Designing inherently short-circuit-proof, potted safety transformers up to 10VA with Rale Design system, in accordance with IEC 61558

Short summary

Important conditions and parameters are isolated for the calculation of inherently short-circuit proof transformers in accordance with IEC61558. In addition, the complete winding data 9, for inherently short-circuit proof transformers are provided.
Normally the primary coil is placed in the larger section of a double-section bobbin. This technical **innovation** is the transfer of the primary coil into the small chamber, with which the core power of the cores EI30/5 and EI30/10.5 can be increased by 15%.
The inherently short-circuit proof transformers above 5VA are normally implemented with the magnetic shunt. An alternative is to apply the "long" EI cores with a double-section bobbin and keeping the operation induction lower than 1T.

In the beginning…

Thirty years ago, designers performed the calculations for transformers on their pocket calculators. Designers had to pencil all the input and output fields into a form and then feed them into the calculator. Today, they can forget the pencil, but they need to enter the figures into spread-sheet programs such as Excel and Lotus 123.

Once the first affordable 8-bit computer became available in 1978, professionals could begin to develop programs for designing transformers and inductors. This development work moved in two directions:

First, companies developed their own computer programs to meet their own specific requirements. These usually used algorithms and experience that were already available. Once an acceptable level had been reached to meet the company's needs, both in terms of technical capability and ease of use, further development ceased.

Secondly, small companies began to develop professional computer programs which were sold or leased to the manufacturers of transformers and inductors.

With the aid of continuous input from the various manufacturers, they were able to develop universal, powerful, easy-to-use tools for use throughout the industry.

Designing with the Rale Design System

The Rale Design system automatically calculates designs for transformers and inductors. Consequently, its database incorporates all the necessary materials including cores, bobbins, wires, steels, etc. in both metric and USA units. This database is totally user-expandable. To use the programs, Designers need only a basic knowledge of transformers or inductors and their operation mode. Designers do not need to use any complicated formulas; they only need to follow two simple phases:

The user normally loads a template-input file from the library and only needs to fill in the input mask with the global parameters (voltage, current, temperature rise, regulation, etc.) and run the program.
Once the program has finished the design work, the user can switch to Test Mode and make manual changes to the parameters of the designed transformer (turns, wire sizes, steel, ...), and run the program in order to redesign it. During this stage the user can also test his design, changing the input voltage, frequency, load, duty cycle, etc.

Design criteria of an inherently short-circuit-proof transformer

IEC 61558

A transformer which is inherently short-circuit-proof as per IEC 61558 is not equipped with any protection. The procedure for designing and testing these transformers is set out in paragraphs **14.2, 15.1** and **15.3**:

1. First the transformer is connected to the rated supply voltage and loaded with an impedance which would give rated output current at rated output voltage, and then the supply voltage is increased by 6%. Following this increase in voltage, no change is made in the circuit until the permanent-operating temperature is reached. In this context, the temperature of the windings must not exceed the value of **θnom** (see the table below).
2. Immediately after this test all secondary windings are short-circuited and operated at 1.06 times the input voltage until the permanent operating temperature is reached. In this context, it is important that the temperature of the windings should not exceed the values **θcc** laid down in the following table.

Insulation class	A	E	B	F	H
Max. winding temperature **θcc** in short-circuit operating mode (°C)	150	165	175	190	210
Max. winding temperature **θnom** in nominal operating mode (°C)	100	115	120	140	165

Normally short-circuit operation governs the design of an inherently short-circuit proof transformer. The prescribed temperature is realised in the short-circuit operation by the delimitation of the short-circuit current with a very high short-circuit voltage from 25 to 50%. Additionally, the cooling of these transformers is increased by potting with a thermally-effective compound into the case. It should also be mentioned that all these transformers (for safety reasons with reference to voltage strength), must be potted.

At the lower end of the output performance up to approx. 5VA (**Pisc**), the short-circuit current is limited exclusively by the ohm resistance of the windings. The temperature of these transformers during nominal operation is **under** the max. temperature of the insulation class

θnom and the short-circuit temperature is just under **θcc**. During the power **Pisc** both the rating temperature and the short-circuit temperature lay marginally below **θnom** & **θcc.**
Above the power **Pisc**, the inductive resistance of the windings must be activated for assistance. For this purpose one uses:

- long EI-core
- square iron cross-section
- Double-section bobbin
- low induction

Insulation class

In these output ranges, the bobbins, the case and the potting compound are employed exclusively together with insulation class E and **B**. Wire insulation and insulation foils are very often employed in insulation class **F**.

Ambient temperature

Normally, the transformer is operated in an environment where the temperature is between 40°C and 70°C.

Case and Chassis

For safety reasons, inherently short-circuit proof safety transformers are almost exclusively potted in a vacuum within a case (Fig.1) and are intended exclusively for the printed board.
The main advantages of a potted transformer are:

The transformer is cooled better.
You can use a bobbin with thin walls and small leakage paths, but with a larger winding space.

You can use a ready core (Fig. 2), from the Waasner Company Forchheim, Germany, and using a special device assemble up to 1000 ready cores per hour with the coil.

In order to have good thermal contact with the print (Fig. 1), the transformer needs to be "fully" potted so that the air gap between the compound and the print is maximum 0.2 –0.5 mm.

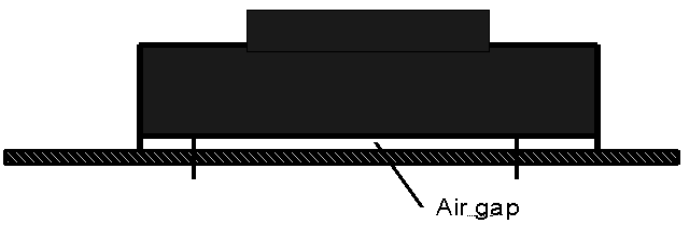


Fig. 1

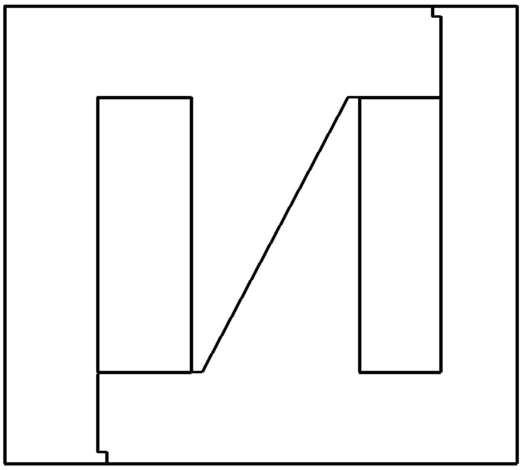


Fig. 2

During construction (Fig. 3) only the coil under pressure is sprayed with polyester. Production costs for this construction are lower than in the case of a potted housing. It must be mentioned, however, that from a thermal standpoint, it is less effective, and is not suitable for use with very thin wires and the ready core.

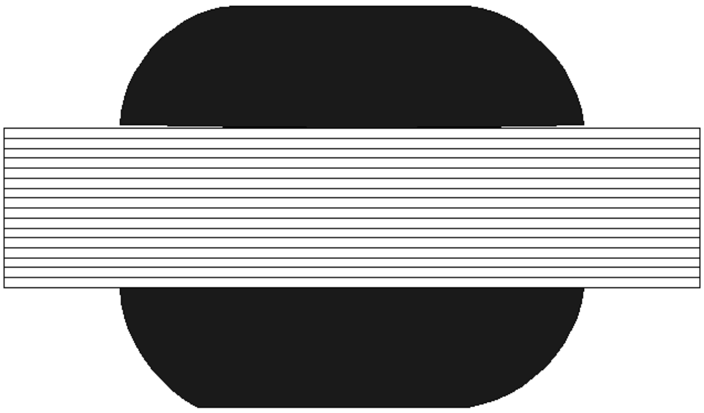


Fig. 3

Thermal resistance of the potting compound

The potting compound which is best from a thermal viewpoint, but is also the most expensive, has a specific thermal conductivity of 0.8W/m/°K. In practice, we usually operate with a potting compound whose thermal conductivity is 0.40-0.55/W/m/°K.

Bobbins

In this output power range, recourse is made almost exclusively to a double-section bobbin. From the viewpoint of design, only the dimensions of the bobbin are important. A bobbin with increased insulation or large leakage paths has a smaller winding space and a smaller cooling surface area.

Normally the double-section bobbin has two unequal chambers. The primary coil is wound exclusively into the larger chamber, so that you can use thicker or cheaper wire. **Below the output power of 2VA, you should wind the primary coil into the smaller chamber(!), which boosts the core power of the core to 15%. Above the power output of 2VA, the chamber distribution should be equal.**

Steel

In nominal operating mode, at full core losses, the temperature rise of the transformers is approx. 30°K to 50°K. The relationship between the copper and iron losses is normally between 5 and 10. In short-circuit mode, in which the magnitude of the temperature rise is extremely relevant, iron losses are practically negligible. For that reason, the optimal steel is the cheapest cold-rolled steel 8.0 W/kg (@ 1.5T and 50Hz). And furthermore, the cheapest cold-rolled steel has the highest saturation induction!

Induction T	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
W/kg	0.45	0.95	1.51	2.35	3.47	4.38	5.50	8.79	11.2	12.4
VAr/kg	0.40	1.17	1.83	2.79	4.00	5.64	9.00	31.0	186	650

Regulation

Up to the power **Pisc**, the optimal regulation of an inherently short-circuit proof transformer amounts to 100%. This rule applies to the transformer with which the no-load operation induction is situated within the linear area of the magnetizing curve. Below the power output of 2-3VA the no-load operation induction is situated in nonlinear area of the magnetizing curve between 1.6 and 1.7T and the actual regulation amounts to less than 100%.

Induction

For an inherently short-circuit proof transformer induction selection plays an important role and has a very difficult function, this is taken over automatically by the program. It depends particularly on the core construction, output power, the insulation class and the ambient temperature, and is normally situated between 0.5T and 1.4T.

Permitted tolerance of output voltage and output current

The output voltage of a transformer, which must be inherently short-circuit proof, is tested in the hot and cold state with the nominal primary voltage and the nominal load resistance. In this context, it must not deviate by more than +-10% from the nominal value.

Procedure for design

The inherently short-circuit-proof is made by using only laminations EI30, EI38, EI38-long and EI48-long. The decision regarding the choice of core sizes is made mainly in relation to output power, ambient temperature, and the insulation class. Thanks to this relatively small number of variants, for 10 output powers in insulation class B and ambient temperatures of 40 ° C , it was possible to record approximately 20 input files to serve as an aid to making entries into the Rale Design Systems library.

The calculation example shown below explains the calculation procedure in brief.

Technical specification relevant only to design

Electrical data

Input voltage	230Vac, -10%, +6%
Frequent	50/60HZ
Nominal output power	0.75VA
Nominal output voltage	6Vac, calculated by –8% = 5.55Vac
Nominal output current	0.125A, calculated by –8% = 0.115Aac

Environment and operating conditions:

Ambient temperature	40°C
Mode of operation	Continuous

Specification

Safety transformer as per IEC 61558
Insulation class B
Potted in case, compound 0.55 W/m/°K
Core and bobbin EI30, stack 5mm, steel M800 (8.W/kg at 1,5T/50Hz)

The above-stated parameters are stored mainly in the ISCP_075VA_6V_T40.TK1 input file.

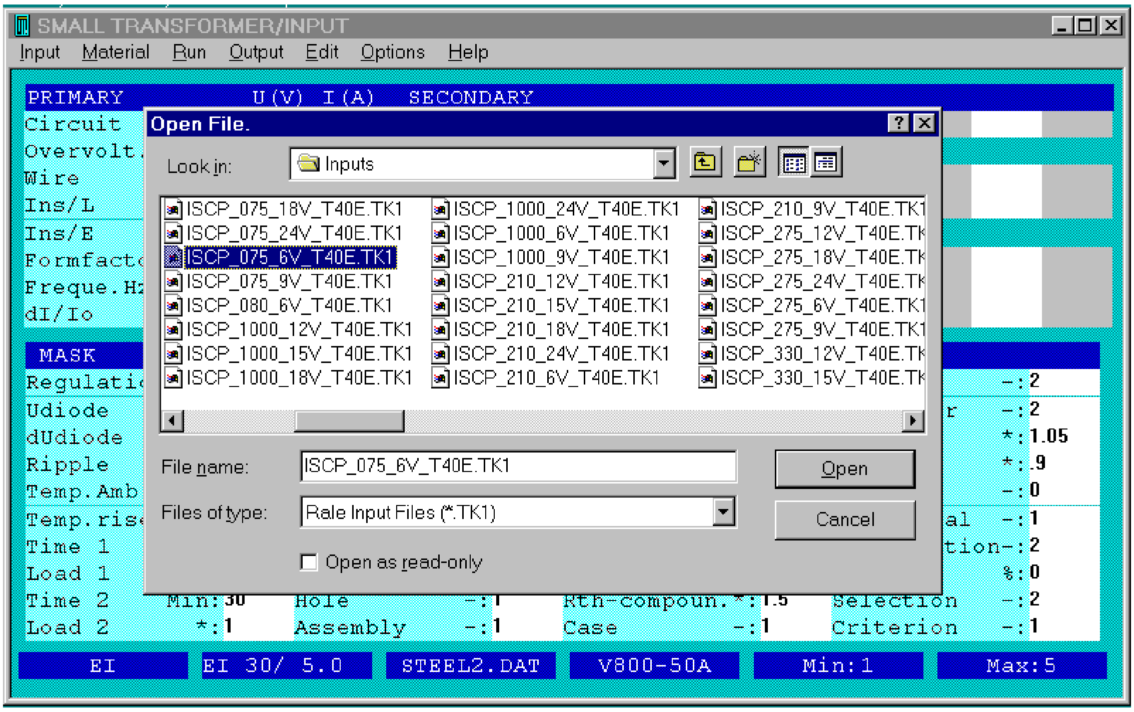


Fig. 4

After loading the input file you normally have to change the input voltage, output voltages and the output currents. If you need help, then press function key F1. For each input field, there is extensive description

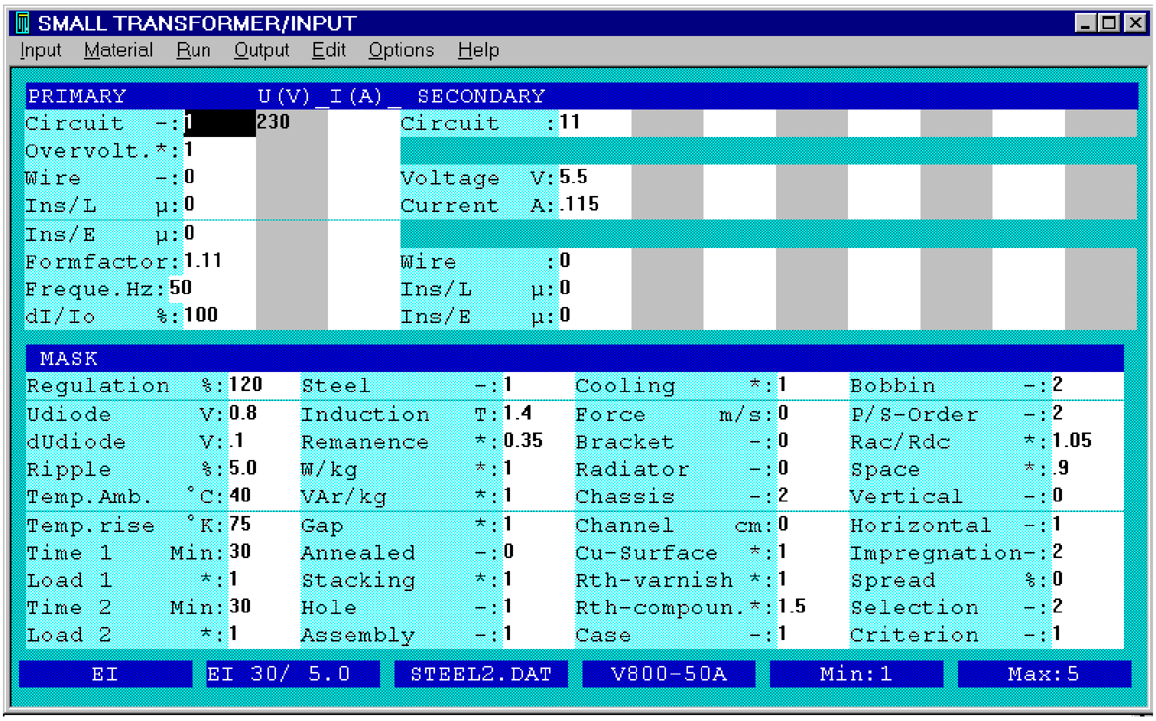


Fig. 5

This is a brief description of the input mask illustrated above:

One secondary coil is designed for 5.55V, 0.115A, in warm conditions, at an input voltage of 230 V, 50 Hz.
The transformer is fed at an ambient temperature of 40 degrees C (Amb. Temp. = 40) first of all under nominal voltage (overvoltage = 1.0) .
The core EI 30/5.0 of V800-50A steel (Steel = 1) has one double section bobbin (Bobbin = 2) and is potted in a case (Case = 1) with a compound of 0.55W/K/m (Rth-compound=1.5). The transformer is placed on a printed board (Chassis = 2).

Note that you can select the core and bobbin with the case. If the record for the core and bobbin which you have selected has no case, then you have to set up the case yourself. The core selected in the following illustration has a case in its record. For this reason, it is enough to mark the core EI 30/5.0 and to click on the **OK** button.

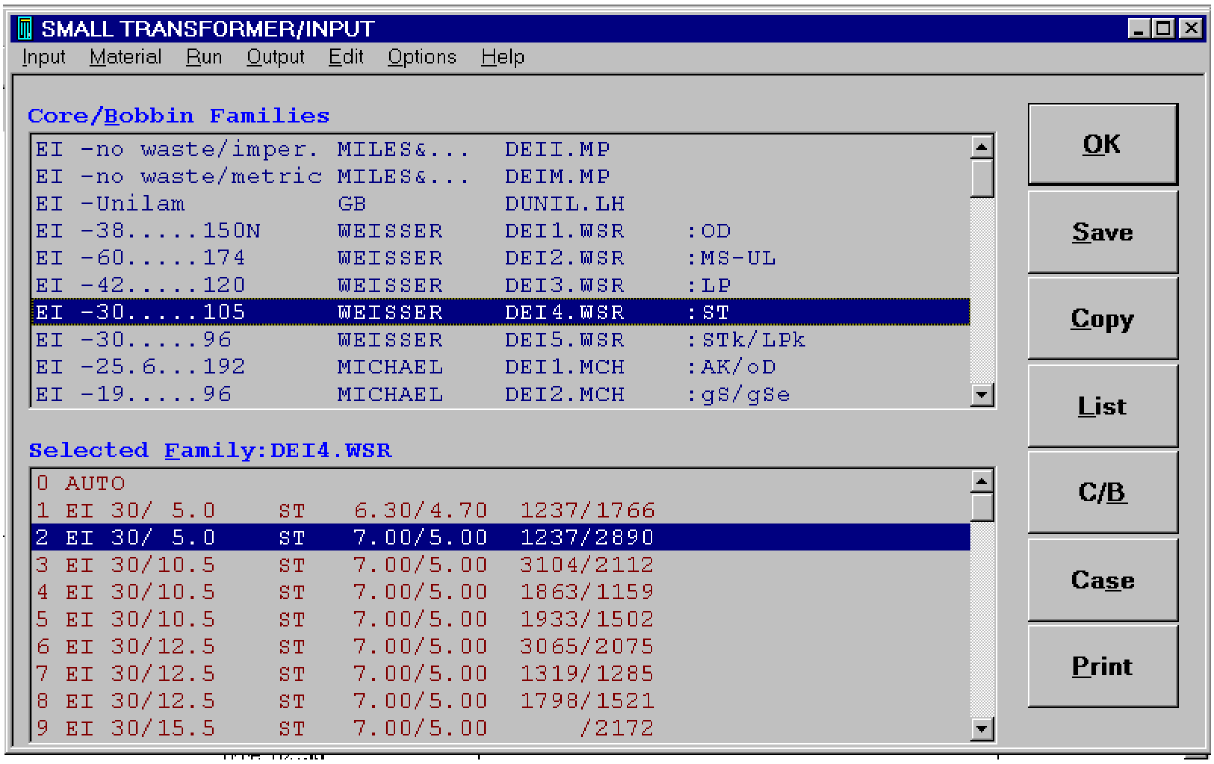


Fig. 6

After the design procedure has been completed, the following design data is available and can be printed on 3 pages.

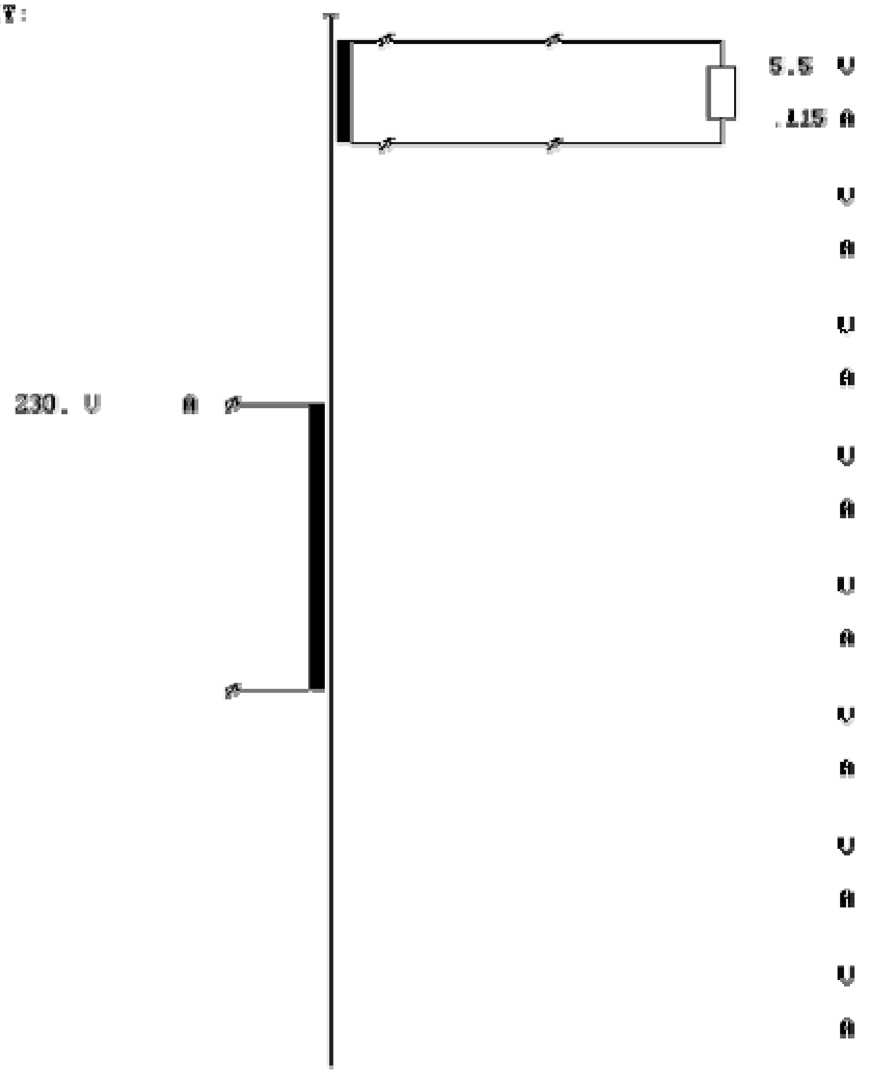
04-13-2000/20:55:58	Input and Circuit	Page 1

PRIMARY	U(V)	I(A)
Circuit- :1	230.	
Overvlt* :1.00	.	
Wire :0.0	.	
I/L. μ:0.	.	
I/E. μ:0.	.	
Formfac. :1.11	.	
Fre.Hz:50	.	
dI/Io %:100	.	

SECOND.	1	2	3	4	5	6	7	8
Circuit-	:11							
Volta. V	:5.5							
Curre. A	:.115							
Wire	:0							
I/L μ	:0.0							
I/E μ	:0.0							

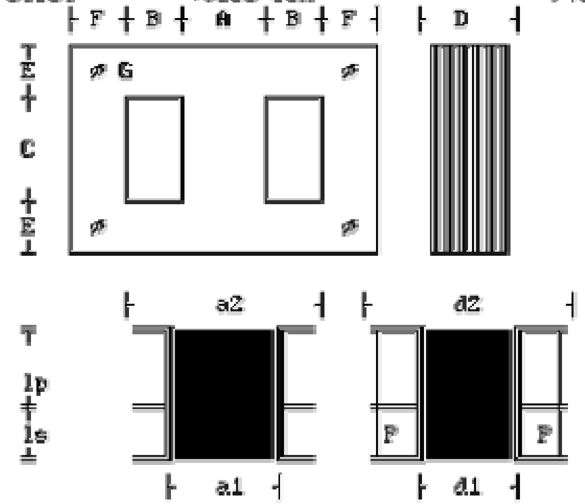
Regulat.	%:120.0	Steel	-:1	Cooling	*:1.00	Bobbin	-:2
Udiode	V:0.8	Induction	T:1.29	Force	m/s:0.00	F/S-Order	-:2
dUdiode	V:.1	Remanence	*:0.35	Bracket	-:0	Rac/Rdc	*:1.05
Ripple	%:5.	W/kg	*:1.00	Radiator	-:0	Space	*:0.90
Tmp. Amb.	°C:40	VAr/kg	*:1.00	Chassis	-:2.00	Vertical	-:0
Tmp.rise	°K:75	Gap	*:1.00	Channel	cm:0.00	Horizontal	-:1
Time 1	Min:30.0	Annealed	-:0	Cu-Surface	*:1.00	Impregnat.	-:2
Load 1	*:1.0	Stacking	*:1.00	Rth-varni.	*:1.00	Spread	%:0
Time 2	Min:30.0	Hole	-:1	Rth-comp.	*:1.50	Selection	-:2
Load 2	*:1.0	Assembly	-:1	Case	-:1	Criterion	-:1

CIRCUIT:



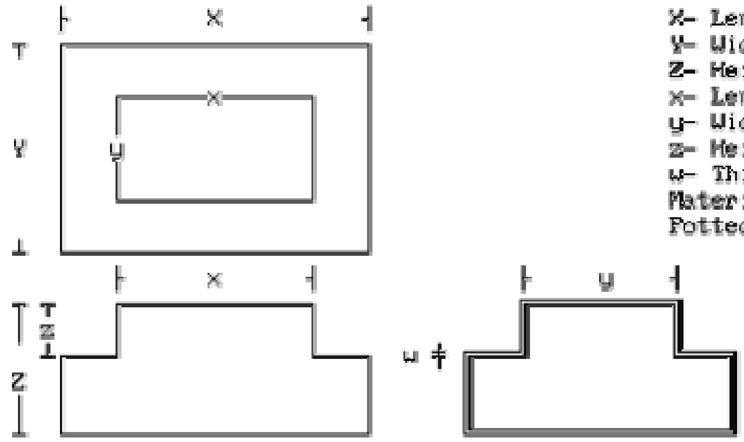
04-12-2000/20:55:58 CORE / BOBBIN / STEEL / CASE Page 2

Name :1XEI 30/ 5.0 ST 7.00/5
Steel :V800-50A /.5



Weight gr:22.7
Gap total cm:0.000
A-Limb cm:1.00
B-Width cm:0.50
C-Height cm:1.50
D-Stack cm:0.50
E-Yoke 1 cm:0.50
F-Yoke 2 cm:0.50
G-Hole cm:0.00
Radiator Fin :0
Radiator Chan. :0

a1 cm:1.20
a2 cm:1.92
d1 cm 0.68
d2 cm 1.36
l cm:
lp cm:0.70
ls cm:0.50



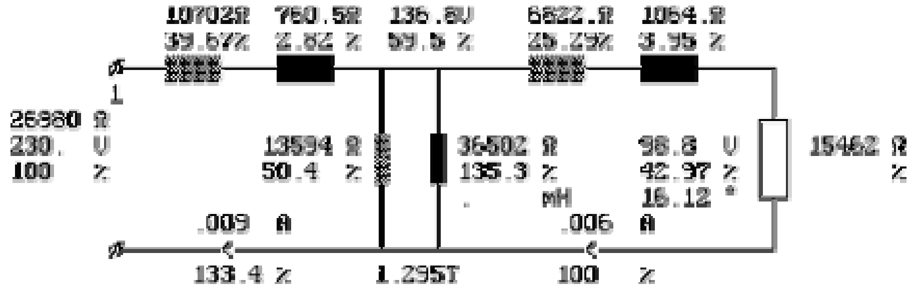
X- Length 1 cm:3.03
Y- Width 1 cm:2.53
Z- Height 1 cm:1.52
x- Length 2 cm:2.20
y- Width 2 cm:1.50
z- Height 2 cm:0.40
w- Thickness cm:0.07
Material :
Potted :

	Typ	Turns	T	WG	WG	Par	W/ø mm	M/ø mm	T/L	L	I/L μ	I/E μ	Weight gr	RWH %
1 2 3 4 5 6 7 8	1	9800.	0	16.0	16.0	1	.034	.034	116	84.79	.	.	3.712	87.
1 2 3 4 5 6 7 8	11	545.0	0	50.0	50.0	1	.18	.18	32	16.95	.	.	5.775	86.
TOTAL													9.487	87.

04-12-2000/20:55:58	General Data	Seite 3

NOMINAL OPERATION at Temperature °C 68.9 and Overvoltage 1.00

Output Power on Load	W:.63	Output Power of Transfor.	W:.63
Cu Losses	W:1.06	Fe-Losses active	W:.18
Short-Circuit-Volt. cold	%:53.47	Regulation	%:132.7
Instantaneous pow. .5/358	W:.7	Efficiency of Transformer	%:33.77
dT Fe average Surface	°K:26.7	dT primary	°K:29.8
dT Gehäuse av. Surface	°K:25.	dT secondary	°K:27.9



DUTY CYCLE OPERATION at Amb.Temperature °C 40. and Overvoltage 1.00

dT Fe average Surface	°K:26.7	dT primary	°K:29.8
dT Gehäuse av. Surface	°K:25.	dT secondary	°K:27.9

NO LOAD OPERATION at Amb.Temperature °C 40. and Overvoltage 1.00

Losses active	W:1.63	Losses reactive	VAr:1.95
Current factor	%:129.8	Induction	T:1.61
dT Fe average Surface	°K:34.1	dT primary	°K:30.3
dT Gehäuse av. Surface	°K:31.8		

SHORT-CIRCUIT OPERATION at Amb.Temperature °C 40. and Overvoltage 1.00

Losses active	W:3.63	Losses reactive	VAr:.54
Current factor cold	%:187.	Induction	T:.818
dT Fe average Surface	°K:53.2	dT primary	°K:60.7
dT Case aver. Surface	°K:49.6	dT secondary	°K:56.9

PRIMARY (Tap:1)	1----	2----	3----	4----	5----	6----	7----	8-----
Voltage Input/Output	V:230.							
Out. Voltage no load	V:							
Current Input/Output	A:0.009							
Current in segment	A:0.009							
Ico-Current cold	A:0.02							
Io -Current	A:0.011							
Inrush Current peak	^A:0.04							
Inrush Current rms	A:0.01							
Cu-Losses	W:.8							
Resistance cold	Ω:8972.							
Reactance	Ω:760.5							
Eddy-Current Factor	:1.							

SECONDARY	1----	2----	3----	4----	5----	6----	7----	8-----
Output Voltage	V:5.5							
Output Current	A:0.115							
Out. Voltage no load	V:9.5							
Sec. Voltage	V:5.5							
Sec. Current	A:0.115							
Sec. Voltage cold	V:6.							
Sec. Load	Ω:47.82							
Icc cold	A:0.27							
Cu-Losses warm	W:.279							
Resistance cold	Ω:17.80							
Reactance	Ω:3.293							
Eddy-Current Factor	:1.							
Capacitor	mF:.							

This is followed by a check of the calculated data at the input voltage 230V.

- First, we check the otput voltage 5.5V > 5.4V) in hot state and the output voltage (6.0V < 6.6V) in cold state
- Then, we check the space factors of the primary winding (87%) and of the secondary winding (86%)

Test Mode

In test mode the transformer can be checked in the same way as on a test rig, and if necessary be altered manually.

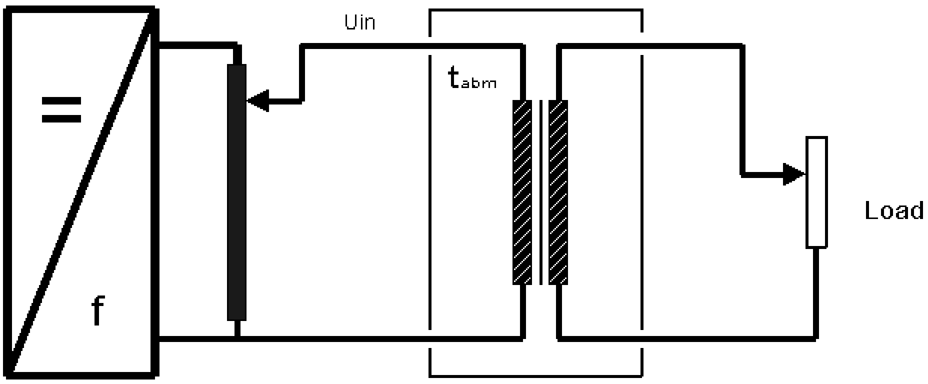


FIG. 7

In Fig 8 the transformer designed above is tested in nominal operation at the input voltage 243V (U input = 1.06).

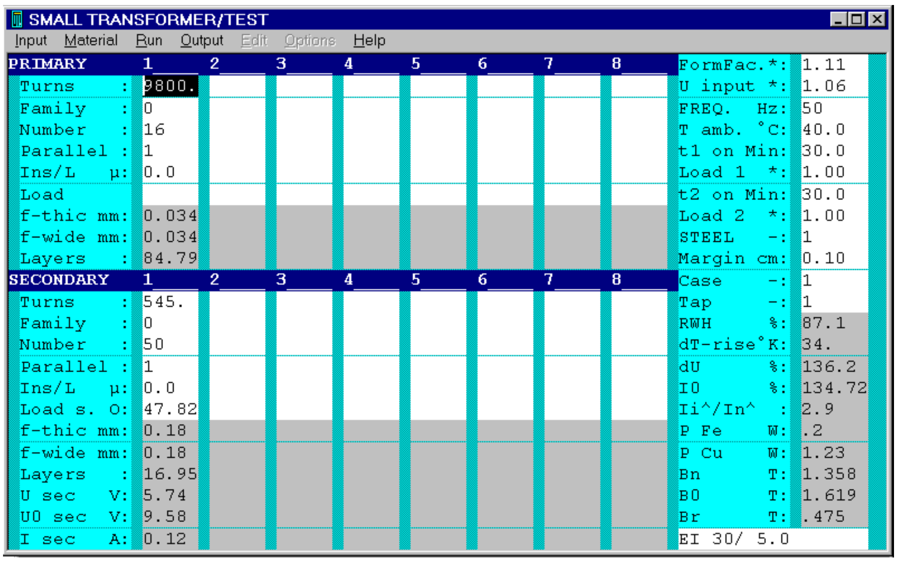


FIG. 8

This is followed by a check of the calculated data.

- First, we check the maximum winding temperature at 243Vac in nominal operating mode = ambient temperature + dTprim in nominal operating mode = 40+34 = 74 < 120°C
- Then, we check the maximum winding temperature at 243Vac in no-load operating mode = ambient temperature + dTprim in no-load operating mode = 40+48.1 = 88.1 < 120°C
- The maximum winding temperature in the short-circuit operation mode is:
  ambient temperature + dT primary = 40 + 65.9 = 105.5 < 175°C
- The mean case temperature in the test mode is:
  Ambient temperature + dT case in short-circuit operation = 40 + 53.7 = 93.7>80°C
  This means that this transformer has to be installed in a unit which cannot be touched during operation.

Technical specification common for all designs

All non-short-circuit proof transformers in the table below were calculated under the same conditions:

Input voltage : 230Vac +6%,-10%
Frequency : 50/60Hz

Steel : M800-50 (8.0W/kg @1.5T and 50Hz or better
Laminations : EI, ready core (Waasner, Germany) or alternated stacking
Bobbin : Double section bobbin (Weisser, Germany)
Insulation class : B

Ambient temperature : 40°C
Case : Potted, compound 0.55 W/m/°K or better
Chassis : Printed board on black wood-plate
Regulation : max. 100%
Build : max. 92.5%, with wire-insulation grad 1

The parameters of the designs are core size, output power, max. regulation in the nominal operation or the temperature (max. 120°K) in the nominal operating mode and the temperature in the short-circuit operating mode (max 175°K).

Core Stack Bobbin ections (mm:mm)	EI30 5.0 5:7 *	EI30 10.5 5:7 *	EI30 12.5 6:6 **	EI30 15.5 6:6 **	EI30 18 6:6 **	EI30 23 6:6 **	EI38 13.5 9.1:6.6 ***	EI38 13.5 18:18 long	EI48 17 22:22 long
Nom. Power (VA) Calculated power	0.75 0.632	2.1 1.78	2.75 2.327	3.3 2.80	3.6 3.0	4.0 3.28	4.5 3.80	6.0 5.07	10,0 .8.5
Input voltages (V) Turns Diameter (mm)	230 9800 0.034	230 5200 0.048	230 4700 0.056	230 4120 0.60	230 3760 0.060	230 3300 0.065	230 4350 0.080	230 5375 0.106	230 4700 0.14
Output nom. volt. (V) Output nom. curr. (A) Turns Diameter (mm)	6 0.133 545 0.18	6 0.35 250 0.265	6 0.46 230 0.265	6 0.55 195 0.28	6 0.60 174 0.30	6 0.66 167 0.30	6 0.75 215 0.315	6 1 194 0.56	6 1.66 172 0.75
Output nom. volt. (V) Output nom. curr. (A) Turns Diameter (mm)	9 0.088 775 0.15	9 0.233 340 0.224	9 0.305 320 0.224	9 0.366 288 0.236	9 0.4 248 0.25	9 0.44 230 0.25	9 0.50 290 0.265	9 0.66 278 0.475	9 1.11 248 0.65
Output nom. volt. (V) Output nom. curr. (A) Turns Diameter (mm)	12 0.066 1040 0.132	12 0.175 520 0.19	12 0.23 410 0.20	12 0.278 190 0.20	12 0.30 350 0.212	12 0.333 334 0.212	12 0.375 380 0.236	12 0.50 380 0.40	12 0.83 334 0.56
Output nom. volt. (V) Output nom. curr. (A) Turns Diameter (mm)	15 0.053 1250 0.118	15 0.140 600 0.17	15 0.183 550 0.17	15 0.22 492 0.18	15 0.24 432 0.19	15 0.266 400 0.19	15 0.30 520 0.20	15 0.4 470 0.355	15 0.66 416 0.50
Output nom. volt. (V) Output nom. curr. (A) Turns Diameter (mm)	18 0.044 1550 0.106	18 0.117 740 0.15	18 0.1525 630 0.16	18 0.183 576 0.17	18 0.20 546 0.17	18 0.22 510 0.17	18 0.25 580 0.19	18 0.33 550 0.335	18 0.55 500 0.45
Output nom. volt. (V) Output nom. curr. (A) Turns Diameter (mm)	24 0.033 2220 0.090	24 0.0875 1000 0.132	24 0.144 920 0.132	24 0.137 780 0.14	24 0.15 720 0.15	24 0.166 660 0.15	24 0.1875 820 0.16	24 0.25 774 28	24 0.415 666 0.40
Regulation %	<60!	<62!	<80!	<80!	<80	<100	<100	<45	<45
On-load induction at 230V (T) No-load induction at 243V	<1.40 <1.65	<1.22 <1.64	<1.25 <1.64	<1.17 <1.62	<1.10 <1.56	<0.98. <1.43	<1.06 <1.46	<0.90 <1.15	<0.67 <0.86

(T)									
No-load losses (W)	<2.2	<3.1	<2.5	<1.6	<1.5	<1.15	<0.95	<0.75	<0.85
Cu-losses (W)	<1.3	<2.2	<2.3	<2.8	<3.2	<4.1	<4.2	<2.50	<4.0
On/No-load temperature at 243V (°C)	<85 <103	<95 <115	<100 <105	<95 <75	<95 <70	<97 <60	<93 <55	<70 <50	<70 <50
Temperature in short circuit mode at 243V (°C)	<120	<160	<170	<170	<170	<170	<170	<170	<170
Efficiency %	>31	>42	>43	>46	>46	>44	>45	>63	>65
Size (mm): L W H	32 27 17	32 27 22.5	32 27 24.5	32 27 27.5	32 27 30	32 27 35	41 35 30	41 56 30	50.5 66.5 36.5
Cu-Weight (gr)	<11	<13	<14	<16	<17	<19	<29	<63	<120
Fe-Weight (gr)	23	48	56	71	82	105	98	160	300

Comments:

The calculated output voltage and calculated output current are around 8% less than their defined nominal values.
In the case of the application of the potted compound under 0.55W/m/°K,the short-circuit temperature can exceed
the admissible temperature.In this case the ambient temperature should be set lower than 40°C.

*	The primary coil of these transformers is in the small chamber.
**	The chambers of these transformers are equal
**	The primary coil of these transformers is in the larger chamber.
Long	For these transformers the window height of the core is 3 times larger than the tongue (center leg). For all other cores, it is only 1.5 times larger. The regulation of these transformers is less than 100%, because the no-load-induction lies very high.

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