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**How should one design a motor starting
three-phase autotransformer
for 100kVA continuous motor power as per IEC 61558?**

Technical specification relevant only to design

Electrical data and diagram

Input voltages sinusoidal	3 x 400V (phase-phase)
Frequency	50/60Hz
Nominal output voltage	3 x 200V (phase-phase), normally between 50% and 70% of the input voltage
Nominal output current	145A (100kVA)
Motor starting current	2.5 x 145 = 362.5A
Starting time	10 seconds
Pause between two starts	10 minutes

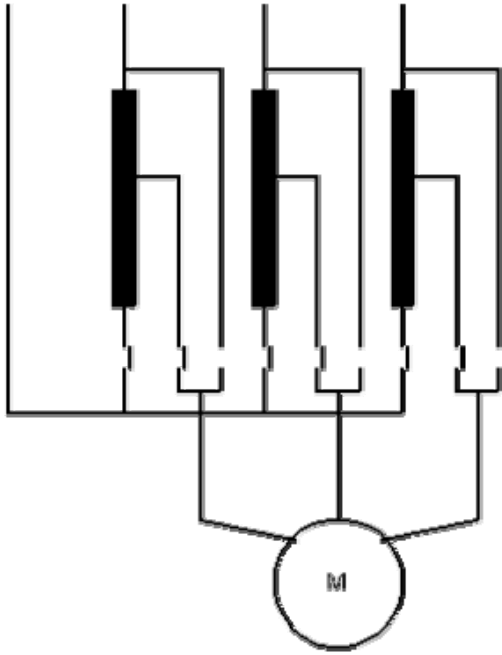
Ambient and operating conditions:

Ambient temperature	40°C
Mode of operation	Duty cycle, 10 seconds on, 10 minutes off
Test conditions	Non-inherently short-circuit proof, protected by a thermal fuse

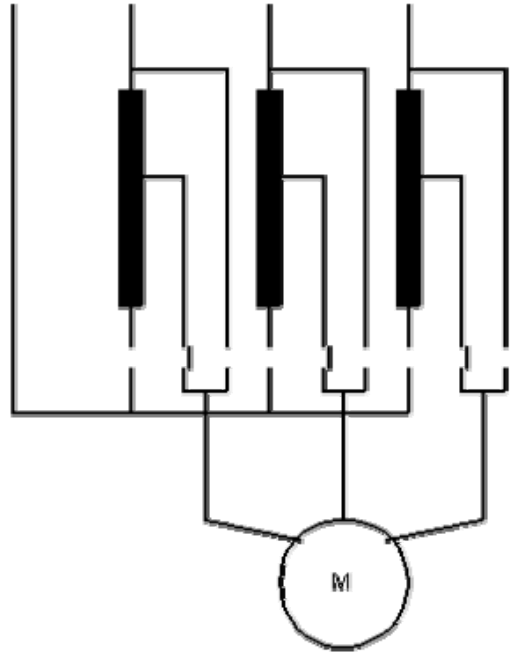
Specification

- **Autotransformer as per IEC 61558**
- **Insulation class E**

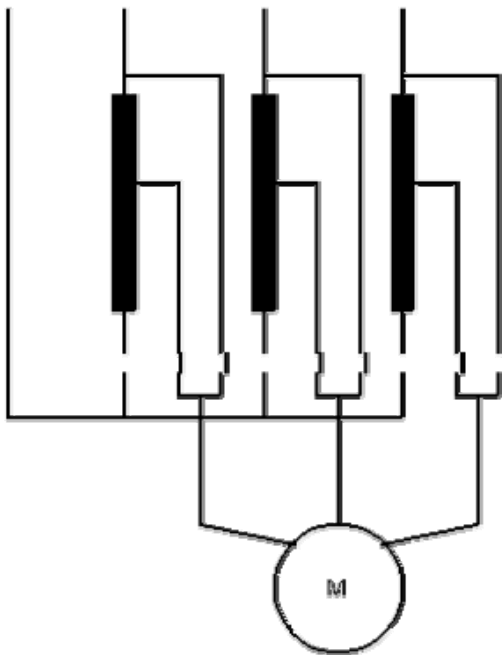
A



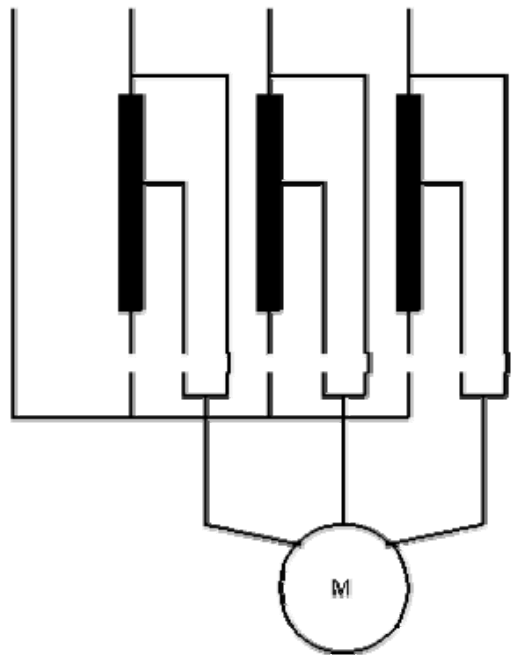
B

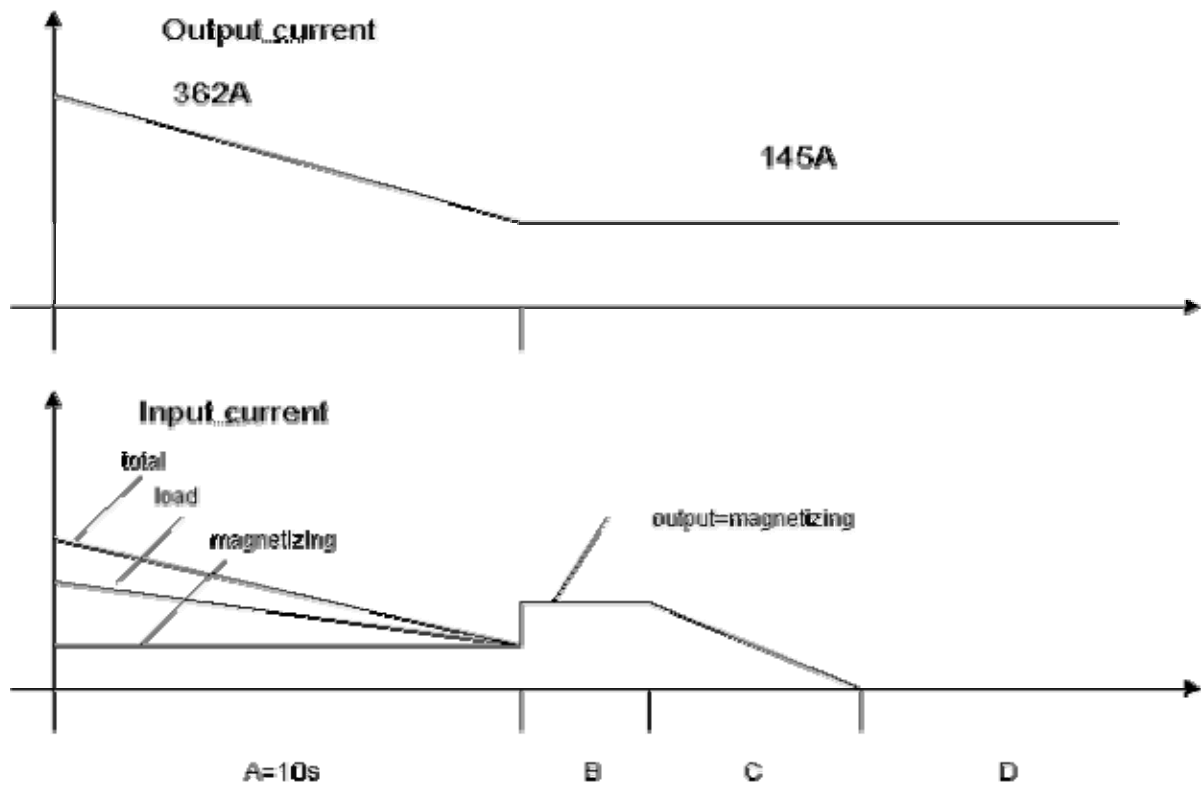


C



D





Design criteria

IEC 61558

An autotransformer with non-inherently short-circuit protection as per IEC 61558 is equipped with an internal protection. Very often, we arrive at a combined protection solution consisting of a primary-side fuse (short circuit protection) and a thermal cut-out (overload protection). For this reason, short-circuit and overload is not design criteria. The criterion for design for purposes of IEC 61558 is only temperature θ **nominal** at the overvoltage of 6%.

Insulation class	A	E	B	F	H
Max. winding temperature in nominal operating mode θ nominal (°C)	100	115	120	140	165

Insulation class

Max winding temperature in nominal operating mode = 115°C
Insulation class E is prescribed.

Criterion for design

The autotransformer has to be designed for the temperature rise $<75^{\circ}\text{K}$ at 40°C ambient temperature, the overvoltage of 6% and insulation class E. The mechanical stress of the windings in short-circuit operation is normally in the power range up to 100kVA not criterion of the design. *The criteria of design is the temperature rise:*

Criterion=2

Bobbin unit

An autotransformer is constructed exclusively with single-chamber bobbin units.

Induction and Fe-quality

A motor starting autotransformer is designed exclusively with cold-rolled steel M45, M50 or 530-50 at the induction approx. 1.6T.

No-load current

In order to avoid high voltage spikes between the operation A and B the no-load current of the autotransformer has to be approx. 50% of the motor nominal current. This can best be achieved if the core is constructed with a defined gap. Note that under this condition the continuous no-load operation isn't normally allowed.

Input current

The output current during the operation A is not constant. Its rms-value should be entered in accordance with the following recommendation:

$$\text{Load1} = (I_{\text{max}}/I_{\text{nom}} + 0.33 * ((I_{\text{max}}/I_{\text{nom}} - 1)^2))^0.5 = 1.8$$

Design procedure

1. If you are not yet acquainted with Rale design software please read the text "**How should I design a small transformer?**" Keep a copy of this text within convenient reach whenever performing design work.
2. Fill in the design input mask as follows. If you need any help, press functions key F1. There is extensive description for each input field.

The screenshot shows the 'INPUT' software interface, Version 9.01 / 26.2.98. The main window displays a table of primary and secondary parameters, followed by a 'MASK' section for design options. The primary parameters include Circuit (4), U (V) (115), I (A) (145), and Overvolt. (*:1.06, 230). The secondary parameters include Voltage (V), Current (A), Wire, Ins/L, and Ins/E. The MASK section contains various design options such as Regulation (%:50), Steel (-:3), Cooling (*:1), Bobbin (-:1), Udiodide (V:0.8), Induction (T:1.6), Force (m/s:0), P/S-Order (-:1), dUdiodide (V:.05), Remanence (*:.05), Bracket (-:2), Rac/Rdc (*:1.05), Ripple (%:5), W/kg (*:1), Radiator (-:0), Space (*:.9), Temp. Amb. (°C:40), VAR/kg (*:1), Channel (cm:0), Vertical (-:1), Temp. rise (°K:75), Gap (*:250), Cu-Surface (*:1), Horizontal (-:1), Time 1 (Min:0.16), Annealed (-:0), Impregnation (-:2), Load 1 (*:1.8), Stacking (*:1), Rth-varnish (*:1), Spread (%:0), Time 2 (Min:10), Hole (-:1), Rth-compoun. (*:1), Selection (-:0), Load 2 (*:0), Assembly (-:2), Case (-:0), and Criterion (-:2). The bottom status bar shows 'DEII.MP', 'AUTO', 'STEEL2.DAT', 'V530-50A', 'Min: 1', and 'Max: 5'.

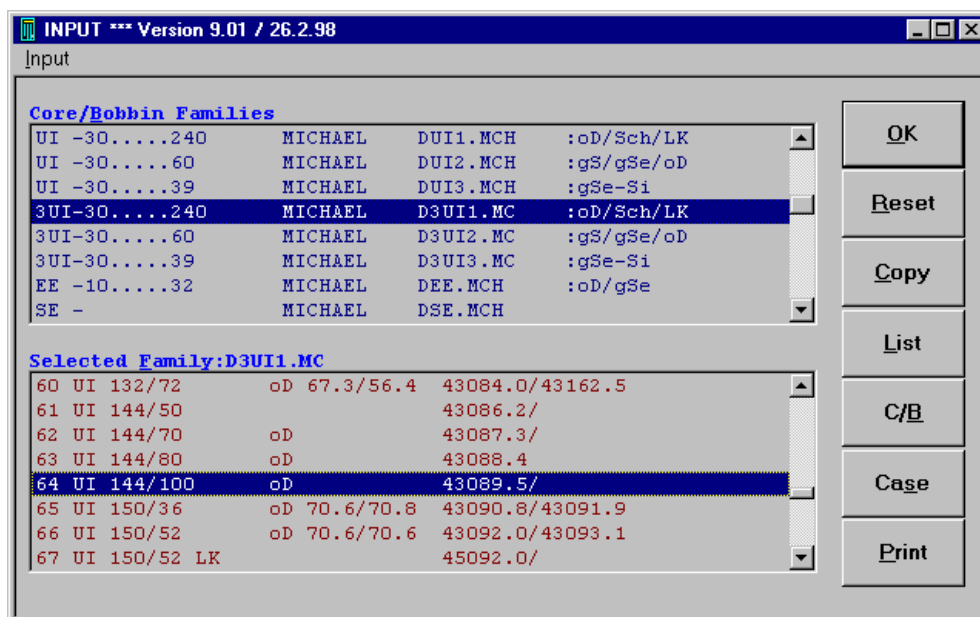
PRIMARY	U (V)	I (A)	SECONDARY
Circuit -:	4	115	145
Overvolt. *:	1.06	230	
Wire -:	0		Voltage V:
Ins/L μ:	0		Current A:
Ins/E μ:	0		
Formfactor:	1.11		Wire :
Freque. Hz:	50		Ins/L μ:
dI/Io %:	100		Ins/E μ:

MASK								
Regulation %:	50	Steel	-:	3	Cooling *:	1	Bobbin -:	1
Udiodide V:	0.8	Induction	T:	1.6	Force m/s:	0	P/S-Order -:	1
dUdiodide V:	.05	Remanence	*:	.05	Bracket -:	2	Rac/Rdc *:	1.05
Ripple %:	5	W/kg	*:	1	Radiator -:	0	Space *:	.9
Temp. Amb. °C:	40	VAR/kg	*:	1		0	Vertical -:	1
Temp. rise °K:	75	Gap	*:	250	Channel cm:	0	Horizontal -:	1
Time 1 Min:	0.16	Annealed	-:	0	Cu-Surface *:	1	Impregnation -:	2
Load 1 *:	1.8	Stacking	*:	1	Rth-varnish *:	1	Spread %:	0
Time 2 Min:	10	Hole	-:	1	Rth-compoun. *:	1	Selection -:	0
Load 2 *:	0	Assembly	-:	2	Case -:	0	Criterion -:	2

DEII.MP AUTO STEEL2.DAT V530-50A Min: 1 Max: 5

3. Checking of the input data follows this.

- The **Selection** input field is set at **0**. This means that the program should search on-line for a suitable core for this application, from your selected core family.
 - The primary **Circuit** is set to **4** for the star connection of the windings. The **Overtoltage = 1.06** means that the prescribed temperature rise of **75°K** must not be exceeded at the **6%** overtoltage of the primary voltage.
 - Note that the core can be provided with one gap per limb if the core assembly is set to value 2. In order to get the value of the no-load input current approx. 50% of the autotransformer nominal current the core is constructed with a defined gap of 6.25 mm (**Gap = 250 x 0.025mm= 6.25mm**).
 - The inputs **Time1 = 0.166** minutes / **Load1 = 1.8** / **Time2 = 10** minutes / **Load2 = 0** describe the motor starting operation.
4. Save your input data file. In this specimen design calculation, we saved the input data in input data file **CAL0013E.TK1**. This input data file was supplied together with this document. Copy it into the directory in which your Rale demo program is installed.
 5. Connect up to the Rale design server.
 6. Load up your input data file.
 7. Now select the three-phase core family and (optional) the core from which a suitable core is to be searched by the computer program.



8. Click on **OK**.
9. Start your design work. In the system for automatic selection of the core from your prescribed core family, the program will offer you an adequately sized core for your application. Click on OK in order to accept the core.

OUTPUT *** Version 9.01 / 26.2.98

Input Material Run Output Edit Options Help

Name : 3XUI 144/100 oD
 Steel : U530-50A / .5

| A | B | A | B | A | | D | |

Weight gr:32643.
 Gap total cm:0.000
 A-Limb cm:4.80
 B-Width cm:4.80
 C-Height cm:14.40
 D-Stack cm:9.98
 E-Yoke 1 cm:4.80
 F-Yoke 2 cm:4.80
 G-Hole cm:1.099
 Radiator Fin :0
 Radiator Chan. :0

with two bobbins

| a1 | | d1 | |

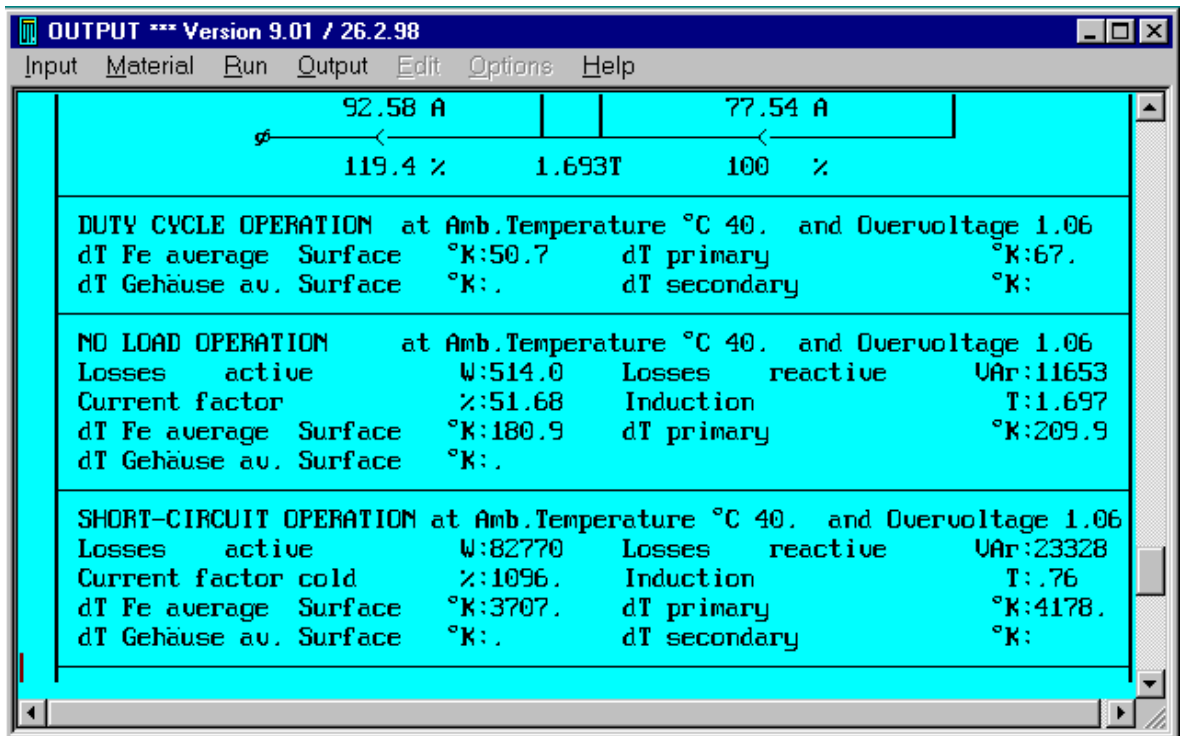
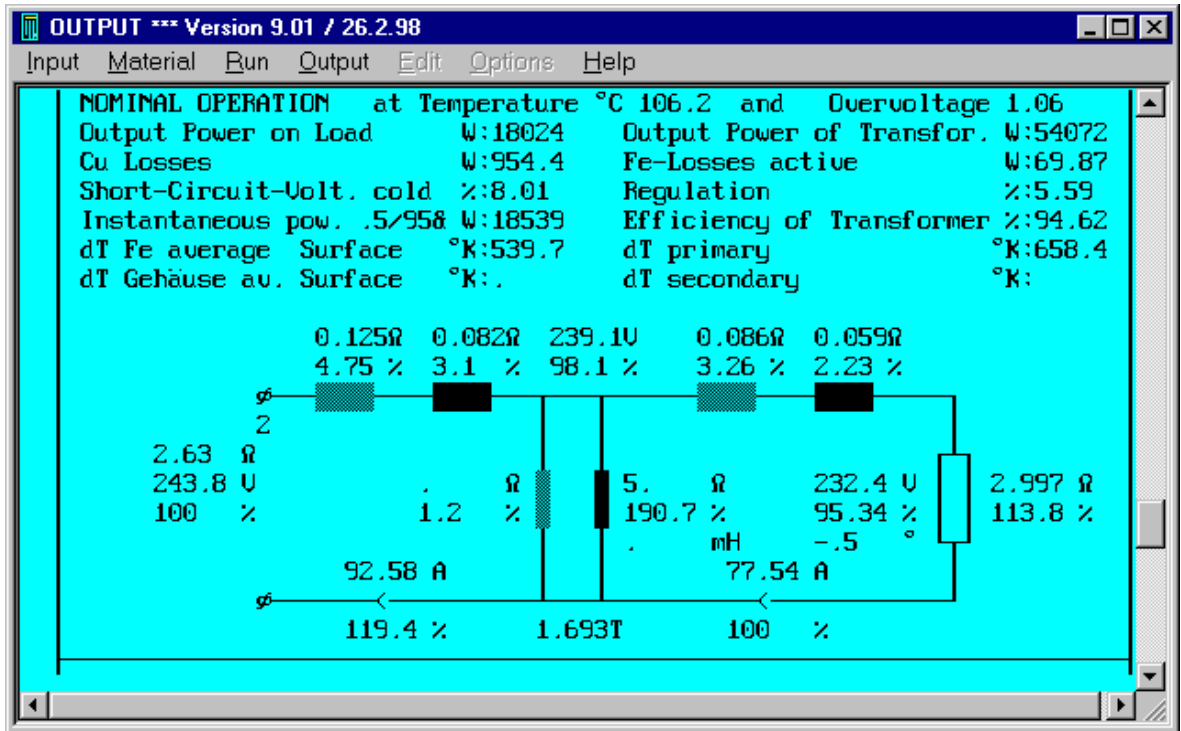
| a2 | | d2 | |

a1 cm:5.33
 a2 cm:9.46
 d1 cm 10.46
 d2 cm 16.32
 l cm:13.68
 lp cm:

OUTPUT *** Version 9.01 / 26.2.98

Input Material Run Output Edit Options Help

	Typ	Turns	T	WG	WG	Par	W/∅ mm	H/∅ mm	T/L	L	I/L μ	I/E μ	Weight gr	RWH %
1	1	71.9	0	103.	13.0	1	3.35	3.35	38	1.91	.	.	1898.6	37.
2	1	136.9	0	104.	14.0	1	3.55	3.55	35	1.84	.	.	2211.7	40.
3														
4														
5														
6														
7														
8														
1														
2														
3														
4														
5														
6														
7														
8														



OUTPUT *** Version 9.01 / 26.2.98					
Input Material Run Output Edit Options Help					
Losses active	W:	82770	Losses reactive	UAr:	23328
Current factor cold	z:	1096.	Induction	T:	.76
dT Fe average Surface	°K:	3707.	dT primary	°K:	4178.
dT Gehäuse av. Surface	°K:	.	dT secondary	°K:	.
PRIMARY (Tap:2) 1---- 2---- 3---- 4---- 5---- 6---- 7---- 8----					
Voltage Input/Output	U:	123.1 243.8			
Out. Voltage no load	U:	128.			
Current Input/Output	A:	146.4 92.58			
Current in segment	A:	82.14 92.58			
Icc-Current cold	A:	1907. 1015.			
Io -Current	A:	47.84			
Inrush Current peak	^A:	471.0			
Inrush Current rms	A:	224.0			
Cu-Losses	W:	954.5			
Resistance cold	Ω:	.0486 .0936			
Reactance	Ω:	.0404 .0816			
Eddy-Current Factor	:	1. 1.			
SECONDARY 1---- 2---- 3---- 4---- 5---- 6---- 7---- 8----					

10. Checking of the design data follows this.

- We now check the winding data and the filling factor ($78.4 < 100\%$).
- The maximum temperature of the windings is $40^{\circ}\text{C} + 67^{\circ}\text{K} = 107^{\circ}\text{C} < 115^{\circ}\text{C}$
- No-Load temperature rise is 209.9°K : **NO-LOAD OPERATION is not allowed!**
- The windings' wire size calculated by the program is not optimized for production. In the test program, only one-wire size with the diameter 3.55mm should be employed.

11. This is followed by checking of the output voltage at the nominal input voltage of 243V: $U_{in} = 1.06$

TEST *** Version 9.01 / 26.2.98										
Input Material Run Output Edit Options Help										
PRIMARY										
	1	2	3	4	5	6	7	8	FormFact.:	1.11
Turns :	71.9	136.9							U input *:	1.06
Family :	0								FREQ. Hz:	50
Number :	104	104							T amb. °C:	40.0
Parallel :	1	1							t1 on Min:	0.16
Ins/L μ:	0.0								Load 1 *:	1.80
Load	0.793								t2 on Min:	10.0
f-thic mm:	3.55	3.55							Load 2 *:	0.00
f-wide mm:	3.55	3.55							STEEL -:	3
Layers :	2.03	1.84							Margin cm:	0.36
SECONDARY										
	1	2	3	4	5	6	7	8	Case -:	0
Turns :									Tap -:	2
Family :									RWH %:	80.9
Number :									dT-rise°K:	66.1
Parallel :									dU %:	5.6
Ins/L μ:									IO %:	51.69
Load s. O:									I1^/In^:	3.2
f-thic mm:									P Fe W:	69.31
f-wide mm:									P Cu W:	952.59
Layers :									Bn T:	1.684
U sec V:									BO T:	1.694
UD sec V:									Br T:	.084

12. Checking of the design data follows this.

We now check the winding data and the filling factor (80.9<100%).

The maximum temperature of the windings is $40^{\circ}\text{C}+66.1^{\circ}\text{K} = 106.1^{\circ}\text{C} < 115^{\circ}\text{C}$

13. If the design data is not satisfactory, then there are two ways by which implement the desired correction:

- You can return to the input mask (function key F2) correct the input data and redesign the transformer.
- Or you can access the test program (function key F5), modify the designed transformer manually and redesign the transformer by that means.
- On completion of the design work, you can print out the design data on-line, or save it on your local PC and print it out off-line. The output data file from this design example; **CAL0013E.TK2** is supplied together with this document. Copy it into the directory in which your Rale demo program is installed.

Tips&Tricks

Mechanical stress of the windings

The following simple calculation has to show that the mechanical stress (N/m²) is smaller than the critical value for Cu 1.18e+8 N/m² and it is no criteria for design of a motor starting autotransformer in the power range up to 100kVA of the nominal motor power. Because of this there is no reason to discuss about to high current density and how big it must be.

$$\text{Stress} = \mu_0 * I_{cc}^2 * W * s / (4 * h * q) = 3.8e+6 \lll 1.18e+8 \text{ (N/m}^2\text{)}$$

Where:

- $\mu_0 = 12.56 \text{ e-7 H/m}$
- $I_{cc} = 1900\text{A}$
- $W = 72 \text{ turns}$
- $s = 0.08\text{m stack}$
- $h = 0.18\text{m height of the winding}$
- $q = 9.61 \text{ e-6 Cu-cross section of the wire}$

Autotransformer for ventilator motor

This autotransformer has one input voltage and between 4 and 8 output voltage s (taps) for control of the output power of the ventilator motor. The typical input for this autotransformer is:

Input voltage	Nominal net voltage
Output voltage	The tap near to 50% of the nominal motor voltage
Output current (if not prescribed by customer)	80% of the nominal motor current

Operation	Continuos
Wire size	Only one wire size
Taps	The taps can be recalculated by hand or in the test mode

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