Losses in Electric Propulsion Motors and How to Reduce Them

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Loss components in electrical machines:

- mechanical loss

  bearing loss

  windage and drag loss

- electromagnetic loss

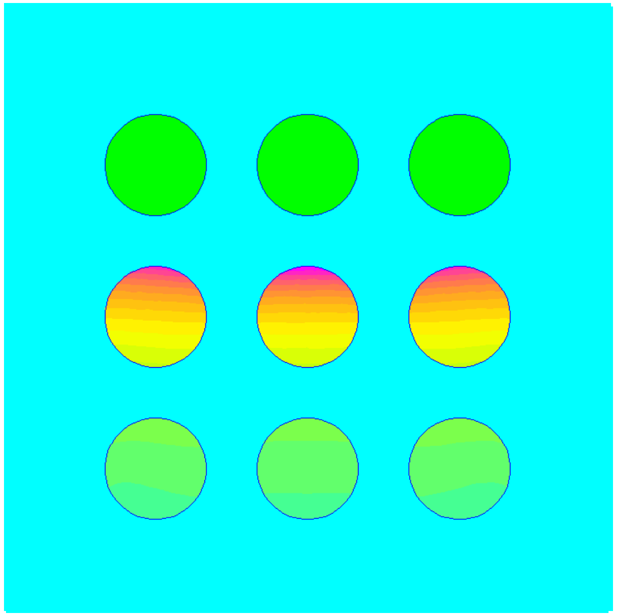
  winding loss

  core loss

  permanent magnet loss

Winding loss effects at ac operation:

- skin effect
- proximity effect
- effect from rotating rotor



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How to assess significance of the ac winding effects for a particular machine design?

- high-speed operation
- high-frequency operation
- other measures or indicators, e.g. skin depth

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}}$$

How to derive the ac winding loss components?

- theoretical approach

  analytical formulae

  numerical techniques, e.g. FEM

- experimental method

  tests on machine subassemblies

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How to quantify the ac winding effects?

$$P_{ac} = P_{dc} + P_{\ ac\ effects}$$

$$\left.\frac{P_{ac}}{P_{dc}}\right|_{T=const} = \left.\frac{R_{ac}}{R_{dc}}\right|_{T=const}$$

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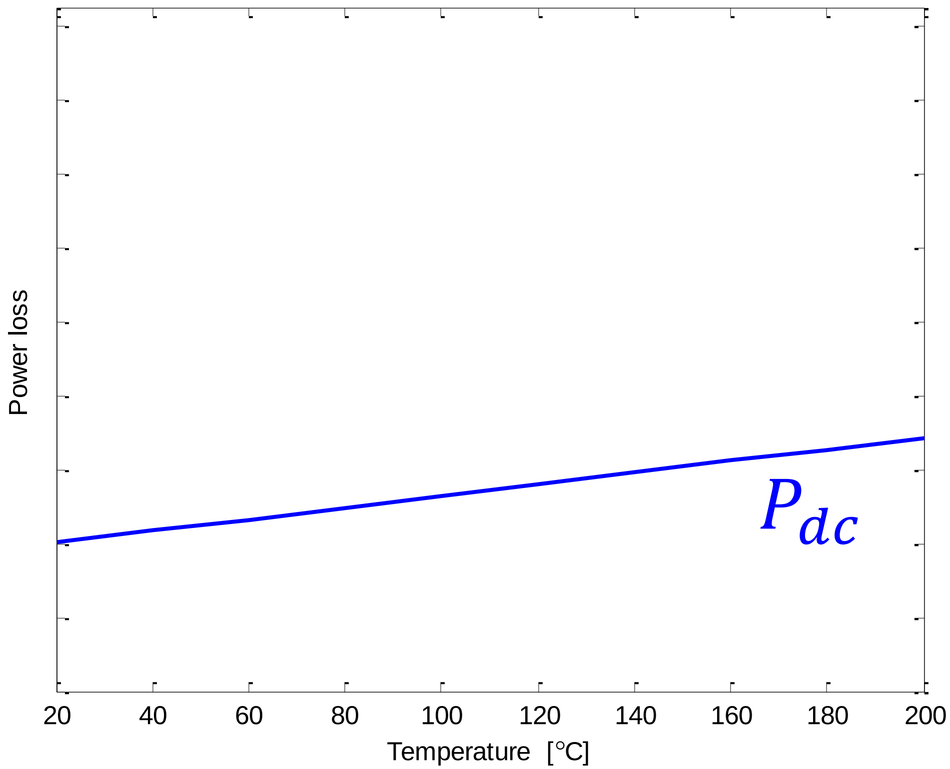
Temperature dependence of loss at ac operation:

$$P_{ac}|_T = \boxed{I^2 R_{dc}|_{T_0}\left(1+\alpha(T-T_0)\right)} + \boxed{I^2\, R_{dc}\Big|_{T_0} \frac{\left(\frac{R_{ac}}{R_{dc}}\right)_{T_0} - 1}{\left(1+\alpha(T-T_0)\right)^{\beta}}}$$

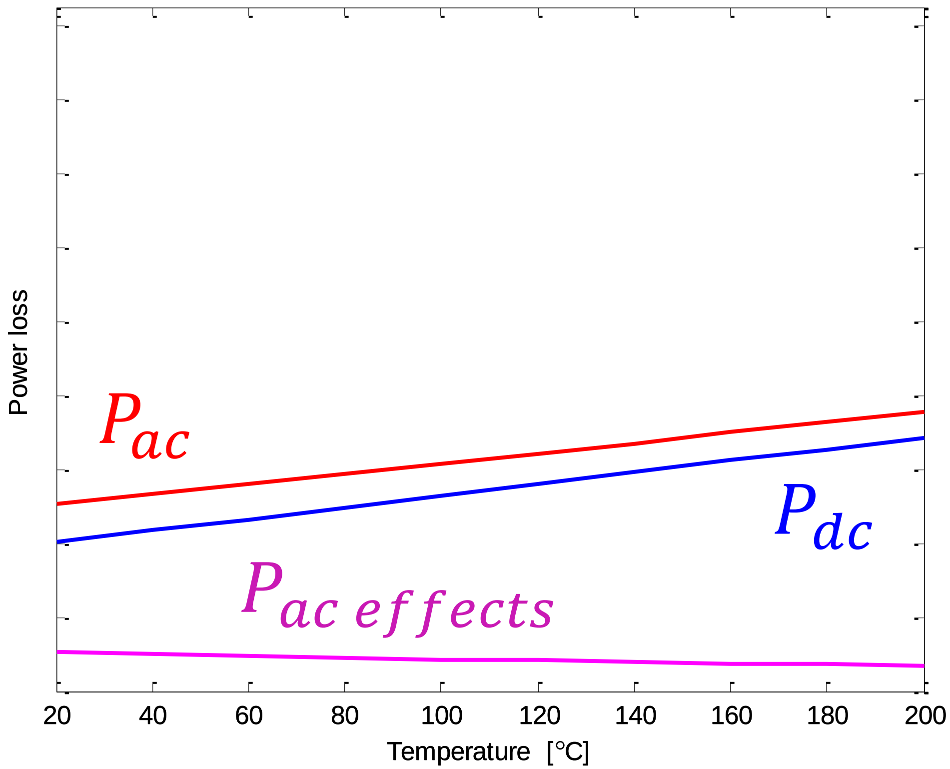
$P_{dc}\Big|_T$

$P_{ac\ effects}\Big|_T$

$$\rho\Big|_T = \rho\Big|_{T_0}\left(1+\alpha(T-T_0)\right)$$



Power loss
20
40
60
80
100
120
140
160
180
200
Temperature [°C]
P_{dc}



Power loss
P_{ac}
P_{dc}
$P_{ac\,effects}$
20
40
60
80
100
120
140
160
180
200
Temperature [°C]

$$n = 1000rpm$$

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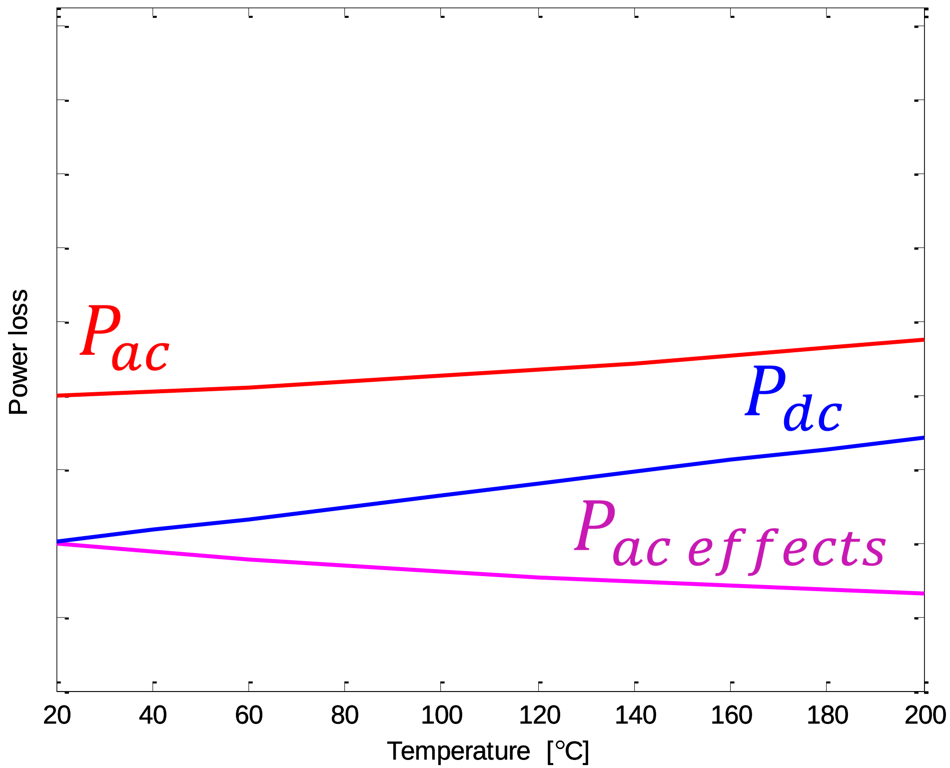

$$n = 2000rpm$$

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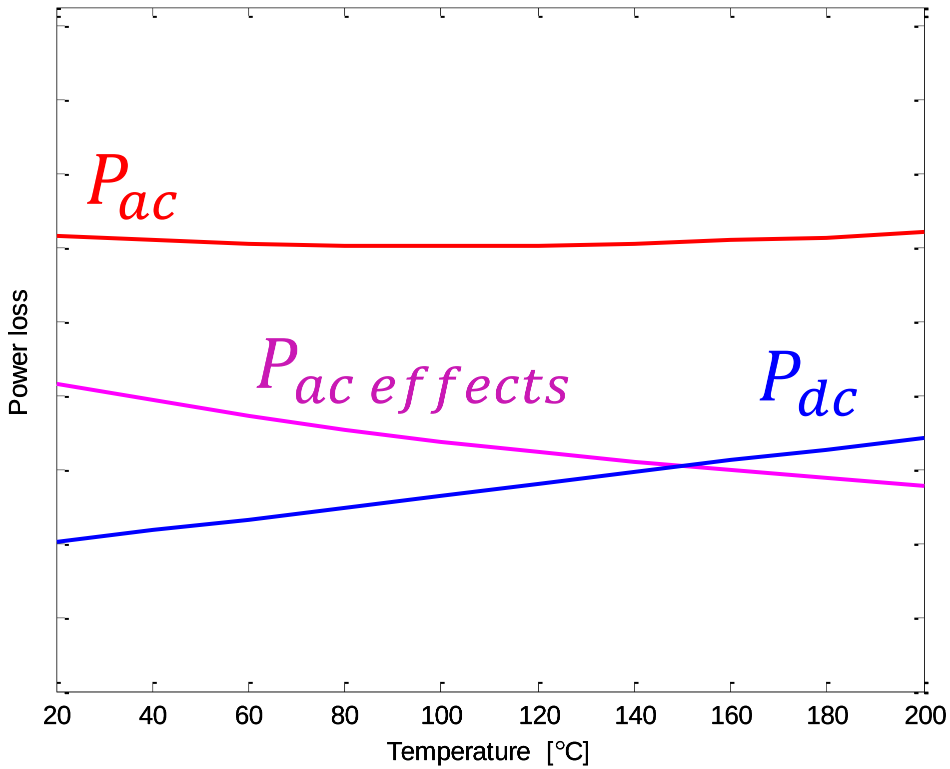
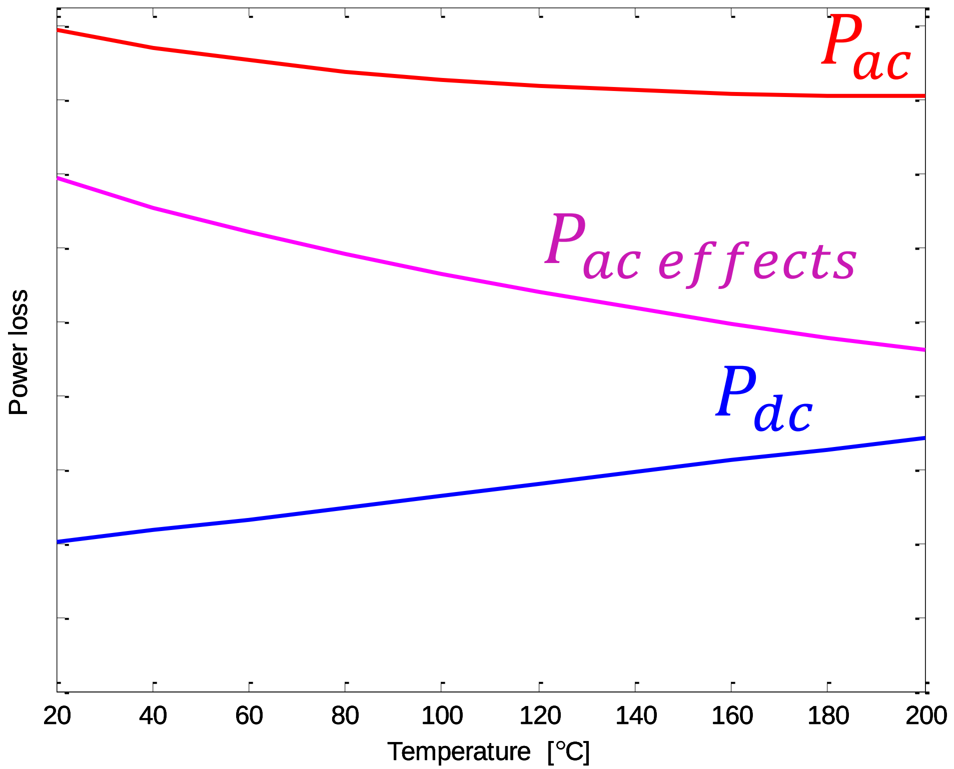


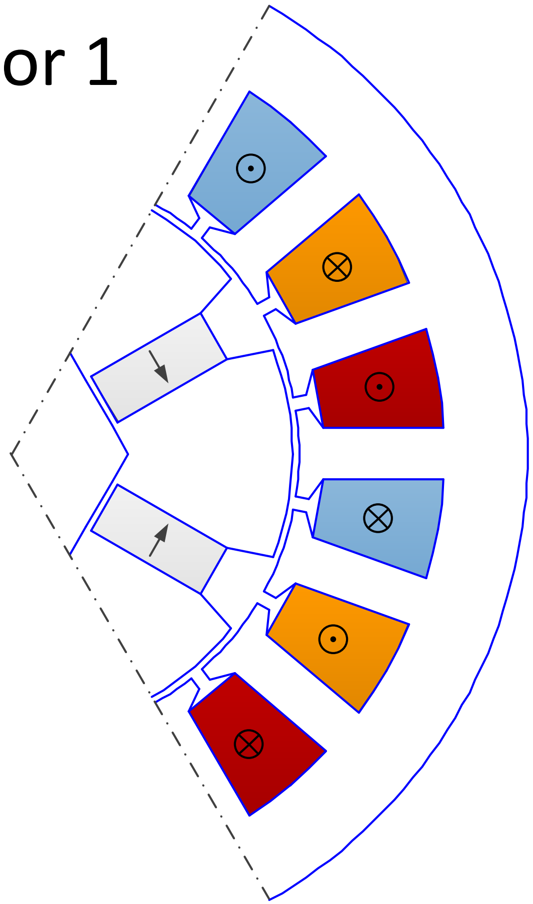
$$n = 3000rpm$$



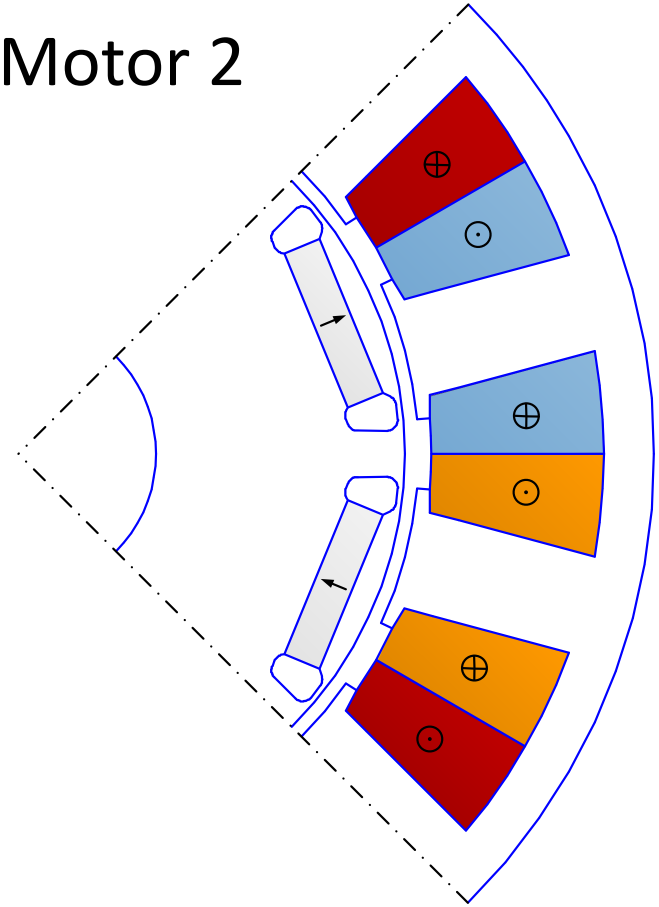
P_{ac}
$P_{ac\ effects}$
P_{dc}
Power loss
20
40
60
80
100
120
140
160
180
200
Temperature [°C]

$$n = 4000rpm$$

Motor 1



Motor 2



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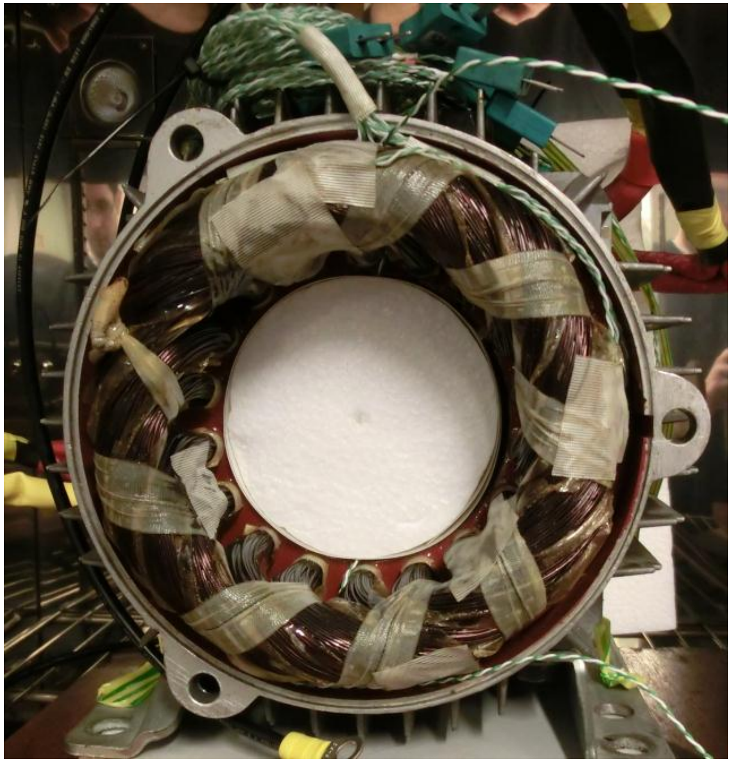
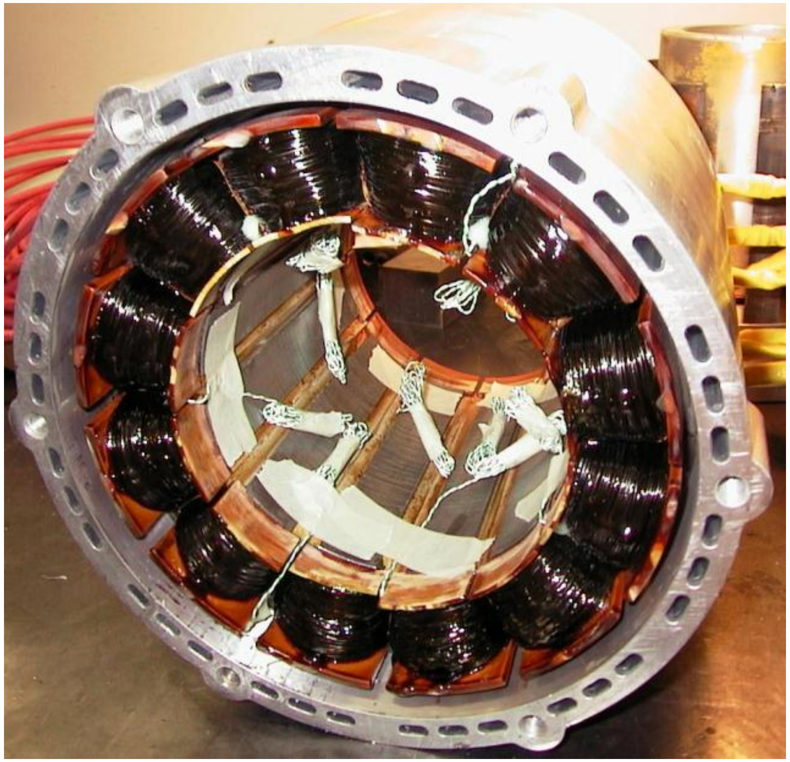
Motor 1

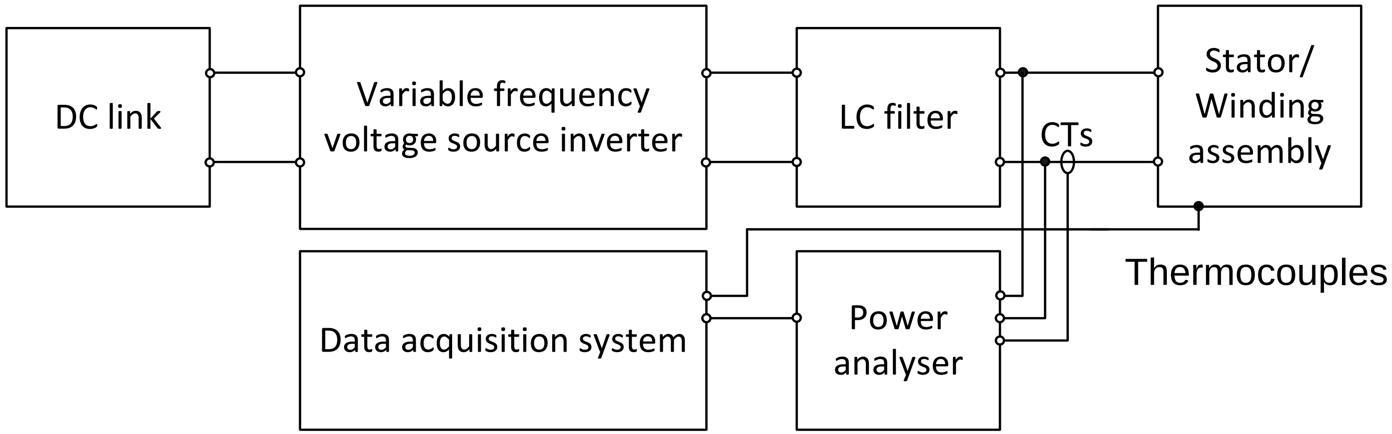


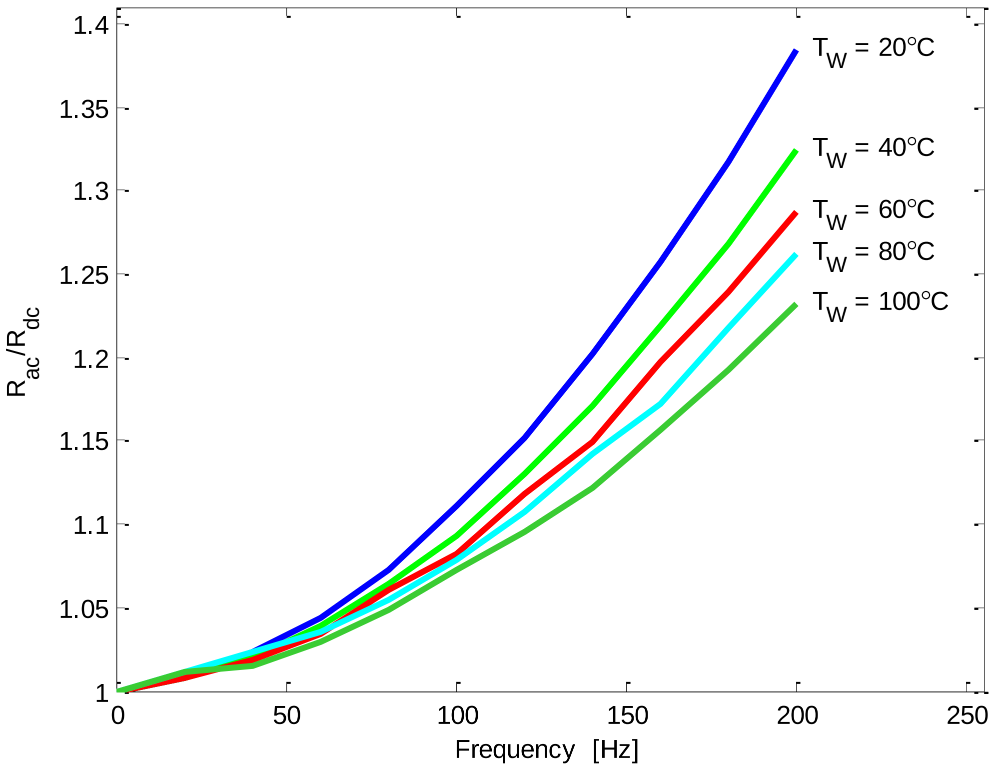
Motor 2



	Motor 1	Motor 2
Rated speed	$n_N = 4000\text{rpm}$	$n_N = 10000\text{rpm}$
Rated power	$P_N = 7.5\text{kW}$	$P_N = 60\text{kW}$
Outer diameter	$D_{O/D} = 155\text{mm}$	$D_{O/D} = 230\text{mm}$
Active length	$l_A = 120\text{mm}$	$l_A = 160\text{mm}$
Number of poles	$p = 6$	$p = 8$
Number of slots	$q = 18$	$q = 12$

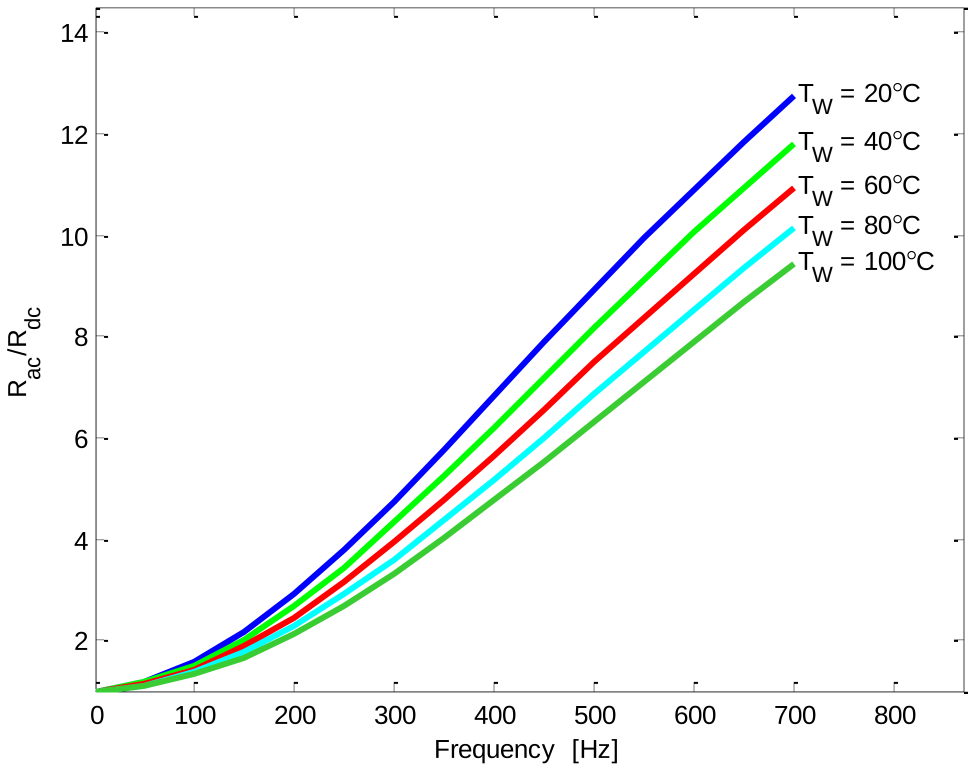
Experimental setup





1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
R_{ac}/R_{dc}
0
50
100
150
200
250
Frequency [Hz]
T_W = 20°C
T_W = 40°C
T_W = 60°C
T_W = 80°C
T_W = 100°C

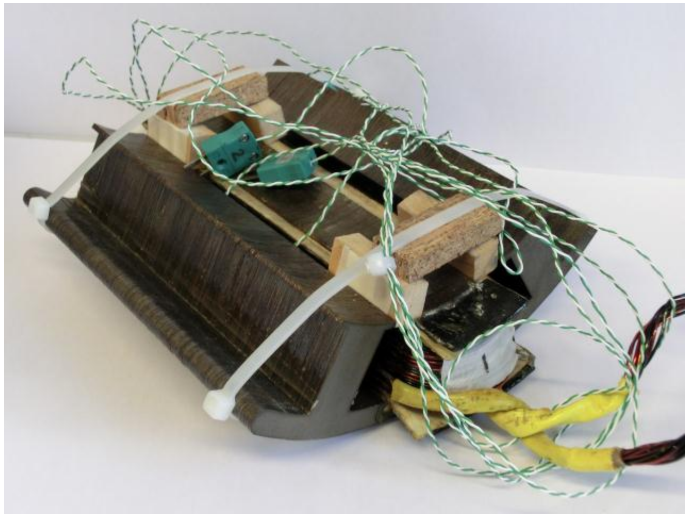
Motor 1



14
12
10
8
6
4
2
0
100
200
300
400
500
600
700
800
Frequency [Hz]
R_{ac}/R_{dc}
T_W = 20°C
T_W = 40°C
T_W = 60°C
T_W = 80°C
T_W = 100°C

Motor 2

Motorette setup



Multi-stranded copper bundle

$$\left.\frac{R_{ac}}{R_{dc}}\right|_{20^0C,700Hz} = 4.9$$

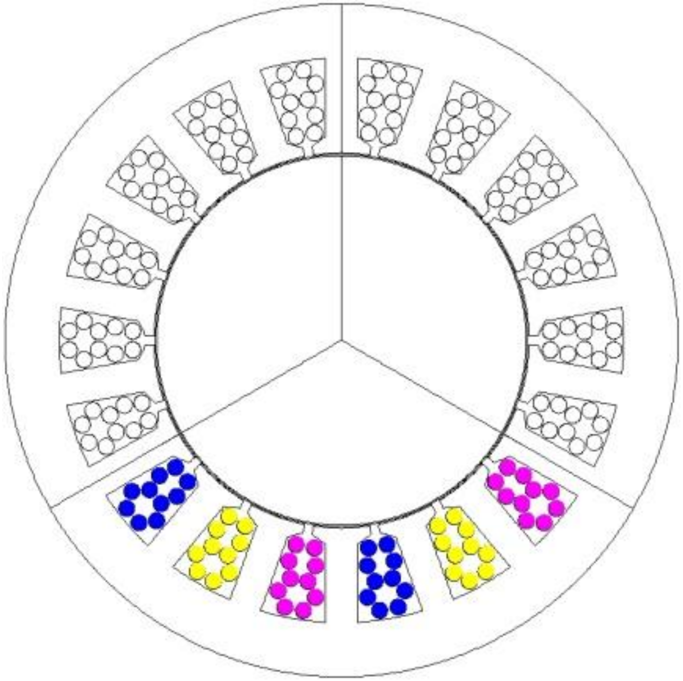
$$\left.\frac{R_{ac}}{R_{dc}}\right|_{100^0C,700Hz} = 4.4$$

Profiled rectangular copper conductor

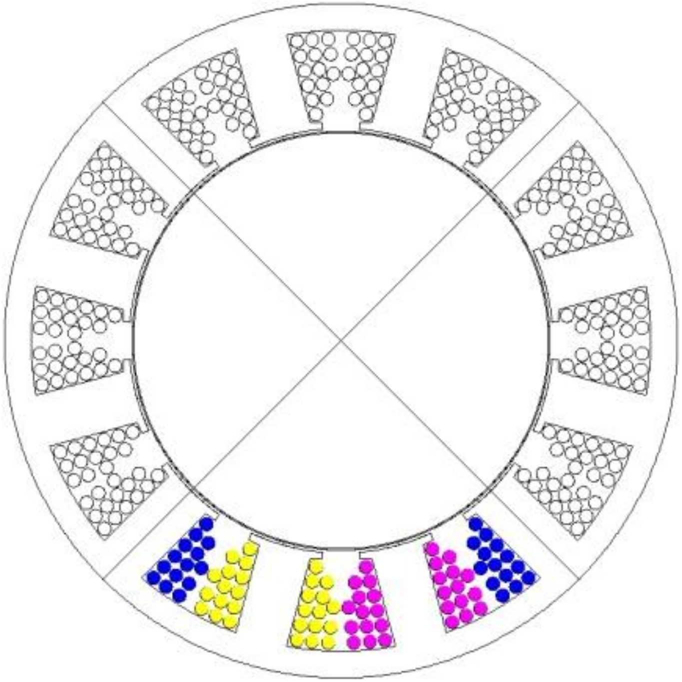
$$\left.\frac{R_{ac}}{R_{dc}}\right|_{20^0C,700Hz} = 11.6$$

$$\left.\frac{R_{ac}}{R_{dc}}\right|_{100^0C,700Hz} = 9.4$$

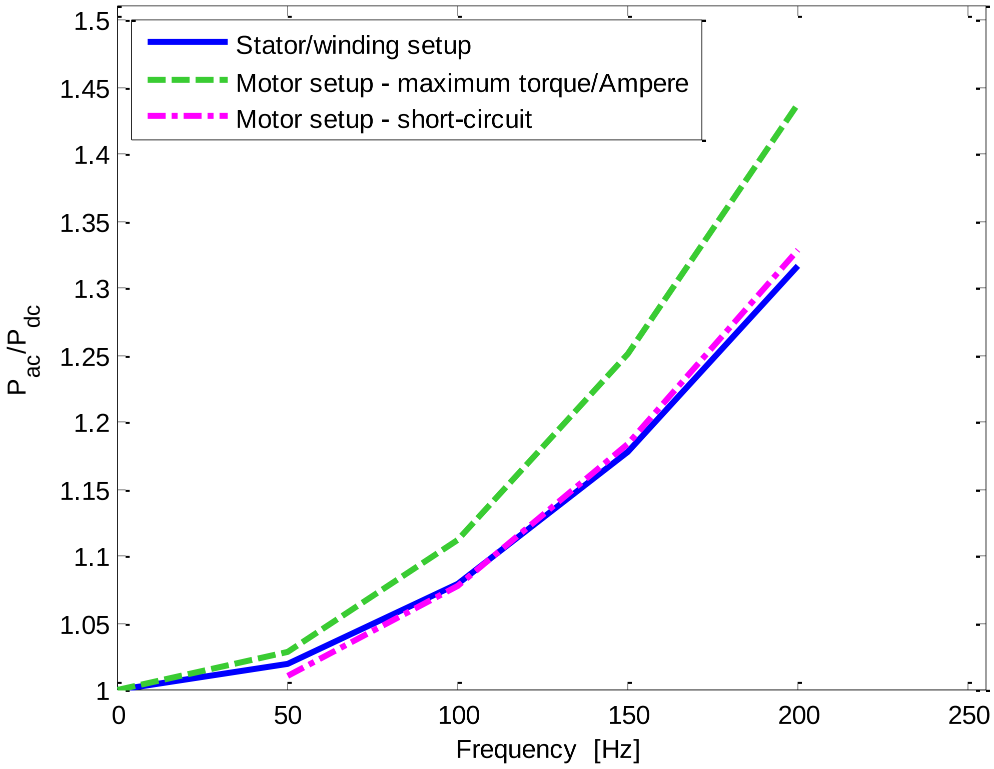
Motor 1



Motor 2

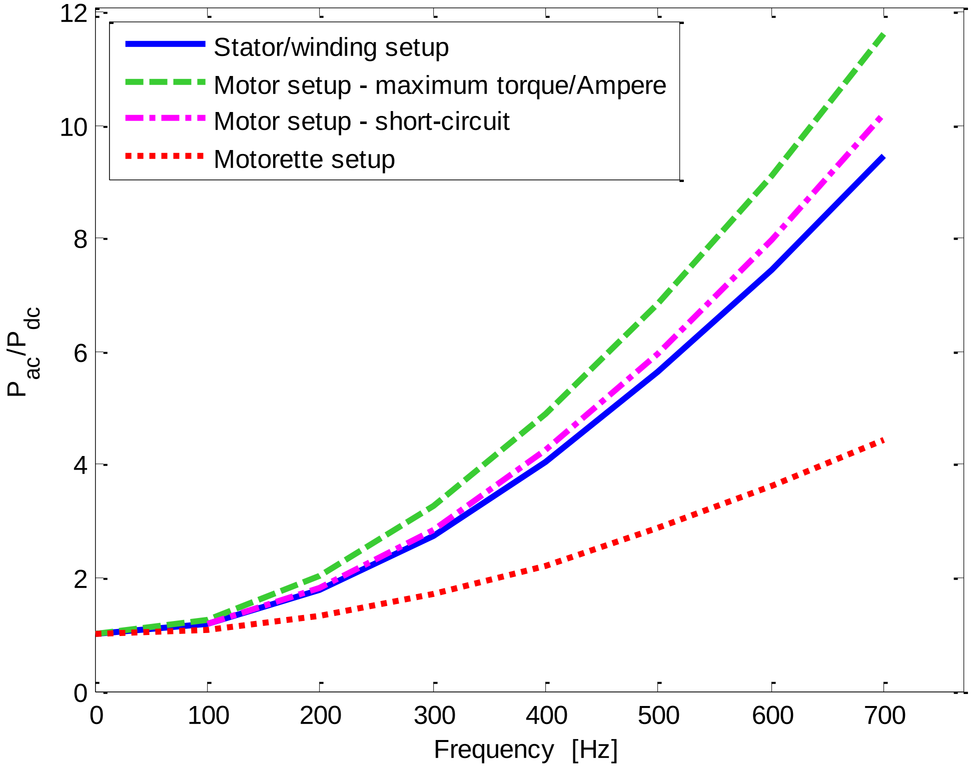


$T = 20^0 C$



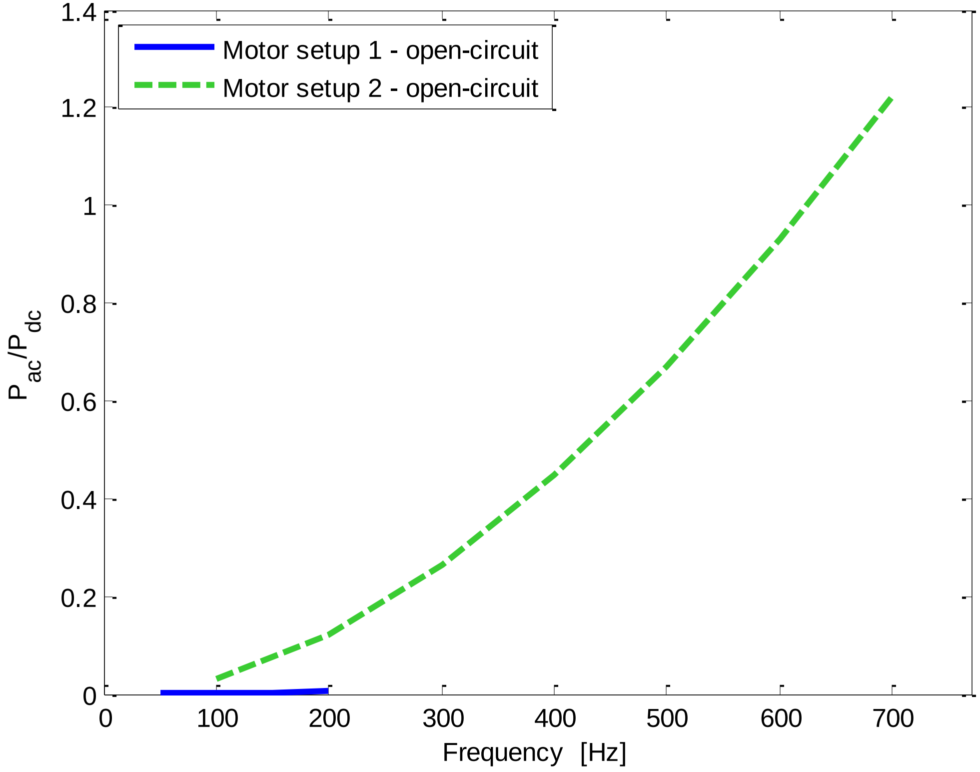
Motor 1

$$T = 20^0 C$$



Motor 2

$T = 20^0 C$



Motor setup 1 - open-circuit
Motor setup 2 - open-circuit
1.4
1.2
1
0.8
0.6
0.4
0.2
0
P_ac/P_dc
0
100
200
300
400
500
600
700
Frequency [Hz]

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So, how to reduce the winding loss at ac operation?

- better understanding of the loss mechanisms
- better understanding of the initial design requirements
- accounting for the multi-physics phenomena in design process
- appropriate use of the existing techniques for loss mitigation