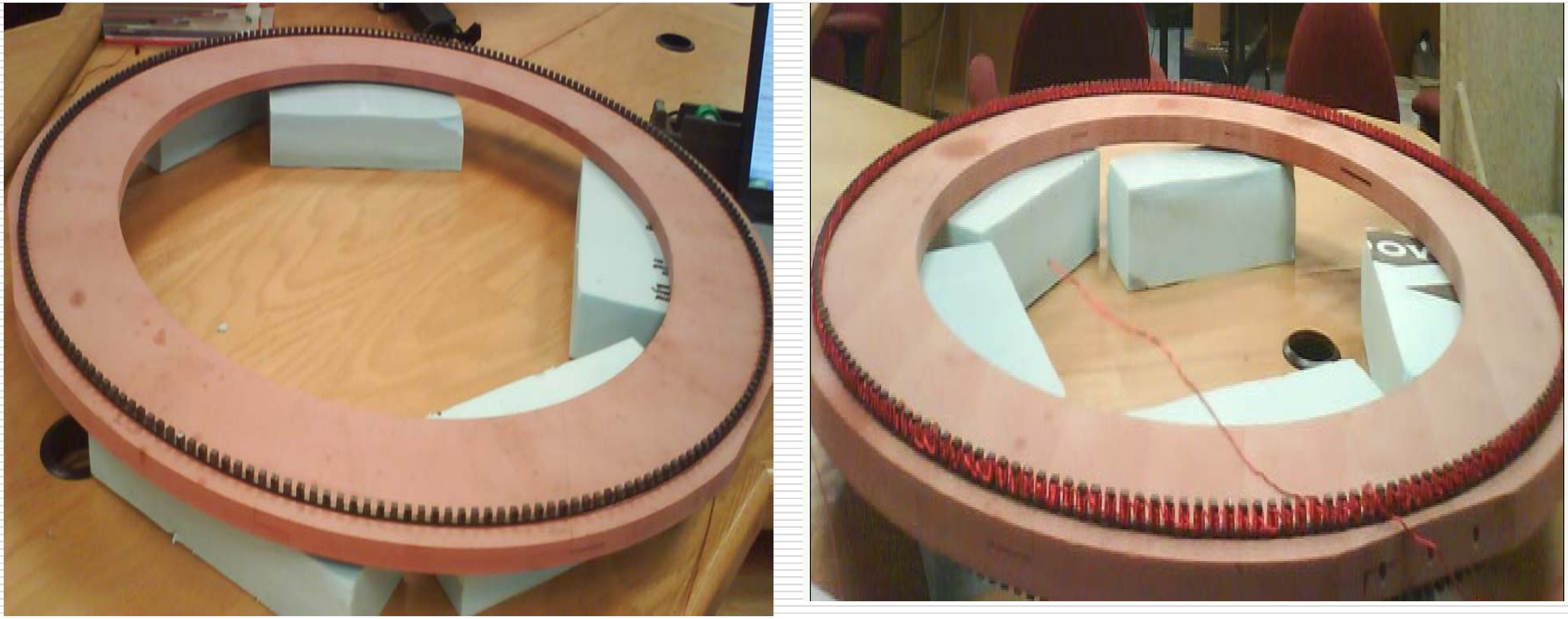


Figure 11: Prototyped stator

Generator Design (Stator Winding) Cont…

Figure 12: Stator winding

Prototyped Generator

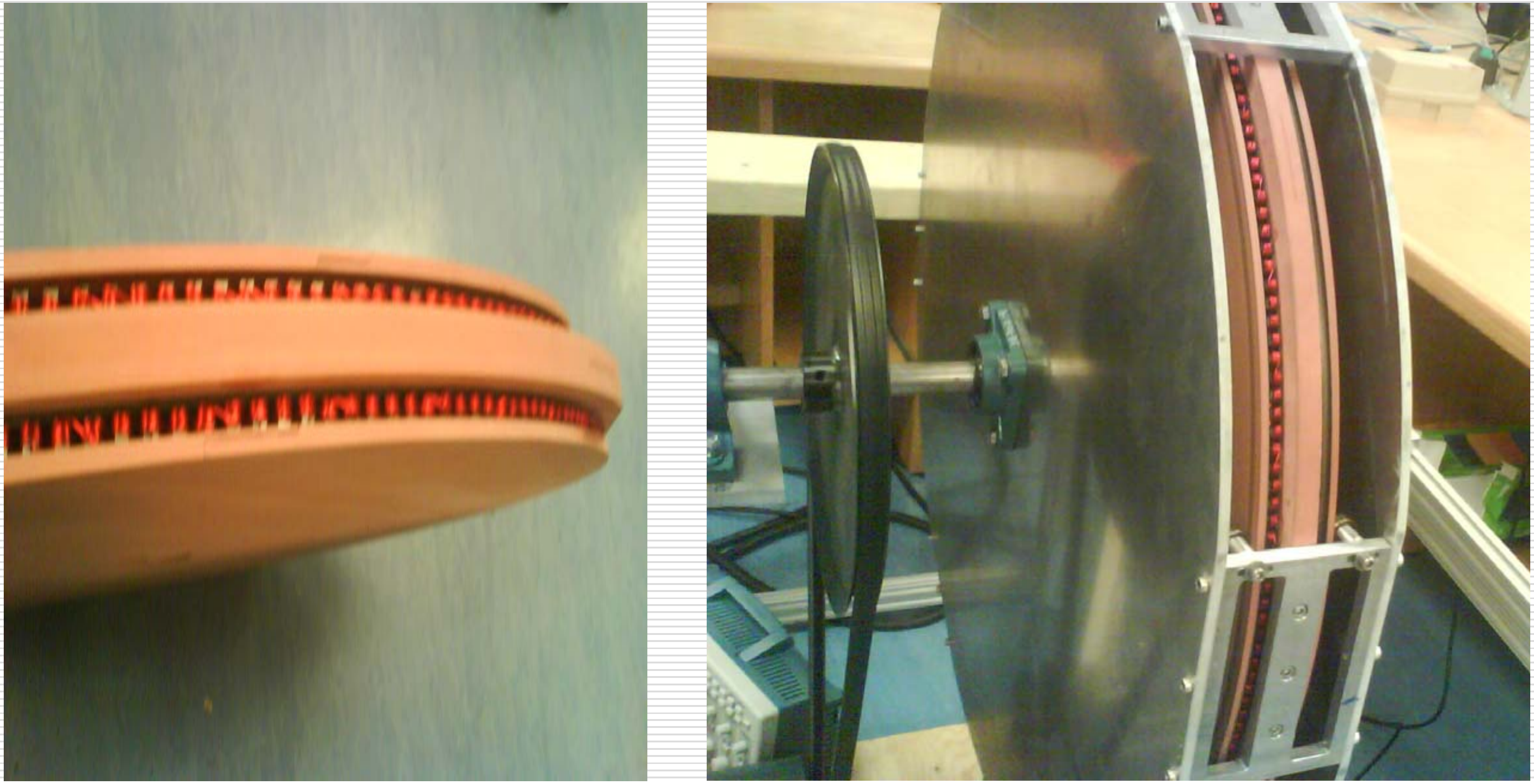
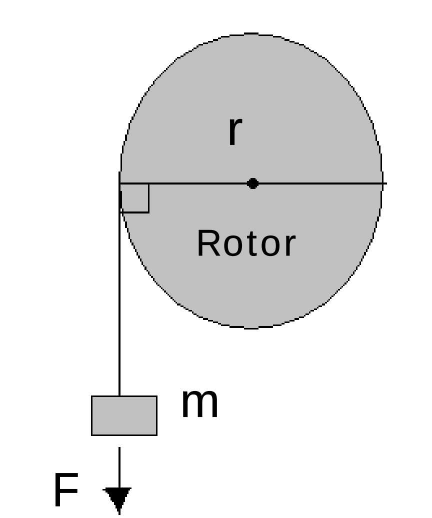


Figure 13: prototyped generator

Test result

- Mechanical Parameter test



$$J = \frac{mr^2}{2}$$

Figure 14: Initial torque Measurement

Test result (cont….)

- Electrical parameter test

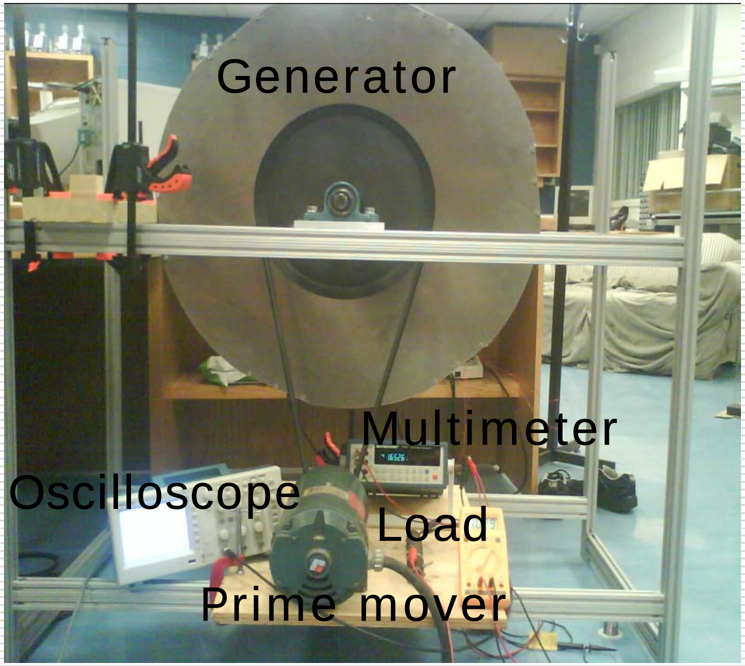


Figure 15: Test setup

Test result (Electrical parameter test) cont….

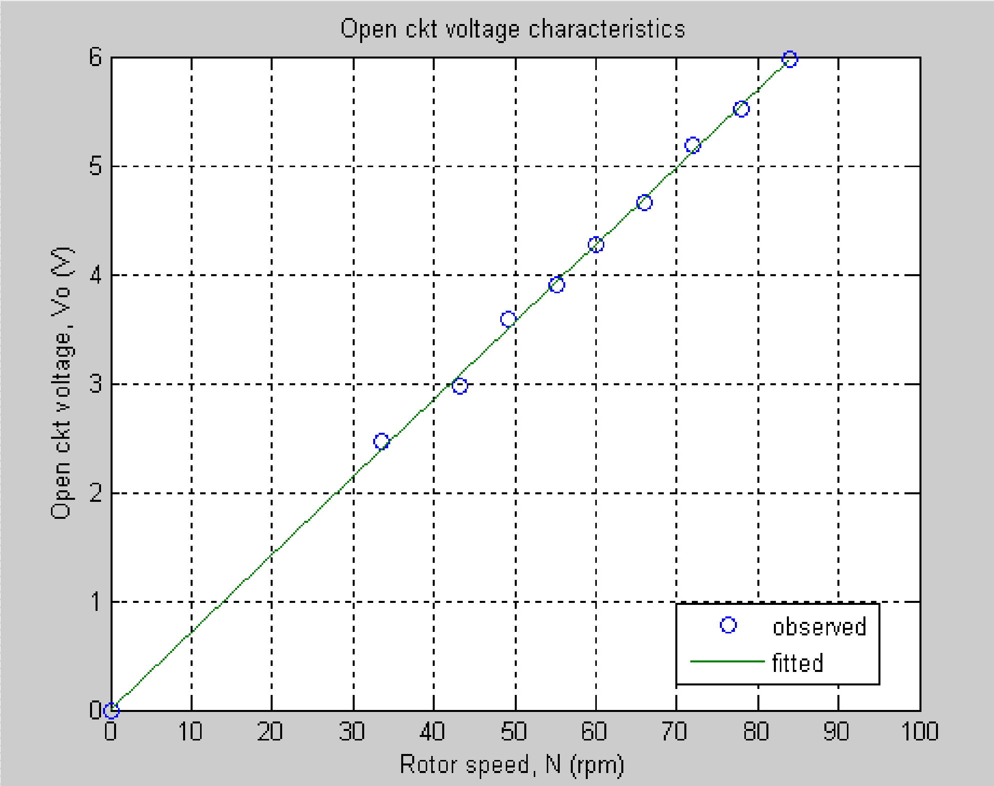


Figure 16: Open Circuit voltage characteristic

Test result (Electrical parameter test) cont….

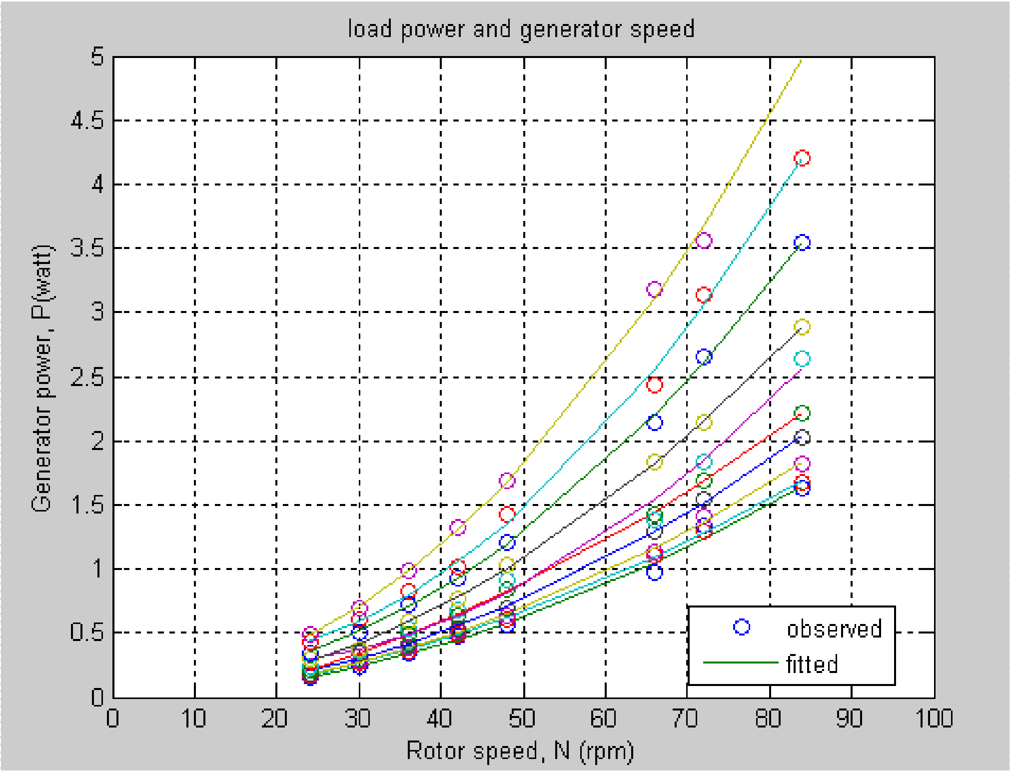
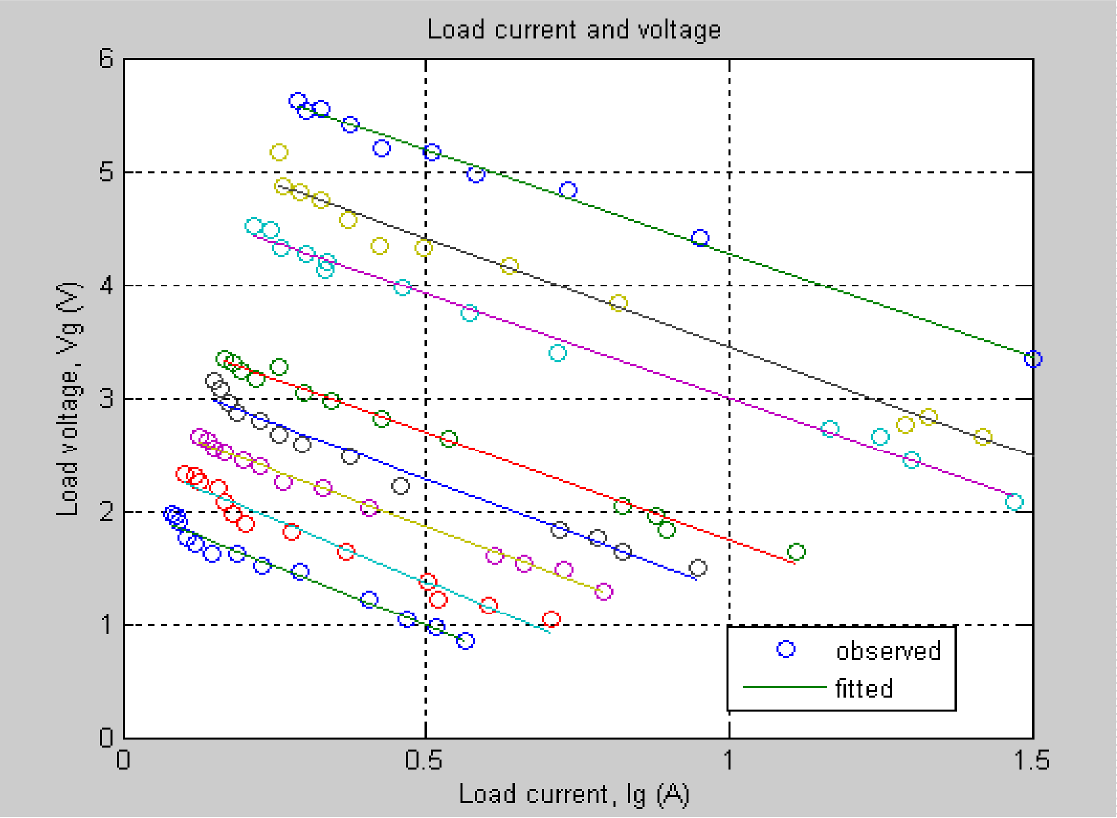


Figure 17: Output Characteristic

Each graph shows the variation of generated power with rotational speed. The different graphs are for different load (2-20 ohm).

Test result (Electrical parameter test) cont….



The graph shows the variation of load voltage with load current as load varies from 0-20 ohm. The different graphs are for different frequencies.

Figure 18:Load current and voltage characteristic

Test result (Electrical parameter test) cont….

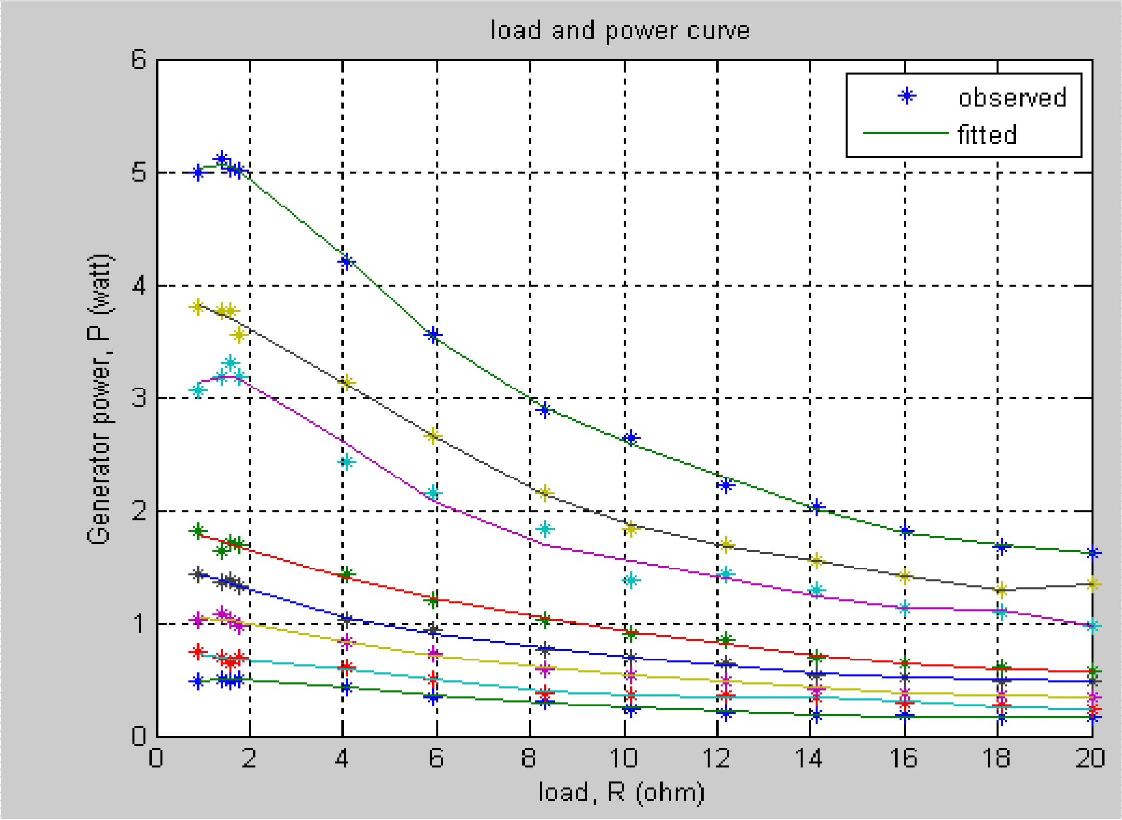


Figure 19: Load characteristic

Each graph shows the variation of generated power with load. The different graphs are for different frequencies.

Test result (Electrical parameter test) cont….

The voltage wave form for the both sides of the stator

Resultant wave form after connecting the both sides of the stator in series

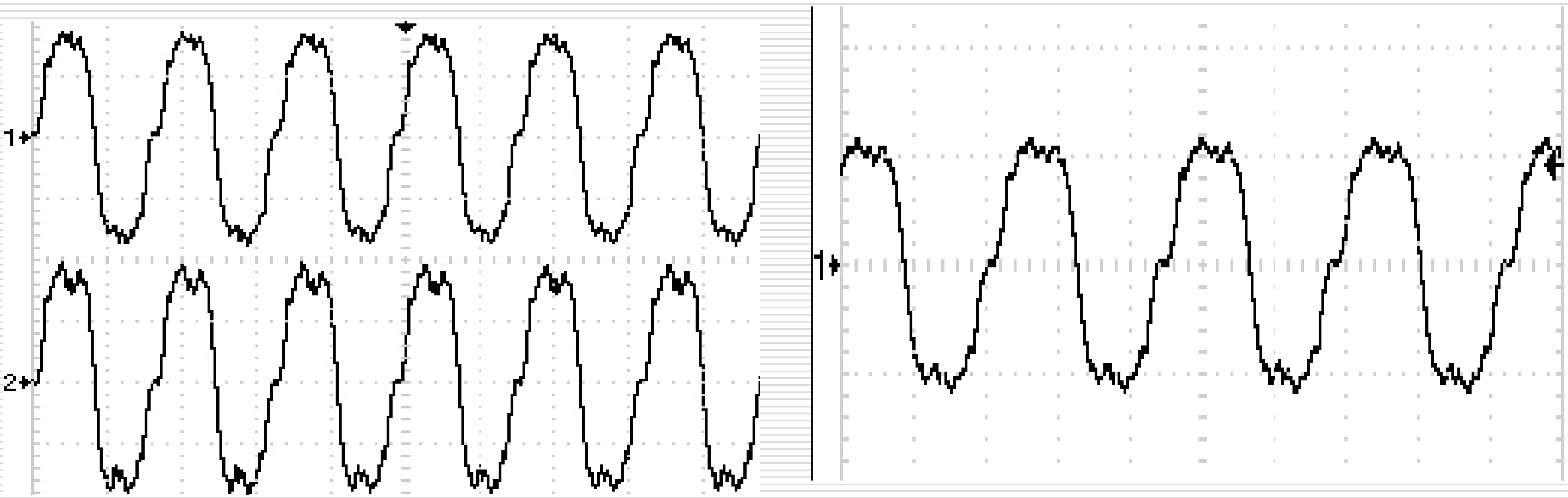


Figure 20: Voltage wave form

System model

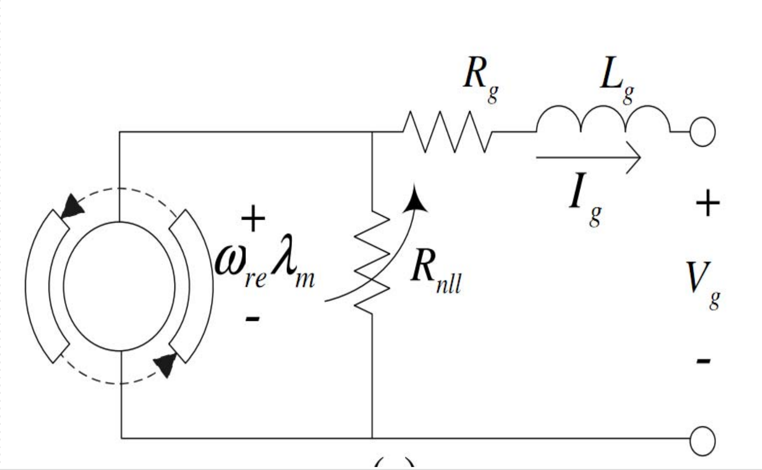


Figure 21: System model

Internal resistance, R_g, [ohm]	1.8
Internal inductance, L_g [µH]	216.7
Machine constant, λ_m	0.071
No load loss. R_{null} [ohm]	$0.003f^2+0.0116f-0.1458$
Inertia, J_m [Kg-m^2]	o.96
Initial torque, T_o [N-m]	14.5
Open Circuit voltage at 72 rpm [volt]	5.18
Load for maximum power point [ohm]	1.8

Conclusion

- Output Power is 3.5 watt at 72 rpm.
- Open circuit voltage is 5.2 volt at designed speed.
- Generating current is high due to thicker wire.
- Cogging torque is minimized.
- Large in size
- More frictional loss

Second Prototype

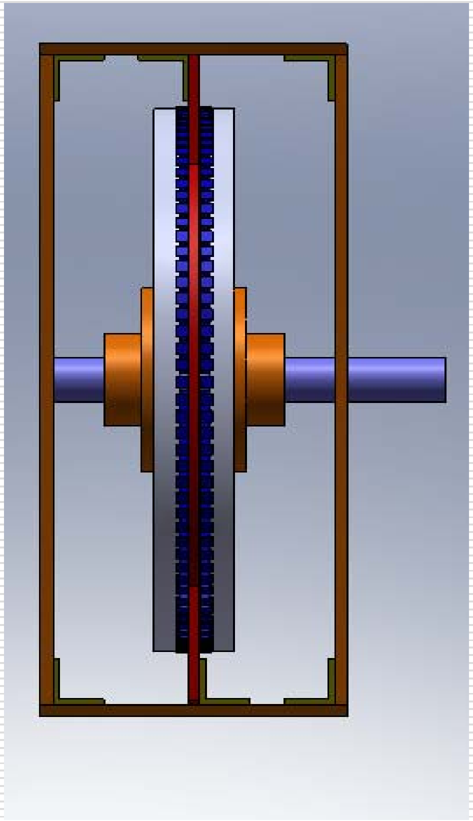


Figure 22: Designed generator

Generator design

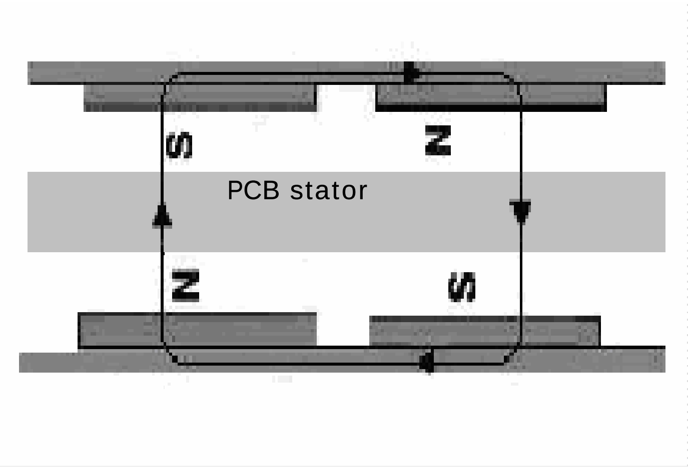
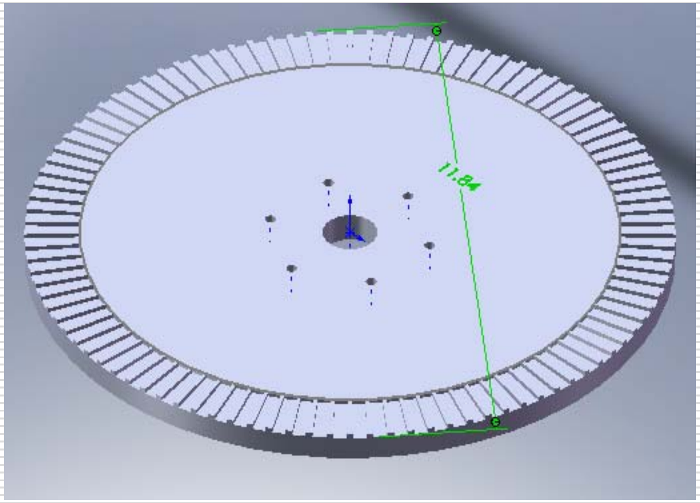


Figure 23: Designed topology of second prototype

Generator design (cont….)

- Rotor



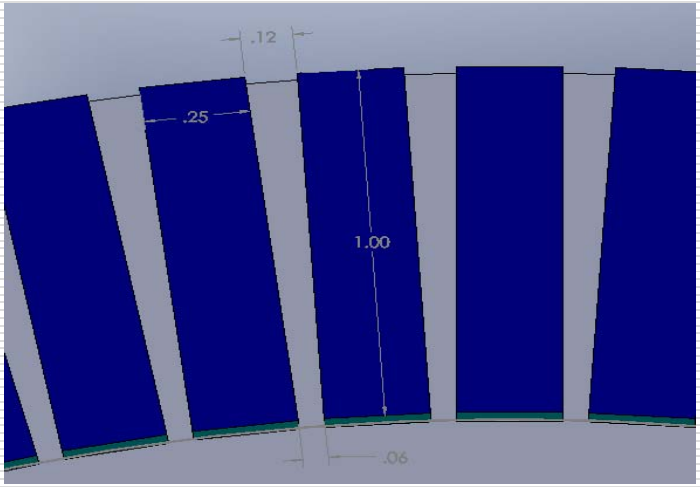


Figure 24: Rotor

Generator design (Rotor)cont….

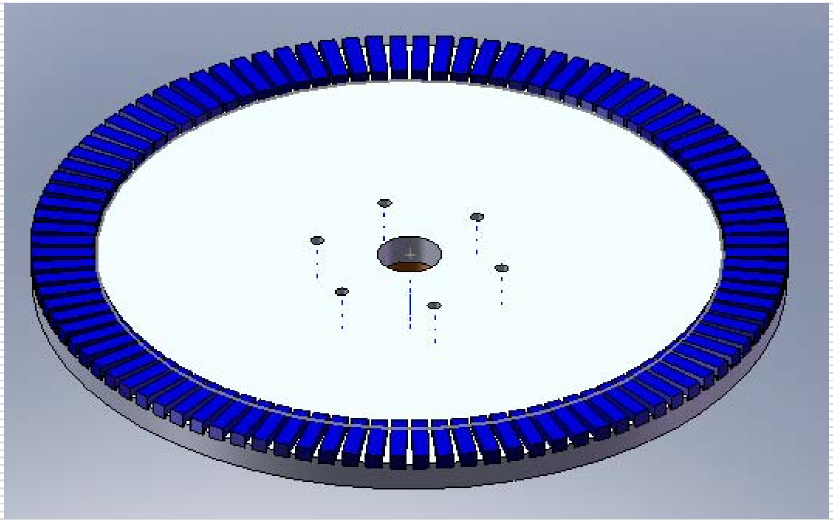


Figure 24: Rotor

Generator design (cont….)

- Stator

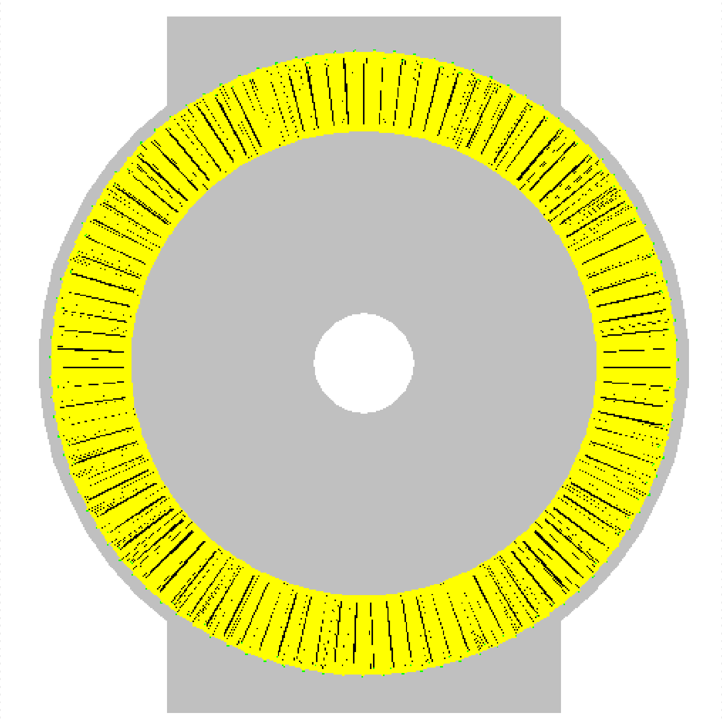


Figure 25: 4 layer PCB Stator

Generator design (cont….)

- Stator Winding

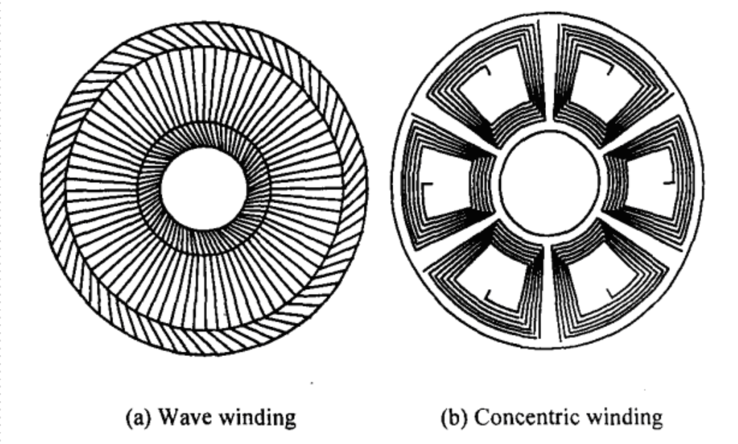


Figure 26: Stator Winding Pattern

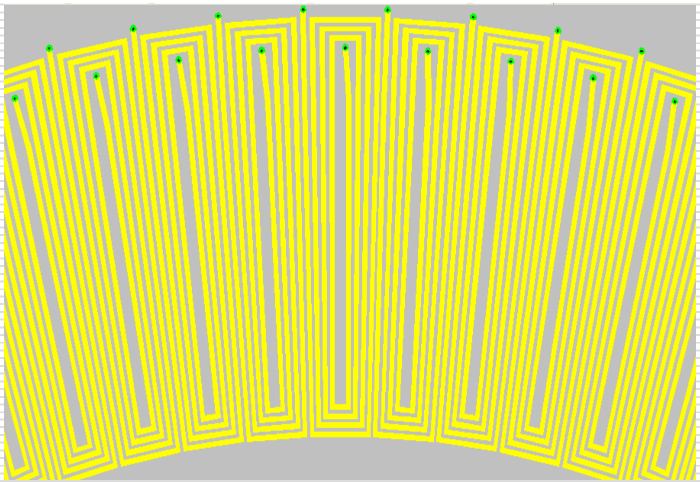


Figure 27: Stator winding

Generator design (Stator winding) cont….

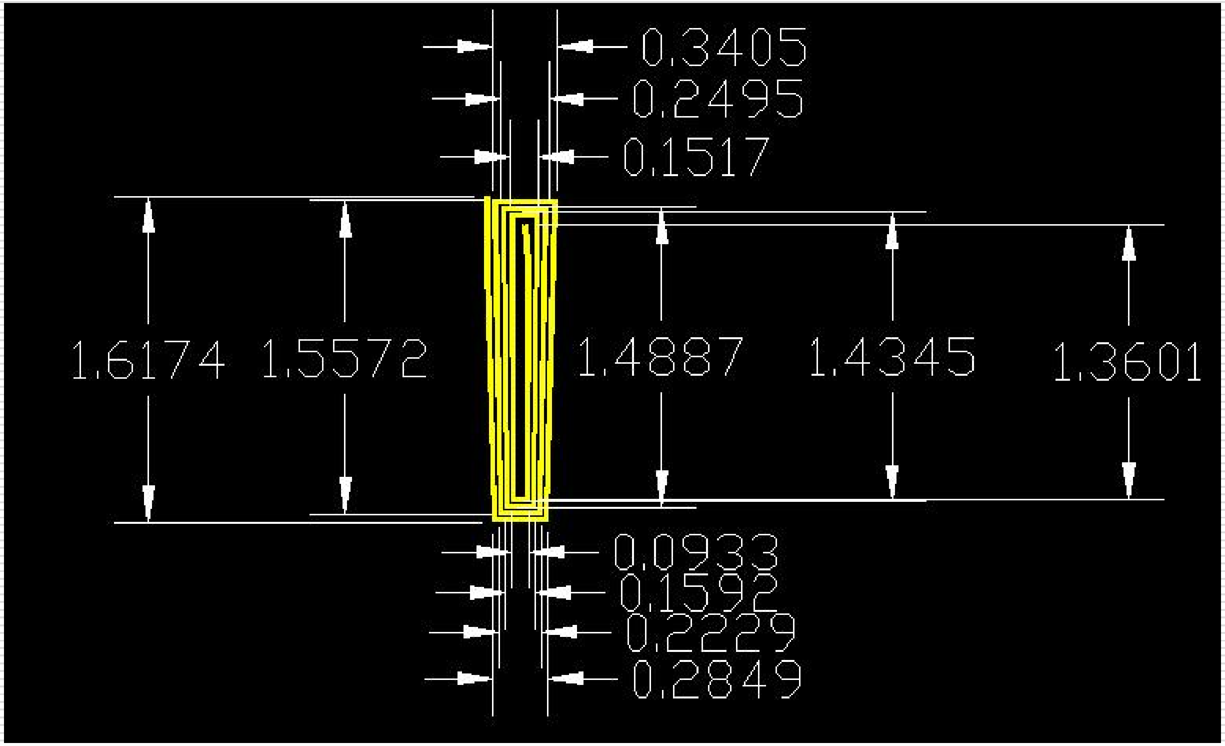


Figure 28: A single winding with dimension (in Inches)

Prototyped generator

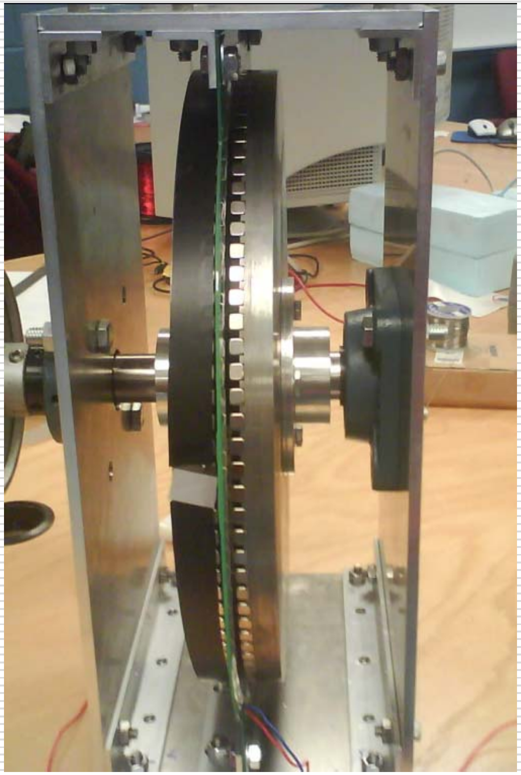
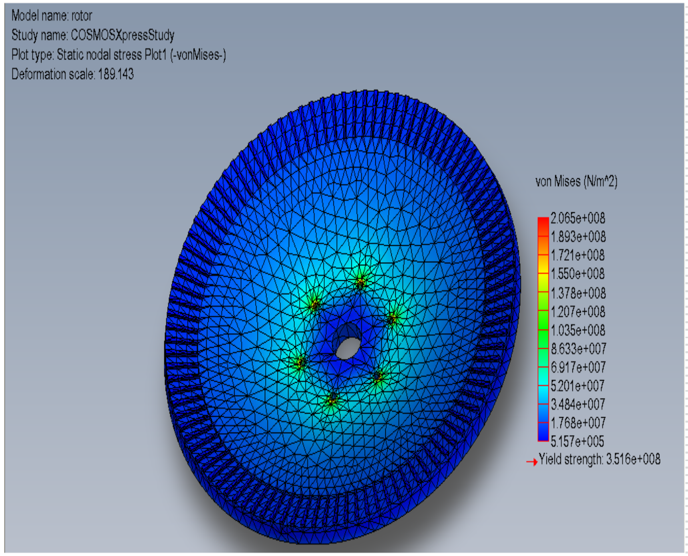


Figure 29: Prototyped Generator

Test Result

- Stress and strain test



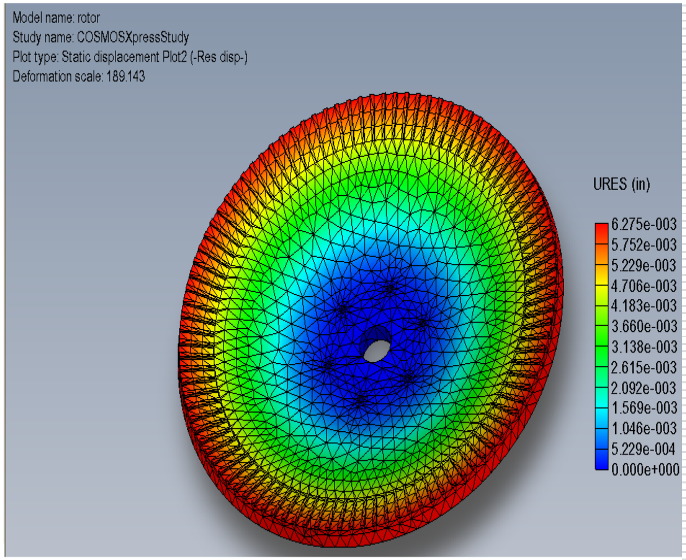


Figure 30: Stress strain test result

Test Result (Cont...)

- Mechanical parameter test

Figure 31: Friction loss test result

$$N1 = No\ (1 - e^{-t1/BJ})$$

Test Result (Cont…)

- Electrical parameter test

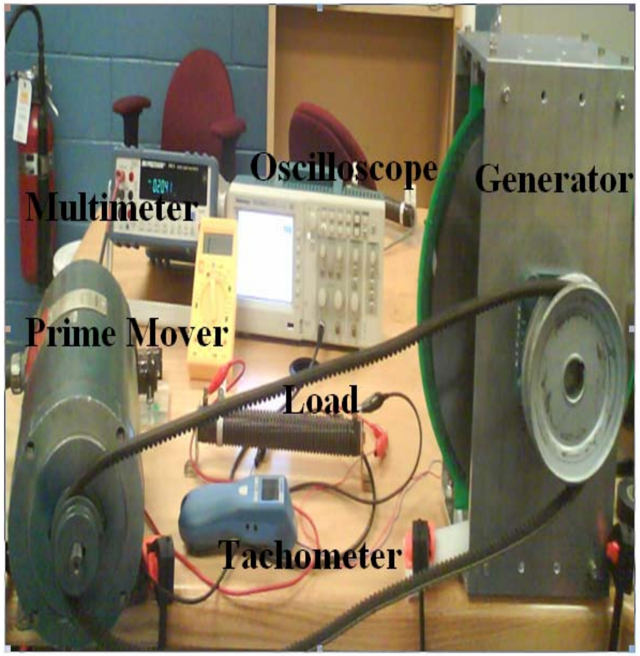


Figure 32: Test setup

Test Result (Electrical parameter test) Cont….

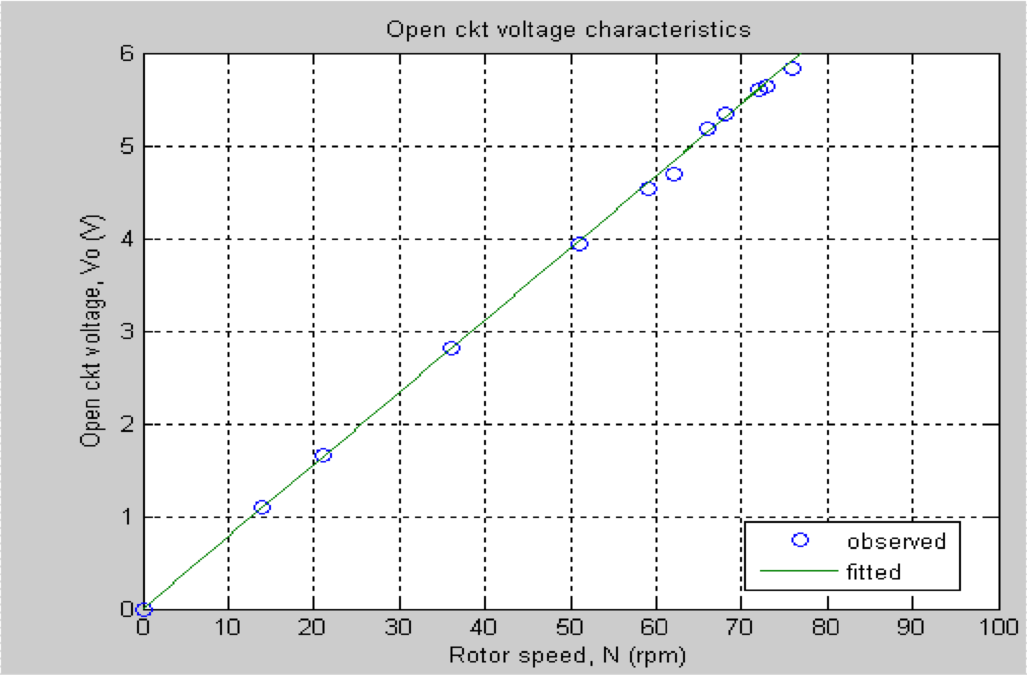
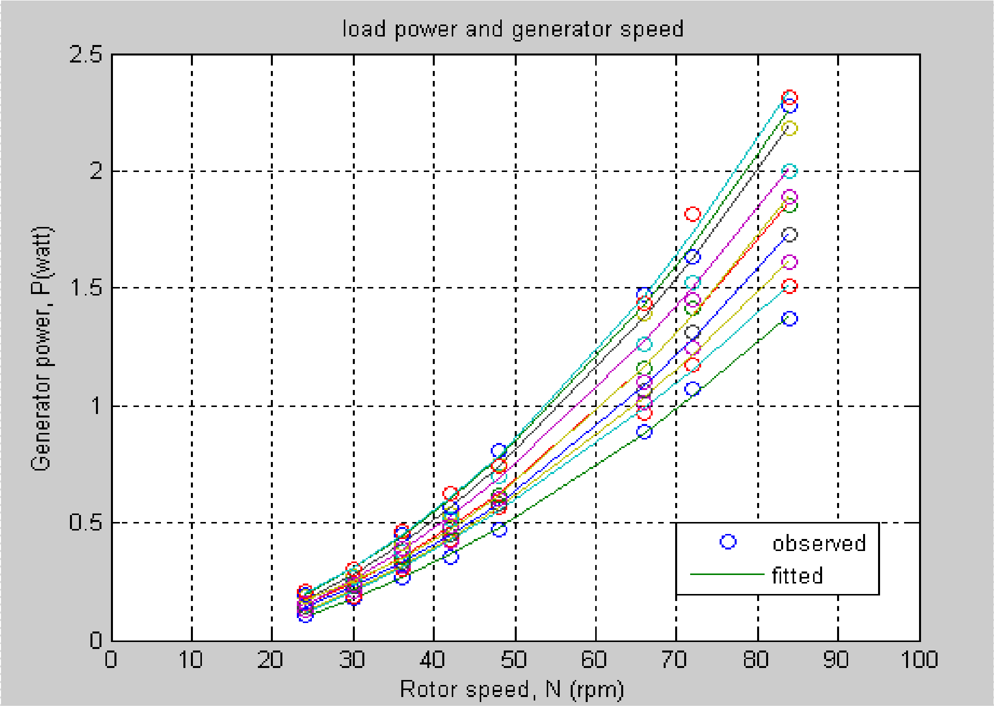


Figure 33: Open Circuit voltage characteristic

Test Result (Electrical parameter test) Cont….



Each graph shows the variation of generated power with rotational speed. The different graphs are for different load (2-20 ohm).

Figure 34: Output Characteristic

Test Result (Electrical parameter test) Cont....

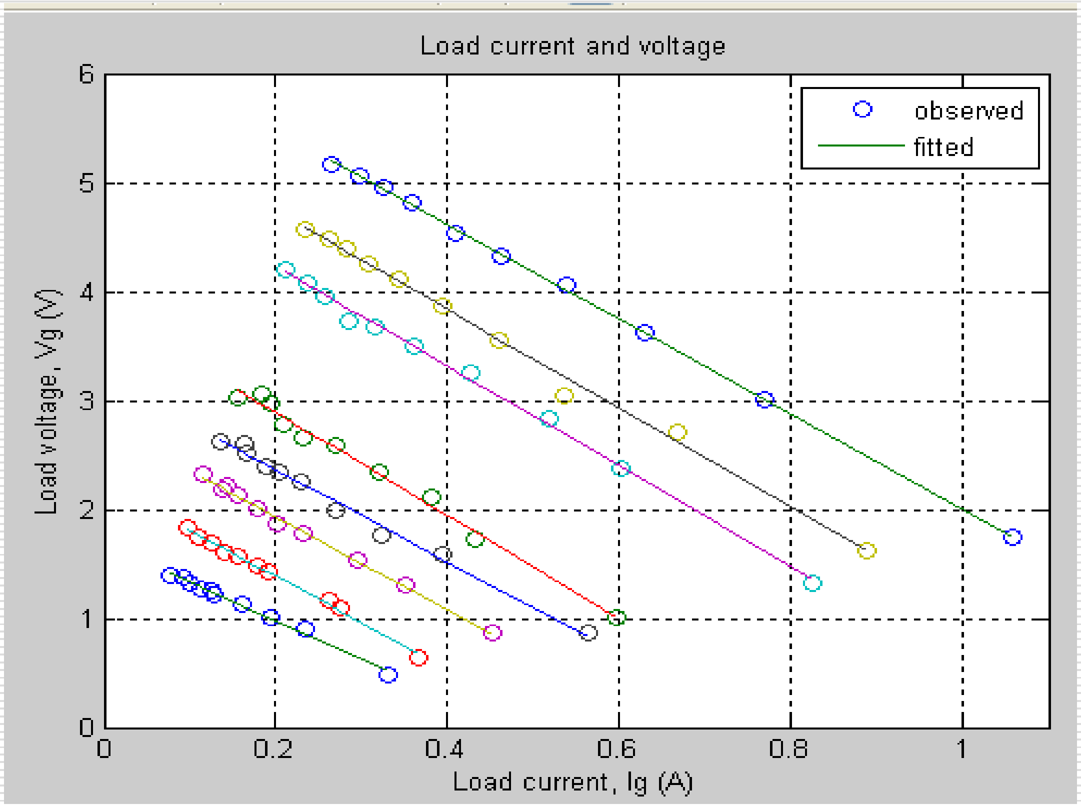


Figure 35:Load current and voltage characteristic

The graph shows the variation of load voltage with load current as load varies from 0-20 ohm. The different graphs are for different frequencies.

Test Result (Electrical parameter test) Cont….

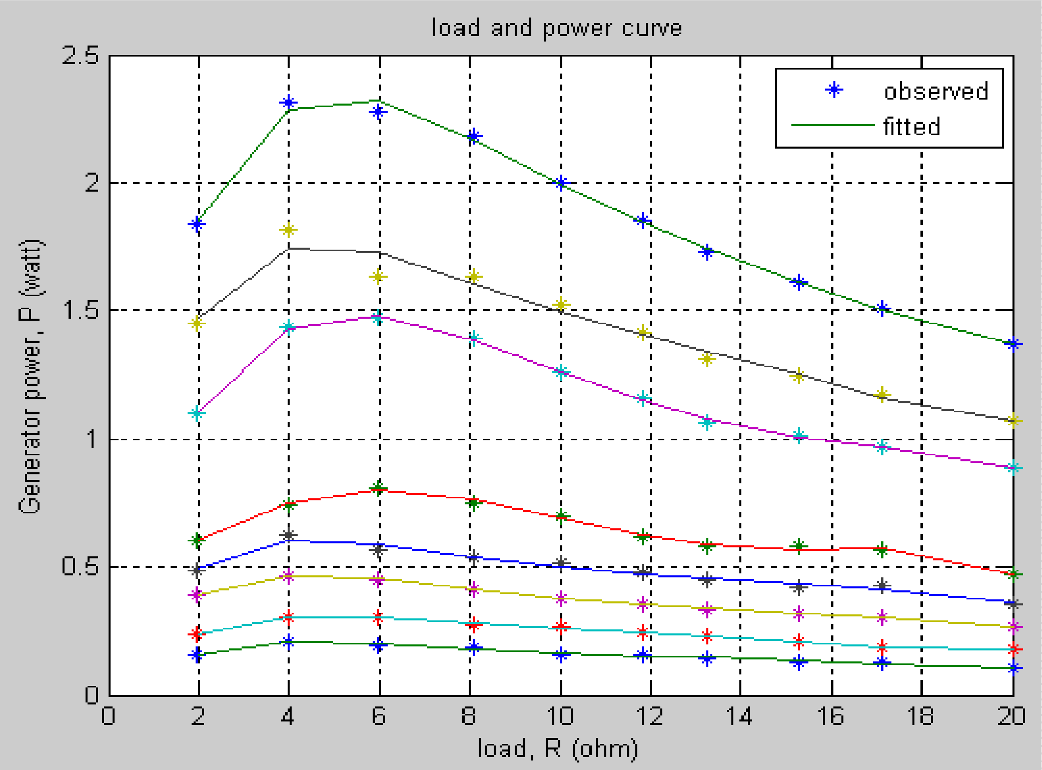


Figure 36: Load characteristic

Each graph shows the variation of generated power with load. The different graphs are for different frequencies

Test Result (Electrical parameter test) Cont….

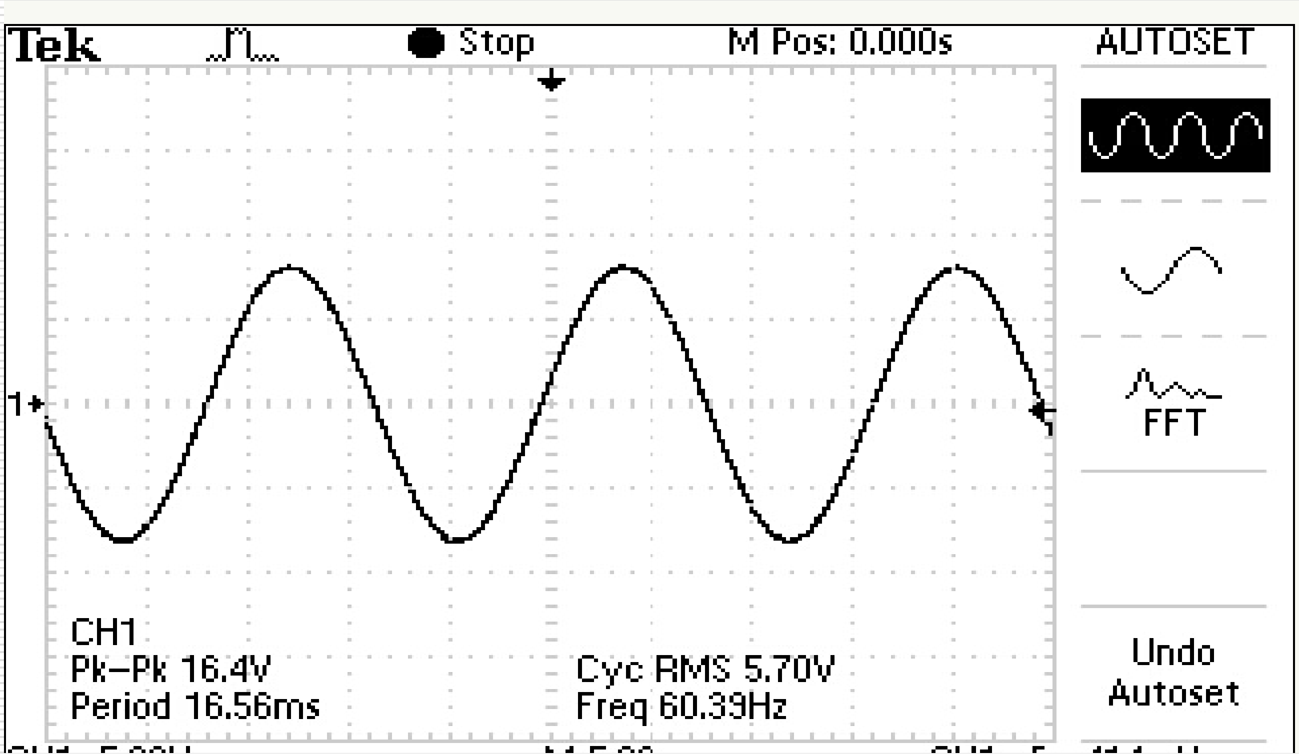


Figure 37: Voltage wave form

System parameter

Internal resistance, R_g, [ohm]	4.4
Internal inductance, L_g [μH]	66.2
Machine constant, λ_m	0.078
No load loss. R_{null} [ohm]	$0.0003f^2+0.0066f-0.1107$
Inertia, J_m [Kg-m^2]	0.213
Friction, B_m	0.3
Initial torque, T_o [N-m]	0
Open Circuit voltage at 72 rpm [volt]	5.6
Load for maximum power point [ohm]	4.5

Conclusion

- Small in size
- No cogging
- Less friction
- Zero initial torque
- Higher voltage, 5.6 volt at 72 rpm.
- Less current and power (1.8 watt)

Comparison between two prototype

- Size
- Output
- Torque
- Manufacturing process

Conclusion

- Two prototypes are built and tested.
- First Prototype
  - New cogging torque minimization technique
  - More power
  - Larger size
  - Higher current
  - Lower voltage
- Second prototype
  - PCB stator
  - Smaller size
  - Higher voltage
  - Lower current and power

Future Work

- Air gap reduction
- Material choice
- Smaller E-core
- More layer PCB
- Optimization

Acknowledgement

- Dr. Tariq Iqbal
- Seaformatics group
- Atlantic Innovation Funds (www.acoa.ca)
- Memorial University of Newfoundland
- All of my friends and family

THANKS

Questions?

Magnet properties

Properties	Values
Tolerances	±0.002" x ±0.002" x ±0.002"
Material	NdFeB, Grade N42
Plating/Coating	Ni-Cu-Ni (Nickel)
Magnetization Direction	Thru Thickness
Weight	0.271 oz. (7.68 g)
Pull Force	13.15 lbs
Surface Field	4871 Gauss
Max Operating Temp	176°F (80°C)
Brmax	13,200 Gauss
BHmax	42 MGOe
Coercive Force(Hc)	>11.0 KOe
Intrinsic Coercive Force (Hci)	>12 KOe

RENSHAPE 440 material properties

Properties	Values
Hardness Shore D	54
Density (g/cc)	0.55
Density (lbs/ft.3)	34
Tensile Strength (psi)	1,300
Compressive Strength (psi)	1,400
Compressive Modulus Elasticity (psi)	105,000
Flexural Strength (psi)	2,300
Flexural Modulus (psi)	106,000
Glass Transition Temp (°F)	203
Coefficient Thermal Expansion (in/in/°F)	34.4 x 10-6
Color	Red. Brown

Properties of AWG 20

Properties	Values
Conductor Diameter (inch)	0.032
Conductor Diameter (mm)	0.8128
Ohms per 1000 ft.	10.15
Ohms per km	33.292
Maximum amps for chassis wiring	11
Maximum amps for power transmission	1.5
Maximum frequency for 100% skin depth for solid conductor copper	27 kHz

Rotor Yoke (mild steel C-1020) data

Chemical composition: C=0.20%, Mn=0.45%, P=0.04% max, S=0.05% max				
Property	**Value in metric unit**		**Value in US unit**	
Density	$7.872 * 10^3$	kg/m^3	491.4	lb/ft^3
Modulus of elasticity	200	GPa	29000	ksi
Thermal expansion (20 ºC)	$11.9*10^{-6}$	$ºC^{-1}$	$6.61*10^{-6}$	in/(in* ºF)
Specific heat capacity	486	J/(kg*K)	0.116	BTU/(lb*ºF)
Thermal conductivity	51.9	W/(m*K)	360	$BTU*in/(hr*ft^2*ºF)$
Electric resistivity	$1.59*10^{-7}$	Ohm*m	$1.59*10^{-5}$	Ohm*cm
Tensile strength (hot rolled)	380	MPa	55100	psi
Yield strength (hot rolled)	165	MPa	29700	psi
Elongation (hot rolled)	25	%	25	%
Hardness (hot rolled)	66	RB	66	RB
Tensile strength (cold drawn)	420	MPa	60900	psi
Yield strength (cold drawn)	205	MPa	50800	psi
Elongation (cold drawn)	15	%	15	%
Hardness (cold drawn)	73	RB	73	RB

FR-4 data

Properties	Values
Dielectric constant (permittivity)	4.70 max, 4.35 @ 500 MHz, 4.34 @ 1 GHz
Dissipation factor (loss tangent)	0.02 @1 MHz, 0.01 @ 1 GHz
Dielectric strength	20 MV/mm (500 V/mil)
Surface resistivity (min)	2×10^5 MΩ
Volume resistivity (min)	8×10^7 MΩ·cm^2/cm
Typical thickness	1.25–2.54 mm (0.049–0.100 inches)
Typical stiffness (Young's modulus)	17 GPa (2.5×10^6 PSI; for use in PCBs)
Water absorption	0.10%
Tg (glass transition temperature)	110–200 °C by manufacture and resin system
Thermal Expansion Coefficient	11ppm/K (glass fiber lengthwise)
Thermal Expansion Coefficient	15ppm/K (glass fiber crosswise)
Density	1.91 kg/L

Generator design parameters

Outer radius, r_o [mm]	380
Magnet spacing, τ_f [mm]	2.5 & 1.5
Number of magnets, N_m	100
Number of coils, N_s	4
Number of phases, N_{ph}	1
Magnet thickness, l_m [mm]	1.55
Air gap, δ [mm]	1
Dimension of larger magnet (inch)	$1.0\times0.25\times0.0625$
Dimension of larger magnet (inch)	$0.75\times0.25\times0.0625$

Generator design parameters

Outer radius, r_o [mm]	150
Magnet spacing, τ_f [mm]	0.12
Number of magnets, N_m	100
Number of coils, N_s	4
Number of phases, N_{ph}	1
Magnet thickness, l_m [inch]	0.25
Air gap, δ [mm]	0.7
Dimension of larger magnet (inch)	$1.0 \times 0.25 \times 0.25$