MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE 564: DESIGN OF ELECTRICAL MACHINES

PROJECT – 3

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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, C_{mech} should be around 250-320 kW.s/m^3. Let C_{mech}=260.

$$P_{mech} = \frac{C_{mech} D^2 l' f}{p}$$

$$D^2 l' = 0.1893$$

Let $\chi = \frac{l'}{D} = 1.5$

$$D = 0.502\ m$$

$$l' = 0.752\ m$$

Let's choose magnetic loading $\boldsymbol{\widehat{B_\delta} = 0.8\ T}$ and assume that winding factor is around 0.95

$$E = \frac{\frac{2\pi}{\sqrt{2}} f k_w N_{ph} B_{avg} l' D\pi}{2p}$$

$$\frac{1350}{\sqrt{3}} = \frac{2\pi}{\sqrt{2}} * 78 * 0.95 * N_{ph} * \frac{2}{\pi} 0.8\pi * 0.502 * \frac{0.752}{6}$$

$$N_{ph} = 23.6$$

This is not possible since number of turns should be an integer. Let's take **N_{ph} as 24** and recalculate D and l'.

$$\frac{1350}{\sqrt{3}} = \frac{2\pi}{\sqrt{2}} * 78 * 0.95 * 24 * \frac{2}{\pi} 0.8\pi * \frac{D^2\chi}{6}$$

$$D^2\chi = 0.3699$$

$$D^3\chi = 0.1893$$

$$\boldsymbol{D = 0.51\ m}$$

$$\boldsymbol{l' = 0.73\ m}$$

Airgap length:

$$\delta = 0.18 + 0.006P^{0.4}$$

$$\boldsymbol{\delta = 1.85\ mm}$$

Stator outer diameter:

$$\frac{D_o}{D_i} = 1.78\ for\ p = 3$$

$$\boldsymbol{D_o = 0.91\ m}$$

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

$$t_{yoke} = \frac{\frac{\widehat{B_\delta}}{\widehat{B_y}} \pi D}{4p}$$

$$\boldsymbol{t_{yoke} = 70\ mm}$$

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

$$S_i = \frac{1280}{0.9 * 0.95} = 1500\ kVA$$

$$S_i = \frac{\pi^2}{\sqrt{2}}\left(\frac{f}{p}\right) k_w A \widehat{B_\delta} D^2 l'$$

$$\boldsymbol{A = 57287\ kA/m}$$

Electric loading value is within boundaries and is acceptable.

Winding Design:

Number of turns per phase is chosen as 24.

$$q = \frac{N_{ph}}{N_{cond}\ p}$$

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

$$Q_S = q * m * 2p$$

$$\boldsymbol{Q_s = 72\ slots}$$

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:

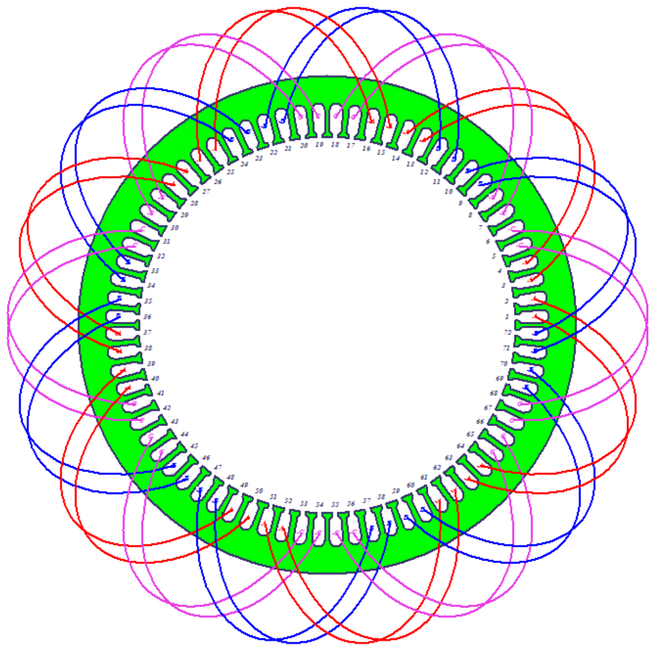

Figure 1: Stator Winding Diagram

Winding Factor:

Winding factor for h^{th} harmonic order:

$$k_p(h) = \sin\left(\frac{\lambda}{2}h\right)$$

$$k_d(h) = \frac{sin\left(\frac{qh\alpha}{2}\right)}{q\,sin\left(\frac{h\alpha}{2}\right)}$$

$$k_w(h) = k_d(h)k_p(h)$$

	k_d	k_p	k_w
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:

$$I_{ph} = \frac{S_i}{3V_{ph}}$$

$$I_{ph} = \frac{1.5E6}{3 * 779} = 642\ A$$

As cooling is achieved by forced air cooling, let's assume J=7 A/mm^2.

$$A_{cond} = \frac{I_{ph}}{J} = 98.8\ mm^2$$

Using two AWG0 size cables in parallel, we obtain A_{cond}= 107 mm^2. D_{cond}=8.25 mm.

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

Slot dimensions are as given in Figure 2.

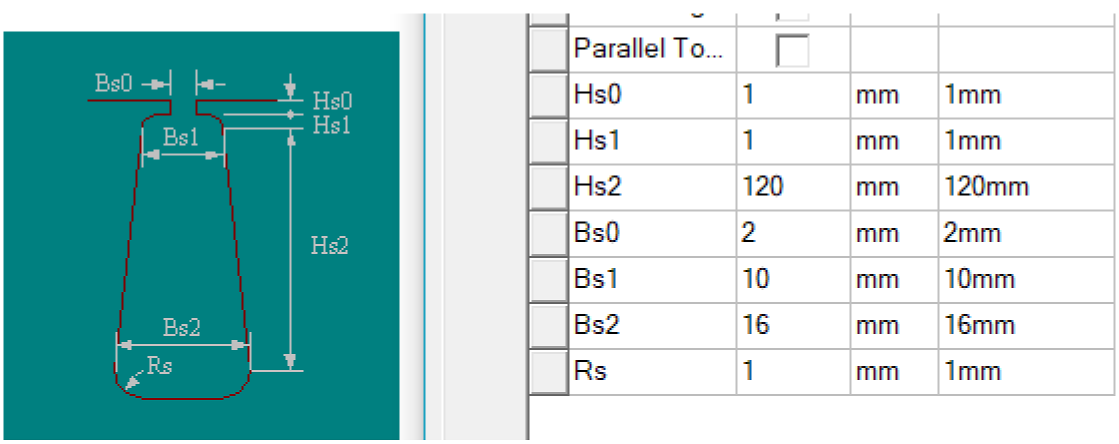

Figure 2: Slot Dimensions

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

$$A = \frac{B_{s1} + B_{s2}}{2} H_s = 1560\ mm^2$$

$$ff = \frac{A_{cond}}{A} = \frac{107 * 2}{1560} = 13.7\%$$

Motor Parameter Estimation:

Teeth Flux Density:

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

$$\hat{B}_{\text{teeth}} = \hat{B}_{\text{gap}} * \frac{\text{A}_{\text{teeth}} + \text{A}_{\text{opening}}}{\text{A}_{\text{teeth}}} = 0.8 * 2 = 1.6\ \text{T}$$

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

Approximate Torque Calculation:

$$\tau = \sigma_{tan} 2\pi (\frac{D_{rotor}}{2})^2 L$$

$$\sigma_{tan} = \frac{A\ \hat{B}}{\sqrt{2}} = \frac{0.8 * 57287}{\sqrt{2}} = 32406$$

$$\tau = 32406 * 2 * \pi * (0.253)^2 * 0.73 = 9514\ Nm$$

Equivalent Circuit Parameters:

- Phase resistance:

$$R_{ph} = \frac{\rho\ N_{ph} l_{turn}}{A_{cu}}$$

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

$$l_{turn} = 2L * 1.1 = 1.606\ m$$

At 75ºC, $\rho = 2.04\ 10^{-8}$ for copper.

$$R_{ph} = \frac{2.04\ 10^{-8} * 48 * 1.606}{107\ 10^{-6}} = 0.0147\ \Omega$$

- Phase inductance:

Phase inductance can be calculated with reluctance of the airgap.

$$R = \frac{l_{gap}}{\frac{\pi D}{2p} l' * \left(\frac{pole}{phase}\right) * \mu_0} = \frac{1.85\ 10^{-3}}{\pi * 0.51 * \frac{0.73}{6}\ \left(\frac{6}{3}\right) * 4\pi 10^{-7}} = 3776$$

$$L = \frac{N_{ph}^2}{R} = \frac{24^2}{3776} = 153\ mH$$

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.

$$V_{stator} = \left(\frac{D_{out} - D}{2}\right)^2 \pi l' = 91.7\ l$$

$$m_{stator} = V_{stator}\rho = 91.7 * 7.75 = 710\ kg$$

$$V_{rotor} = \left(\frac{D_{rotor} - D_{shaft}}{2}\right)^2 \pi l' = 29\ l$$

$$m_{rotor} = V_{rotor}\rho = 227\ kg$$

$$m_{cu} = 3\rho_{cu} l_{ph} A_{cond} = 222\ kg$$

Losses:

- Copper loss:

$$P_{cu} = 3 * I_{ph}^2 * R_{ph} = 3 * (642)^2 * 0.0147 = 18.2\ kW$$

- Core loss:

$$P_{core,max} = k * m_{core} = 5.62 * (710 + 227) = 5.3\ kW$$

RMXprt and Maxwell 2D Design:

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

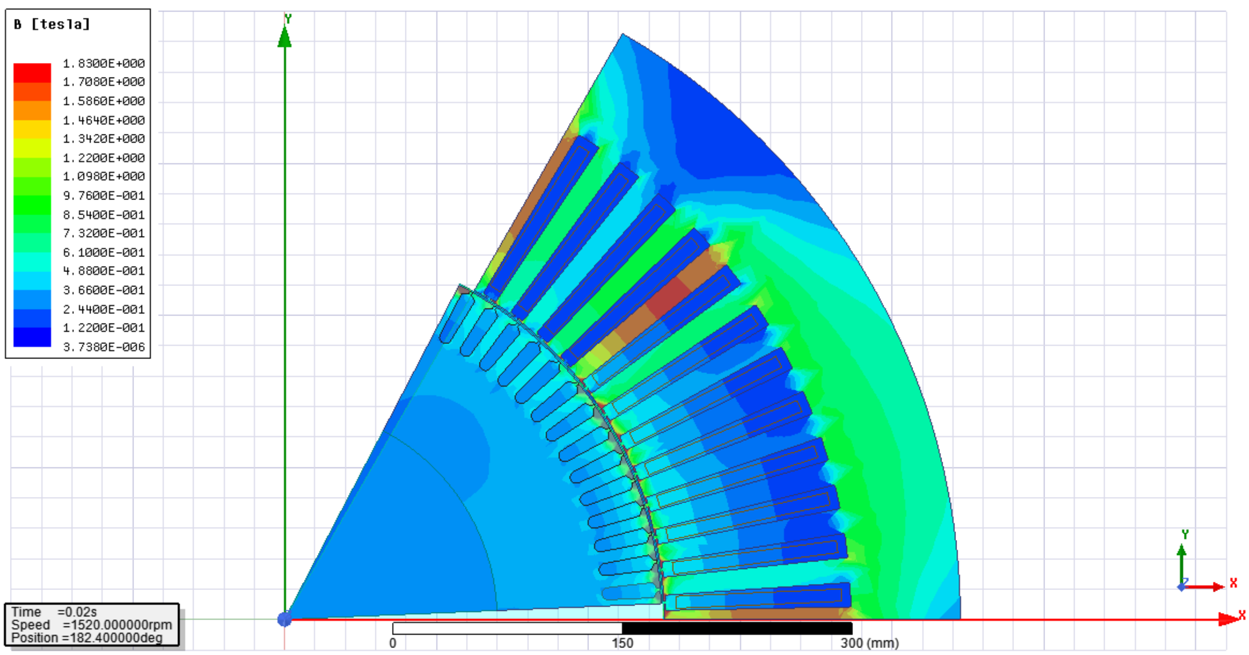

Figure 3: Flux Density Distribution

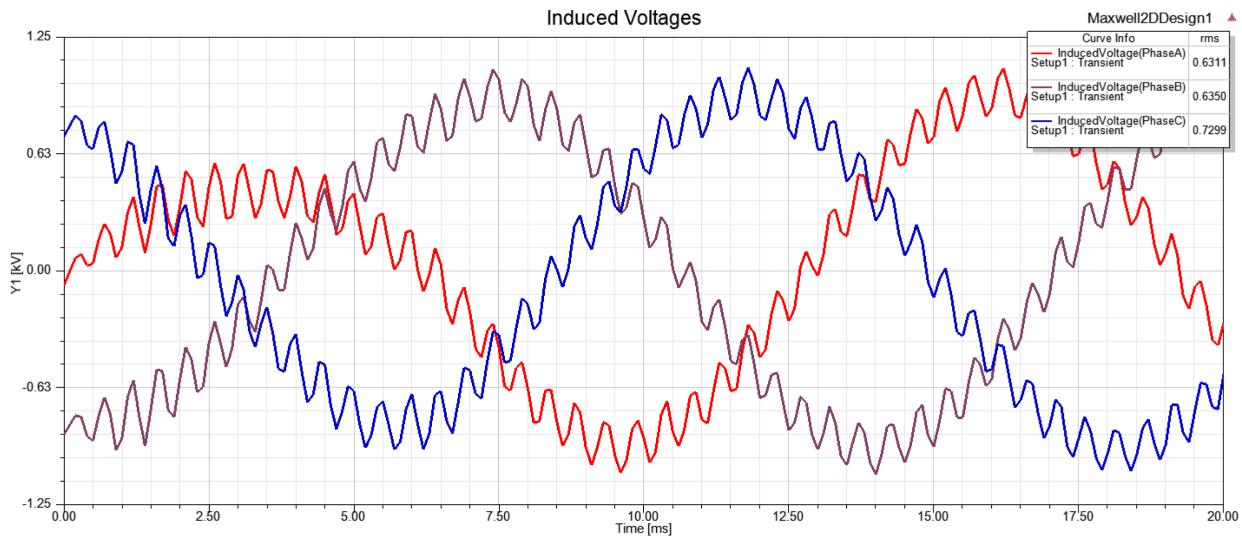

Figure 4: Induced Voltages

Figure 5: Phase Currents

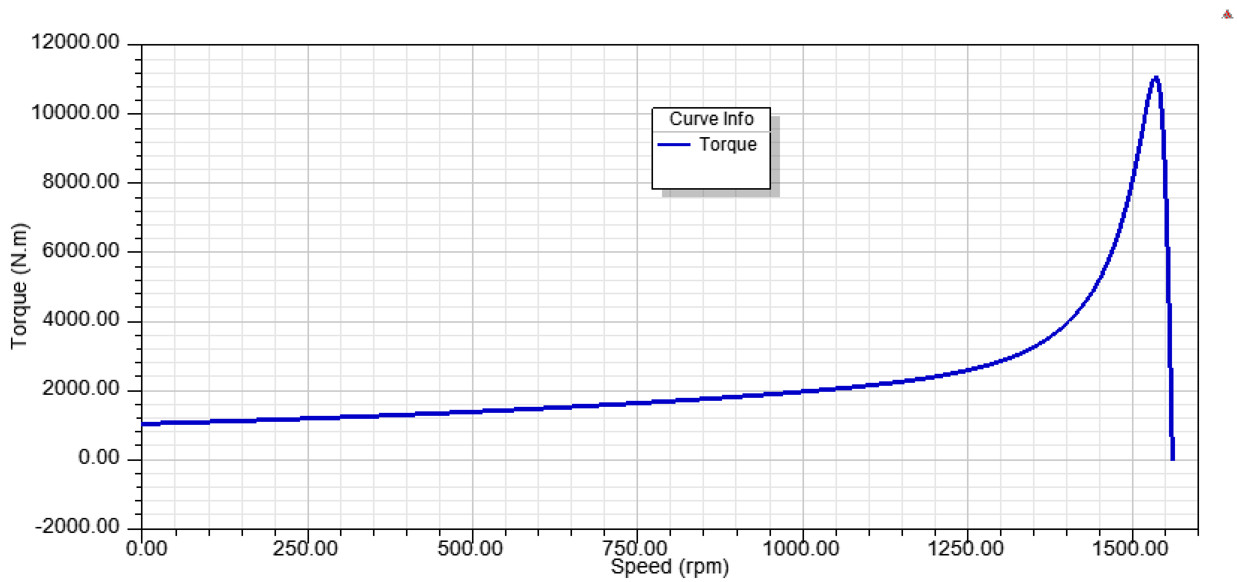

Figure 6: Torque-Speed Curve of the Machine

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