Constant current transformer for airfield lighting

Base circuits

The constant current transformer (CCT) used to supply power for the airfield lighting is illustrated in figure 1. In principle, it consists of four magnetic components L1L2, T, Lsrc and L3, the resonance capacitor C and 2 anti-parallel wired SCR thyristors. The output of the constant current transformer is loaded with the variable load impedance Z.
In nominal operation mode the inductance L1 is in resonance operation mode with the capacitor C and supplying the maximum constant current through load Z. This output current is "impressed" and does not depend on the size of the load impedance Z. When the SCR controller is switched on, the Lscr inductance and the C capacity are switched on in parallel and resonance mode is interrupted. This controls the amount of output current Iout within a certain area.

At 3-times mains frequency, inductance L3 is in resonance with capacity C and derives the third current harmonic from the constant current transformer.

Transformer T is used to adjust the voltages. Figure 2 shows a version of the constant current transformer illustrating the transformer's combined primary winding and the L1 winding for the L1L2 choke. For design reasons, the laminations for transformer T and choke L1L2 must be identical which always results in higher material costs. To this must be added the extra costs for fitting a common winding. However, when supplying power at several input voltages, only one set of connection terminals is required.

To optimise the size of the Lscr choke, it is possible to provide 2-3 taps at the secondary winding.

The taps on the primary side are used to connect the various primary voltages: 208V, 240V, 347V, 400V and 480V.

Figure 3 shows the auto-transformer connection between the C winding and the load winding. This design saves on materials and it would be an advantage for constant current transformers with output power up to 15-20 kVA.

Figure 4 shows the design for a 4kVA constant current transformer (U2=U3=500V) and figure 5 shows a 1-2 k VA constant current transformer (U2=U4=225-250V).

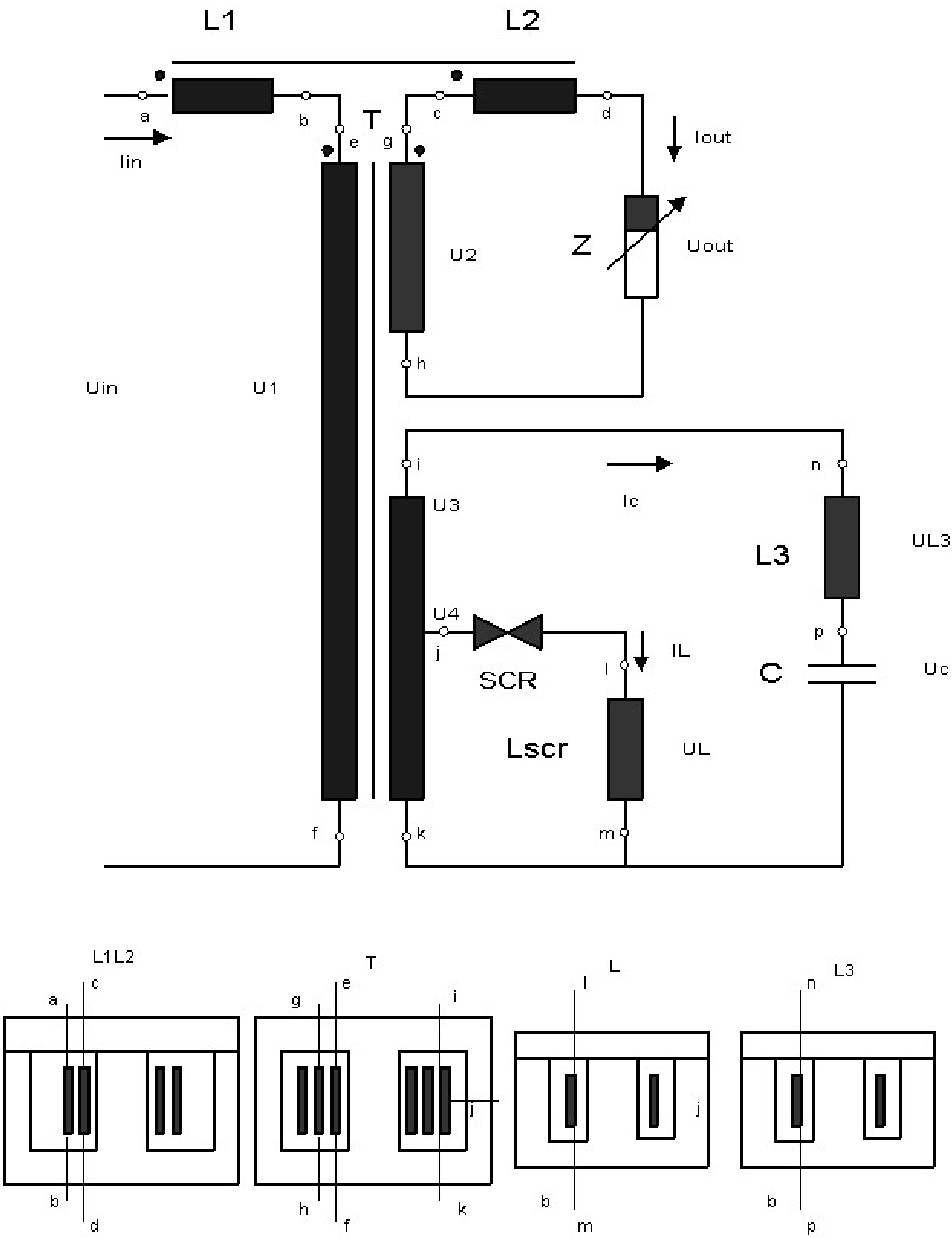
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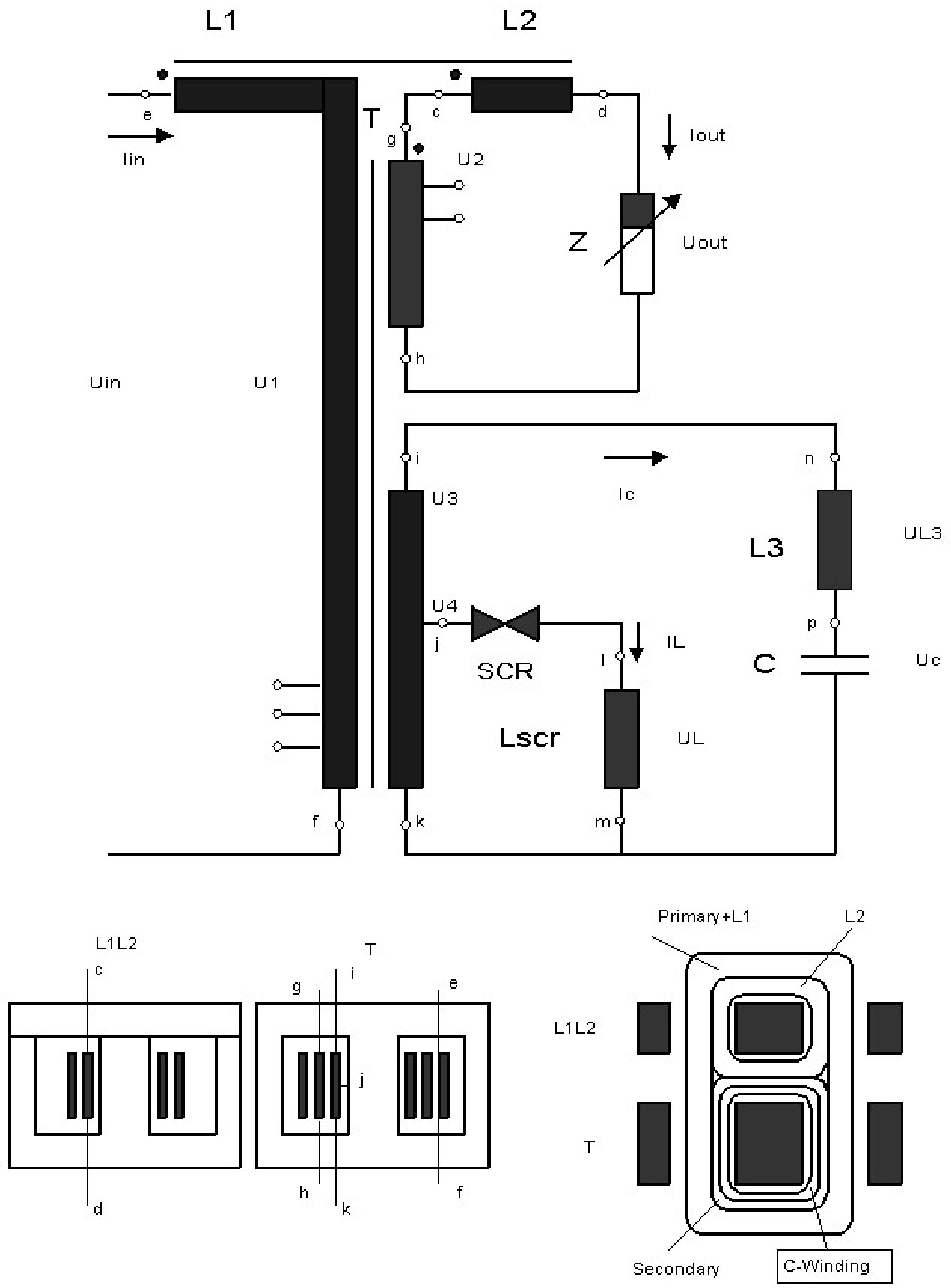
Fig. 1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Primary+L1
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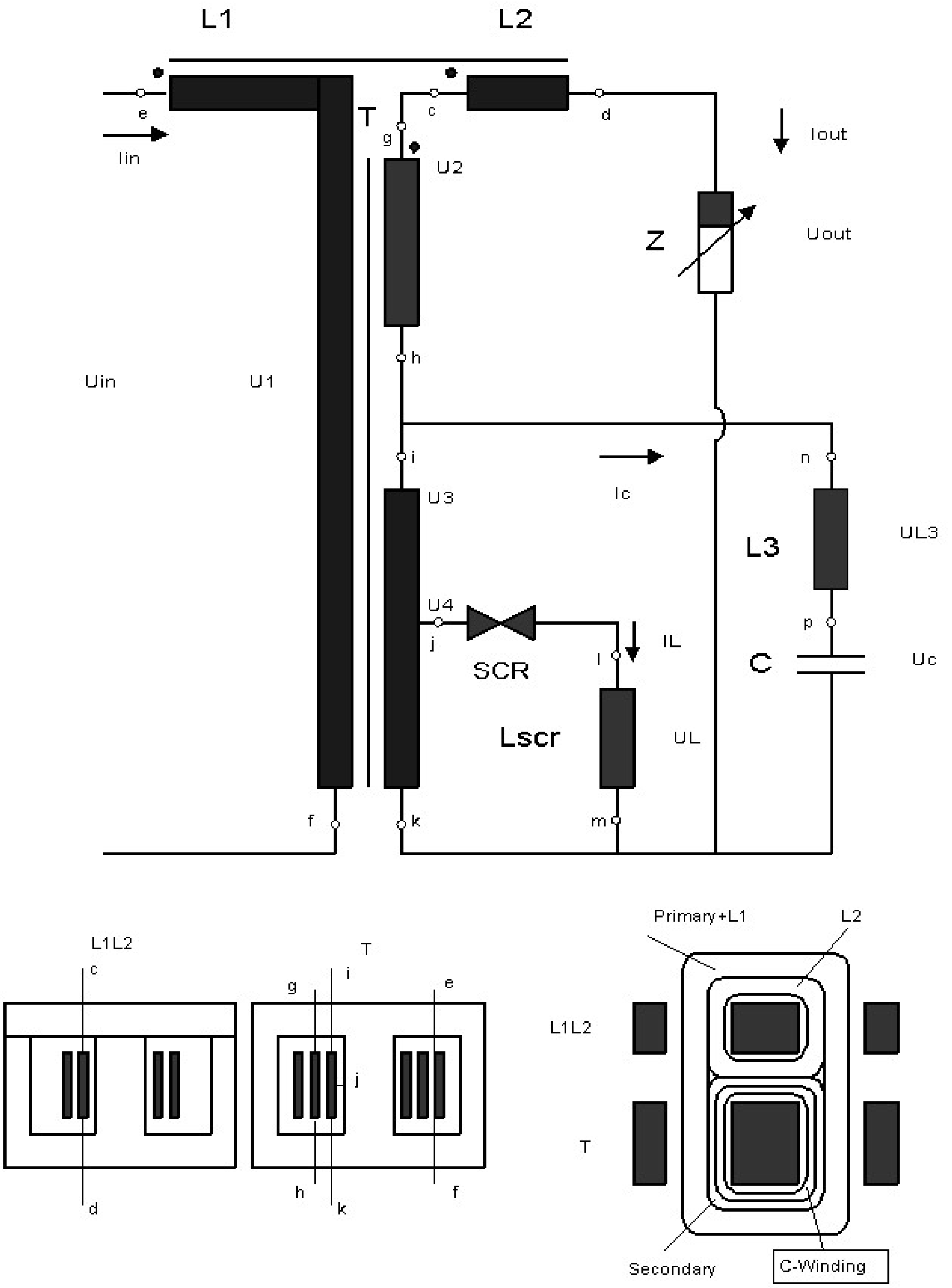
L1L2
T
Secondary
C-Winding

Fig. 2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UL3
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SCR
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IL
C
Uc
Lscr
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Primary+L1
L2
L1L2
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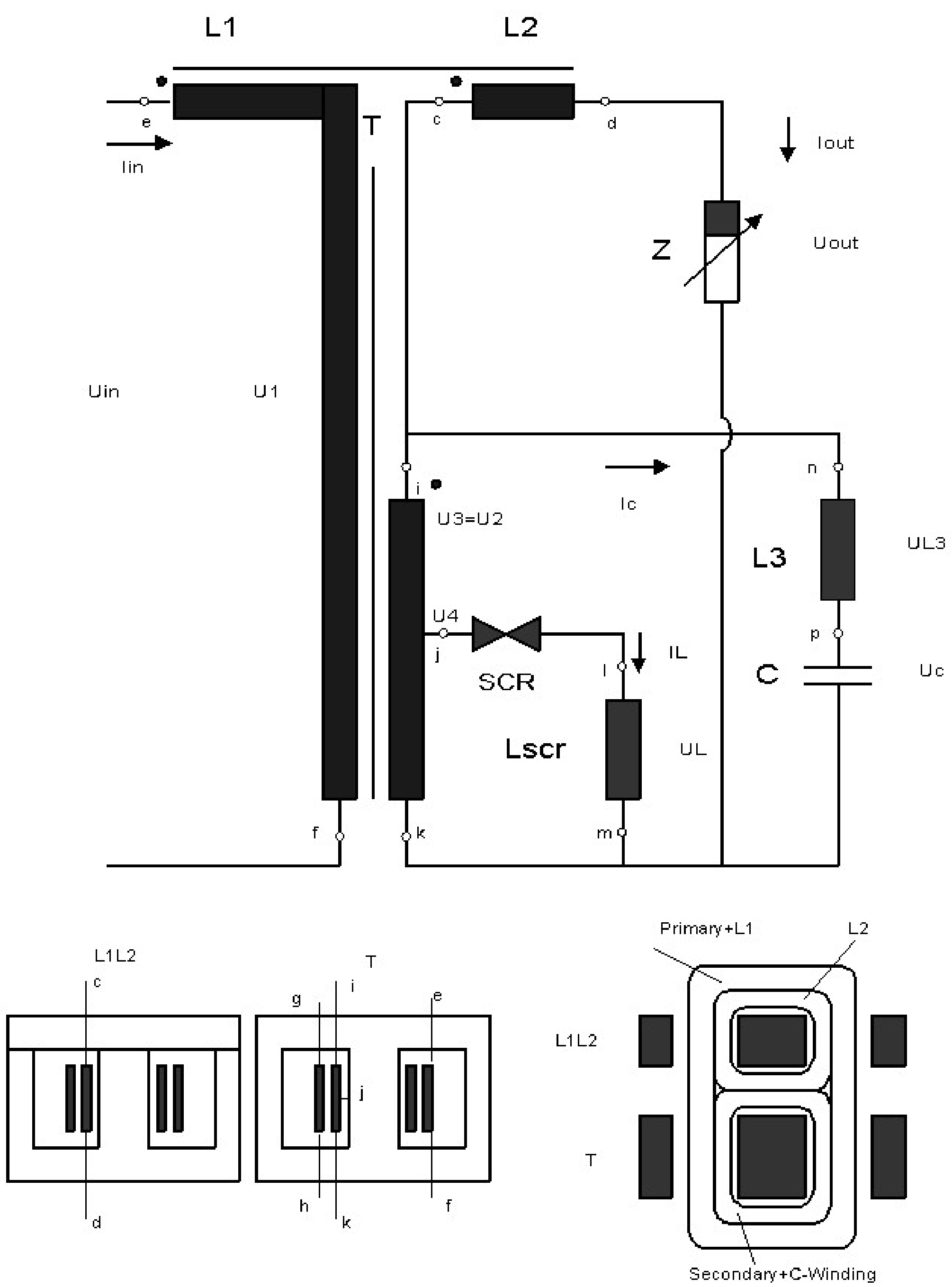
k
f
Secondary
C-Winding

Fig. 3



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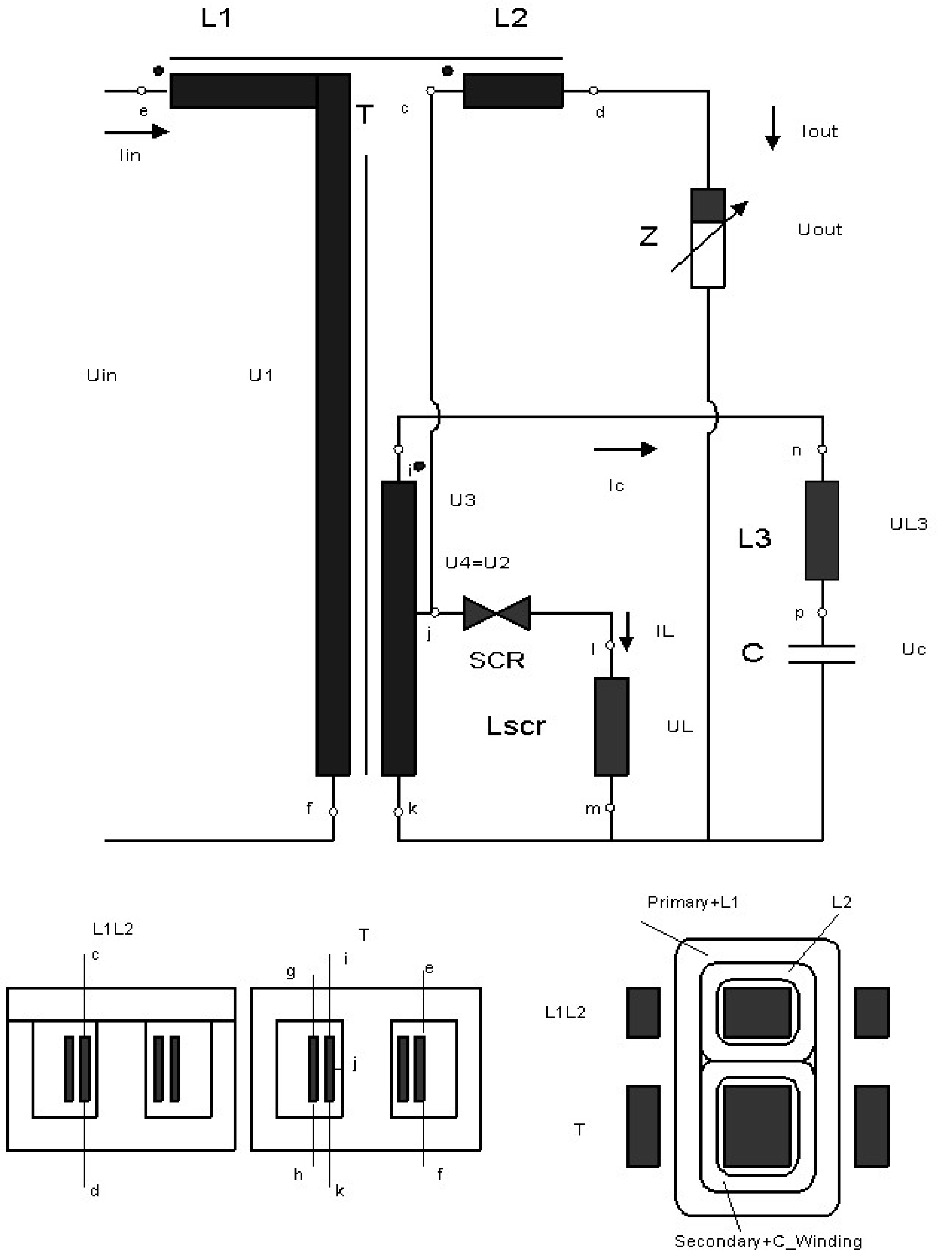
Primary+L1
L2
L1L2
T
Secondary+C-Winding

Fig. 4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UL
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m
Primary+L1
L2
L1L2
T
c
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i
e
j
L1L2
T
d
h
k
f
Secondary+C_Winding

Fig. 5

Basic circuits and basic equations

The basic circuit for a constant current transformer is shown in figure 6. The following applies:

- R1 - ohmic resistance of L1 winding and the primary winding
- R'2 ohmic resistance of L2 winding, of load winding, of C winding, of Lscr winding and of L3 winding, converted to number of turns on primary winding.
- L1 - inductance of L1 winding (when L2 winding is open) and the leakage inductance on primary winding
- L'2 - inductance of L2 winding /when L1 winding is open) and the leakage inductance on secondary winding, converted into number of turns on primary winding
- Mutual inductance of inductances L1 and L'2 : M = K*(L1*L'2)^.5
- C'e - capacity of capacitor, converted to number of turns on the primary winding
- Z' - load impedance, converted to number of turns on primary winding

The basic equations now read as follows:

- $\mathbf{Uin = R1*\underline{Iin} + j\omega L1*\underline{Iin} + j\omega M*\underline{I'out} - j/(\omega C'e)*\underline{I'ce}}$ **(1)**
- $\mathbf{Uin = R1*\underline{Iin} + j\omega L1*\underline{Iin} + j\omega M*\underline{I'out} + j\omega L'2*\underline{I'out} + j\omega M*\underline{Iin} + (R'2+\underline{Z'})*\underline{I'out}}$ **(2)**
- $\mathbf{\underline{Iin} = \underline{I'out} + \underline{I'ce}}$ **(3)**

where:

The underlined parameters are the complex variables, referred to the input voltage Uin.

M = K*(L1*L'2)^0.5
K => factor of the mutual inductance (0.90 - 0.95)
ω = 2*π"f
j = (-1)^0.5
f => mains frequency (50/60Hz)

The calculation is made as follows:

$$\mathbf{\underline{I'out} = Uin*j(\omega M+1/\omega/C'e)/[\, j(\omega M+1/\omega/C'e)*(R1+j\omega L1+ j\omega M) - (R'2+Z'+ j(\omega L'2+1/\omega/C'e))*(R1+j\,\omega L1-j/\,\omega/C'e)]} \quad \mathbf{(4)}$$

Once the following simplifications have been made, the load current I'out is calculated as follows

R1 = R'2 = r
L1 = L'2 = L
M = K*(L1*L'2)^0.5 = K*L

$\omega L1 = \omega * L = 1/\omega/C'e$
$Q = \omega * L/r$

$\underline{I'out}$ = -jUin*Q*(K+1)/[r*Q²*(K+1)² + $\underline{Z'}$ - jr*Q(K+1)] **(5)**

$$\underline{I'out} = -jUin*Q*(K+1)/[r*Q^2*(K+1)^2 + \underline{Z'} - jr*Q(K+1)] \quad (5)$$

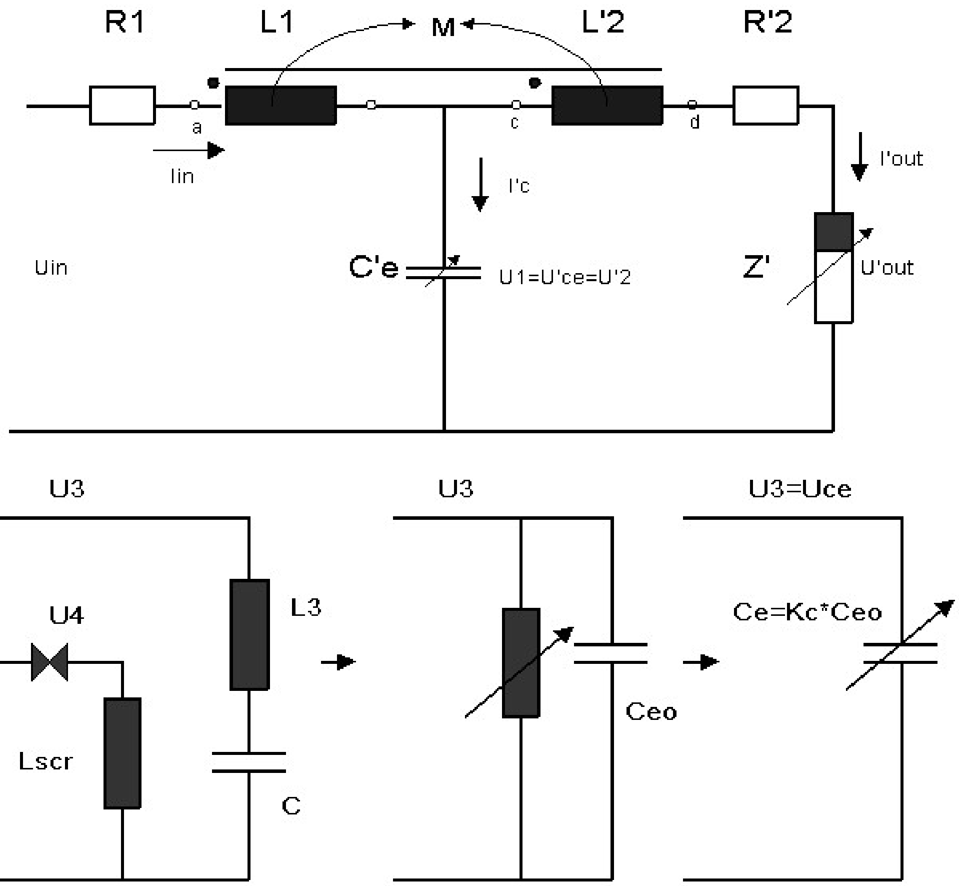

Fig. 6.

For Q(K+1)<< Q^2(K+1)^2 equation (5) can be further simplified:

$$\underline{I'out} = -jUin*Q*(K+1)/[r*Q^2*(K+1)^2 + \underline{Z'}] \quad (6)$$

In the same way, it is possible to derive the formulae for calculating the input current and the capacitor current:

$$\underline{I'in} = (Uin/r)*(\underline{Z'}+r)/[r*Q^2*(K+1)^2 + \underline{Z'}] \quad (7)$$

and

$$\underline{I'ce} = (Uin/r)*[\underline{Z'}+r*(1+jQ*(K+1))]/[r*Q^2*(K+1)^2 + \underline{Z'}] \quad (8)$$

Constant current transformer parameters in resonance operation mode

Inductance of chokes L1 and L2

Normally R*Q^2*(K+1)^2 is much bigger than Z'. This simplifies equation (6) :

$$\mathbf{\underline{I'out.nom} = -jUin.min/(r*Q*(K+1)) = -jUin.min/(\omega L*(K+1))} \qquad \textbf{(9)}$$

On the other hand,the following applies:
I'out.nom = U'out.nom/R'nom
and

$$\mathbf{L = L1 = R'nom/(\omega*(K+1))} \qquad \textbf{(10)}$$

$$\mathbf{U'out.nom=Uin.min} \qquad \textbf{(11)}$$

The nominal output current I'out.nom should be supplied in resonance operation mode at the minimum input voltage Uin.min. At a different, greater input voltage the resonance operation mode is controlled with the current by the Lscr choke, and the nominal output current is kept constant.

Nominal current for capacitor

First, equation (8) is simplified:

$$\mathbf{\underline{I'ce.nom} = Uin.min*(\underline{Z'}+j\omega L*(K+1))/(\omega L*(K+1))^2} \qquad \textbf{(12)}$$

If you replace Z' with R'nom and R'nom = ωL*(K+1), you obtain the following

$\underline{I'ce.nom} = \underline{I'out.nom} - j\underline{I'out.nom}$
and

$$\mathbf{I'ce.nom = I'out.nom\ (2)^{1/2} = 1.41*I'out.nom} \qquad \textbf{(13)}$$

Nominal voltage for C winding

$\underline{U'3.nom} = \underline{I'ce.nom}/(j\omega C'e) = -j\underline{I'ce.nom}*\omega L = -jI'ce.nom*R'nom/(K+1)$
and
U'3.nom = 1.41*U'out.nom/(K+1)
or

$$\mathbf{U3,nom = U'ce.nom = 1.41*Uout.nom/(K+1)} \qquad \textbf{(14)}$$

Capacity Ce is a resultant value from the serial circuit of the L3 choke and capacitor C (see figure 6).

Nominal voltage for capacitor with L3 choke

The L3 choke and capacitor C (see figure 6) are in resonance at 3-times mains frequency.

$$(3 \cdot \omega o)^2 = 1/(L3 \cdot C) \qquad (15)$$

Thus :

$Zc = j\,[\omega oL3-1/(\omega oC)] = j[1/(9\omega oC)- 1/(\omega oC)]= -j8/(9\omega oC)$
and

$$Uc.nom = 1.13 \cdot Uce.nom \qquad (16)$$

At the same time the equivalent capacity Ce of the L3-C serial circuit must be in resonance with inductance L1.

$Z'c = 1/(\omega o \cdot C'e)]= \omega oL1$
and

C'e=1/ ωo^2/L1 bzw. **$C'e=1/\ \omega o^2/L'2$** **(17)**

$$C = 8 \cdot Ce/9 \qquad (18)$$

Nominal power for capacitor

$$Pce.nom = U'ce.nom \cdot I'ce.nom =2 \cdot Pout.nom/(K+1) \qquad (19)$$

$$Pc.nom = U'c.nom \cdot I'ce.nom =(9/8) \cdot Pce.nom \qquad (19a)$$

Vector diagram

Figures 7a and 7b illustrate the vector diagrams for the constant current transformer in resonance operation mode with the pure ohmic load and K=1 resp. K=0.9.
Figure 7c shows short circuit operation. In Figure 7d K=0.9 and the power factor of the load is 0.7 (inductive). In this operating mode the capacitor voltage can be considerably greater than in nominal operation mode, which may result in an increase of the capacitor current and can cause an induction in the core of transformer T. At this point, it should also be mentioned that the power factor of the input current is capacitive with an inductive load.

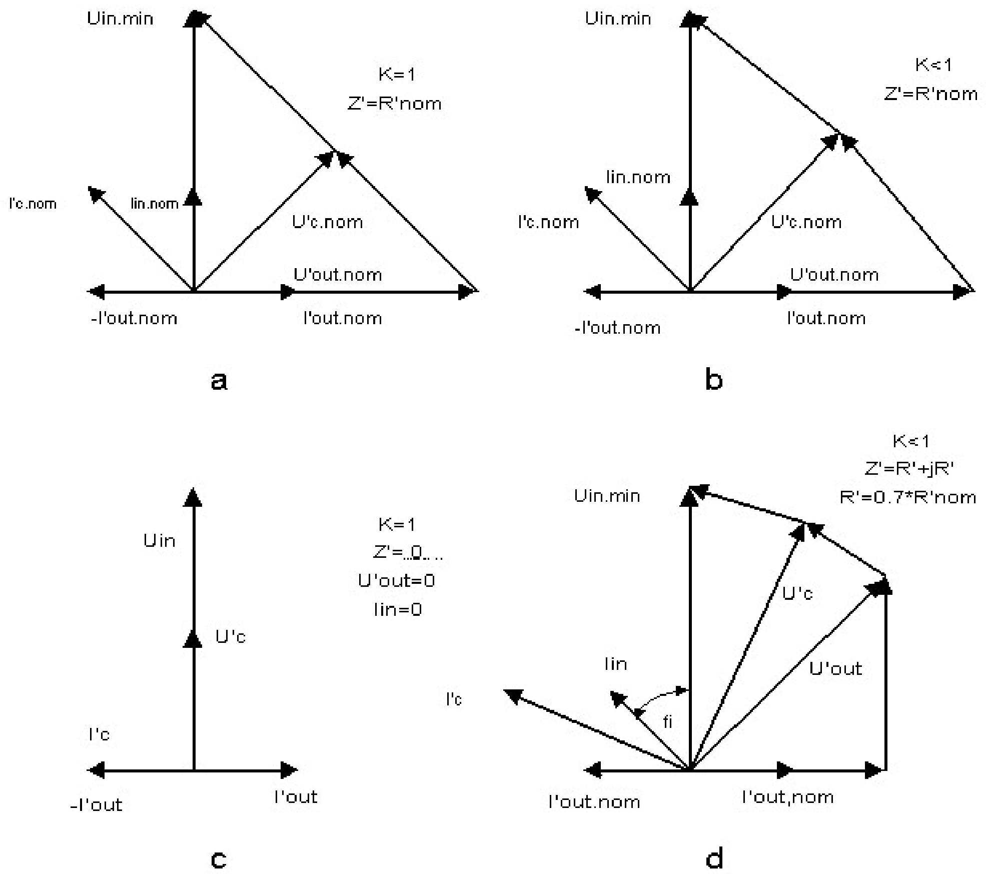

Fig. 7

Example of a calculation for the resonance operation mode

Input data:

Uin.min = 228V
f=60Hz
ωo = 2*π*f = 377
Output power=15kVA
Output current = 6.6 A
Capacitor's nominal operating voltage Uc.nom=550V
Factor of mutual inductance K = 0.9

Calculated data:

- Uout.nom = 15000/6.6 = 2272V
- Rnom = Uout.nom/Iout.nom = 2272/6.6 = 344 Ohm
- L2 = Rnom/ ωo/(K+1) = 344/377/1.9 = 480mH
- U2.nom = 1.41*Uout.nom/(K+1)= 1686V
- U1.nom = 1.41*Uin.min/(K+1) = 1.41*228/1.9 = 170V
- L1 = L2*(U1.nom/U2.nom)^2 = 480*(170/1686)^2 = 4.83mH
- Pce.nom = 2*Pout.nom/(K+1) = 15789 (for Pout - pure ohmic load)

- Ice.nom = Pce.nom/Uc.nom = 15789/550 = 28.7A
- Uc3.nom = Uce.nom = Uc.nom/1.13 = 486V
- Ce = $(1/L2/\omega o^2)*(U2.nom/U\underline{3.nom})^2 = (1/0.480/377^2)*(1686/486)^2$ = 176µF
- C=8*Ce/9 = 156
- L3 = $1/(9\omega oCe)=1/(9*377^2*156e-6)$ =5mH
- Pce.nom = U3.nom^2*ωCe = 15670Var (OK)

Power factor of constant current transformer in resonance operation mode

The power factor of the input current is calculated using equation (7): This equation can be simplified as follows:

$\underline{I'in.nom}$ = Uin.min* $\underline{Z'}/((\omega L**(K+1))^2$ = Uin.min* $(R'+jX')/((\omega L**(K+1))^2$

Thus :

$$\mathbf{Cos(\varphi) = R'/Z' = R'/(R'^2+X'^2)^{1/2}} \qquad \mathbf{(20)}$$

where:
R' => Ohmic value of load impedance $\underline{Z'}$
X' => Inductive value of load impedance $\underline{Z'}$

With a pure ohmic load, the power factor in resonance operation mode is always equal to 1. With an inductive load, the power factor is lower than 1 and is of a capacitive nature! (see figure 7d)

Operating efficiency of constant current transformer in resonance operation mode

The operating efficiency of the constant current transformer is first calculated without taking into account magnetic losses of the magnetic components.

$$\mathbf{\eta = R'nom*I'out.nom^2/(R'nom*I'out.nom^2+r*(Iin^2+I'out^2)) = 1/(1+(r/R')*(1+(Iin/I'out)^2))} \qquad \mathbf{(21)}$$

Starting from resonance operation mode:

R'nom = ω L*(K+1)
Z' = R'nom >>r

it is easy to establish the following from equations (6) and (7):

Iin.nom/I'out.nom ˜ 1

and

$$\boldsymbol{\eta = Q^*(K+1)/[Q^*(K+1)+2]} \qquad \textbf{(22)}$$

In power range from 1 to 70kVA, the Q factor of choke L1L2 is normally between 50 and 200. Taking into account Fe and Cu magnetic losses in the other magnetic components, we can talk about an equivalent Q factor for the constant current transformer of 10-80. Thus equation (10) results in an operating efficiency of 90.5% to 98.7%.

Non-resonance operation mode of constant current transformer

Lscr-Drossel

This choke is wired via the C winding parallel to capacitor C (see figure 1). Choke Lscr generates an inductive current by means of the two anti-parallel wired thyristors (SCR). This compensates the capacitive current of capacitor C, the resonance operation of the constant current transformer is disturbed and the output current is reduced.
The circuit shown in figure 8 is used to calculate the output current in non-resonance operation mode.

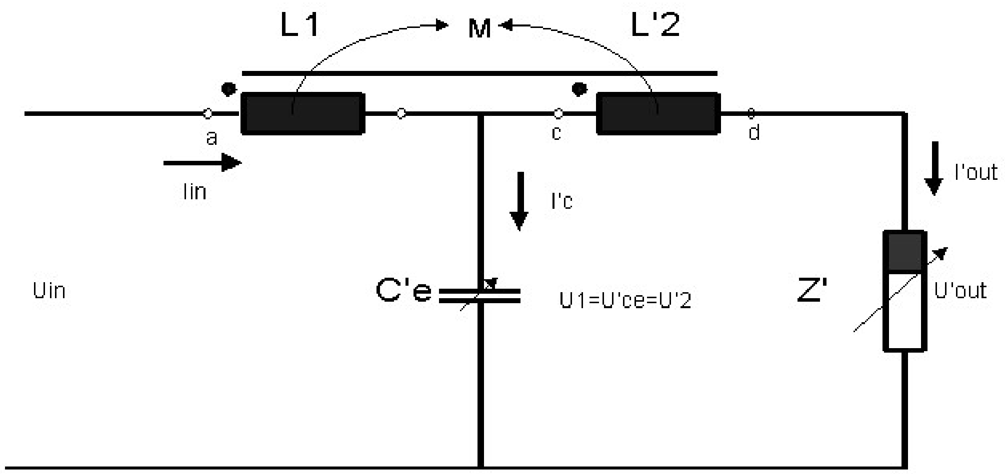

Fig. 8

Starting with equation (4) and using the following relations:

r = 0
L1 = L = Kl*Lo
L'2 = Ka*L
M = K*Kl*Lo
C'e = Kc*C'eo
ω = Kω*ωo
K=1
1/(C'eo*Lo) = ωo^2 (Resonance operation mode)

the output current in non-resonance operation mode can be calculated as follows:

<u>I'out</u>=Uin*(Kω^2*Kc*Kl*$Ka^{1/2}$+1)/[<u>Z'</u>*($K\omega^2$*Kc*Kl-1) - jωoLo*$(1+Ka^{1/2})^2$] (23)

Calculating the inductance of the Lscr choke

This investigation calculates the factor Kc. The other factors are set to 1.

<u>I'out</u> = Uin*(Kc+1)/[<u>Z'</u>*(Kc-1) - 4*jωoLo] **(24)**

The required control range for the output current can be described as follows:

1. The output current is I'out.nom, in resonance operation mode (Kc=1) at the minimum input voltage Uin.min.
2. The output current is I'out.min, at maximum input voltage Uin.max and load <u>Z'</u>=R' = 0.

The calculation is now made out of (22)

(I'out.min/I'out.max)= (Uin.max/Uin.min)*(Kc+1)/2

For I'out.min/I'oit.max=2/7 = 0.285
and
Uin.max/Uin,min=1.1/0.95=1.157
we can calculate:

Kc= - 0.5

This means that the impedance of the Lscr choke must be smaller than the impedance of the capacitor by a factor of 1.5.

ωoL'scr = 0.67/(ωoC'eo) **(25)**

It follows that the core power on the Lscr choke is around 50% greater than for capacitor Ceo.

Pl.nom = 1.5*Pce.nom = 3*Pout.nom/(K+1) **(25a)**

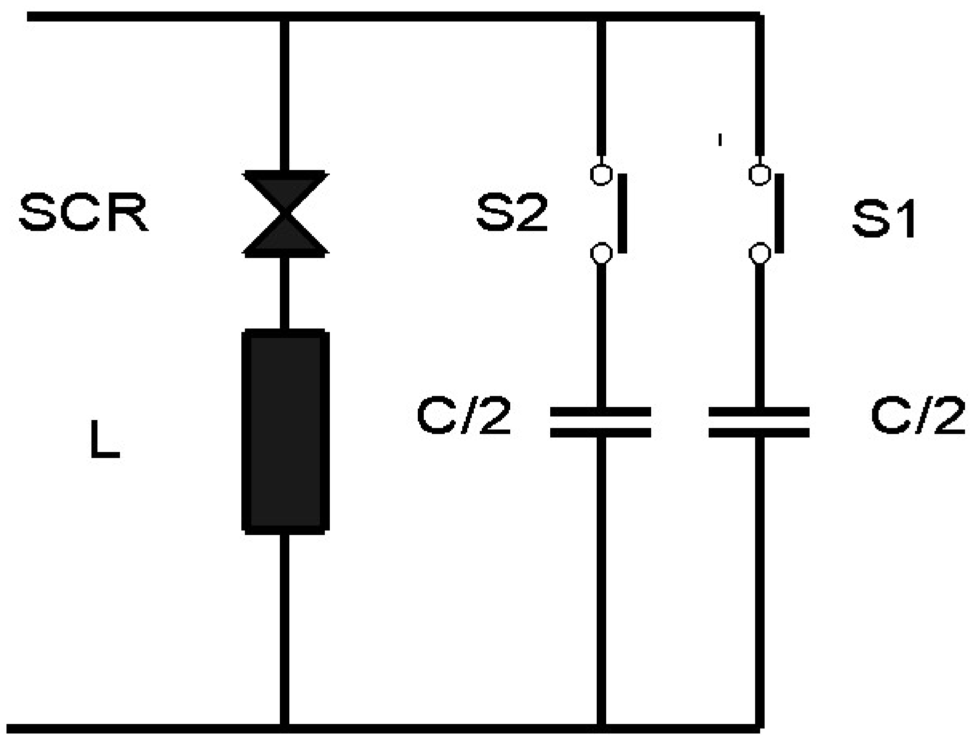

Fig. 9

Optimum core power for for Lscr choke

Variable capacity of capacitor Ce without choke L3

Using the changes in capacity of the capacitor illustrated in figure 9 at 3 levels (0, 50% and 100%), the core power for the Lscr choke can be reduced by a factor of 3.

ωoL'scr = 2/(ωoC'eo)
and
Pl.nom = 0.5*Pce.nom = Pout.nom/(K+1)

Variable output voltage U2

When taps are provided on the output winding, only parameters Z' and Ka, or L'2 change in equation (23). In resonance operation mode of inductance L1 and capacitor Ce, equation (23) reads as follows:

I'out=Uin/(- jωoLo*(1+$Ka^{1/2}$)) = Uin/(- jωoLo*(1+(W2.1/W2.2)))

where:

W2.1 = Turns of the load winding
W2.2 = Turns of the tap on the load winding
and:
$Ka = (W2.1/W2.2)^2$

For a change in output current between 7A and 2A, the number of turns on the tap must be the smallest output voltage.

W2.2 = W2.1/6

The main advantage of this version can be described as follows:
1. The power factor is always approx. equal to 1
2. With some taps the core power of the Lscr choke can be reduced by a factor of 3-5.

Maximum capacitor operating voltage

The maximum operating voltage for capacitor C has an important role to play when selecting the nominal operating voltage for capacitor C and nominal induction for transformer T.
This selection is normally made in the following conditions:
- For maximum input voltage Uin.max = 1.1 Uin.nom
- For controlled output current Iout.nom
- For power factor for load cosφ.min = 0.82 (operation with 30% open current transformer) or Z'=0.7*R'nom+j0.5*R'nom = 2ωoLo*(0.7+j0.5)

In the above-stated operating conditions, the output current Iout.nom is kept constant with a current by the Lscr choke. In doing so, the constant current transformer operates in non-resonance mode.
First the factor Kc is calculated with the aid of equation (24) in resonance operation mode with Uin.min and from non-resonance operation mode at Uin.max, as follows:

$Iout._{Kc=1} = Iout._{Kc<1} = Iout.nom$
and
Uin.max*(Kc+1)/[(0.7+j0.5)*(Kc-1) - j2] = Uin.min/(- j]
and
$Uin.min/Uin.max)^2 = 0.75 =(Kc+1)^2/[(0.7*(Kc+1))^2+(2-0.5*(Kc+1))^2]$

Thus :
Kc= 0.82

Now, using figures 6 and 8, we can calculated the capacitor current:
I'ce = j<u>Iout</u>*[Z'+jω(L'2+M)]/(ωM+1/(ωC'e)) = j<u>Iout</u>*Kc*ωoCo [Z'+j2ωoLo)]/(Kc+1)

With Kc = 0.82 and Iout = Iout.nom, we form the following relation:
<u>I'ce.max</u> = j<u>I'out.nom</u>*Kc*[0.7+j1.5)]/(Kc+1)
and
<u>I'ce.nom </u>= j<u>I'out.nom</u>*[1+j]/2

Thus :

I'ce.max/I'ce.nom = 0.75/0.71=1.05
and

Uce.max/Uce.nom = I'ce.max/I'ce.nom/Kc = 1.28 **(26)**

L3 choke and current harmonics

Normally current harmonics are not present in a constant current transformer. When installing the constant current transformer for airfield lighting as shown in the circuit illustrated in figure 1, 3 sources of harmonics are recorded.

1. The two thyristors (SCR) wired anti-parallel.
2. Heavily saturated current transformers for load Z
3. Magnetizing current of the transformer

In a professional design for a constant current transformer, the transformer's magnetizing current is not a source of harmonics. Above all, with an induction of over 1.7T (17000 Gaus), the third harmonic must be taken into account.

Figure 10 shows the replacement circuit for the constant current transformer for the calculation of the effect of harmonics. $\mathbf{L'}s_{.T+L1}$ is the total leakage inductance of choke L1 and of the primary winding of transformer T and $\mathbf{L'}s_{.T+L2}$ is the total leakage inductance of choke L2 and the secondary winding of transformer T. Inductivity L'3 and capacity C' are in resonance with at three times mains frequency and "extract" the third current harmonic of the constant current transformer.

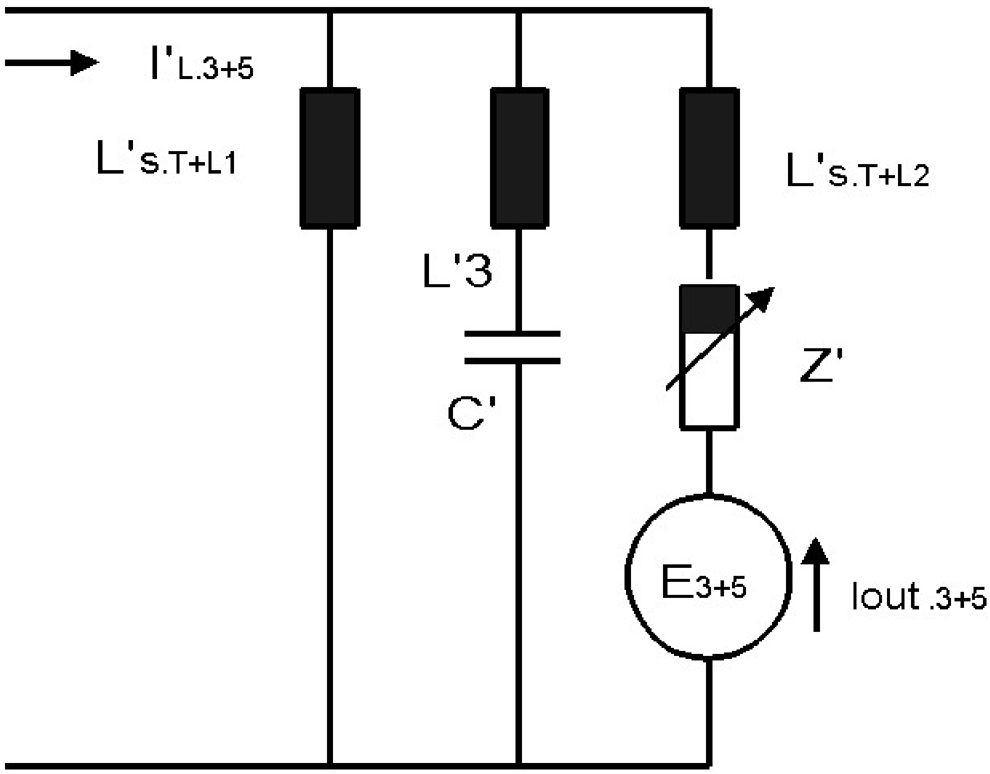

Fig. 10

The two thyristors (SCR) wired anti-parallel.

The control angle for the 2 anti-parallel thyristors lie virtually between 90 and 180 degrees.
The maximum harmonic current is generated at approx. 150 degrees and is:

IL.3 = 0.1 * IL.max (3rd harmonic)
and
IL.5 = 0.045*IL.max (5th harmonic)
where:
IL.max = U4/ (ωoLscr)

When designing the Lscr throttle for:

Pl = 1.5*Pce.nom = 1.5*Pout.nom

Iout.3 = 0.1*IL.max*(U4/U2)
and
Iout.5 = 0.045 IL.max*(U4/U2)

Heavily saturated current transformers for load Z

Figure 11 shows the primary voltage and the primary current of the current transformer in nominal operation and in "no-load operation" In both cases the same "impressed" current Iout flows through the primary winding. At a ratio between the induction in nominal operation and the saturation induction of the transformer of approx. 0.7, the mean value of voltage Uout in "no-load operation" is approximately 50% greater than in nominal operation. For a constant current transformer operating at 30% current transformers in "no-load operation", the mean value of the voltage drop is:

Eav = 0.9*Uout.nom*(1/0.7)*0.3 = 0.385*Uout.nom

Assuming that the no-load current of the transformer in nominal operation is approximately 10%, width X of the pulse is approximately 0.15π. We can now estimate the size of the harmonics as follows:

Erms.1 = Eav*sin(X/2)*(π /X) = 0.385*Uout.nom*sin(0.075*π)/0.15) = 0.5*Uout.nom
Erms.3 = 0.33*Eav*sin(3*X/2)*(π /X) = 0.53*Uout.nom
Erms.5 = 0.2*Eav*sin(5*X/2)*(π /X) = 0.47*Uout.nom
and
Iout.3 = Erms.3/(0.7*Rnom^2+(3ωL2)^{2})$^{1/}$ = 0.53*Uout.nom/(1.66*Rnom) = 0.32*Iout.nom
Iout.5 = Erms.5/(0.7*Rnom^{2}+(5ωL2)^{2})$^{1/2}$ = 0.47*Uout.nom/(2.6*Rnom) = 0.18*Iout.nom

We can now calculate the current through the L3 choke:
IL3.1 = Ic.nom
IL3.3 = 0.32*Iout.nom*(U2/U3) **(27)**
IL3.5 = 0.18*Iout.nom *(U2/U3)

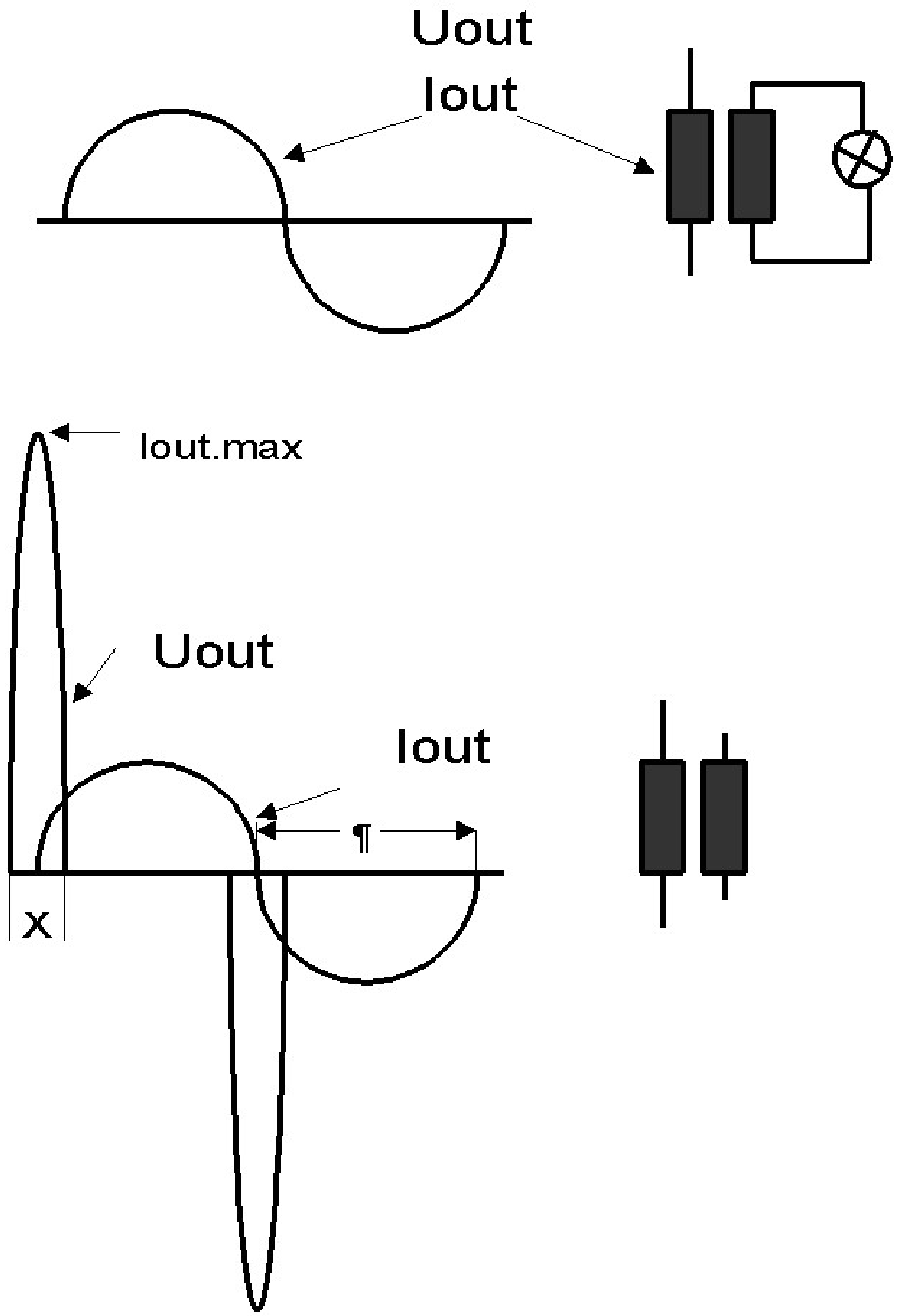

Fig. 11

No-load operation

In no-load operation, the induction in transformer T rises sharply by 30%-50%. For this reason, special attention should be paid to the choice of nominal voltage for the capacitor.

Input voltage

The same constant current transformer should be designed for several input voltages: 208V, 240V, 347V, 400V and 480V. This is achieved using taps on the primary winding and the L1 choke in figure 1, or simply on the common winding shown in figure 2. The number of turns on the primary winding is calculated using the following equation:

W1 = 1.41*Uin.min/(K+1)/(4.44*f*Kfe*B)

where:
W1 =>Turns of the calculated tap
Uin.min => 95% of the following values: 208V, 240V, 347V, 400V, 480V
B =>Induction in T (1T = 10000Gaus)
f => Frequency:
Kfe => stacking factor
K => factor of mutual inductance of L1 and L2, taking into account the leakage inductance of transformer T.

In this design of primary winding and inductance, L1 resonance operation can be calculated and installed only with a tap. The different leakage inductances of the taps and the different factors of mutual inductance of the two taps result in slightly differing resonance frequencies, which can be easily compensated with the current of the Lscr choke.

Resonance frequency of tap 1:

$\omega o.1^2 = 1/(L1.1*C'e.1)$

Resonance frequency of tap 2:

$L1.2 \sim L1.1*(W1.2/W1.1)^2$
$C'e.2 = C'e.1*(W1.1/W1.2)^2$

$\boldsymbol{\omega o.2^2 = 1/(L1.2*C'e.2) \sim 1/(L1.1*C'e.1) \sim \omega o.1^2}$