Sustainable Extraction and Processing of Raw Materials, 2025

DETERMINATION OF THE RESISTANCES IN THE ROTOR'S COILS OF A MINE LOCOMOTIVE MOTOR

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Abstract: A possibility has been found for determining the resistances in a loop that cannot be disconnected, by measuring with an ohmmeter. Such loops form the rotor windings of collector motors. To showcase the method, a fictitious example with a small number of collector plates has been described. The method has been applied by studying a motor for a mine locomotive DRT – 10A2 with 105 collector plates. The resistances of the sections of the wave winding have been determined.

Key words: DC motor, rotor, sections, windings

Introduction

The rotor of a DC motor is a shaft on which a cylindrical magnetic core and a collector ring are mounted. Channels are cut on the magnetic core, where the sections of the winding are located. The individual sections are connected to the collector plates of the collector. There are two main schemes for connecting the sections, which are called - a simple lap winding and a simple wave winding (Kasiar et al., 2016; Turygin et al., 2018; Polnik et al., 2020; Xiao et al., 2021; Yang et al., 2021).

Determination of the resistances of the sections under different conditions

We will consider a rotor with a small number of collector plates for simplicity of description. Let k=7 be the number of collector plates.

Figure 1 a) shows a section of a lap winding connected to two adjacent collector plates. Figure 1 b) shows a section of a wave winding connected to two opposite plates in the collector circle (shown in an expanded form) (Iliev J.,et al., 2004; Martinez et al., 2009; Hadziselimovic et al., 2011; Tasev L., 2017, 2019; Maraaba et al., 2020; Li et al., 2021). All sections are connected in series in a loop.

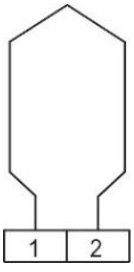


Fig. 1. a)
Section of a lap winding

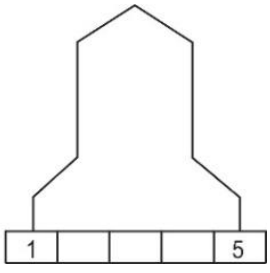


Fig. 1. b)
Section of a wave winding

Figure 2 shows the loop of a lap winding with k=7. The points from 1 to 7 are the collector plates, and the segments marked with $r_1, r_2 \ldots r_7$ are the resistances of the sections. Now with an ohmmeter we measure the resistances between the adjacent collector plates. Between p.1 and p.2 we measure the value m_1 and so on up to m_7 (between p.7 and p.1).

Determination of the resistances of the sections at equal values of m

If $m_1 = m_2 = \cdots = m_7 = m$
then $r_1 = r_2 = \cdots = r_7 = r$

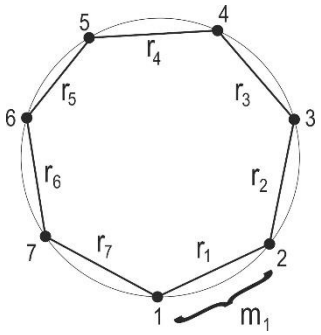


Fig. 2. Loop of a lap winding

When measuring m_1, the resistance r_1 turns out to be connected in parallel with the other 6 resistances connected in series. The measured value m is presented through equation (1).

$$m = \frac{r.(k-1).r}{r+(k-1).r} = \frac{r.(k-1).r}{k.r} = \frac{k-1}{k}.r \quad (1)$$

The equation for r is presented by (2), respectively.

$$r = \frac{k}{k-1}.m \quad (2)$$

When $k = 7$, $r = \frac{7}{6}m$.

Determination of the resistances of the sections at different values of m_i

Given the measured resistances $m_1 \ldots m_k$, the resistances $r_1 \ldots r_k$ need to be defined.

The total resistance of the loop is presented by (3)

$$T = r_1 + r_2 + \cdots + r_k \quad (3)$$

Here the measured value m is presented using equation (4):

$$m_i = \frac{r_i.(T-r_i)}{r_i+(T-r_i)} = \frac{T.r_i - r_i^2}{T} \quad (4)$$

The quadratic equation (5) is obtained for r_i

$$r_i^2 - T.r_i + m_i T = 0 \quad (5)$$

The roots of the quadratic equation (5) are given in equation (6):

$$r_i = \frac{T \pm \sqrt{T^2 - 4m_i T}}{2} \quad (6)$$

In (6) we take only the "–" sign because it is true for a large number of resistances $r_i < \frac{T}{2}$ for each i. Thus, we obtain for r_i an expression given by (7).

$$r_i = \frac{T}{2} - \frac{T}{2}.\sqrt{1 - \frac{4m_i}{T}} \quad (7)$$

In (7) we substitute: $a_i = \sqrt{1 - \frac{4m_i}{T}}$, respectively $r_i = \frac{T}{2}.(1 - a_i)$. Then, the full resistance is $T = \sum_1^k r_i = \sum_1^k \frac{T}{2}.(1 - a_i)$. Hence, equation (8) is obtained for the sum of a_i.

$$\sum_1^k a_i = k - 2 \quad (8)$$

Now, we set a value for T and at this value we determine $a_1, a_2 \ldots a_k$.

We check whether (5) is satisfied. If $\sum_1^k a_i < k - 2$, we set another value for T, greater than the first one.

If $\sum_1^k a_i > k - 2$, we set a value of T smaller than the first.

Thus, through several iterations we determine the exact values of T and $a_1 \ldots a_k$.

Finally, through (4) we determine the desired resistances: $r_1, r_2 \ldots r_k$

We shall do and example calculation for k = 7. For the purpose of describing the method only, we record some sample values of m_i in Table 1.

Table 1. *An example for determining r_i*

i	For example, Measured m_i, mΩ	T=60 a_i	T=62 a_i	T=60.5 a_i	T=60.5 r_i , mΩ
1	7.1	0.7257	0.7362	0.7284	8.216
2	7.2	0.7211	0.7318	0.7239	8.352
3	7.3	0.7165	0.7273	0.7193	8.491
4	7.4	0.7118	0.7229	0.7147	8.630
5	7.5	0.7071	0.7184	0.7100	8.773
6	7.6	0.7024	0.7139	0.7054	8.912
7	7.7	0.6976	0.7094	0.7006	9.057
	Sum	4.9822	5.0599	5.0023	60.43

The first column records the example values of measured resistances between adjacent collector plates – $m_1 \ldots m_7$.

A value of T= 60 is set in the second column and the values of a_i are calculated for this T = 60.

On the last row, the sum of a_i is found: $\sum_1^7 a_i = 4.9822$

According to criteria (8) $\sum_1^7 a_i = 5$

Since 4.9822 < 5 we choose another value of T = 62 and in the third column we determine a_i and their sum is 5.0599.

Since 5.0599 > 5 we make another correction to T in the fourth column.

The sum increases in one area proportional to T and we can determine this correction.

The amount increases by 0.0777, and T increases by 2.

If we want the amount to become equal to 5, it must increase by (5 – 4.9822) = 0.0178.

Then, by proportion, we determine the increase ΔT above the value of 60. We obtain $\Delta T = \frac{0.0178.2}{0.0777} = 0.46$

In the fourth column we take the value of T = 60.5 and calculate a_i and the sum 5.0023. Using (4) we determine the values of the resistance $r_1 \ldots r_7$ and their sum which are written in the last column. The difference between the given value of T = 60.5 and the calculated value 60.43 is 0.07Ω, which means that we are very close to the exact value of T.

Determination of the resistances of the sections of a wave winding

Figure 3 shows the loop that forms the sections of a simple wave winding at k=7. The resistances of the sections are denoted by $n_1 \ldots n_7$ and are shown by lines connecting the corresponding points (collector plates).

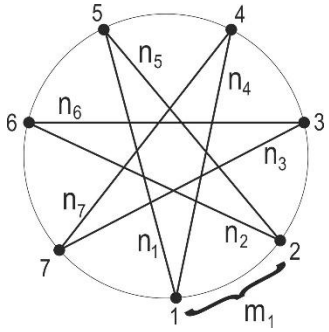


Fig.3. Loop of a wave winding, k = 7
1–5–2–6–3–7–4–1

Geometrically, the figure represents a seven-rayed star formed by the large diagonals of a regular heptagon. Electrically, the seven resistances $n_1 \ldots n_7$ are connected in series in a closed loop – 1–5–2–6–3–7–4–1.

Let the measurements $m_1 \ldots m_7$ that we have made correspond to those in Figure 2.

The resistance r_1 between point 1 and point 2 in Figure 2 now (in Figure 3) consists of the series-connected n_1 and n_5 , $r_1 = n_1 + n_5$.

Let all resistances $r_1 \ldots r_7$ be determined and have the values from Table 1. Using these values, we can determine the resistances $n_1 \ldots n_7$ of the sections of the rotor wave winding.

$$\begin{aligned}
r_1 &= n_1 + n_5 = n_1 + n_5 \\
r_2 &= n_2 + n_6 = n_6 + n_2 \\
r_3 &= n_3 + n_7 = n_3 + n_7 \\
r_4 &= n_4 + n_1 = n_1 + n_4 \\
r_5 &= n_5 + n_2 = n_5 + n_2 \\
r_6 &= n_6 + n_3 = n_6 + n_3 \\
r_7 &= n_7 + n_4 = n_7 + n_4
\end{aligned} \quad (9)$$

In these sums (9), we rearrange the addends in the 2nd and 4th rows and group them in (10).

$$\begin{aligned}
&r_1 + r_2 + r_3 + r_4 + r_5 + r_6 + r_7 = \\
&= 2n_1 + 2r_5 + 2r_6 + 2r_7
\end{aligned} \quad (10)$$

We obtain n_1 – equation (11)

$$n_1 = \frac{1}{2}.(r_1 + r_2 + r_3 + r_4 - r_5 - r_6 - r_7) \quad (11)$$

There are 3 minuses in the sum of (11).
Now we repeat the same procedure to determine n_2.

$$\begin{aligned} r_1 &= n_1 + n_5 = n_1 + n_5 \\ r_2 &= n_2 + n_6 = n_2 + (n_6) \leftarrow r_6 \\ r_3 &= n_3 + n_7 = (n_7) + (n_3) \leftarrow r_7 \\ r_4 &= n_4 + n_1 = (n_4) + (n_1) \leftarrow r_1 \\ r_5 &= n_5 + n_2 = n_2 + (n_5) \\ r_6 &= n_6 + n_3 = n_6 + n_3 \\ r_7 &= n_7 + n_4 = n_7 + n_4 \end{aligned} \quad (12)$$

In the sums (12) we rearrange the addends in the 3rd and 5th row and we group them in (13).

$$\begin{aligned} &r_1 + r_2 + r_3 + r_4 + r_5 + r_6 + r_7 = \\ &= 2n_2 + 2r_1 + 2r_6 + 2r_7 \end{aligned} \quad (13)$$

We obtain n_2 – equation (14)

$$n_2 = \frac{1}{2}.(-r_1 + r_2 + r_3 + r_4 + r_5 - r_6 - r_7) \quad (14)$$

If we continue to define $n_3, n_4 \ldots n_7$, we notice that the form of (11) and (14) is preserved, while the position of the minuses changes symmetrically. The marked squares in Table 2 are the locations of the minuses. In the first row, the last 3 squares are minuses.

Table 2. *Determining the sign in front of r*

	r_1	r_2	r_3	r_4	r_5	r_6	r_7
n_1					■	■	■
n_2	■					■	■
n_3	■	■					■
n_4	■	■	■				
n_5		■	■	■			
n_6			■	■	■		
n_7				■	■	■	

On each subsequent row, the squares (minuses) are moved one position to the right, the one that comes out of the table goes to the first position.

For $n_3, \ldots n_7$ the following equations are defined (15).

$$\begin{aligned} n_3 &= \frac{1}{2}.(-r_1 - r_2 + r_3 + r_4 + r_5 + r_6 - r_7) \\ &\ldots \\ n_7 &= \frac{1}{2}.(r_1 + r_2 + r_3 - r_4 - r_5 - r_6 + r_7) \end{aligned} \quad (15)$$

This table can be constructed for any *k*, as long as it is an odd number.

The minuses of the first row are the last $\frac{k-1}{2}$ squares, and in the next row they change in the described way, which allows us to determine $n_1 \ldots n_k$ .given the calculated $r_1 \ldots r_k$ are available.

The resistances of the wave winding from Figure 3 calculated in this way are given in Table 3 together with the measurement data from Table 1.

Table 3. *Calculated values of n_i*

i	r_i, mΩ	n_i, mΩ
1	8.216	3.496
2	8.352	4.008
3	8.491	4.568
4	8.630	5.133
5	8.727	4.720
6	8.912	4.345
7	9.057	3.923
Σ	60.43	30.21

r_i – resistances of the lap winding
n_i – resistances of the wave winding

Determination of the resistances of the sections in the rotor of a mine locomotive motor

The rotor has the following characteristics:
Motor: type – DRT–10A2
Supply voltage: 80 V
Power: 6 kW
Speed: 1500 min^{-1}
Housing: Explosion-proof
Number of collector plates: k = 105
Winding type: simple wave
Brushes: Two brushes at 90˚ from each other.

We designate each collector plate clockwise with the number from 1 to 105. The number of sections of the wave winding is also 105. All 105 sections are connected in series as shown in Figure 3, forming a closed loop in the following order:
1–54–2–55–…–52–105–53–1.

The ends of every two sections are connected to a collector plate in a special channel, in which they are pressed in and soldered (Tasev L., 2017, 2019).

Determination of the resistances between adjacent collector plates

We measure the resistance between two adjacent collector plates with an accuracy of 1 μΩ using a four-wire circuit that includes a current source I = 1 A and a millivoltmeter with three decimal places, Figure 4.

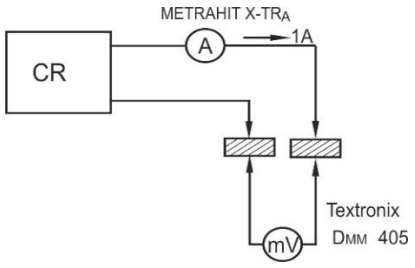


Fig. 4. CR - adjustable rectifier

The measurements made were 105, denoted by m_i from 1 to 105. m_1 corresponds to the resistance between plate 1 and plate 2 of the collector, m_2 is the resistance between 2 and 3, and so on.

The minimum measured value is 3.615 mΩ, and the maximum is 3.690 mΩ.

To limit the number of calculations (with some loss of accuracy) we distribute all measured values into 20 groups of 0.005 mΩ → 3.600, 3.605, 3.610, 3.615, …, 3.690, 3.695.

There is no measured value in the first 3 groups and in the last one. Thus, we observe 16 groups, marked with numbers from 1 to 16 in the first column of Table 4. The discretized measured values m_i distributed in 16 groups are recorded in the second column. The number of measured values in the respective group is recorded in the third column.

Calculations are made by iterations in columns 4, 5 and 6 according to the method described above. We set values of T until the sum $\sum a_i$ approaches $k-2$ = 103 as close as possible. At T = 387 the sum $\sum a_i$ = 102.996 is very close to 103. At this value of T in column 7 we have determined $r_i = \frac{T}{2}(1-a_i)$.

These numbers should be the resistance values between two adjacent collector plates in case the winding loop in the rotor is disconnected. Using them, in the next item, we have determined the resistances of the sections of the wave winding.

Table 4. *Grouping the measurements and determining* r_i

group	$\overline{m_i}$, mΩ	number	T=400	T=390	T=387	T=387
			a_i	a_i	a_i	r_1, mΩ
1	3.615	2	0.98176	0.98129	0.98114	3.649
2	3.620	2	0.98173	0.98126	0.98111	3.655
3	3.625	2	0.98171	0.98123	0.98109	3.659
4	3.630	10	0.98168	0.98121	0.98106	3.665
5	3.635	8	0.98166	0.98118	0.98103	3.671
6	3.640	9	0.98163	0.98116	0.98101	3.675
7	3.645	12	0.98161	0.98113	0.98098	3.680
8	3.650	14	0.98158	0.98110	0.98096	3.684
9	3.655	10	0.98155	0.98108	0.98093	3.690
10	3.660	10	0.98153	0.98105	0.98090	3.696
11	3.655	6	0.98150	0.98103	0.98088	3.700
12	3.670	7	0.98148	0.98100	0.98085	3.706
13	3.675	7	0.98145	0.98097	0.98082	3.711
14	3.680	0	0.98143	0.98094	0.98080	3.715
15	3.685	4	0.98140	0.98092	0.98077	3.721
16	3.690	2	0.98138	0.98089	0.98074	3.727
Σ	383.8		103.067	103.013	102.996	387.072

Determination of the resistances of the sections of the wave winding

The method for determining the resistances of a wave winding n_i at given r_i is described above. According to equation (16), for k = 105, we determine the value of n_1:

$$\begin{aligned} n_1 &= \tfrac{1}{2}.\{r_1+\cdots+r_{53}-(r_{54}+\cdots+r_{105})\} \\ r_1+\cdots+r_{105} &= T \\ r_{54}+\cdots+r_{105} &= T-(r_1+\cdots+r_{53}) \\ n_1 &= \tfrac{1}{2}.(r_1+\cdots+r_{53}-T+r_1+\cdots+r_{53}) \\ n_1 &= r_1+\cdots+r_{53}-\tfrac{T}{2} \end{aligned} \quad (16)$$

The value of n_2 is determined according to equation (17) taking into account the shift of the minuses (Table 2):

$$n_2 = (r_2+\cdots+r_{54})-\frac{T}{2}$$

$$+\left|\begin{matrix} r_1+\cdots+r_{53} = n_1+\dfrac{T}{2} \\ -r_1+r_{54} = -r_1+r_{54} \end{matrix}\right. \quad n_2 = (r_2+\cdots+r_{54})-\frac{T}{2}$$

$$n_2 = n_1 - r_1 + r_{54} \quad (17)$$

It turns out that we can determine n_2 using the previous value n_1.

Similarly, further on equations (18), (19) and so on van be used:

$$n_3 = n_2 - r_2 + r_{55} \quad (18)$$
$$n_4 = n_3 - r_3 + r_{56} \quad (19).$$

The calculations according to these expressions are made and are shown in Table 5. The first column contains the measurement number. The second column contains the group in which the respective measurement falls. The third column contains the value of r_i, taken from Table 4. The fourth column contains n_i – the sought resistances of the sections of the wave winding. Thus, the 105 resistance values of the sections of the wave winding in the motor rotor were determined with an accuracy of four digits.

Table 5. *Calculated values for the wave winding*

N	group	r_i , mΩ	n_i , mΩ
1	1	3.649	1.834
2	1	3.649	1.850
3	12	3.706	1.891
4	13	3.711	1.869
5	11	3.700	1.829
6	4	3.665	1.809
7	4	3.665	1.803
8	9	3.690	1.803
9	4	3.665	1.788
10	16	3.727	1.788
11	12	3.706	1.788
12	8	3.684	1.772
13	9	3.690	1.784
14	7	3.680	1.769
15	8	3.684	1.769
16	13	3.711	1.785
17	6	3.675	1.764
18	10	3.696	1.760
19	15	3.721	1.744
20	8	3.684	1.688
21	6	3.675	1.684
22	7	3.680	1.684
23	7	3.680	1.675
24	12	3.706	1.691
25	10	3.696	1.691
26	7	3.680	1.666
27	8	3.684	1.682
28	2	3.655	1.678
29	5	3.671	1.688
30	8	3.684	1.713
31	7	3.680	1.713
32	9	3.690	1.708
33	11	3.700	1.729
34	15	3.721	1.750
35	6	3.675	1.719
36	12	3.706	1.755
37	9	3.690	1.760
38	8	3.684	1.745
39	8	3.684	1.782
40	10	3.696	1.804
41	5	3.671	1.773
42	7	3.680	1.786
43	10	3.696	1.796
44	2	3.655	1.784
45	3	3.659	1.794
46	11	3.700	1.819

N	group	r_i, mΩ	n_i, mΩ
47	11	3.700	1.815
48	5	3.671	1.815
49	13	3.711	1.840
50	6	3.675	1.819
51	7	3.680	1.828
52	12	3.706	1.859
53	5	3.671	1.837
54	4	3.665	1.815
55	9	3.690	1.799
56	8	3.684	1.815
57	5	3.671	1.842
58	7	3.680	1.871
59	3	3.659	1.856
60	4	3.665	1.862
61	6	3.675	1.887
62	4	3.665	1.877
63	16	3.727	1.939
64	9	3.690	1.918
65	10	3.696	1.912
66	6	3.675	1.906
67	7	3.680	1.911
68	11	3.700	1.915
69	9	3.690	1.926
70	5	3.671	1.911
71	7	3.680	1.936
72	4	3.665	1.977
73	7	3.680	1.996
74	6	3.675	1.991
75	5	3.671	1.996
76	10	3.696	2.005
77	12	3.706	2.015
78	5	3.671	2.005
79	10	3.696	2.014
80	7	3.680	2.002
81	4	3.665	1.977
82	10	3.696	1.983
83	8	3.684	1.971
84	6	3.675	1.967
85	13	3.711	1.982
86	15	3.721	1.971
87	9	3.690	1.971
88	13	3.711	1.956
89	13	3.711	1.951
90	6	3.675	1.930
91	15	3.721	1.939
92	12	3.706	1.902
93	4	3.665	1.892
94	8	3.684	1.898
95	9	3.690	1.894
96	8	3.864	1.900
97	4	3.665	1.871
98	8	3.684	1.865
99	10	3.696	1.881
100	11	3.700	1.885
101	10	3.696	1.856
102	9	3.690	1.871
103	8	3.684	1.856
104	13	3.711	1.852
105	8	3.684	1.847

Conclusion

An engineering method is proposed for determining the individual resistances in a closed loop of series-connected resistances that cannot be interrupted. Such loops form the rotor windings of collector motors. The resistances of the sections in the rotor winding of a mine locomotive motor are determined. The calculations are made on the basis of the measured resistances between the collector plates. The mathematical apparatus is simplified and easy to apply in practice in the diagnostics of mine locomotive motors.

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