

Chapter 6

Experimental model refinement

Chapters 3, 4 and 5 introduced the components needed to derive a thermal model for a high speed PMSM. Most parameters can be determined using geometry and material properties. Other parameters need to be determined through empirical testing, which is the main objective of this chapter.

6.1 Overview

Empirical studies are an important part of thermal modelling due to the difficulty in solving complex flows and uncertainties in material properties and manufacturing. The convection coefficients and thermal interface resistances of electric machines are commonly determined through empirical testing. As discussed in section 2.4.1, the interface resistance depends on a range of factors, including surface roughness, material hardness, interface pressure and the properties of the fluid trapped inside the interface [48]. It is also influenced by manufacturing techniques and temperatures of the materials involved. The interface resistances are usually determined through tests, which are presented in this chapter.

The convection heat flow is proportional to the fluid movement, which is dependent on the geometry and how the fluid is set into motion. Empirical methods are mostly used to determine the correlation formulas since the analysis using fundamental principles becomes extremely complex in all but the simplest of cases. Turbulent flow is difficult to model due to the highly irregular fluid movement and velocity fluctuations [3].

In order to determine the above mentioned resistances and explore the effect of various loss types, five tests are done and documented in this chapter. These are the DC, no-load, resistive load, rectifier and resistive load tests as well as the switched test. Table 6.1 summarises the types of losses that exist during each of the tests. Figure 6.1 shows the test setups where the machine under test is shown in the dotted block. The motor is driven with a VSI.

During the DC test, a DC current is applied to the series connected stator phases, thus causing conduction loss (I^2R) in the winding. This scenario is shown in Figure 6.1(a). The natural convection resistance $R_{nat,conv}$ can be calculated from the DC test using (6.1). This method is

Table 6.1: Test summary: Location and types of losses

	Rotor				Stator				
Location	Laminations		PM	Shielding cylinder	Winding		Laminations		Figure 6.1
Type	E	H	E	E	C	E	E	H	
Test:									
DC					x				(a)
No-load						x	x	x	(b)
Resistor					x	x	x	x	(c)
Rectifier	x	x	x	x	x	x	x	x	(d)
Switched	x	x	x	x	x	x	x	x	(e)
C - Conduction, E - Eddy current, H - Hysteresis									

based on the conservation of energy: the thermal energy leaving a control volume is equal to the thermal energy entering the control volume minus the energy stored inside the control volume. When steady state is reached, there is no change in stored energy, thus the energy input equals the energy output. During the DC test, all the losses induced in the windings (P_{DC}) must flow through the natural convection resistance to the ambient air [66]. The same method can be used to calculate the forced convection resistance.

$$R_{nat,conv} = \frac{T_s - T_\infty}{P_{DC}} \quad (6.1)$$

The TWINS test setup consists of two identical machines where the rotors are mechanically coupled. One of the machines' rotor can thus be driven by the other. During the no load test, one of the machines' windings are left unconnected and its rotor is driven by the other machine, as shown in Figure 6.1(b). Rotational losses like bearing loss and frictional loss are present. Losses due to the rotor magnetic field movement, like stator lamination hysteresis loss and eddy current losses in the winding and laminations are also present during this test.

During the generator test with a resistive load, one of the machines will be operated in generator mode and the other in motor mode as was the case during the no-load test. If a resistive load is connected to the generator, the currents flowing in the stator winding will cause some I^2R loss. Figure 6.1(c) shows a diagram of this scenario. All the possible loss mechanisms are present in the stator. The stator current is sinusoidal at the fundamental frequency; no other harmonics are present. Thus the rotor does not experience a varying magnetic field and no hysteresis or eddy current losses are present in the rotor at this stage.

When a rectifier and resistive load is connected to the generator, the diodes' switching causes

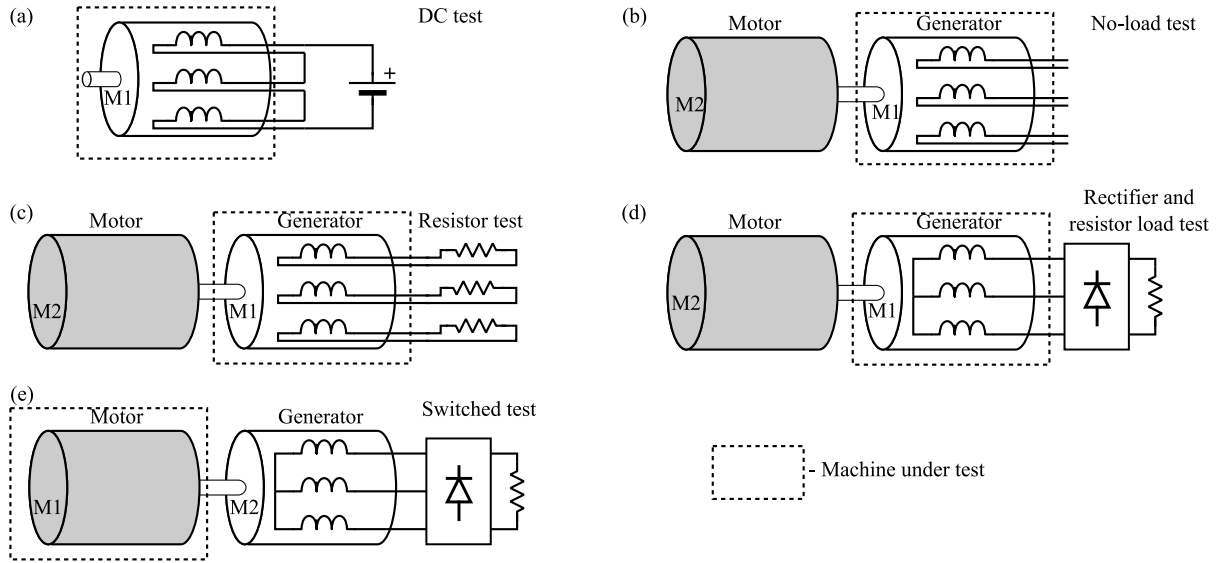


Figure 6.1: Test setup diagrams: (a) DC test, (b) no-load test, (c) resistor test, (d) rectifier and resistance test and (e) switched test.

harmonic currents to flow in addition to the fundamental frequency current. These currents cause the rotor to experience a varying magnetic field which causes hysteresis and eddy current losses in the rotor. The harmonic currents have frequencies that are multiples of the rotational frequency and reduce in amplitude as frequency increases. This test is illustrated in Figure 6.1(d).

In the switched test, the test machine is operated in motor mode as shown in Figure 6.1(e). The sinusoidal winding voltage is supplied using a voltage source inverter (VSI), using pulse width modulation (PWM). The stator winding voltage and current thus have high frequency switching components in addition to the fundamental frequency. The penetration depth of the magnetic fields is frequency dependent, thus it is expected that these high frequency currents will increase the eddy current loss in the PM and shielding cylinder.

6.1.1 Rotational velocity used in experiments

Even though the TWINS are designed to operate at 30000 r/min, the thermal tests are done at 10000 r/min. This is due to mechanical reliability uncertainties. At 30000 r/min, the number of rotations in an hour equals 1.8 million. The results included in this chapter required more than 11 hours, which would have been 20 million rotations at 30000 r/min. By reducing the rotational speed the bearing life is extended. The set of four hybrid bearings used in the TWINS machines costs more than R 3100 to replace. Rotor dynamic behaviour causes a significant increase in vibration around 21000 r/min. Even after the rotors had been balanced by Schenck Rotec in Darmstadt, Germany, the vibrations were still present. An investigation into this phenomenon should be done, but it was decided not to risk rotor fatigue by working at high rotational speeds for extensive periods. Rotor dynamics fall outside the scope of this thesis.

6.2 Test platform details

The temperatures in one of the two machines of the TWINS platform will be used during the experimental procedure. The machine under test is marked with a dotted block in Figure 6.1 for each of the tests. The phase resistances must be known to determine the I^2R loss during the DC test. Since temperature is greatly geometry dependent, the exact locations of the RTDs is discussed in this section.

6.2.1 Phase resistance measurement

The phase resistance can be calculated from the DC current and voltage. Two measuring devices were used to measure the current and voltage: a Lecroy Waverunner 6030A oscilloscope and a Fluke 179 multimeter. The resistances are shown in Table 6.2. All the measurements were taken once thermal steady state has been reached. It can clearly be seen that the rise in temperature causes a rise in resistance. Note that phase b has a larger resistance than the other two phases. A needle and thread manufacturing technique was used for the stator winding, thus the difference in resistance can be attributed to uneven total length of wire used in the different stator phases.

Table 6.2: Phase resistance

Current [A]	Phase a [$m\Omega$]		Phase b [$m\Omega$]		Phase c [$m\Omega$]		ΔT [K]
	Lecroy	Fluke	Lecroy	Fluke	Lecroy	Fluke	
5	64.84	61.65	75.78	72.9	66.3	62.6	6.5
10	70	65.5	79	78	66	66	22
12	70	66	83.9	79.3	68.5	67.3	28.5

6.2.2 Temperature measurement locations and combination

Resistive thermal devices (RTDs) and infrared (IR) temperature measurement probes are used to measure temperatures in the TWINS machines. Each machine has 6 RTDs and a single IR sensor which measures the PM temperature. Figure 6.2 shows the temperature measuring locations of TWINS A. Three RTDs (A1-3) are placed in the winding and A4 is placed inside the end winding. These RTDs were inserted before the stator was vacuum impregnated with resin. The lamination outside temperature is measured with A5 and the stator housing inside temperature in the endgap region with A6. Three probes of TWINS B are used to measure temperatures on TWINS A: end plate outside temperature (B4), stator housing outside temperature (B5) and the ambient temperature (B6).

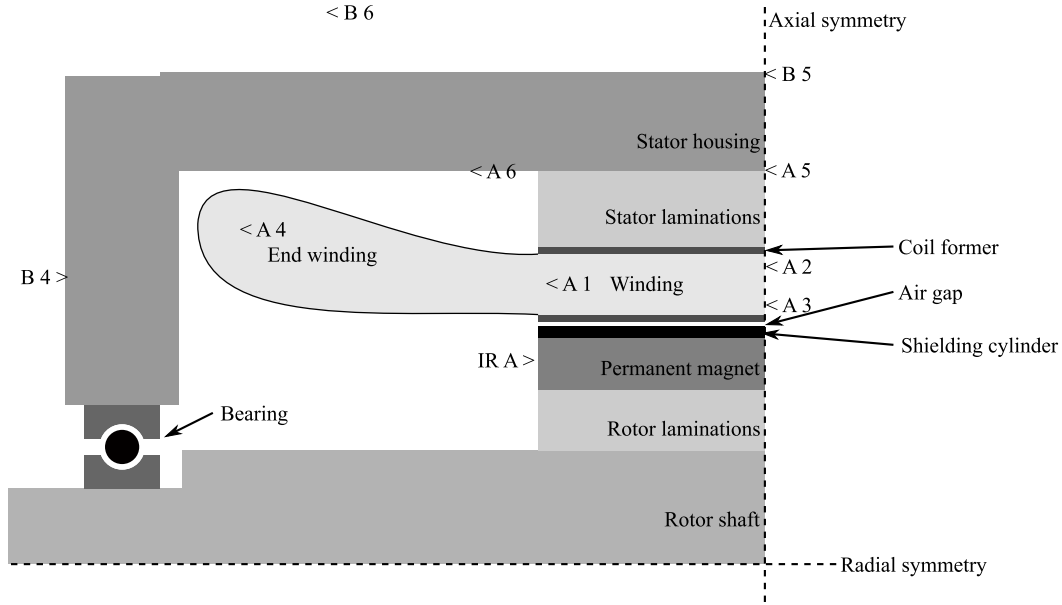


Figure 6.2: Temperature measure locations in TWINS A machine

In order to compare measured and modelled results, some of the RTD measurements will be combined into a single value. Ideally, all the RTD measurements should correlate to a temperature point in the thermal model, but this would only complicate the thermal model in the non-critical (stator housing and stator laminations) areas. More measuring points on the rotor would have given a better resolution of this critical component, but this is not possible due to space limitations. The use of an infrared sensor to measure the PM temperature has the advantage of being contactless, but can only give an average value of the side temperature of the PM. Using RTDs on the rotor is very difficult due to the rotor movement. Slip rings have been used in the past but only in low speed machines and with limited success [79].

The measured temperatures for the DC test of 12 A with natural convection are shown in Figure 6.3. It is clear that all the RTDs placed inside the winding (A1-3) have similar values, thus the average of these measurements will be used as the winding temperature (T_W). This is also true for A5 and A6, which are combined to give the stator lamination outside temperature (T_{Sl}). The stator housing outside temperature (T_{Sh}) will be the average of B4 and B5. The end winding temperature (T_E) is A4, the PM temperature (T_{PM}) is IR A and the ambient temperature (T_∞) is B6.

Figure 6.3 also shows the temperatures of a 12 A DC test with forced cooling active. As with natural convection, the RTDs placed in the winding (A1-3) all have similar values and can be combined to give T_W . Unlike the natural convection case, A5 and A6 differ significantly as well as B4 and B5. These differences can be attributed to the forced cooling removing heat in the end winding area. Both A6 and B4 are located close to the end windings, thus the lower temperature is expected. Only the value of A5 will be used to determine T_{Sl} and T_{Sh} will be the average of A6, B4 and B5. The next section discusses the DC test and its results.

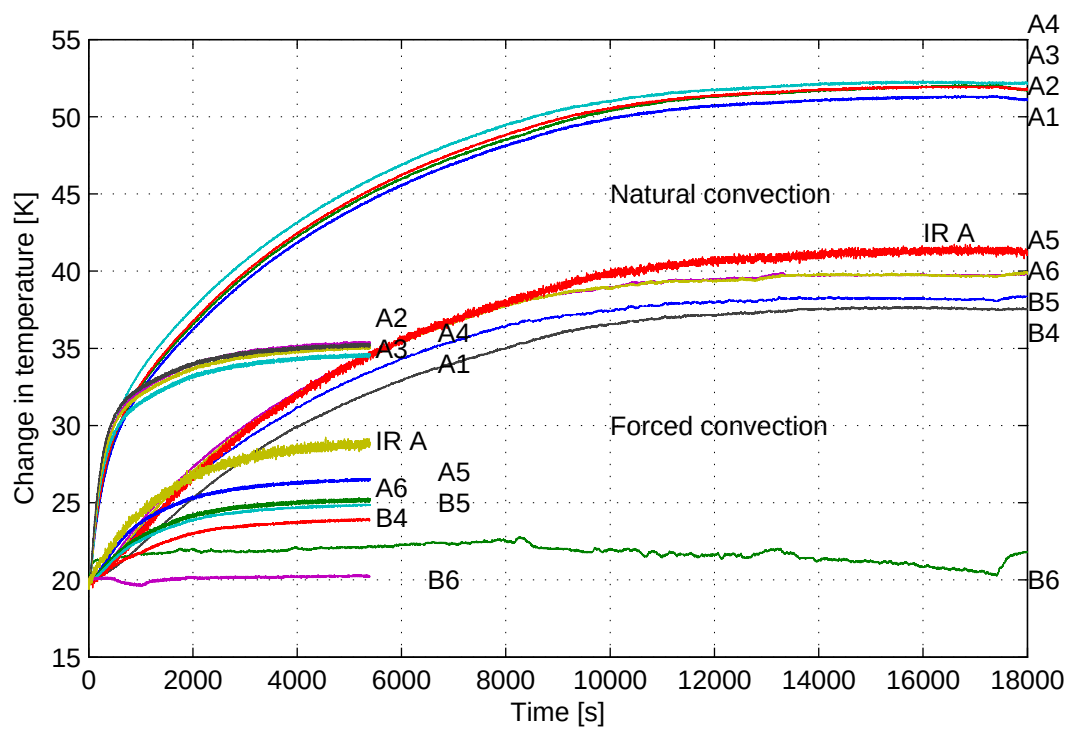


Figure 6.3: RTD values for 12 A DC test, natural convection and forced convection. RTD names according to Figure 6.2
[RTD values for 12 A DC test, natural convection and forced convection.]

6.3 DC test

The DC test was done for natural and forced convection cooling. The three phases were connected in series and constant current supplied using a DC power supply. The temperatures were captured using dSPACE®.

6.3.1 Thermal results

Figure 6.4 shows the change in temperature when 12 ADC is applied to the series connected stator winding. The I^2R loss can be calculated using (2.24) and the stator resistance, giving 30 W when combining the losses in all three phases. Since the heat generation is restricted to the winding and end winding, these parts experience the largest increase in temperature. The large rise in temperature in the winding supports the need for forced cooling.

The measured temperatures with forced cooling active, are also shown in Figure 6.4 when 14 ADC, 16 ADC and 12 ADC are applied sequentially. The effect of natural and forced convection cooling can be compared by observing the winding temperatures with 12 ADC flowing. When forced convection is active, the winding temperature is 20 K lower and the PM temperature is 13.5 K lower. This indicates the cooling system can effectively reduce the winding temperature. The settling time is also greatly influenced by the convection cooling type. For

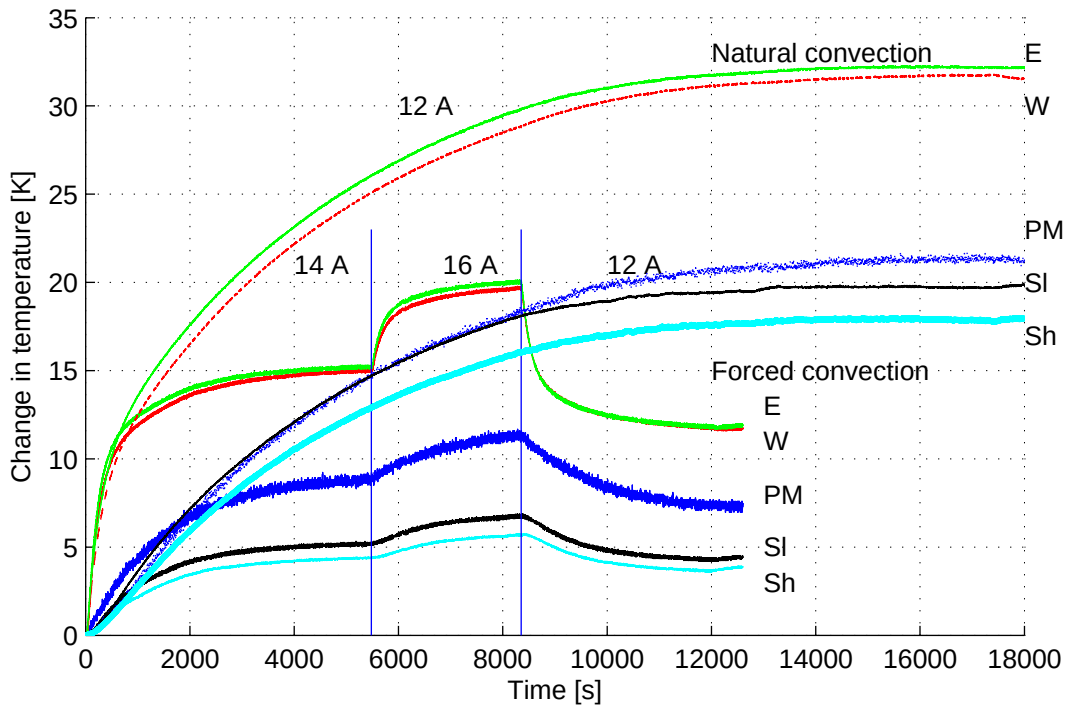


Figure 6.4: DC test temperatures at: end winding(E), winding (W), permanet magnet (PM), stator housing (Sh) and stator laminations (SI). Natural convection: 12 ADC, forced convection: 14, 16, 12 ADC.

natural convection, the settling time is around 250 minutes when 12 ADC is flowing. When 14 ADC is applied and forced cooling is active, the machine temperatures settle in less than 80 minutes. This is expected since less heat is stored in the machine when it is at a lower temperature.

6.3.2 Convection coefficients

As stated earlier, the objective of all the tests performed in this chapter is to determine the interface resistances and convection resistances. In this subsection, the convection resistances will be calculated using the measured data as well as the textbook relations given in section 2.4.

Natural convection

The natural convection coefficient can be calculated using the surface temperature measured during the DC test and (2.13):

$$h_{nat} = \frac{0.59k}{L} \left(\frac{g\beta L^3 \text{Pr}(T_s - T_\infty)}{\nu\alpha} \right)^{1/4} = 4.6 \text{ [W/(m}^2\text{.K)]} \quad (6.2)$$

where the air properties are given in Table 6.3. The convection resistance is inversely proportional to the convection coefficient and the surface area where the heat is removed. As shown in the assembly sketch of the TWINS, Figure B.7 in Appendix B, the machine is mounted in two large pillar blocks. The heat removal area is thus much larger than the stator housing shown in Figure B.1. The convection resistance can be calculated for the TWINS as:

$$\begin{aligned} R_{nat,conv} &= \frac{1}{h_{nat}A} \\ &= \frac{1}{(4.6)(0.308)} \\ &= 0.699 \text{ [K/W]} \end{aligned} \quad (6.3)$$

The natural convection resistance can also be calculated from the measured temperature and DC loss. Assuming all the loss is removed from the machine through natural convection,

$$R_{nat,conv} = \frac{T_{Sh} - T_\infty}{q_{dc}} \quad (6.4)$$

can be used to calculate the natural convection resistance ($R_{nat,conv}$). The difference in stator housing temperature (T_{Sh}) and air temperature (T_∞), as well as the conduction loss during the DC test (q_{dc}) are needed. The results are shown in Table 6.4.

Forced convection

The forced convection resistance can be calculated from the measured air speed, geometry and fluid properties. The air speed is measured using Gill Instrument's WindSonic sensor,

Table 6.3: Air properties at 293 K [38]

Density [kg/m ³] ρ	Dynamic viscosity [kg/(m.s)] μ	Kinematic viscosity [m ² /s] ν	Thermal diffusivity [m ² /s] α	Prandtl number Pr
1.204	18.25×10^{-6}	15.16×10^{-6}	20.74×10^{-6}	0.7309

Table 6.4: Natural convection resistance from DC test data

$T_{Sh} - T_{\infty}$ [K]	Phase current [A]	$R_{nat,conv}$ [K/W]
10	10	0.5
15	11	0.53
17	12	0.59

which uses ultrasonic waves to measure air speed. The WindSonic is placed in the input air stream, between the blower and the machine. The measured air speed is 2.76 m/s and the cross-sectional area of the sensor is 0.0045 m². Figure 6.5 shows the WindSonic sensor location and the air flow area in the machine. The air flows between the stator housing and end winding, thus the single air stream is divided into four air streams: two on each side of the machine. The mass flow must be constant in a closed system, thus

$$\rho u_{m,sens} A_{sens} = \rho u_{m,mach} A_{mach} \quad (6.5)$$

where ρ is the density of the air and $u_{m,sens}$ and $u_{m,mach}$ are the mean air speeds in the sensor and machine, respectively. The cross-sectional areas of the sensor and machine are represented by A_{sens} and A_{mach} , respectively. The values of the fluid constants are given in Table 6.3. If the total flow path cross-sectional area in the machine is 0.33×10^{-3} m², the air speed is 37 m/s. The flow path can be assumed to have a triangular cross-section; thus (2.18) must be used

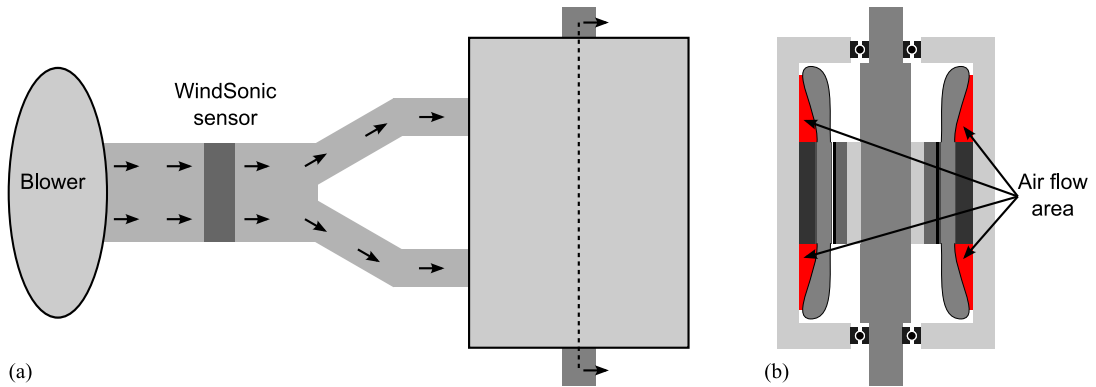


Figure 6.5: Forced convection flow area: (a) side view; and (b) sectional view.

to find the hydraulic diameter. If the width and height of the triangle is 0.03 m and 0.013 m, respectively, $D_h = 0.0103$ m. The Reynolds number can now be calculated:

$$\text{Re}_D = \frac{\rho u_m D_h}{\mu} = 24108. \quad (6.6)$$

Turbulent flow is expected since $\text{Re} > 10000$. To calculate the Nusselt number, the friction factor is needed. It can be calculated using (2.20b) and equals 0.025. Then the Nusselt number can be calculated:

$$\text{Nu} = \frac{(f/8)\text{RePr}}{1.07 + 12.7(f/8)^{0.5}(\text{Pr}^{2/3} - 1)} = 57.5. \quad (6.7)$$

The forced convection coefficient (h_{for}) can now be calculated using:

$$h_{for} = \frac{\text{Nu}k}{D} = 146.8 \text{ [W/(m}^2\text{.K)]}. \quad (6.8)$$

The forced convection resistance of one of the fluid streams is 1.287 K/W and the combined resistance is 0.32 K/W since the resistances are connected in parallel.

The forced convection resistance ($R_{for,conv}$) can also be calculated from the measured temperatures and conduction loss. Assuming all the heat generated inside the winding is extracted through forced convection, (6.9) can be used to calculate $R_{for,conv}$.

$$R_{for,conv} = \frac{T_E - T_\infty}{q_{dc}} \quad (6.9)$$

The difference in end winding temperature (T_E) and air temperature (T_∞), as well as the conduction loss during the DC test (q_{dc}) is needed. Using the steady state temperatures for DC tests with currents of 12, 14, 16 and 18 A flowing, the forced convection resistance ranges between 0.39 and 0.41 K/W. The difference can be attributed to errors in the current and temperature measurements. It is also assumed that all heat is removed through the forced convection. There is still some heat being removed by the natural convection which can account for the difference in $R_{for,conv}$.

6.3.3 Interface resistances

All interface resistances are modelled as air filled cylinders placed between the two surfaces creating the interface. The width of the cylinders are determined using measured data and has the conductivity of air ($k = 0.0263 \text{ [W/(m.K)]}$). The width of the cylinders are shown in Table 6.5. Interface resistances were added to the sides of the winding. These can be attributed to the unmodelled insulation material surrounding the windings as well as post winding machining done to the coil former. The loose fit of the coil former caused misalignment, which caused contact between the rotor and stator. Part of the coil former was machined away, resulting in a larger air gap. Differences in interface resistance width can be attributed to the way the forced cooling is modelled. The locations of the interface resistances can be seen in Figure 3.7.

The correlation between the modelled and measured temperatures for natural and forced convection can be seen in Figure 6.6. In each case the transient measurements were subtracted

Table 6.5: Interface resistance width: DC test

Outer part - inner part (Interface resistor)	Width [mm]: Natural convection	Width [mm]: Forced convection
Stator housing - stator laminations (R_{rSI})	0.15	0.02
Stator laminations - winding	0.7	0.03
End winding - stator housing (R_{EI})	0.8	0.85
Winding - rotor	1.5	0.3
Permanent Magnet - rotor laminations (R_{RI})	0.25	0.25

from the transient model result and this difference represented using boxplots. The line in the center of the box represents the median. The sides of the box represent the first ($Q(0.25)$) and third ($Q(0.75)$) quartiles, respectively. The difference between $Q(0.25)$ and $Q(0.75)$ is called the interquartile range (IQR). The lines terminating the whiskers of the boxplot is at $Q(0.25) - 1.5 \text{ IQR}$ and $Q(0.75) + 1.5 \text{ IQR}$, respectively. All the data points outside this range is plotted individually. The numbers on the x-axis represent the temperatures in the following way: 1 - permanent magnet, 2 - winding, 3 - end winding, 4 - stator laminations and 5 - stator housing. The medians differ less than 0.5 K and the maximum error is 3.5 K and 3 K in the natural and forced cooling cases, respectively.

The influence of the interface resistances can be seen by comparing Figure 6.6 and Figure 6.7. In the latter, all the interface resistances were made very small in order to see the influence on

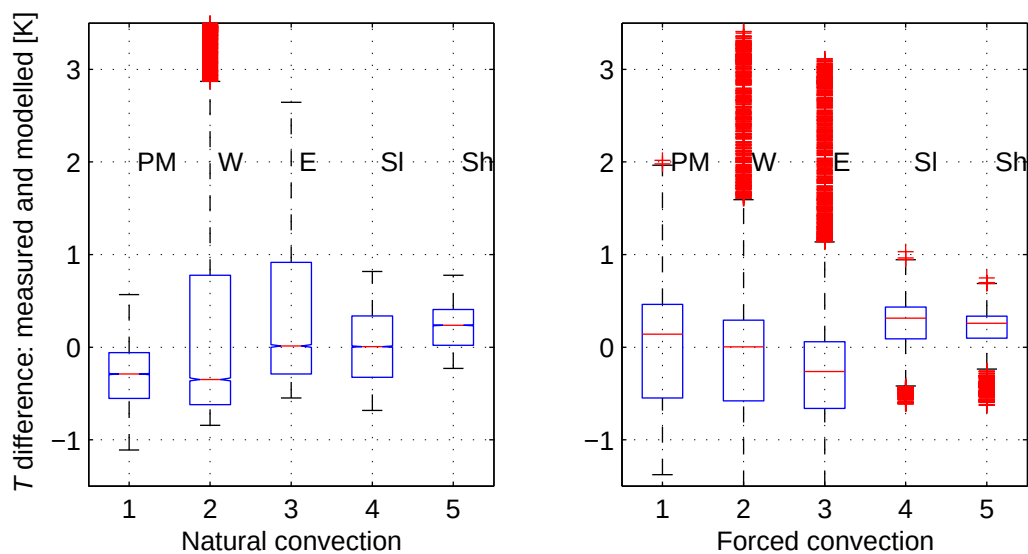


Figure 6.6: Difference in measured and modelled temperatures for the DC test when interface resistances are included.

the modelled temperatures. All of the temperatures are influenced by the interface resistance, the greatest being the winding and end winding temperatures. These components have the highest temperature during the DC test since all the losses are generated inside the winding and end winding. This concludes the DC test. The next section will discuss the no-load test.

6.4 No-load test

As stated in the beginning of this chapter, the TWINS setup makes it possible to drive one of the machines with the other. During the no-load test, the temperature-monitored machine is driven with the other machine and the windings are left open circuit. The conduction loss used to heat up the machine during the DC test will not be present. Mechanical losses like bearing loss and surface friction will be present as well as losses caused by the rotor magnetic field. These include hysteresis and eddy current losses in the stator laminations and windings. Table 6.1 summarizes the loss mechanisms that are present in this test.

6.4.1 Measured results

It is assumed that the no-load losses will be small, thus the no-load test was conducted with natural convection cooling. The resulting temperatures are shown in the top part of Figure 6.8 when the machine is driven at 10000 r/min. All the temperatures rise with more than 30 K, the winding and stator housing rising by 38 K and 33 K, respectively. It is clear that the no-load losses are significant. Using the natural convection resistance determined from the DC test and (6.4), the temperature rise in the stator housing equates to a 55 W loss inside the machine. It is clear that the machine should not be operated for long periods without forced convection.

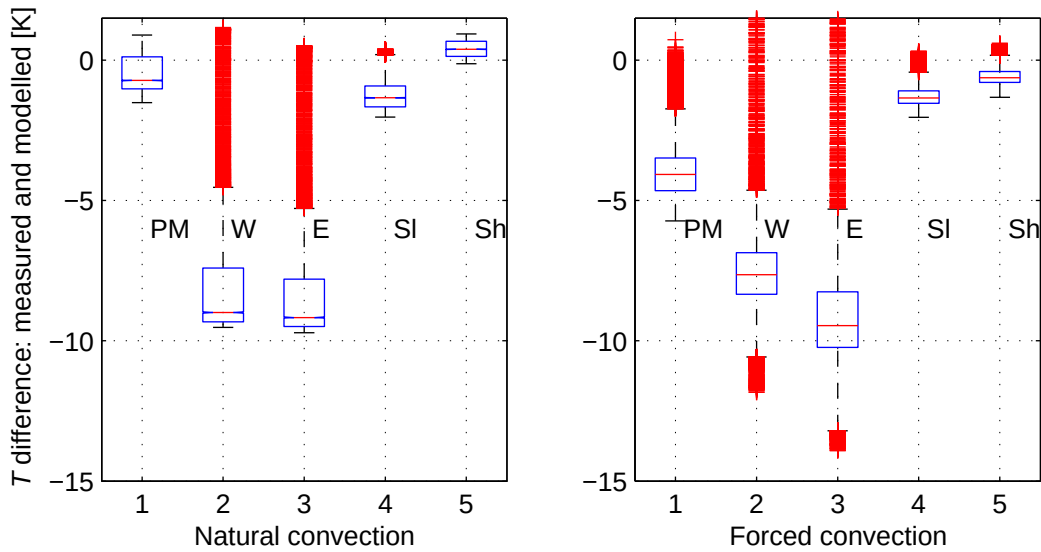


Figure 6.7: Difference in measured and modelled temperatures for the DC test when interface resistances are ignored.

In order to improve the forced convection model, the no-load test was repeated for forced cooling and the resulting temperatures are shown in the bottom part of Figure 6.8. Due to the close proximity of the RTDs to the machines' winding, the temperature measurements contained high frequency noise. Both sets of data were filtered for easier visualization using a low-pass filter in MATLAB®. As expected, the temperature rise was much smaller when the forced cooling is active but a difference in the highest temperature can be noted. With natural convection, the winding and end winding were the hottest parts, but with forced convection the PM and stator laminations were the hottest. This can be attributed to the location of the forced cooling: around the end windings. It is clear that there will be a difference between the natural and forced convection thermal models. In the next section the expected losses are calculated.

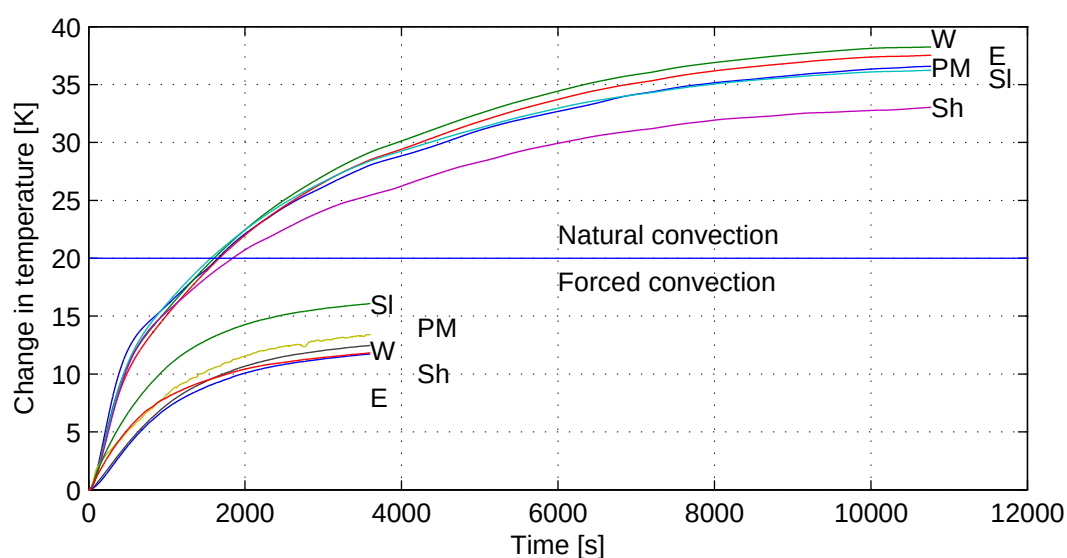


Figure 6.8: No-load test temperatures

6.4.2 Loss modelling at 10000 r/min

A complete discussion on loss modelling in high speed PMSMs was presented in chapter 5 for the rated speed of the TWINS; 30000 r/min. In this subsection, the calculations are repeated for 10000 r/min.

Stator iron

The stator current loss can be calculated using (5.8). Table 6.6 shows the results for 10000 r/min which is a frequency of 166 Hz.

Table 6.6: Calculated iron loss at 10000 r/min

f [Hz]	f_0 [Hz]	$\hat{B}$ [T]	$\hat{B}_0$ [T]	$k_{fe,0}$ [W/kg]	$c_{Fe,0}$	k_{Fe} [W/kg]	P_{iron} [W]
166	200	0.35	0.4	1.31	2	1.51	1.83

Stator windings

Eddy currents caused by the varying magnetic field due to the rotor movement can be calculated using (5.9):

$$\begin{aligned}
 P_{s,Cu,e} &= \frac{1}{8} \omega^2 r_{strand}^2 \sigma \left(\hat{B}_r^2 + \hat{B}_\phi^2 \right) A_{Cu} l_s \\
 &= \frac{1}{8} (2\pi 166)^2 (0.2 \times 10^{-3})^2 (58 \times 10^6) (0.4122^2 + 0.0547^2) (0.588 \times 10^{-3}) (0.06) \\
 &= 1.92 \text{ W}
 \end{aligned} \tag{6.10}$$

at 10000 r/min.

Bearing loss

Another possible contributor to the high no-load loss is bearing loss. This can be calculated using (5.21) or the online calculator found on SKF's website. The data for the hybrid bearing used in the TWINS (6004-2RSLTN9/HC5C3WT) is not available online, thus a similar bearing with metal balls is used (6004-2RSL). The rotor weigh 1.38 kg and the machine was mounted vertically. Assuming the radial and axial loading is 10 N and 20 N, respectively, the bearing loss is 9 W. Since the bearings are designed to carry a radial load, axial loading has a large effect on the bearing loss. In the TWINS, axial loading can result from rotor axial expansion due to a change in temperature. The dynamic forces can be significantly higher than the static forces used in the calculation. According to SKF, the bearing loss in a hybrid bearing should be lower than that of a bearing with metal balls. A thorough analysis of the bearing loss is not included in the scope of this thesis, but should be investigated when designing a high speed machine.

Windage loss

Friction between the rotor surface and the air gap air will cause loss inside the air gap. This is significant in machines with a high surface speed. For the TWINS rotating at 10000 r/min, the

Reynolds number can be calculated using:

$$\begin{aligned}
 \text{Re}_D &= \frac{\rho u_m l_A}{\mu} \\
 &= \frac{\rho \omega r_{sc} l_A}{\mu} \\
 &= \frac{(1.2)(2\pi 166)(0.0315)(0.5 \times 10^{-3})}{18.25 \times 10^{-6}} \\
 &= 1080.
 \end{aligned} \tag{6.11}$$

For this Reynolds number, C_M must be calculated using (2.29c):

$$\begin{aligned}
 C_M &= 1.03 \frac{(2L_g/d)^{0.3}}{\text{Re}^{0.5}} \\
 &= 1.03 \frac{[(2 \times 0.5 \times 10^{-3})/0.0315]^{0.3}}{1080^{0.5}} \\
 &= 11.13 \times 10^{-3}.
 \end{aligned} \tag{6.12}$$

The surface frictional loss at 10000 r/min in the TWINS is:

$$\begin{aligned}
 P_{wind} &= \frac{1}{32} k_s C_M \pi \rho \omega^3 d^4 L \\
 &= \frac{1}{32} (1.4) (11.13 \times 10^{-3}) \pi (1.2) (2\pi 166)^3 (0.0315)^4 (0.06) \\
 &= 0.1 \text{ W}
 \end{aligned} \tag{6.13}$$

6.4.3 Including the no-load losses into the model

The no-load losses calculated in the previous subsection are used in the 2-D LP model to test the model for this senario. The loss values used are given in Table 6.7 and the correlation between measured and modelled temperatures can be seen in Figure 6.9. The no-load losses inside the machine were equal for both cooling methods, but distributed differently inside the machine. The largest contributor is the bearing loss. The differences between the natural and forced convection loss distribution can be attributed to the complexity of the forced cooling and the locations of the temperture sensors.

The interface resistances widths used in the no-load model are shown in Table 6.8. Large differences can be seen when comparing these interface resistances with the ones determined during the DC test. Usually only the DC test is used to determine the interface resistances and convection coefficients. Since the heat sources are distributed differently during the DC test and normal operation, the DC test is not sufficient when high speed slotless PMSMs are concerned.

Table 6.7: No-load loss summary

Loss location	Calculated [W]	Natural convection [W]	Forced Convection [W]
Stator laminations	1.83	14.3	19.5
End winding		2.5	1.5
Winding	1.92	3.5	1.5
Shielding cylinder	0.1	2.4	2.4
Bearing	20	30	28.6
Total loss	23.85	52.7	53.5

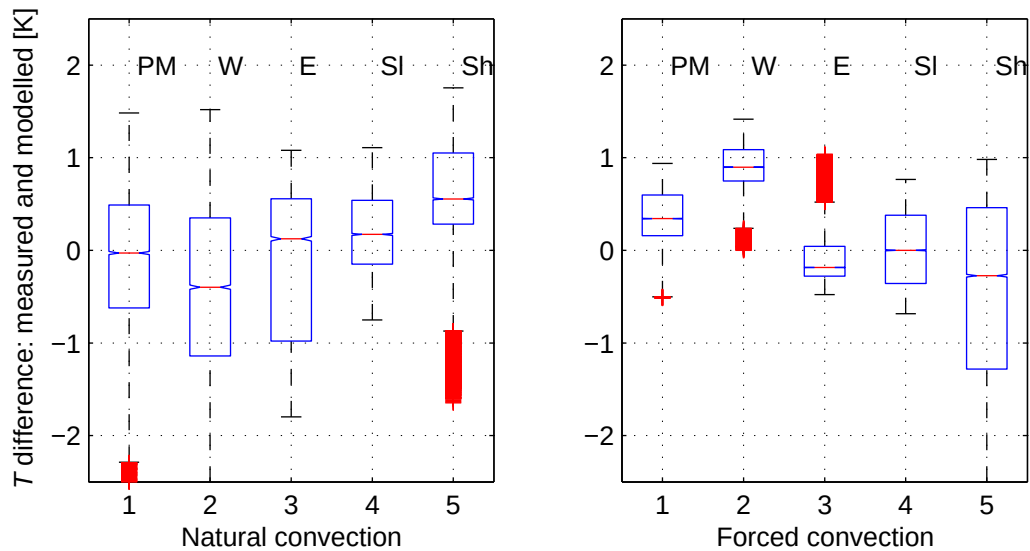


Figure 6.9: Difference between modelled and measured temperatures for no-load test

Table 6.8: Interface resistance width: No-load test

Outer part - inner part (Interface resistor)	Width [mm]:	Width [mm]:
	Natural convection	Forced convection
Stator housing - stator laminations (R_{rSI})	0.08	0.15
Stator laminations - winding	0.3	0.025
End winding - stator housing (R_{EI})	0.42	0.5
Winding - rotor	1.5	0.5
Permanent Magnet - rotor laminations (R_{RI})	0.05	0.5

6.5 Generator test with resistive load

The next step in deriving a thermal model for a high speed PMSM is to operate it in generator mode with a resistive load. One of the TWINS machines is used to drive the other at a constant 10000 r/min. A resistive load is connected to each of the phases of the stator winding of the generator machine; $33\ \Omega$ when only natural convection occurs and $17\ \Omega$ when the forced convection cooling is active. Wound 500 W, $33\ \Omega$ resistors were used for all the loading during the tests. To achieve significant temperature increase when forced convection was applied, two resistors were placed in parallel. Figure 6.10 shows the filtered temperatures measured for both of these scenarios. The natural and forced convection results correlate well with the no-load results (compare Figure 6.8). This is expected since the conduction loss during this test is small and is the only additional loss component during this test.

The voltage and current waveforms for the generator tests with resistive load are shown in Figure 6.11. The sinusoidal induced voltages result from the solid cylindrical, radially magnetized PM and slotless stator design. As shown in Table 6.1, the losses present during this test will be all those present during the no-load test as well as winding conduction loss. This can be calculated using (2.24). From the RMS current and resistance of each phase, the total copper loss for a $33\ \Omega$ load is 0.21 W and for the $17\ \Omega$ load is 0.8 W. This is added to the stator winding eddy current loss in the 2-D model.

The difference between the modelled temperatures and measured temperatures are shown in Figure 6.12. The correlation is good for both natural and forced convection.

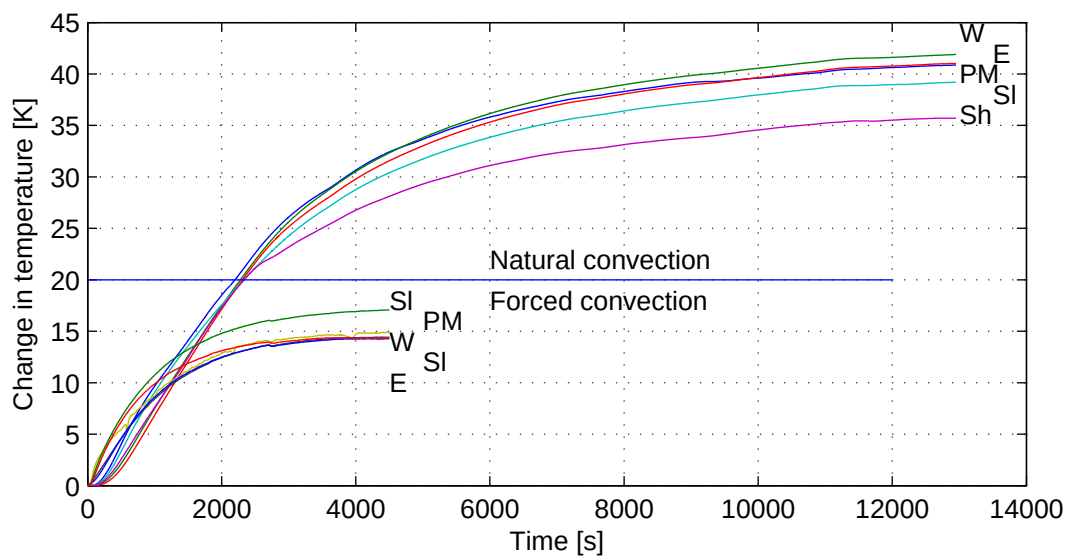


Figure 6.10: Generator test: Resistive load

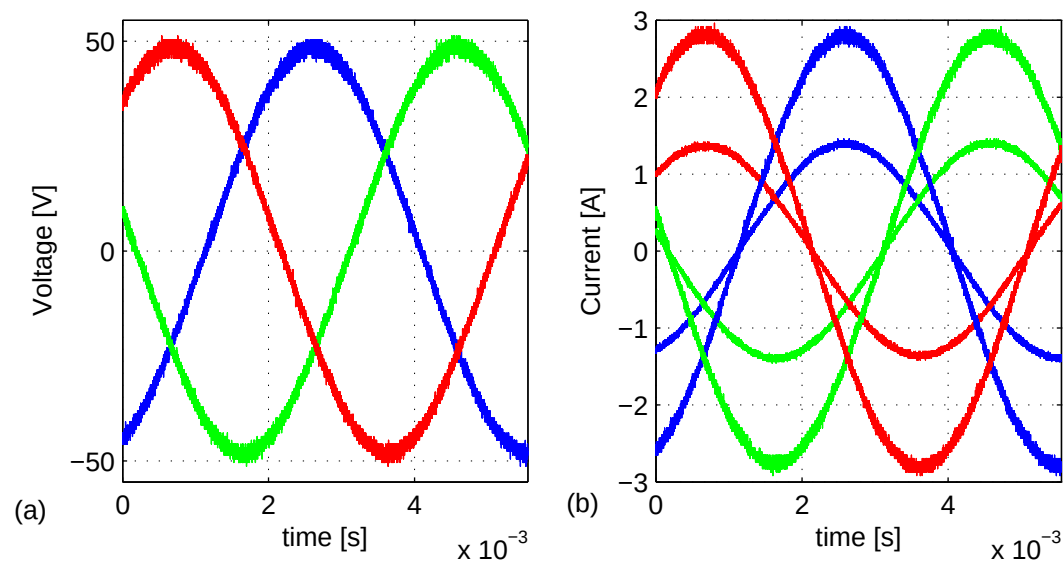


Figure 6.11: Generator test voltage (a); and (b) current waveforms for resistive load.

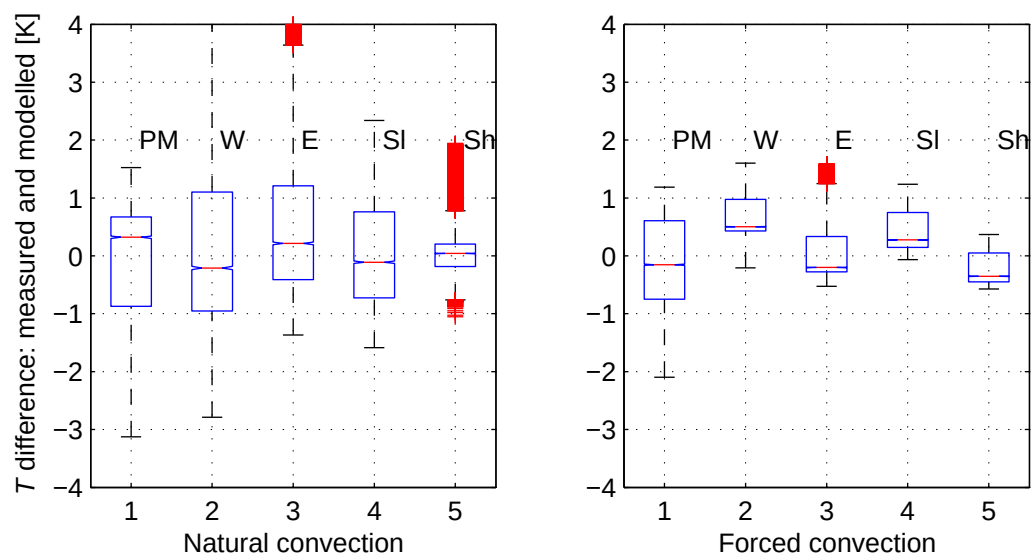


Figure 6.12: Differences between modelled and measured temperatures for generator test with resistive load.

6.6 Generator test with rectifier and resistive load

As shown in Table 6.1, when a rectifier and resistive load is used, all the possible rotor loss components will be present. This is due to the varying magnetic field caused by the non-fundamental frequency currents. A full wave rectifier is placed between the machine (generator) and the resistive load, causing phase currents as shown in Figure 6.13. The current harmonics caused by the rectifier switching are shown on the right of Figure 6.13; the fifth and seventh harmonic being the largest.

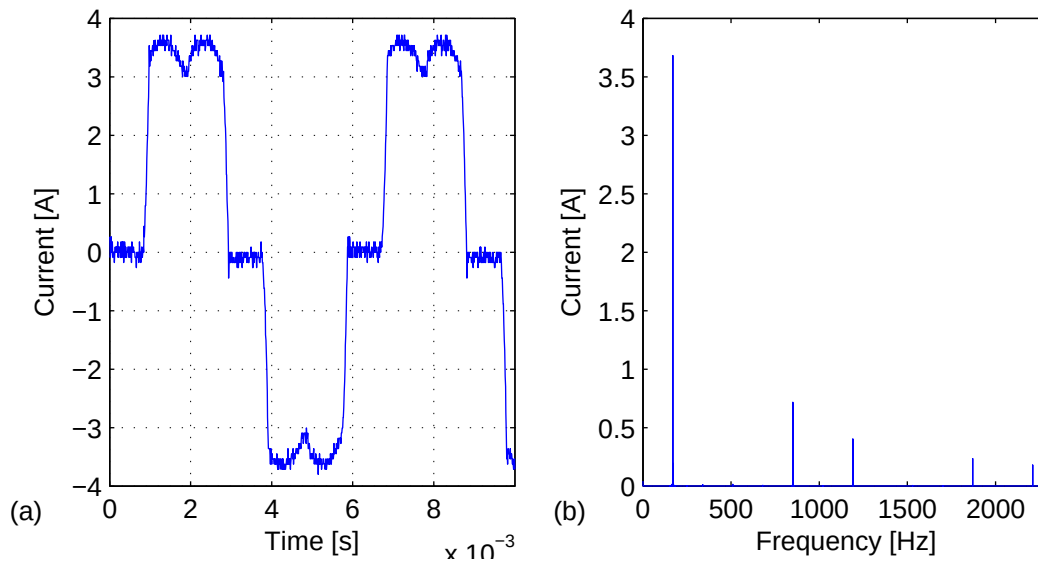


Figure 6.13: Phase current time (a); and frequency domain (b) plots for generator test with rectifier and resistive load

Figure 6.14 shows the temperature rise for a $33\ \Omega$ (left) and a $22\ \Omega$ (right) load connected to the rectifier. In the $33\ \Omega$ test the load was applied from the start of the test. The $22\ \Omega$ load was only connected after the no-load temperatures settled. With the smaller load resistor causing a larger load current, the temperatures are higher in the $22\ \Omega$ test, as expected. Note that these signals were not filtered. It can be seen on the right of Figure 6.14 that the noise increases when the load is connected.

6.6.1 Eddy current loss calculation

As discussed in section 5.5, the shielding cylinder loss can be calculated using a resistive model. The harmonic currents can be determined from the measured current using the FFT, and are given in Table 6.9 when a rectifier and $22\ \Omega$ resistive load is used. The resistor values are also given for each frequency, thus accounting for the penetration depth. The total eddy current loss is 0.66 W. The eddy current loss at low frequencies were expected to be small since the penetration depth is large, thus the resistances are small. The small rise in PM temperature also confirms the calculated eddy current loss.

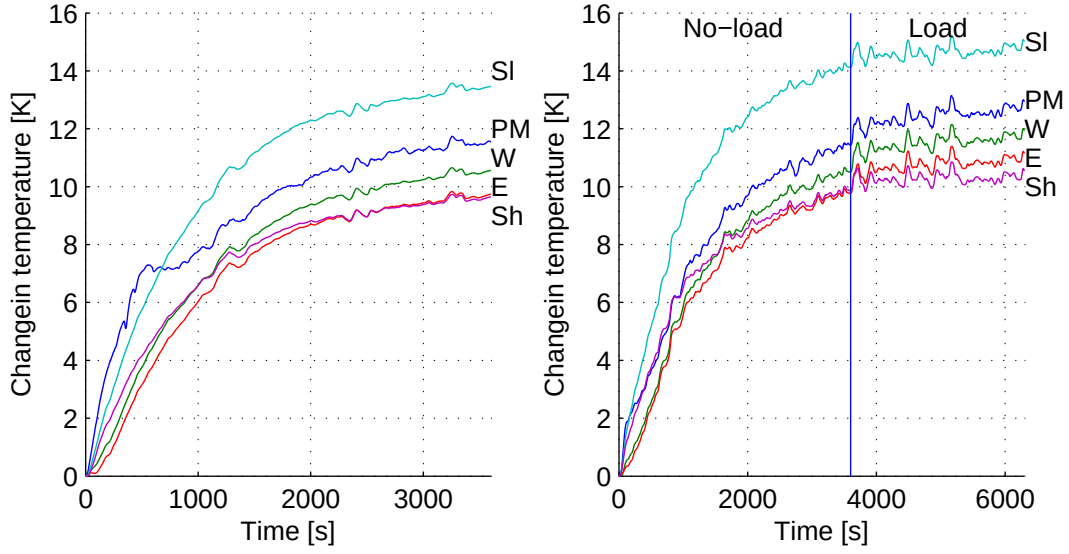


Figure 6.14: Measured temperatures for generator test with rectifier and resistive loads: $33\ \Omega$ and $22\ \Omega$. (Forced cooling active)

The interface resistances and convection constants have all been determined using empirical tests. The model can now be verified using the switched test.

6.7 Switched test

6.7.1 Measured results

As stated in section 6.1, the machine under test is operating in motoring mode and the other machine is operating in generating mode. Figure 6.15 shows the temperatures in the motor when the load is not connected to the generator. The generator's temperatures of the PM (PM B) and winding (W B) are also shown. The signals were also filtered but noise are still visible. This can be attributed to the high frequency switching of the VSI. Note that the PM temperature is significantly higher (around 10 K) in the motor machine than in the generator machine. This can be attributed to eddy current loss in the rotor, which is discussed next.

Table 6.9: Harmonic currents of $22\ \Omega$ resistor and rectifier load

Frequency [Hz]	5×166	7×166	11×166	13×166	17×166	19×166
RMS current [A]	0.506	0.283	0.166	0.128	0.113	0.059
R_z [m Ω]	0.136	0.161	0.202	0.219	0.251	0.265
R_ϕ [m Ω]	0.108	0.152	0.238	0.281	0.368	0.411

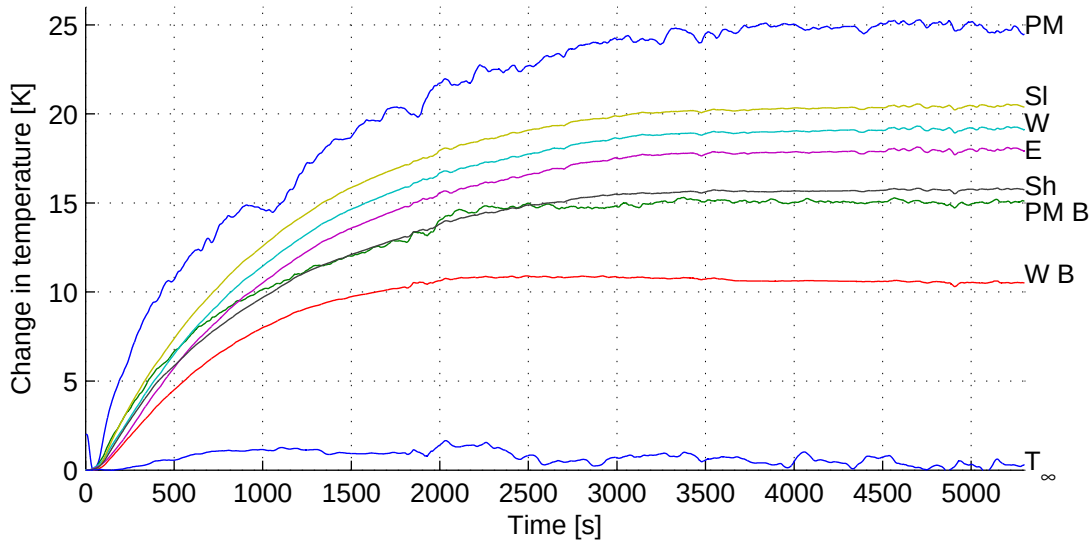


Figure 6.15: Change in temperature during the switched test

6.7.2 Rotor eddy current loss

Since a VSI is used to drive the motor, high frequency harmonics due to the switching is expected. Figure 6.16 shows the measured phase current of the motor when the rectifier and $22\ \Omega$ resistive load is connected to the generator. The high frequency switching can clearly be seen in the current waveforms and the frequency spectrum domain plot. The measured current can be used to determine the rotor eddy current loss. Note that the second harmonic current of the switching frequency (around 100 kHz) is larger than of the switching frequency (around 50 kHz). This shows that the VSI is operating in the linear region, thus $m_a < 1$. This can be explained by the back emf of the machine being a third of what it would be at 30000 r/min since the machine is only rotating at 10000 r/min.

Figure 6.17 shows the rotor eddy current loss against tangential current width (w_t), as well as the predicted loss at 30000 r/min. The switching harmonic voltages are dependent on m_a and $\hat{V}_{control}$, thus the harmonic current will be much larger at 30000 r/min than at 10000 r/min. The quadratic relation between the current and loss causes a significant increase in rotor eddy current loss. The method discussed in section 5.5 and the measured harmonic currents are used to calculate the rotor eddy current loss. The measured temperatures and thermal model of the TWINS can be used to find the rotor eddy current loss.

The correlation between the measured and modelled temperatures is shown in Figure 6.18 when the rotor eddy current loss is 7.6 W. The correlation is very good and it can thus be concluded that the tangential current width should be around 11 mm. It should be pointed out that the method used to model the eddy currents is only a 1-D, lumped approximation of the rotor. A 2-D or 3-D model should be used to explore the eddy current loss on the rotor in more detail.

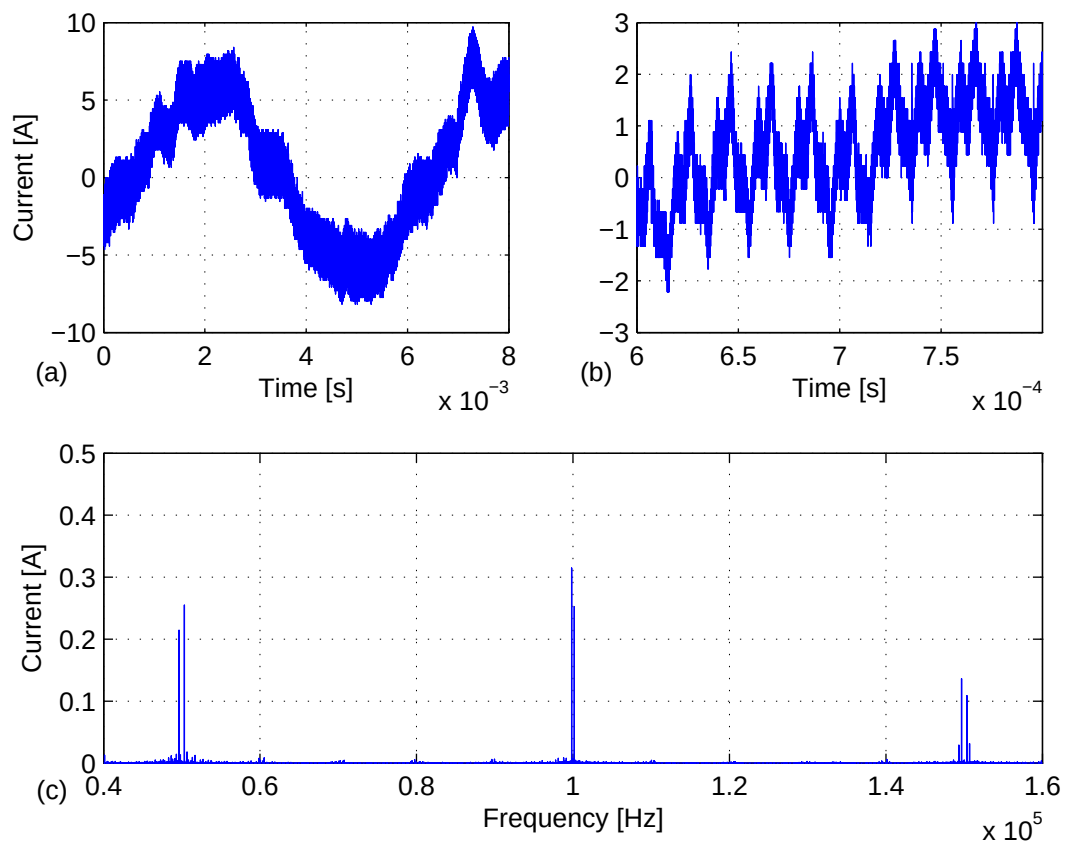


Figure 6.16: Stator winding current in motor when driving a generator with a 22 Ohm resistor load connected to a rectifier. (a) one fundamental period; (b) switching currents; and (c) frequency domain.

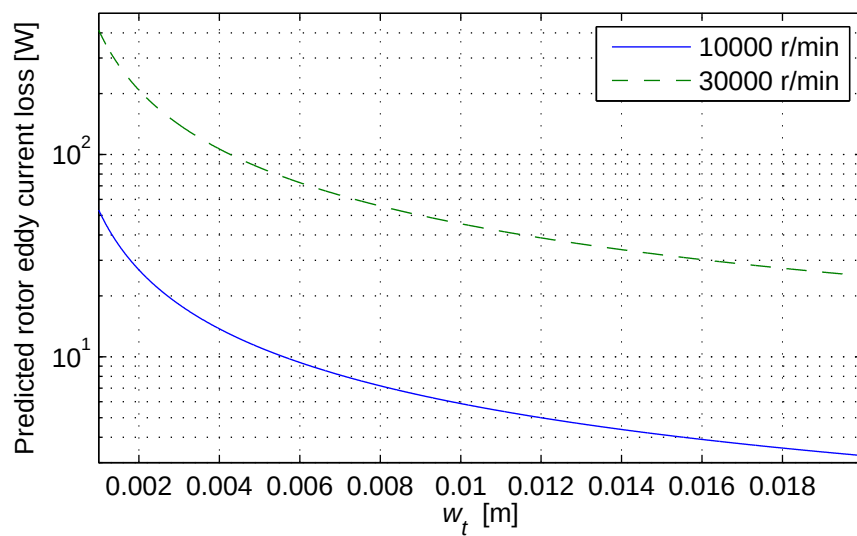


Figure 6.17: Calculated rotor eddy current loss vs. w_t

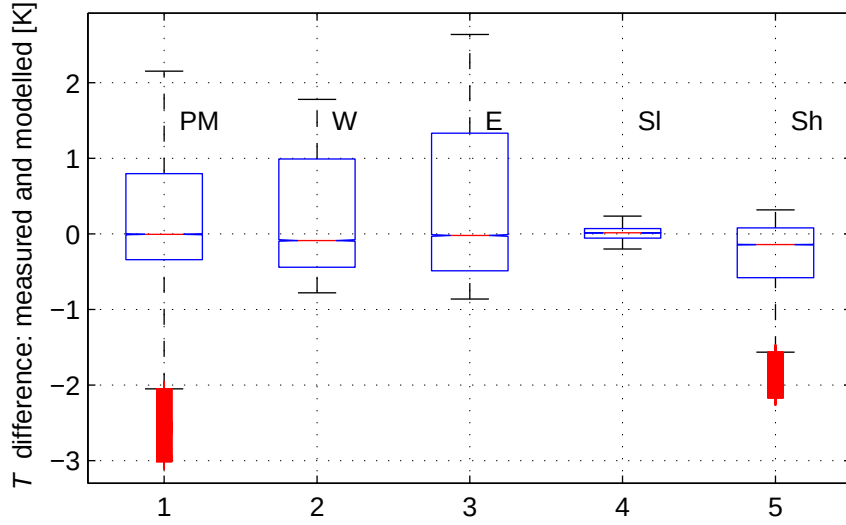


Figure 6.18: Difference between measured and modelled temperatures for the motor when driving the generator with a 22 Ohm resistive load connected through a rectifier

6.8 Final model

The LP model shown in Figure 3.7 needs to be modified to account for the results of the experiments discussed in this chapter. Figure 6.19 shows the final LP model. The interaction between the LP and distributed model is as discussed in section 3.1. It was found that the bearing loss (q_B) is significant and is included in the modified model. It was shown that the machine will not be able to operate for extensive periods with only natural convection present, thus the modified model assumes forced convection is always present. In the modified model, the link between the stator housing and end winding is removed. The end windings and bearings are thus directly connected to the forced convection resistance. Only the stator housing is connected to the natural convection resistance.

Removing the link between the stator housing and end winding also resulted in the removal of the end winding interface resistances (R_{aEI} and R_{rEI}). Two additional interface resistances were added, between the coil former and winding, on both sides (R_{rC1I} and R_{rC2I}). These account for the larger air gap and insulation between the winding and coil former. The experimentally determined values of the interface and convection resistances are listed in Table 6.10. The width of the resistances are also given. The influence on the PM temperature of the interface resistances is discussed in section 7.3. Note that all the other resistances and capacitances are summarized in Appendix A.

As discussed in section 2.4, natural convection is influenced by the surface temperature since this influences the fluid movement. The natural convection resistance given in Table 6.10 is much larger than those determined through the DC test as shown in Table 6.4. This can be explained by noting that most heat is removed through forced convection. Since the surface temperature is lower, the convection coefficient is lower (see Figure 2.2) and the natural convection resistance is higher. The forced convection resistance closely correlate with those calculated

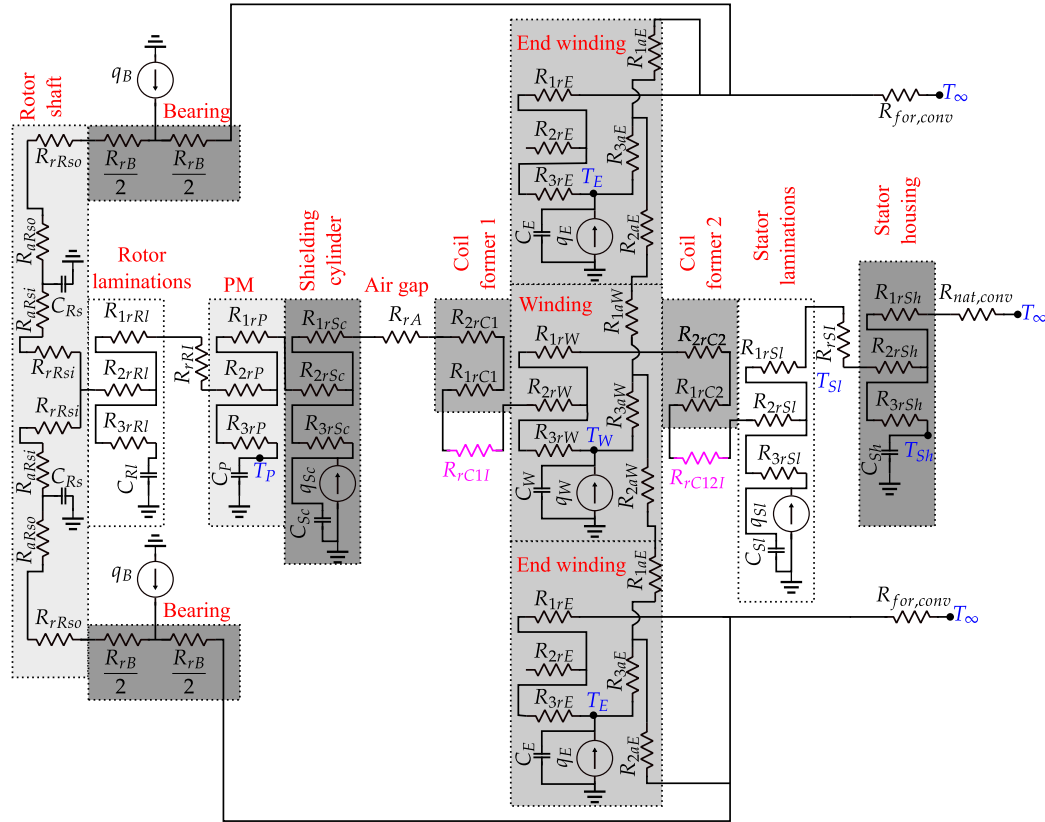


Figure 6.19: Modified LP model for the TWINS

from the air speed measurement during the DC test.

Table 6.10: Final interface and convection resistances

Interface	Width	[mm]	Resistance	[K/W]
Stator housing - laminations	l_{SI}	0.15	R_{rSI}	0.3048
Coil former - winding	l_{C2I}	0.2	R_{rC2I}	0.5012
Coil former - air gap	l_{C1I}	0.5	R_{rC1I}	1.6109
PM - rotor laminations	l_{RI}	0.2	R_{rRI}	0.9215
Convection type				
Natural			$R_{nat,conv}$	1.05
Forced			$R_{for,conv}$	0.33

6.9 Conclusion

This chapter set out to find the convection resistances and interface resistances usually determined through experiments. To achieve this, and also explore the losses found inside a high speed PMSM, five tests were performed. The DC test used conduction heat generation to heat the windings and end windings. It was found that the forced cooling removes a large portion of the generated heat, resulting in a 20 K reduction in winding temperature compared to when only natural convection is present. Thermal steady state is also reached three times faster when forced convection is active. The convection resistances calculated using textbook relations showed good correlation with the measured ones.

During the no-load test, the machine winding was left open circuit and the rotor was rotated at 10000 r/min. All the stator losses, except conduction loss in the winding, were present. The large no-load loss can be attributed to large bearing loss, possibly due to axial loading. Comparing the interface resistances determined during the DC test and those calculated from the no-load test showed some differences. This shows that using only a DC test to determine these important thermal resistances is not sufficient in the case of a high speed PMSM. The location of the losses has a significant influence, especially when heat removal is on different surfaces as in the TWINS.

During the generator test with resistive load, all the stator loss components were present and good correlation between the measurements and the model was found. When a rectifier and resistive load is connected to the generator, harmonic currents cause eddy current loss in the rotor. Due to the effect the penetration depth has on the eddy current loss, the calculated eddy current loss was small. This was supported by the measured PM temperature.

In order to find the rotor eddy current tangential width (w_t), the switched test was performed. The VSI caused significant harmonic currents in the stator winding which resulted in large eddy current loss. From the measured currents, temperatures and methods discussed in section 5.5, $w_t = 11$ mm. The final model was presented and modifications following from the test were applied.