# MIDDLE EAST TECHNICAL UNIVERSITY

# DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

# EE 564: DESIGN OF ELECTRICAL MACHINES

# PROJECT – 3

## Göksenin Hande Bayazıt – 2093441

## Submission Date: Jun. 4, 2018

# Introduction:

In the scope of this project, a traction squirrel cage induction machine is designed. Motor parameters will be analyzed in detail using both analytical calculation techniques and computational tools. Specifications of the machine are as follows:

* Rated Power Output: 1280 kW
* Line-to-line voltage: 1350 V
* Number of poles: 6
* Rated Speed: 1520 rpm (72 km/h) (driven with 78 Hz inverter)
* Rated Motor Torque: 7843 Nm
* Cooling: Forced Air Cooling
* Insulating Class: 200C
* Train Wheel Diameter: 1210 mm
* Maximum Speed: 140 km/h
* Gear Ratio: 4.82

# Sizing:

For size estimation, initially an appropriate mechanical machine constant is chosen and throughout the design process (iterations), mechanical machine constant kept within the appropriate boundaries. For a 6 pole 1280 kW machine, Cmech should be around 250-320 kW.s/m3. Let Cmech=260.

Let

Let’s choose magnetic loading and assume that winding factor is around 0.95

This is not possible since number of turns should be an integer. Let’s take **Nph as 24** and recalculate D and l’.

Airgap length:

Stator outer diameter:

Back core length (assuming peak flux density in back core will be 1.5 T):

Input apparent power (assuming 95% efficiency and 0.9 power factor):

Electric loading value is within boundaries and is acceptable.

# Winding Design:

Number of turns per phase is chosen as 24.

Let q=4 and number of turns per conductor be 2.

For this case, an appropriate **slot number for rotor is 84** (with a skew width of 2 slots).

Winding diagram of stator is as follows:

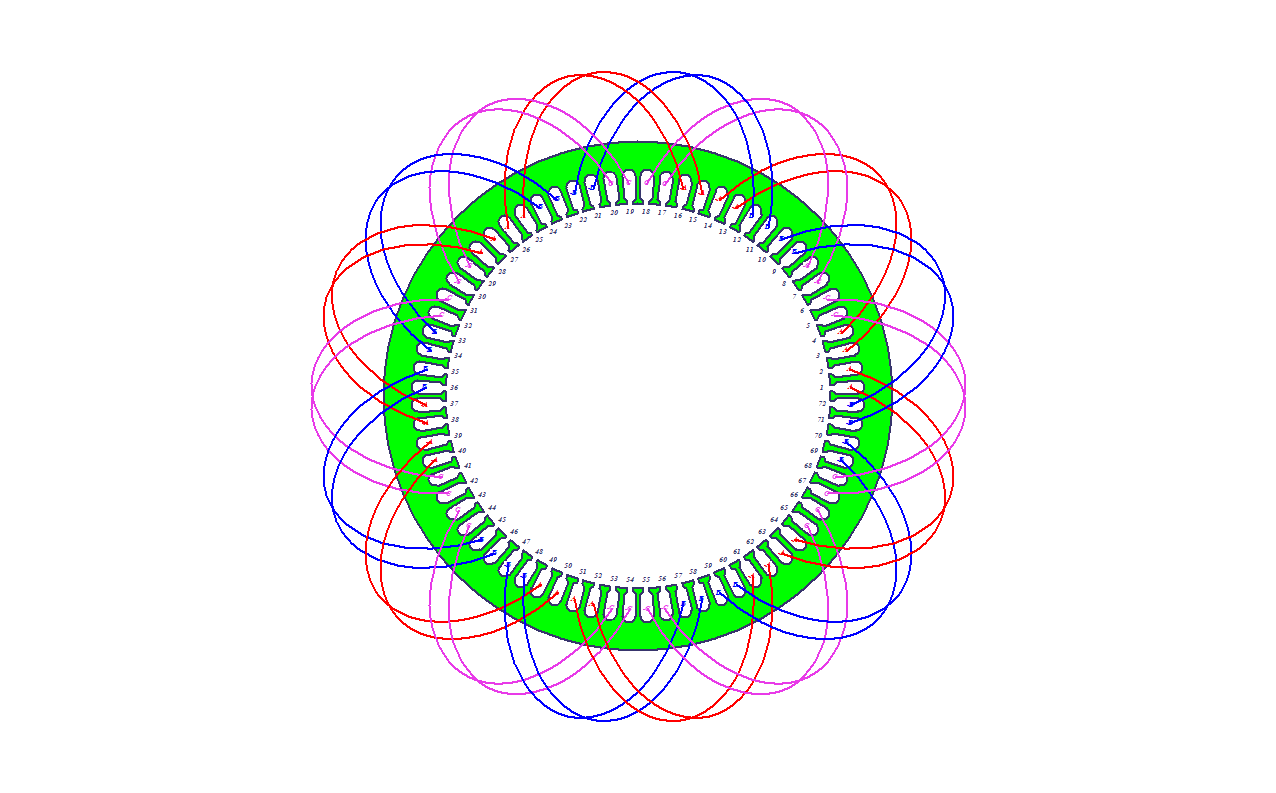


Figure 1: Stator Winding Diagram

## Winding Factor:

Winding factor for hth harmonic order:

|  |  |  |  |
| --- | --- | --- | --- |
|  | kd | kp | kw |
| 1 | 0.9577 | 1 | 0.9577 |
| 3 | 0.6533 | -1 | -0.6533 |
| 5 | 0.2053 | 1 | 0.2053 |
| 7 | -0.1576 | -1 | 0.1576 |
| 9 | -0.2706 | 1 | -0.2706 |

# Conductor and Slot Size:

As cooling is achieved by forced air cooling, let’s assume J=7 A/mm2.

Using two AWG0 size cables in parallel, we obtain Acond= 107 mm2. Dcond=8.25 mm.

Slot width should be at least a bit larger than conductor diameter.

Slot dimensions are as given in Figure 2.

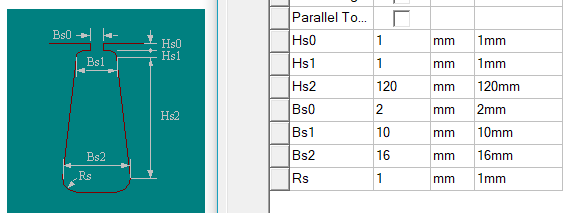


Figure 2: Slot Dimensions

Assuming that the slot is trapezoidal, slot area can be calculated as:

# Motor Parameter Estimation:

## Teeth Flux Density:

While calculating the flux per pole, (magnetic loading) is chosen as 0.8 T, which is safe. As the teeth and tooth openings have approximately same length, at teeth may be calculated as:

This value is also safe, where stator steel is far from saturation point.

## Approximate Torque Calculation:

## Equivalent Circuit Parameters:

* Phase resistance:

Assuming that end windings will be 10% of the coil length:

At 75oC, for copper.

* Phase inductance:

Phase inductance can be calculated with reluctance of the airgap.

# Material Properties and Mass:

Core: JFE\_Steel\_50JN600 type steel is used since it has relatively low core loss compared to the materials that have high flux density ratings.

# Losses:

* Copper loss:
* Core loss:

# RMXprt and Maxwell 2D Design:

RMXprt design results are given in Appendix. Below, on Figures 3-6, Maxwell 2D results are presented.

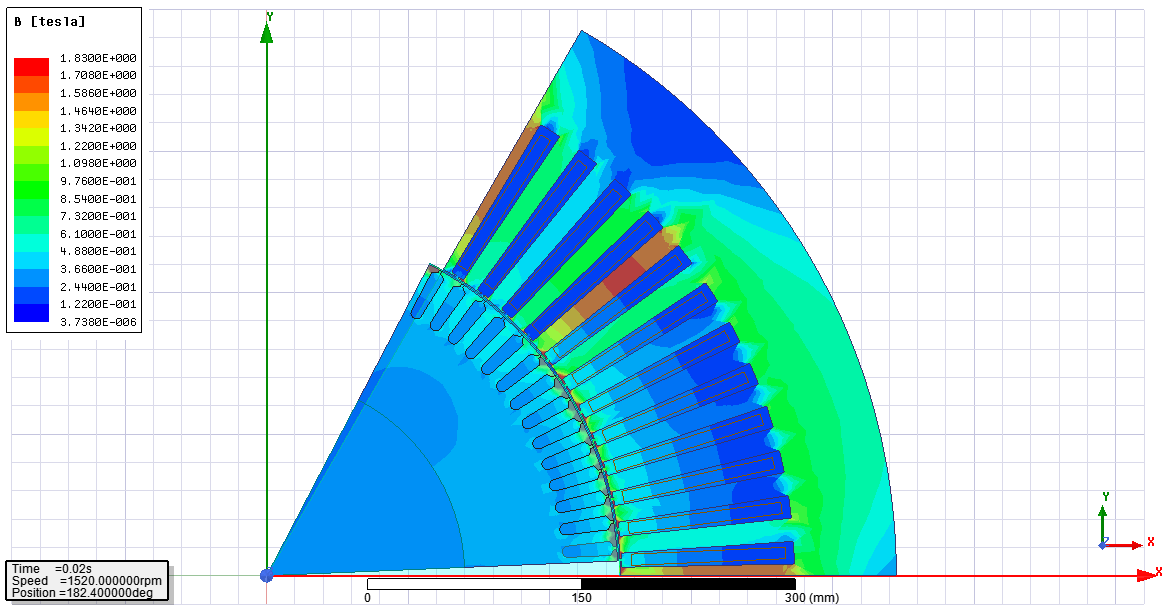


Figure 3: Flux Density Distribution

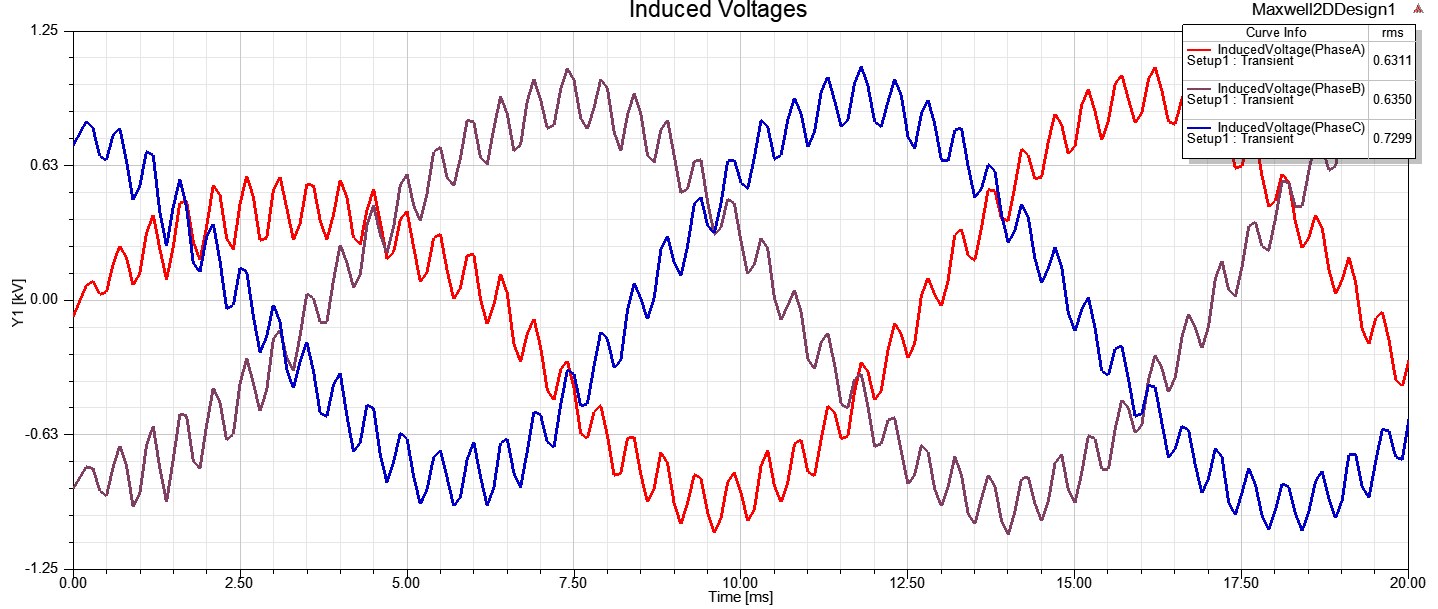


Figure 4: Induced Voltages

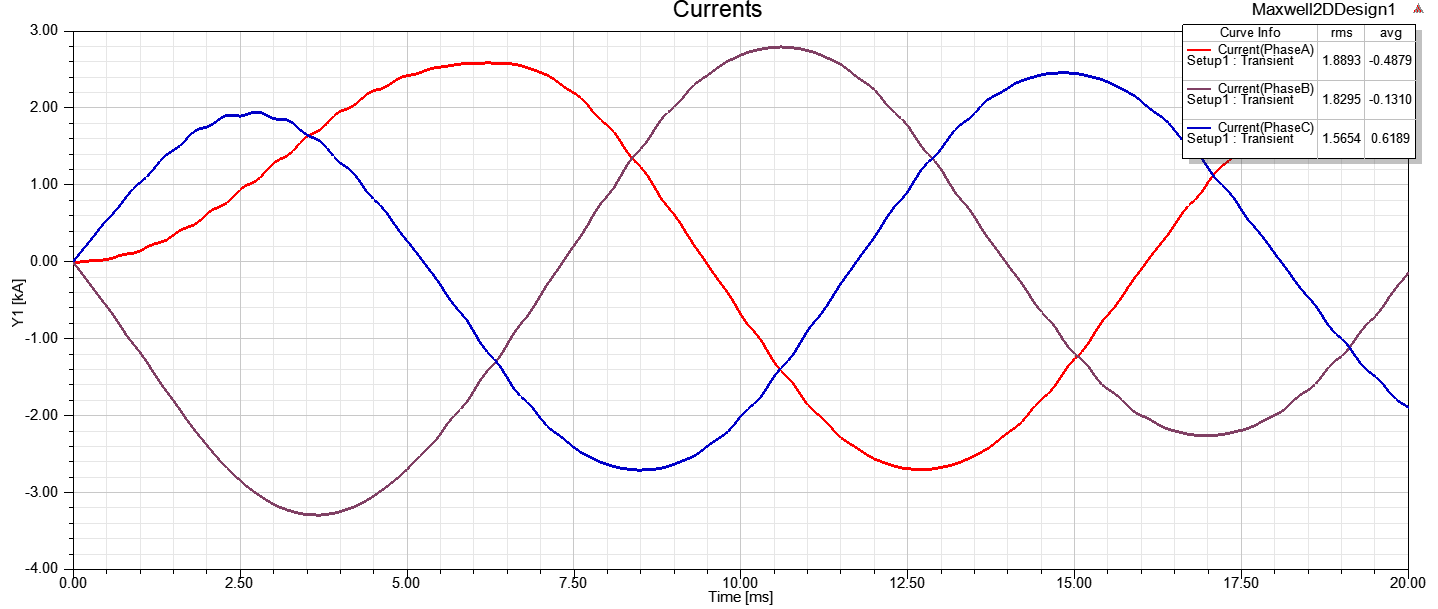


Figure 5: Phase Currents

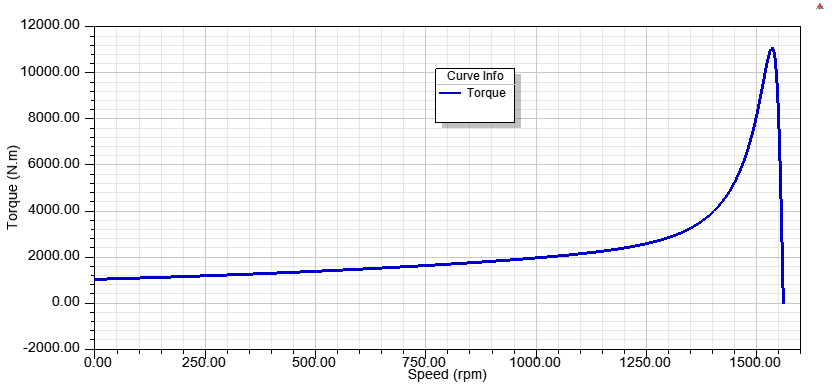


Figure 6: Torque-Speed Curve of the Machine

# Conclusion:

To summarize, we can conclude that analytical results are compatible with FEA results in a large extent. However, loss, resistance and inductance calculations are not quite reliable since they are calculated with rough assumptions.

# Appendix: Rmxprt Design Results

Three-Phase Induction Machine Design

GENERAL DATA

Given Output Power (kW): 1280

Rated Voltage (V): 1350

Winding Connection: Wye

Number of Poles: 6

Given Speed (rpm): 1520

Frequency (Hz): 78

Stray Loss (W): 12800

Frictional Loss (W): 48.7179

Windage Loss (W): 0

Operation Mode: Motor

Type of Load: Constant Power

Operating Temperature (C): 75

STATOR DATA

Number of Stator Slots: 72

Outer Diameter of Stator (mm): 910

Inner Diameter of Stator (mm): 510

Type of Stator Slot: 4

Stator Slot

hs0 (mm): 1

hs1 (mm): 1

hs2 (mm): 120

bs0 (mm): 2

bs1 (mm): 10

bs2 (mm): 16

rs (mm): 1

Top Tooth Width (mm): 12.4297

Bottom Tooth Width (mm): 16.9041

Length of Stator Core (mm): 730

Stacking Factor of Stator Core: 0.95

Type of Steel: JFE\_Steel\_50JN600

Number of lamination sectors 0

Press board thickness (mm): 0

Magnetic press board No

Number of Parallel Branches: 2

Type of Coils: 11

Coil Pitch: 1

Number of Conductors per Slot: 4

Number of Wires per Conductor: 1

Wire Diameter (mm): 8.252

Wire Wrap Thickness (mm): 0

Wedge Thickness (mm): 0

Slot Liner Thickness (mm): 0

Layer Insulation (mm): 0

Slot Area (mm^2): 1587.14

Net Slot Area (mm^2): 1575.98

Slot Fill Factor (%): 17.2833

Limited Slot Fill Factor (%): 50

Wire Resistivity (ohm.mm^2/m): 0.0217

Conductor Length Adjustment (mm): 0

End Length Correction Factor 1

End Leakage Reactance Correction Factor 1

ROTOR DATA

Number of Rotor Slots: 84

Air Gap (mm): 1.85

Inner Diameter of Rotor (mm): 280

Type of Rotor Slot: 2

Rotor Slot

hs0 (mm): 2

hs1 (mm): 2.5

hs2 (mm): 30

bs0 (mm): 2

bs1 (mm): 10

bs2 (mm): 8

Cast Rotor: Yes

Half Slot: No

Length of Rotor (mm): 730

Stacking Factor of Rotor Core: 0.95

Type of Steel: steel\_1010

Skew Width: 2

End Length of Bar (mm): 0

Height of End Ring (mm): 20

Width of End Ring (mm): 12

Resistivity of Rotor Bar

at 75 Centigrade (ohm.mm^2/m): 0.0172414

Resistivity of Rotor Ring

at 75 Centigrade (ohm.mm^2/m): 0.0172414

Magnetic Shaft: No

MATERIAL CONSUMPTION

Armature Copper Density (kg/m^3): 8900

Rotor Bar Material Density (kg/m^3): 8933

Rotor Ring Material Density (kg/m^3): 8933

Armature Core Steel Density (kg/m^3): 7750

Rotor Core Steel Density (kg/m^3): 7872

Armature Copper Weight (kg): 148.963

Rotor Bar Material Weight (kg): 172.073

Rotor Ring Material Weight (kg): 6.49689

Armature Core Steel Weight (kg): 1783.47

Rotor Core Steel Weight (kg): 618.893

Total Net Weight (kg): 2729.9

Armature Core Steel Consumption (kg): 4480.12

Rotor Core Steel Consumption (kg): 1416.05

RATED-LOAD OPERATION

Stator Resistance (ohm): 0.0105816

Stator Resistance at 20C (ohm): 0.0087042

Stator Leakage Reactance (ohm): 0.298541

Rotor Resistance (ohm): 0.00709357

Rotor Leakage Reactance (ohm): 0.163762

Resistance Corresponding to

Iron-Core Loss (ohm): 63.1582

Magnetizing Reactance (ohm): 5.53723

Stator Phase Current (A): 675.637

Current Corresponding to

Iron-Core Loss (A): 10.8273

Magnetizing Current (A): 123.497

Rotor Phase Current (A): 635.329

Copper Loss of Stator Winding (W): 14491

Copper Loss of Rotor Winding (W): 8589.82

Iron-Core Loss (W): 22212.2

Frictional and Windage Loss (W): 49.6666

Stray Loss (W): 12800

Total Loss (W): 58142.7

Input Power (kW): 1337.71

Output Power (kW): 1279.56

Mechanical Shaft Torque (N.m): 7885.23

Efficiency (%): 95.6536

Power Factor: 0.838644

Rated Slip: 0.00666806

Rated Shaft Speed (rpm): 1549.6

NO-LOAD OPERATION

No-Load Stator Resistance (ohm): 0.0105816

No-Load Stator Leakage Reactance (ohm): 0.299532

No-Load Rotor Resistance (ohm): 0.00708999

No-Load Rotor Leakage Reactance (ohm): 0.165139

No-Load Stator Phase Current (A): 134.087

No-Load Iron-Core Loss (W): 25961.5

No-Load Input Power (W): 40838.2

No-Load Power Factor: 0.0894269

No-Load Slip: 6.51178e-006

No-Load Shaft Speed (rpm): 1559.99

BREAK-DOWN OPERATION

Break-Down Slip: 0.016

Break-Down Torque (N.m): 11073.4

Break-Down Torque Ratio: 1.40432

Break-Down Phase Current (A): 1210.33

LOCKED-ROTOR OPERATION

Locked-Rotor Torque (N.m): 1051.16

Locked-Rotor Phase Current (A): 1857.68

Locked-Rotor Torque Ratio: 0.133308

Locked-Rotor Current Ratio: 2.74953

Locked-Rotor Stator Resistance (ohm): 0.0105816

Locked-Rotor Stator

Leakage Reactance (ohm): 0.293154

Locked-Rotor Rotor Resistance (ohm): 0.0173796

Locked-Rotor Rotor

Leakage Reactance (ohm): 0.128444

DETAILED DATA AT RATED OPERATION

Stator Slot Leakage Reactance (ohm): 0.194765

Stator End-Winding Leakage

Reactance (ohm): 0.063248

Stator Differential Leakage

Reactance (ohm): 0.0405284

Rotor Slot Leakage Reactance (ohm): 0.0838629

Rotor End-Winding Leakage

Reactance (ohm): 0.00749033

Rotor Differential Leakage

Reactance (ohm): 0.0257008

Skewing Leakage Reactance (ohm): 0.046708

Stator Winding Factor: 0.957662

Stator-Teeth Flux Density (Tesla): 1.08306

Rotor-Teeth Flux Density (Tesla): 1.5934

Stator-Yoke Flux Density (Tesla): 0.809616

Rotor-Yoke Flux Density (Tesla): 0.824

Air-Gap Flux Density (Tesla): 0.672859

Stator-Teeth Ampere Turns (A.T): 17.0405

Rotor-Teeth Ampere Turns (A.T): 141.235

Stator-Yoke Ampere Turns (A.T): 16.1677

Rotor-Yoke Ampere Turns (A.T): 43.9895

Air-Gap Ampere Turns (A.T): 1037.49

Correction Factor for Magnetic

Circuit Length of Stator Yoke: 0.7

Correction Factor for Magnetic

Circuit Length of Rotor Yoke: 0.7

Saturation Factor for Teeth: 1.15256

Saturation Factor for Teeth & Yoke: 1.21054

Induced-Voltage Factor: 0.877358

Stator Current Density (A/mm^2): 6.31648

Specific Electric Loading (A/mm): 60.7234

Stator Thermal Load (A^2/mm^3): 383.558

Rotor Bar Current Density (A/mm^2): 3.36371

Rotor Ring Current Density (A/mm^2): 19.4077

Half-Turn Length of

Stator Winding (mm): 1086.64

WINDING ARRANGEMENT

The 3-phase, 1-layer winding can be arranged in 24 slots as below:

AAAAZZZZBBBBXXXXCCCCYYYY

Angle per slot (elec. degrees): 15

Phase-A axis (elec. degrees): 112.5

First slot center (elec. degrees): 0

TRANSIENT FEA INPUT DATA

For one phase of the Stator Winding:

Number of Turns: 48

Parallel Branches: 2

Terminal Resistance (ohm): 0.0105816

End Leakage Inductance (H): 0.000129054

For Rotor End Ring Between Two Bars of One Side:

Equivalent Ring Resistance (ohm): 1.29583e-006

Equivalent Ring Inductance (H): 3.62853e-008

2D Equivalent Value:

Equivalent Model Depth (mm): 730

Equivalent Stator Stacking Factor: 0.95

Equivalent Rotor Stacking Factor: 0.95

Estimated Rotor Inertial Moment (kg m^2): 36.7324