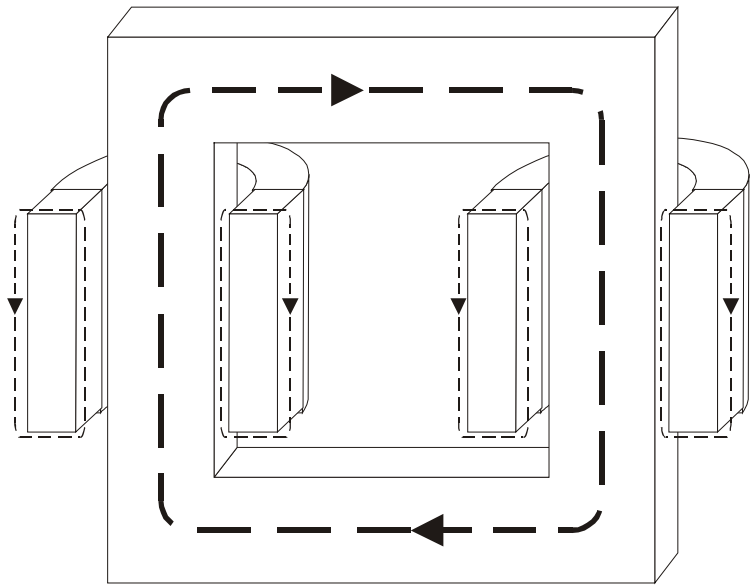
APPLICATION NOTES

TRANSFORMERS



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1. GLOSSARY

r_1: Primary windings resistance

r_2: Secondary windings resistance

r_e: Primary windings resistance plus Secondary windings resistance seen from the primary

RL: Load Resistance

x_1: Primary leakage inductance

x_2: Secondary leakage inductance

x_e: Primary leakage inductance plus Secondary leakage inductance seen from the primary

Z_1: Primary impedance consisting of the vectorial sum of r_1 and x_1

V_1: Primary voltage

V_2: Secondary voltage

I_1: Primary current

I_2: Secondary current

I_m: Magnetizing current generating the flux

I_p: Eddy current in laminations (core losses)

I_φ: Vectorial sum of $I_m + I_p$ also called magnetizing current since $I_m > I_p$ on power transformer

m_1: Number of winding on primary

m_2: Number of winding on secondary

f: Voltage frequency

c1: Electromagnetic force on primary

c2: Electromagnetic force on secondary

2. PRINCIPLES

How works a transformer?

The principle on which works the transformer is based on general low of electromagnetic induction

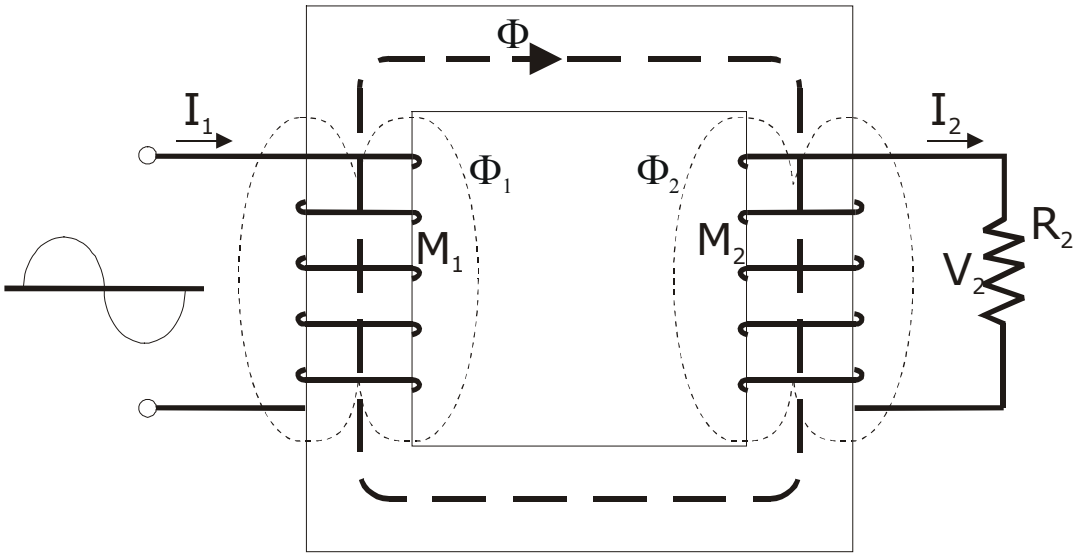
$$e = -\frac{d\varphi}{dt}$$

The magnetizing current generate a magnetic flux that is concatenated with the secondary.

This flux is variable on time and it is sinusoidal, on secondary circuit that is metallically insulated from primary is inducted on electromagnetic voltage that give a voltage between the secondary terminals.

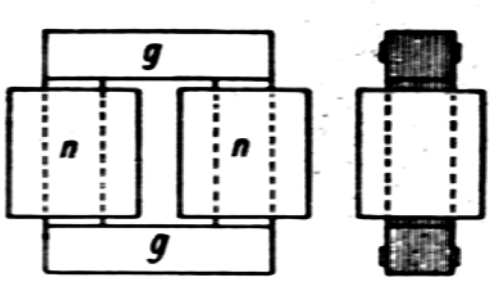
If we apply to primary a D.C. voltage the transformer does not work. Infact the derivative of a constant value is zero, so "*e*" became zero.

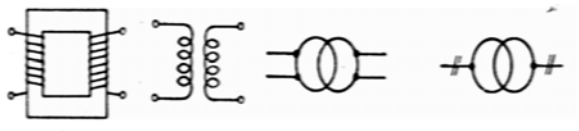
3. THE TRANSFORMER



Transformers are used to modify parameters of electric power. They receive energy with a certain value of voltage and current(primary of transformer) and they delivery a voltage on secondary that is K time bigger in voltage and K time lower in current or vice versa.

The apparance of the transformer are below represented





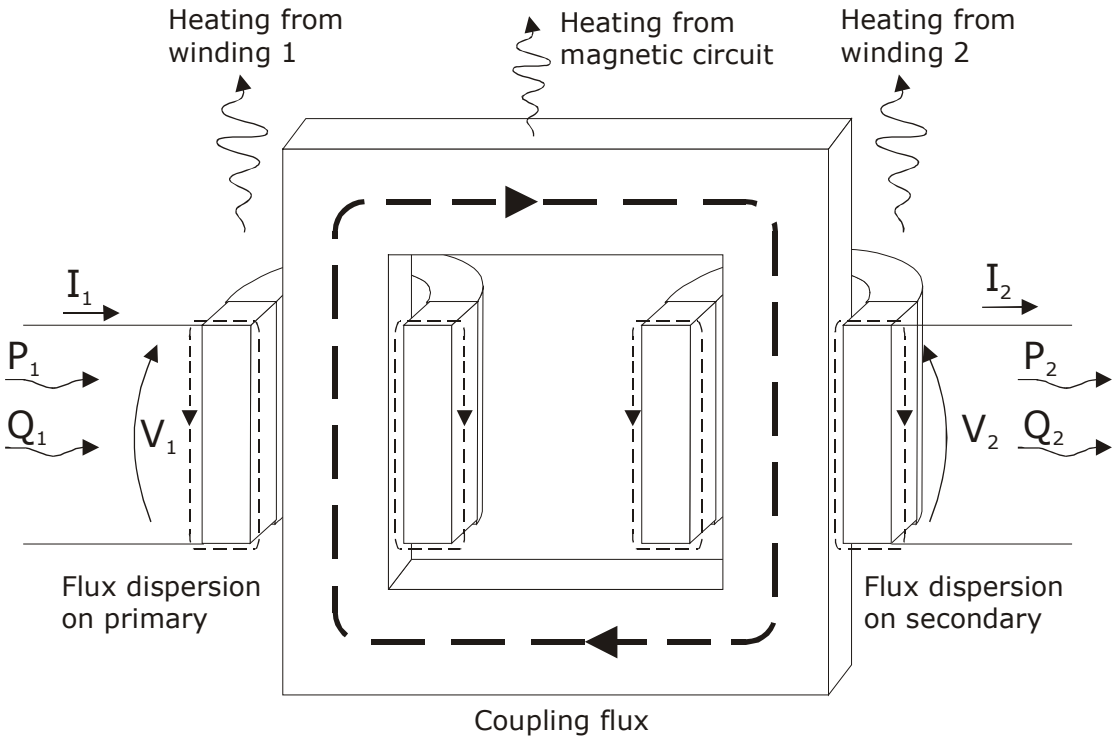
$$V_1 = M_1 \frac{d\Phi}{dt} \rightarrow V_2 = M_2 \frac{d\Phi}{dt} \rightarrow \Phi = \frac{1}{M_1}\int_0^t V_{(0)}dt \rightarrow \frac{V_1}{V_2} = \frac{M_1 \frac{d\Phi}{dt}}{M_2 \frac{d\Phi}{dt}} \rightarrow$$

$$\rightarrow \frac{V_1}{V_2} = \frac{M_1}{M_2} \rightarrow V_1 I_1 = V_2 I_2$$

3.1 Real transformer

The transformer represented in the precedent paragraph is an ideal transformer.

In a real transformer there is a power dissipation and flux dissipation.



The balance of power is represented above .

If we consider the principle of preservation of energy and in first hypothesis we don't consider power los.

$P_1 \cong P_2 \qquad Q_1 \cong Q_2 \qquad A_1 \cong A_2$

$$V_1 I_1 \cong V_2 I_2 \Rightarrow \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

$\frac{V_1}{V_2} = K$ Voltage Ratio $\qquad$ $\frac{I_2}{I_1} = K$ Current Ratio

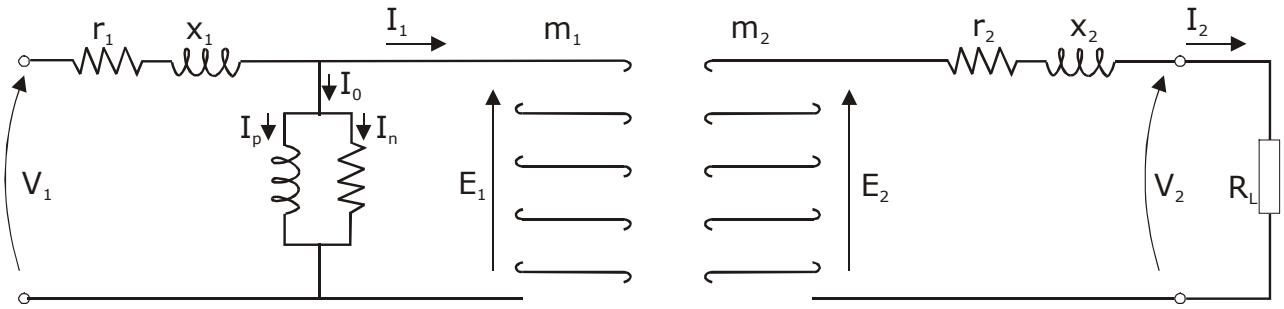
$$V_1 = V_2 \frac{I_2}{I_1} = V_2 K \qquad I_1 = \frac{1}{K} I_2$$

3.1.1 Indicative value for realistic transformer

Heat from core	≅	1÷5% of Input Power
Heat from winding	≅	1÷5% of Input Power
Leakage fluxes	≅	1÷10% of Flux ϕ
Efficiency η	≅	90 ÷ 97% Depending on nominal power. With big transformers the efficiency is very high ~ 97%
Noise	≅	20 ÷ 60dB Depending on magnetostriction of lamination and windings vibration

3.2 The transformer and equvalent circuit

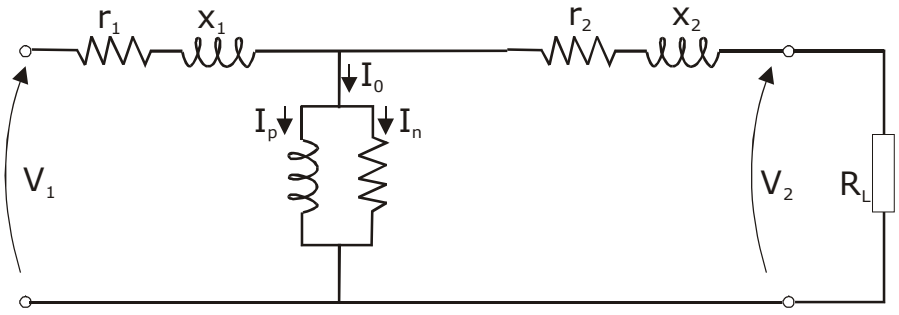
Equivalent circuit of a loaded transformer



In a ideal transformer

$$\frac{E_1}{E_2} = \frac{M_1}{M_2} \qquad E_2 = \frac{M_2}{M_1} E_1$$

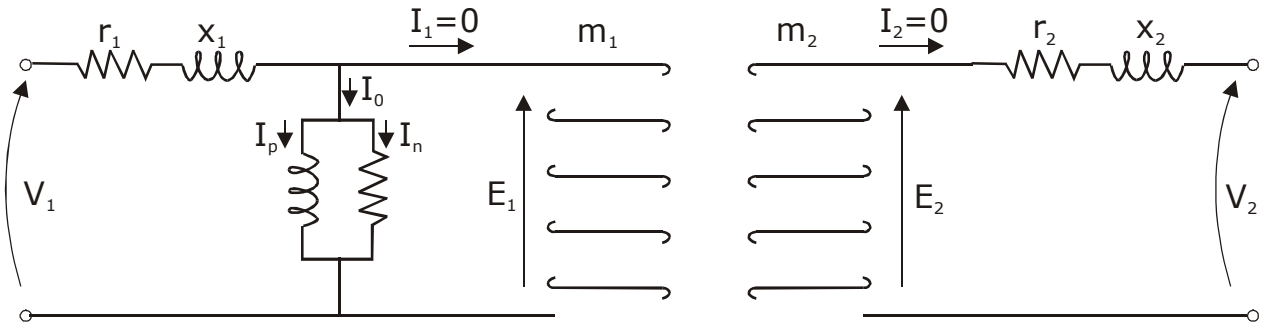
If we assume that that transformer has K=1 we have the following equivalent circuit.

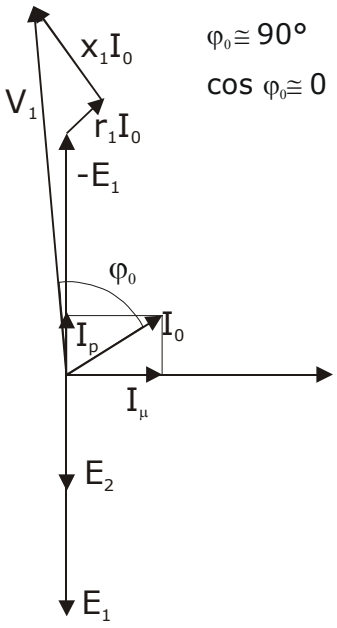


This circuit is used in next pages to have more intuitive equivalent circuit.

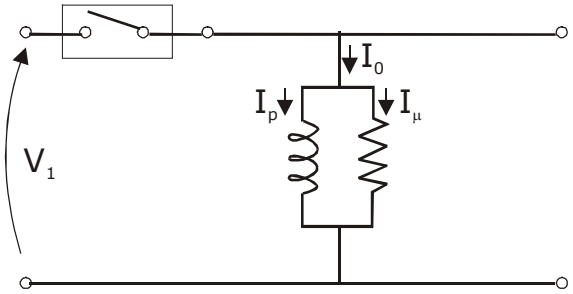
3.3 Unloaded transformer

Equivalent circuit of a unloaded transformer





We can simplify the circuit assuming $K = \frac{M_2}{M_1} = 1$. The unloaded transformer seen by thyristor unit is

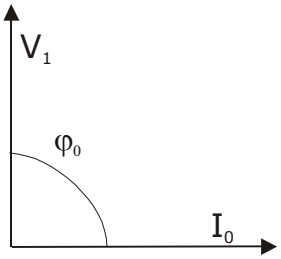


this means to have secondary open and to apply voltage on primary.

The magnetizing current $\bar{I}_0 = \bar{I}_\mu + \bar{I}_p$ and there a pick of current that is normally bigger than nominal current. The fuses blow.

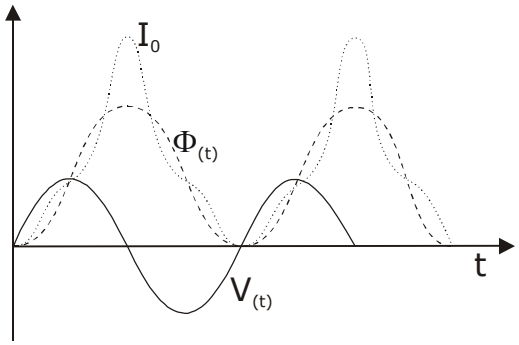
$$I'_1 = \frac{1}{x_1}\int Vdt$$

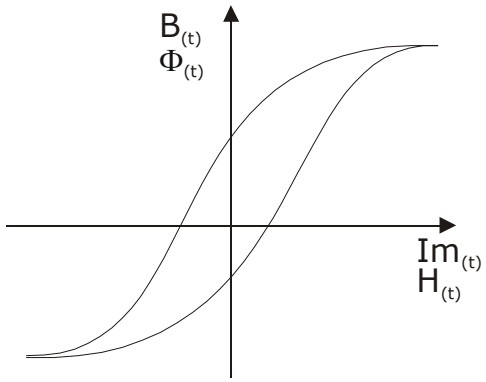
In this case the thyristor unit see the transformer as a pure inductive load.

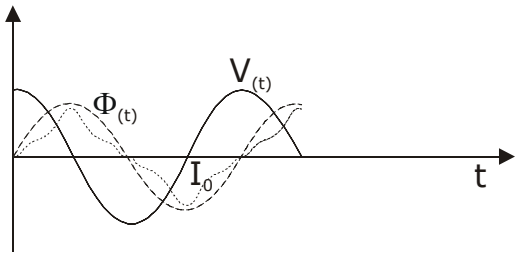


Very close to 90° delay.

cos φ close to 0





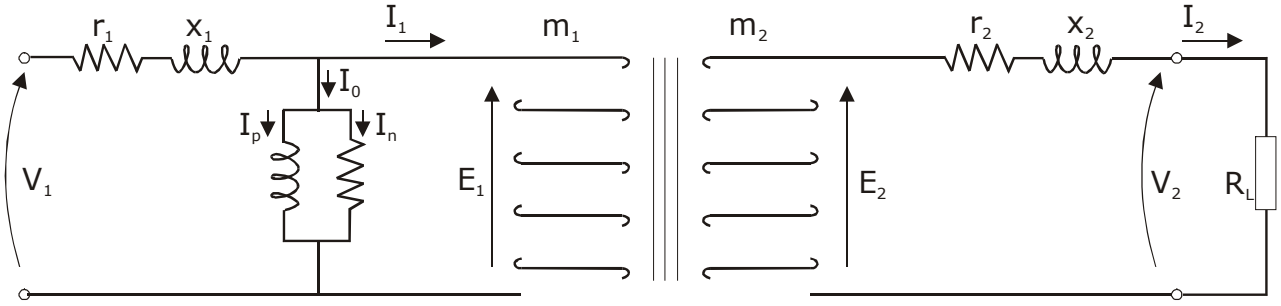


To avoid to have the pick current I_0 can be used two technique:

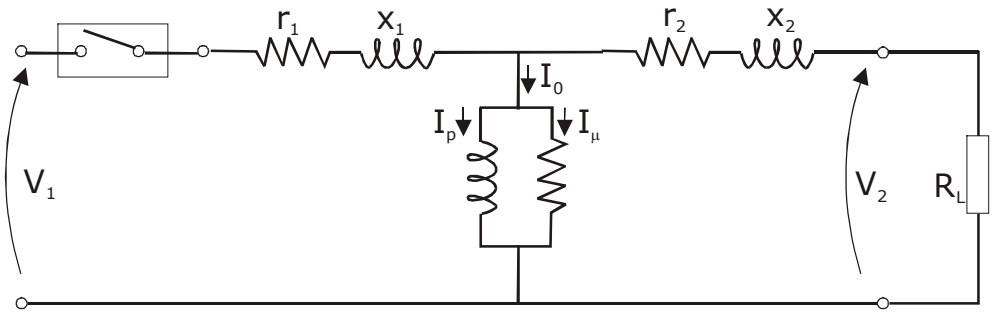
1. Phase angle firing with soft start and current limit
2. Burst firing using the Delay Triggering (DT) technique.
   To avoid magnetic circuit saturation, the thyristor unit switch OFF when load voltage is negative and switch ON only when is positive with a setted delay on voltage zero crossing. In this way is possible to switch ON when current is zero.

3.4 Loaded transformer

If the secondary of transformer is closed on a resistive load R_L, the equivalent circuit is:



If we assume $K = \frac{M_2}{M_1} = 1$. The unloaded transformer seen by thyristor unit is

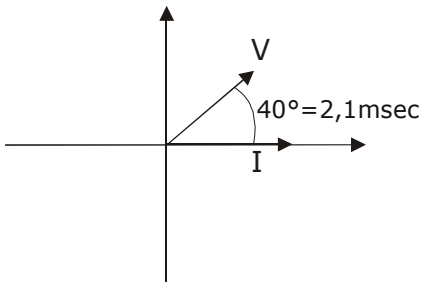


- The load seen by thyristor is mostly resistive
- Power factor $\cong 0.8 \div 0.9$
- In burst firing is required a small phase delay from 15 to 40°.

If we consider that a complete cycle of voltage waveform is 20 msec. and is equal to 360°

$$\frac{20}{360} 40 \cong 2{,}1 m\sec$$

When delayed triggering is used, the delay that must be setted is 2,1 msec. The electric circuit is based on zero crossing of voltage and the signal to fire thyristor is given with the setted delay. In our example is 2,1msec and this allow to fire the thyristor when current is zero



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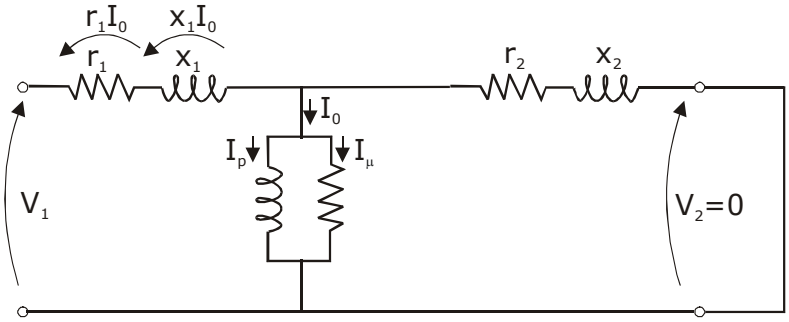
3.5 Trasformer working in short circuit

Short circuit voltage V_{sc} is the value of voltage on primary able to give a circulating current equal to nominal with the secondary terminals in short circuit.

In normal transformer is 5% of V_1.

This means that if is done a short circuit on secondary with nominal voltage on primary the circulating current becomes 20 times the nominal one.

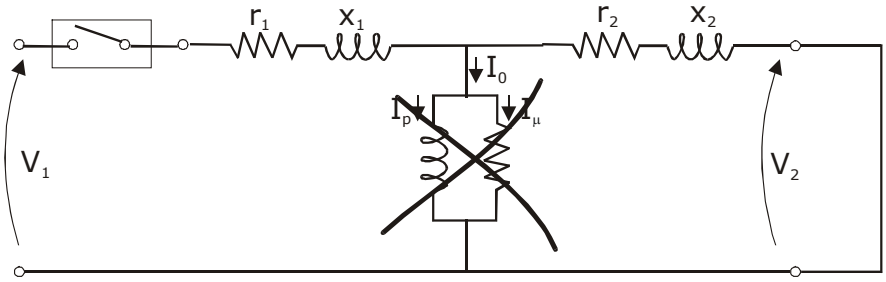


If for example V_{sc} is 5% this means that also E_1 is 5% and the flux is small.

The power loss are small and negligible because are proportional to $(0,05)^2=0,025$

Of nominal value when the transformer is loaded

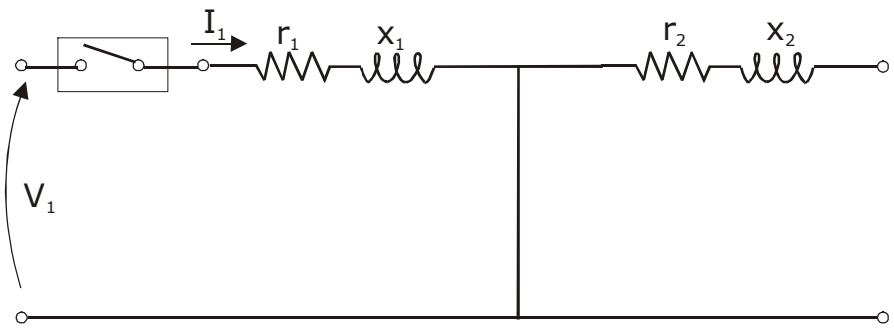
The equivalent circuit assuming $K = \frac{M_2}{M_1} = 1$ is:



The current is limited only by impedance of primary an secondary winding.

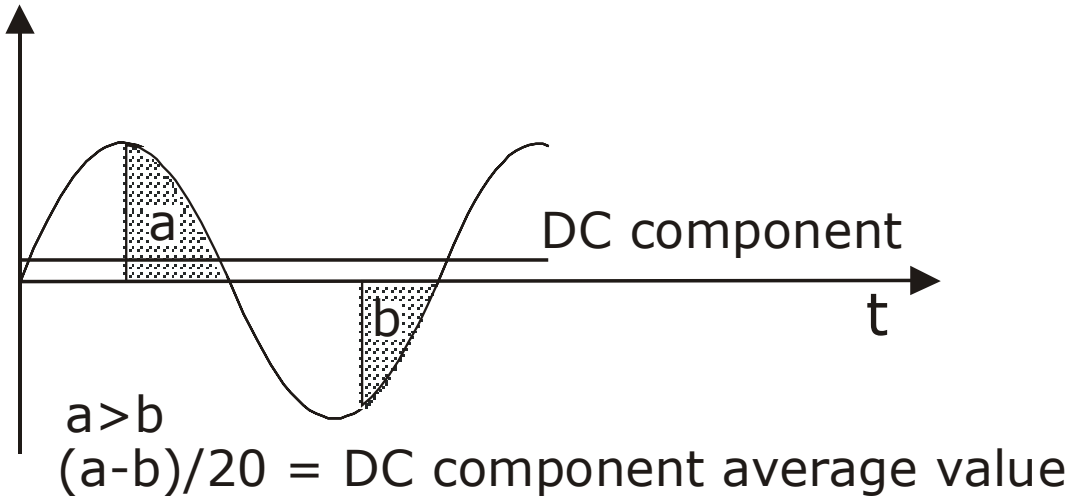
- V_{sc} = 5% of V_1
- I_{sc} is 20 time the nominal current with full voltage
- Power factor $\cong 0.7 \div 0.8$
- Current limited by winding impedance only
- Leakage inductance is equivalent to an air coil it does not saturate

3.6 Transformer working in saturation

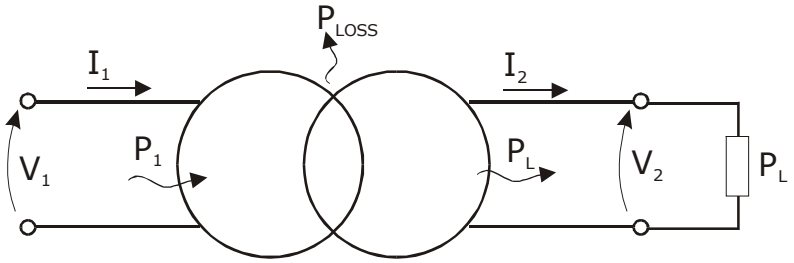


This circuit is simplified considering $K = \frac{M_2}{M_1} = 1$

- The current I_1 is limited by r_1 x_1 only
- The fuse of thyristor unit will blow and if is not properly sized for i^2t will blow also the thyristors
- A normal transformer must never saturate
- To avoid to have saturation, positive and negative must be equal. Other ways a dc component will appear.



3.7 Formulas



Data	*Incognita*
V_1=400V	I_1= ??
V_2=100V	
KVA=100	
P_L=80KW	

Solution 1

$V_1 I_1 = V_2 I_2$ $\qquad 400 * I_1 = 100 * 800$

$P_L = V_2 I_2$ $\qquad I_1 = \frac{100 * 800}{400} = 200\,A$

$I_2 = \frac{P_L}{V_2}$ $\qquad I_2 = \frac{80.000}{100} = 800\,A$

Solution 2

$\frac{V_1}{V_2} = K$ $\qquad \frac{400}{100} = 4$

$\frac{I_2}{I_1} = K$

$I_1 = \frac{1}{K} I_2$ $\qquad I_1 = \frac{1}{4} * \frac{80.000}{100} = 200\,A$

The maximum current on primary is:

$P_{no\min al(KVA)} = V_1 I_1$

$I_1 = \frac{P_{n(KVA)}}{V_1} = \frac{100.000}{400} = 250\,A$

We suggest to size the thyristor unit for 250A because in future is possible to add other loads.

Solution 3

This is the easier solution based on balance of power

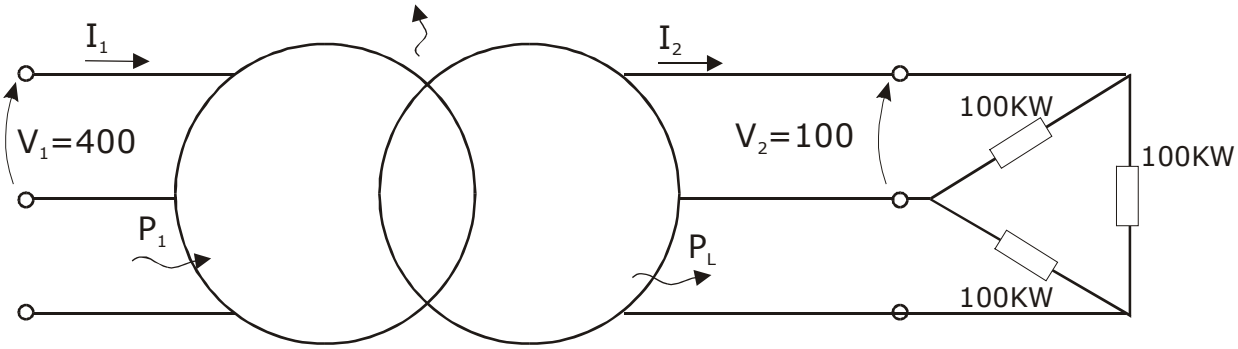
$P_1 = P_{LOSS} + P_L$ We consider P_{LOSS} negligible

$P_1 \equiv P_L$

$P_1 = V_1 I_1$

$I_1 = \frac{P_1}{V_1} = \frac{80.000}{400} = 200 A$

3.8 Three phase transformer



Data	*Incognita*
V_1=400V	I_2= ??
V_2=100V	
P_L=300KW	

$$P_L \equiv 100 + 100 + 100$$

To found total power it's possible to do arithmetical sum (boucherout low). With 3 phase loads we don't suggest to use solution 1-2 used for 1 phases transformer because K value depend on the different connection on primary and secondary Y/Δ - Δ/Δ - Y/Y - Δ/Y etc.

Solution

$P_1 = P_{LOSS} + P_L$ We consider P_{LOSS} negligible

$P_1 \equiv P_L$

$P_1 \cong \sqrt{3} V_1 I_1$ $P_1 \cong 1{,}73 * V_1 I_1$

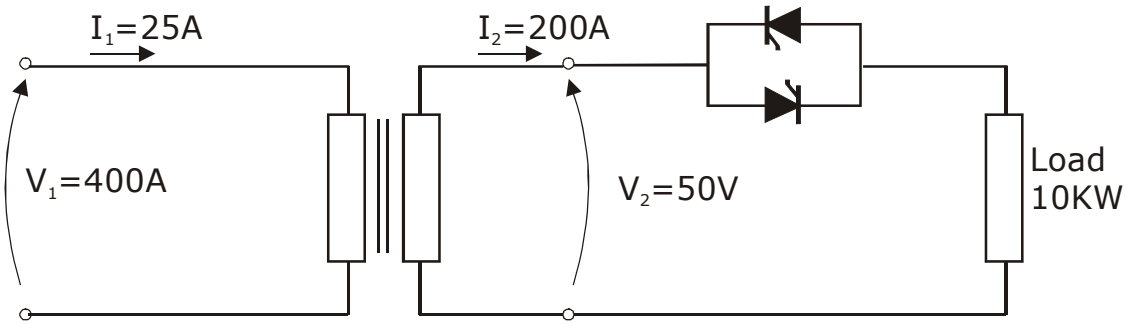
$$I_1 = \frac{P_1}{1{,}73 * V_1} = \frac{300.000}{1{,}73 * 400} = 433\,A$$

4. THYRISTOR STACKS TO DRIVE TRANSFORMER

We have seen in previously pages that one transformer is used for following purposes:

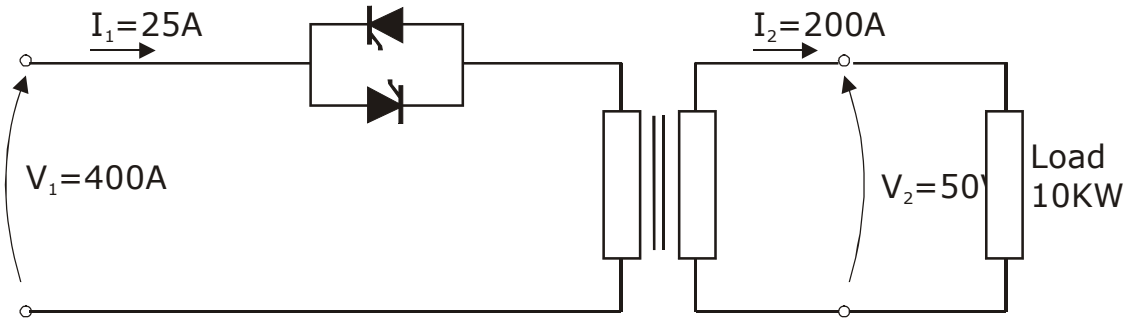
- To have galvanic isolation between primary and secondary
- To adapt the main supply voltage to the nominal load voltage
  Ex.: main supply 400V, load supply 60V,
  you need a tranformer 400/60V

4.1 Thyristor stack connected betwen secondary and load



- Normally this solution is not used because the current of secondary is higher than primary. In our example I_1=25A I_2=200A. It's easy to understand that one unit of 200A cost a lot more than one of 25A
- Advantage of this connection is that no attention must be paid to the transformer but just to the load features.
  In this case we can use a normal zero crossing firing.
  Ex: CD3000S or CD3000A or CD3000M without option.
- Same consideration for three phase load and is this case the thyristor units will be CD3000A-2PH or CD3000A-3PH.
  If you need communication use M family.

4.2 Thyristor stack connected on primary



- this solution is used because the current on primary is less than on secondary and thyristor stack cost less
- Attention to this connection must be paid because the inrush current when transformer is switched on can be up to 20 times the nominal current.

  This over current causes fuse failure or thyristor failure if fuses are not properly sized (i^2t of fuse higher that i^2t of thyristor , this can happen only when the original fuses has been substituted without to respect the proper i^2t)
- How is possible to reduce the inrush current??

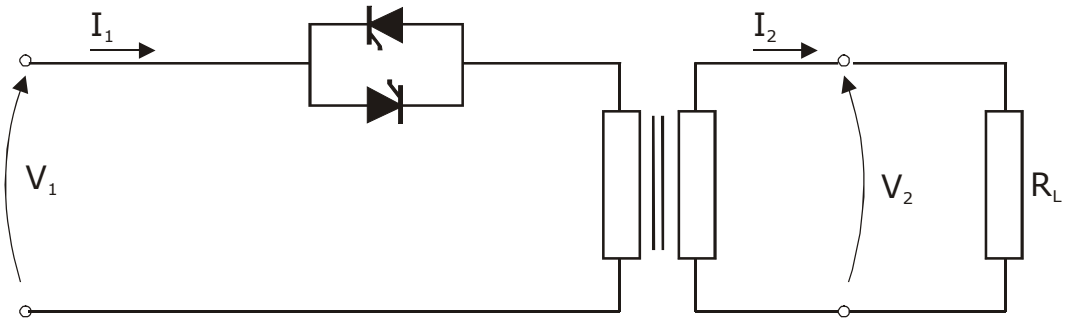
  Is necessary to select a thyristor unit with following features:

  - Soft-Start
  - Current Limit
- Use CD3200 or CD2200 for 1 phase transformer
- Use CD30, Multidrive or CD3000E-3PH for 3 phases transformer.

Note: For small transformer can be enough to use soft-start to avoid inrush current. There are not rules to establish when this can be done so we suggest to use every time current limit in addition to Phase Angle Soft Start

4.3 Thyristor stack connected on primary using Burst Firing (BF)

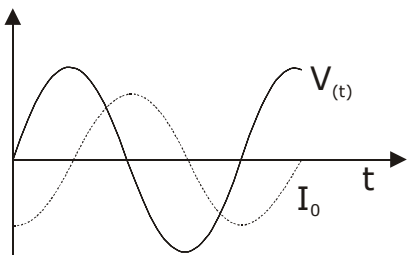
This firing mode is used to switch ON-OFF a transformer on primary.



With this circuit the power is controlled in non continuous mode.
The firing technique used is Burst Firing (BF)

Ex.:
If we set Power at 50% = 4 Cycles ON – 4 Cycles OFF
we will have at 75% = 12 Cycles ON – 4 Cycles OFF
(see Duty Cycle Tecnique in application note)

This technique allows to use zero crossing avoiding to have electrical noise and interference typical of Phase Angle Firing.
Unfortunately Burst Firing used on primary transformer generate an inrush current in the transformer able to blow fuses.
To avoid this problem CD Automation uses a technique named "Delay Triggering" (DT).
The most important features of this firing are :
Switch OFF when current is negative and goes to 0
Switch ON when current is zero and immediately after became positive.

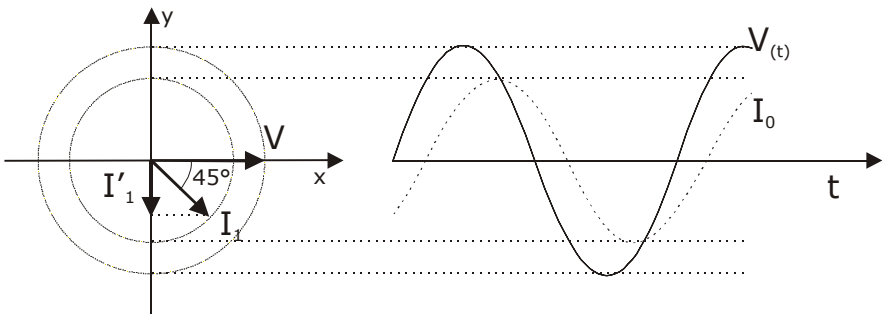


CD Automation thyristor units with Delayed Triggering switch OFF when voltage is negative and switch ON only when voltage is positive, this

feature is necessary to avoid saturation of magnetic circuit of transformers.

To understand we have refer to the curve of Flux Intensity(B) related to Ampere Turns $m_1 x I_1(H)$.

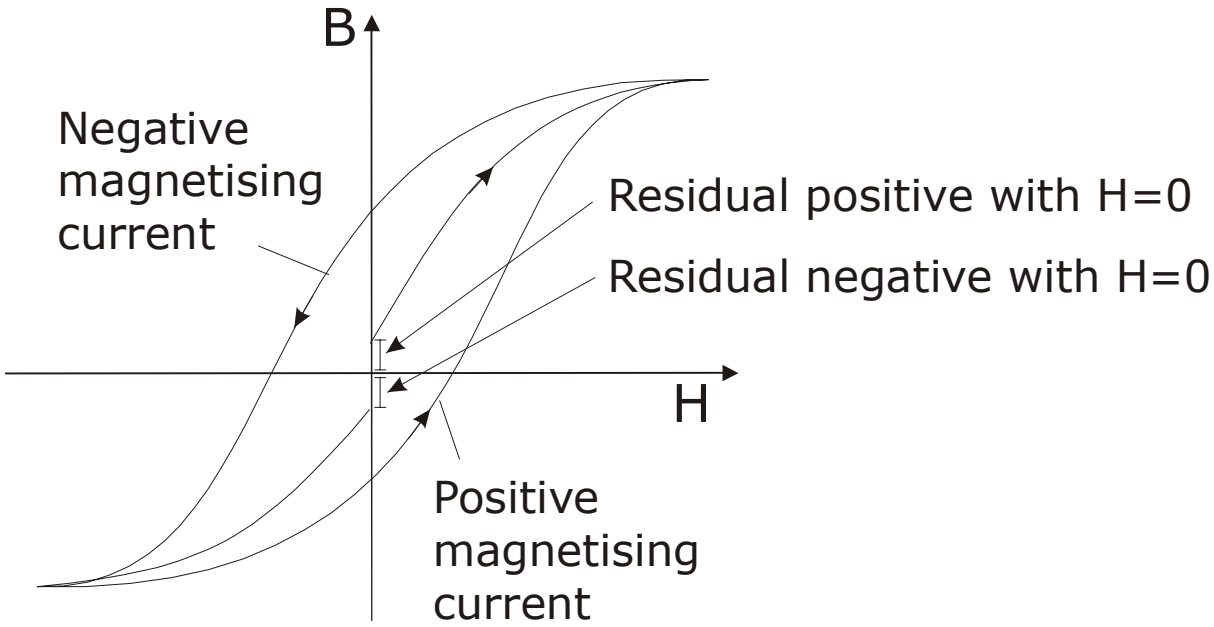
It's important to consider that the current is not in phase with voltage but has a delay. The electronic circuit detect the zero voltage but when the voltage is zero the current has a negative value.



- The instantaneous value is the projection on y axis I'_1 that is a negative value that is in same direction of residual flux and allow excess current to flow with consequent fuse failure. The technique used is to switch ON after a delay time from the V_1 zero crossing.
- The vectors are rotating anticlockwise. Complete rotation of 360° that is complete period. One period is 20msec at 50Hz.

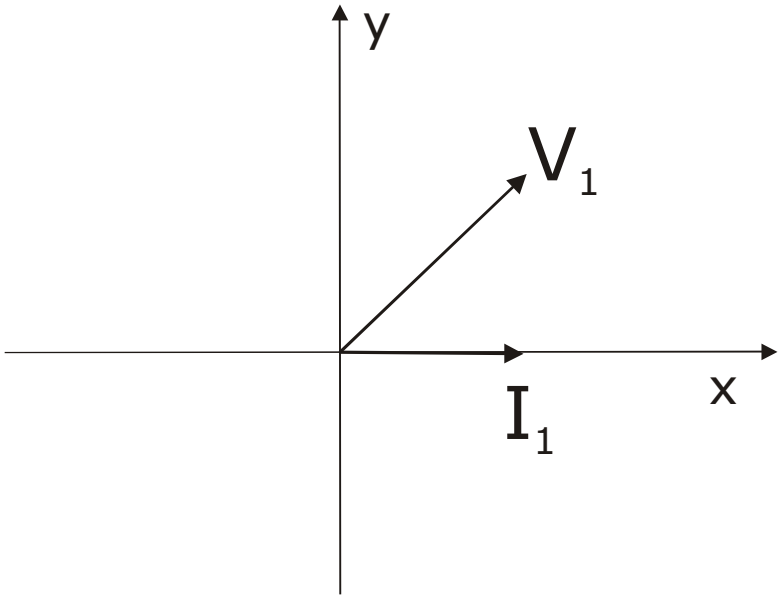
  Thus if delay of current is 45° the unit must switch ON with a delay.

$$\frac{360}{45} = \frac{20}{X_{delay}} \qquad X_{delay} = \frac{20 * 45}{360} = 25 m\sec$$



In magnetic circuit there is a residual magnetism that can be positive or negative depending on when the current was switched OFF. If we have residual flux positive and we switch ON when the current is positive we have the magnetic saturation due the sum of (residual positive + flux positive). In this case the current rise and fuses blow.
If we switch OFF negative the residual flux is negative and switching ON positive the total flux is smaller than normal one.

Residual flux + flux positive < Normal flux.
In this mode we have no saturation.



Delayed angle depend on the feature of the transformers with delay of 2,5 msec we switch ON when current is zero and after which becomes positive.

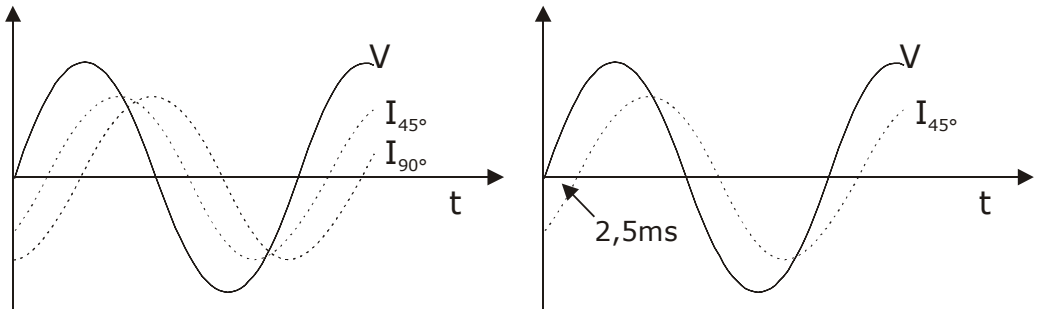
Residualnegative + Flux positive = Flux value below nominal.

In this case there are no problems for saturation and there is no inrush current. The fuses does not blow.

4.4 CD Automation unit to for one phase applications

For this application use CD3000A or M configured for delayed triggering.

For 3 phase application use: *CD3000E-2PH configured for delay triggering*.
On CD3000E the enhanced type of CD3000 family is possible to set the delay of firing and the number of half cycle on which to apply it. In the majority of transformer is enough to set one half cycle. When the delay is not known because we don't know the angle between the vectors of voltage and current set 2,5msec = 45° delay.
The delay is adjustable from zero to 90°(5msec).



The inrush current will be minimized and the benefits of Burst Firing will be realised.
The use of this technique has been experimented with normal resistive loads and silicon carbide elements.
Don't use this technique with cold resistance like KantalSuper or other resistance that have a very low value when cold. In this case for the thyristor unit is like to switch ON a transformer with secondary in short circuit.
For this application use Phase Angle with Soft Start and current limit.
The suggest unit for one phase loads are CD2200 or Cd3200.
The suggest unit for three phase loads are CD3000E-3PH , CD30 or MULTUDRIVE.

4.5 Application with three phase transformers

It's important to keep in mind that the tree limb fluxes must be equal by maintaining the three voltage on primary equal with Phase Angle Firing. This means that if the loads on each phase are equal also the currents will be equal and viceversa. If loads are unequal and customer want to adjust the voltage to equalise the power in the 3 zones is not easy and can be done just with cautions and for small percentage. Avoid to do it is too dangerous. This means that a three phase transformer can not be treaded like three one phase transformers because there is an interaction between the phases.

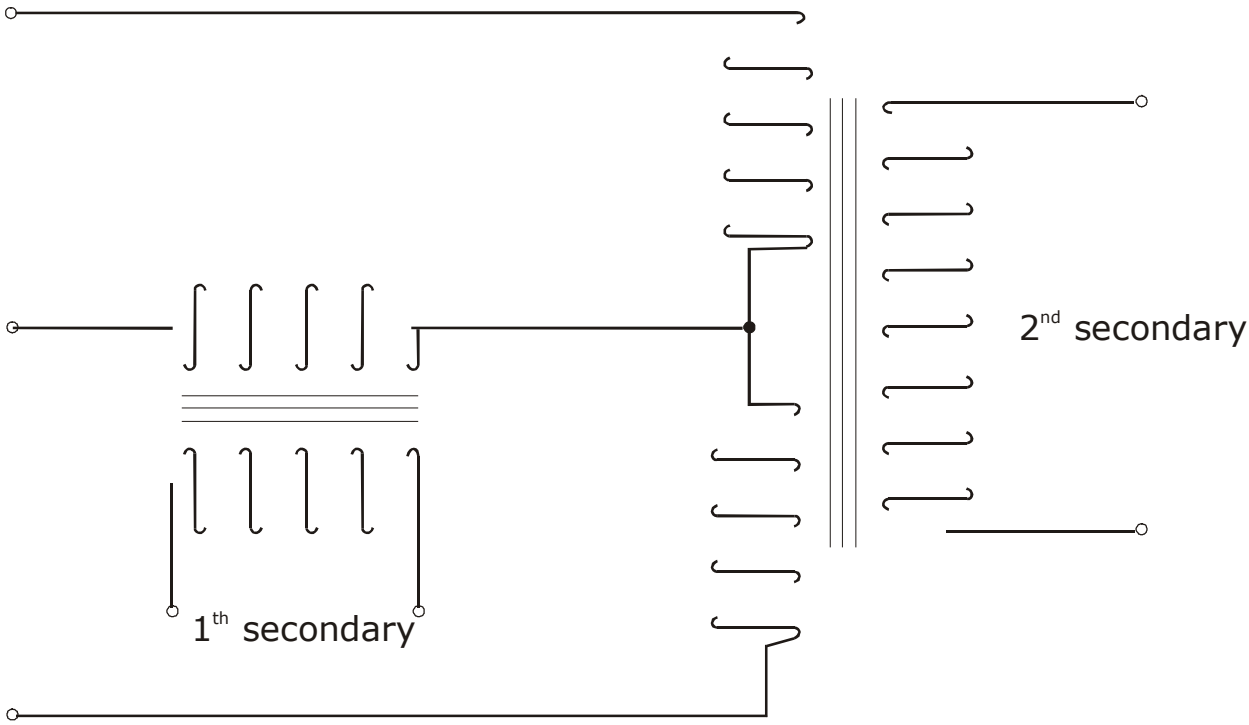
A extra complication are the harmonics generated by phase angle. To maintain the harmonics inside the transformer is used a delta connection on primary. The current in the windings consist of a range of harmonics in addition to the fundamental current. The effect of the harmonics an a core transformer is an overheating on the transformer core and on metallic steel case because the lost fluxes try to close via any metals in the vicinity. With delta connection the flux of the harmonics will add in a ring round the core with a resultant of zero.
Anyway in the field three applications where the primary is a star connection. Despite the guideline these applications are working with satisfaction probably because the transformers are lightly loaded and designed to work with low induction. One of the rules used by CD Automation when a transformer is ordered is:

- Increase the nominal power of the transformer of 20%
- Increase the nominal value of primary and secondary voltage of 10%.

  The transformer ratio remain the same but the transformer works at low value of induction..

4.6 Scott transformers

The Scott-wound Transformer is designed to have one three phase primary (normally star connected) and two one phase secondaries.



This type of transformer is not very popular but there are application where there are two zones and is necessary to balance the load on the three phases. The solution is a Scott-Transformer.

Typical applications are two zone furnaces and salt baths where, for supply reasons, energy for only two zones is taken from a three phase main voltage supply.

All the attentions paid for normal three phase transformers must be used also for Scott Winding Transformer.

Flux patterns are more critical than in normal transformers and so it's necessary to use a longer soft start.

It's suggested to have a Soft Start (Ramp) of 2 sec minimum.

In this application must be used Phase Angle and the harmonic content in load current are reflected on primary and on primary star connected the current on the three limbs can be different.

Another precaution is to use thyristor rated 1600V (reverse pick voltage) because can happen to have parasite voltage that damage Thyristers when are in off conditions. This happens when the secondary are not galvanically isolated.
If supply voltage is 400V use thyristor unit for 500V that as standard uses 1600V RPV. The Scott Transformers must work at low induction value 1 Wb/m^2

A good practice is also to use on primary a filter rated for 50 Hz.

The CD Automation Thyristor units to drive Scott Transformer are:

- CD30
- MULTIDRIVE

4.7 Why use thyristor unit in fournace

Electrical powered fournaces are becoming more important mainly for these reasons:

a) Clean ambient inside furnace;
b) Very high efficiency;
c) High capacity to maintain a stable temperature over a wide range of set points;
d) Capacity to optimising temperature uniformity;

Anyway to maintain points c) and d) using contactors is necessary to use a temperature cycle time of 20 sec. This means that at 50% power demand, that is a normal working condition after the Start up of the furnace, the contactors switch ON every 20 sec. and in one day 4.320 times considering 24 hours (normally furnaces don't stop)
In one year there are 320 working days:

total switches →4320 x 320= 1.382.400

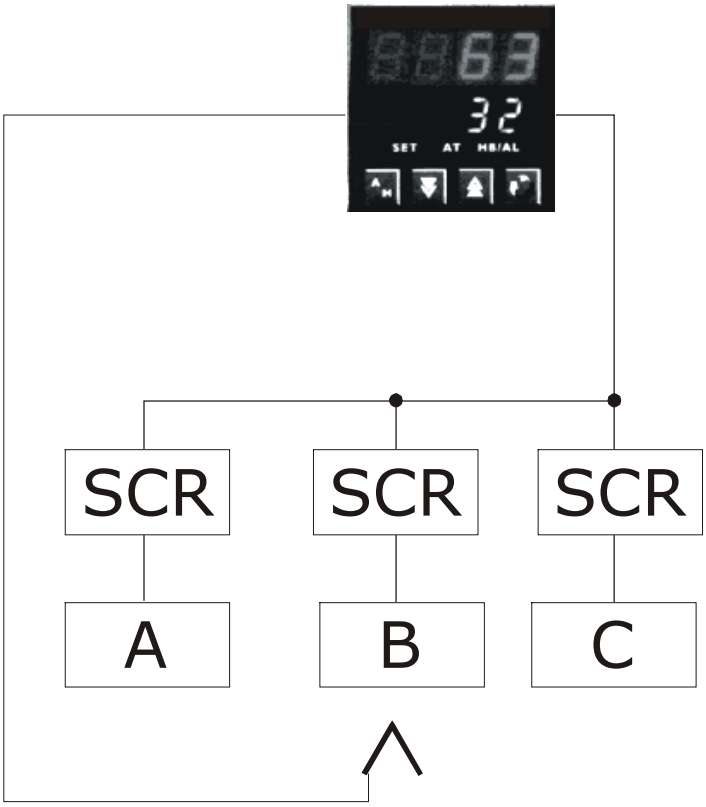
After 0,5 million of operation the contacts of contactor must be substituted. This is a big cost because:

- Every month the contacts done with precious metals have to be substituted.
  The cost of a medium size contactor 200A is 150 Euro;
- Every year the contactor has to be substituted because the mechanical life is finished. The 200A contactor cost is 500 Euro
- in addition when service or maintenance are done, there is a stop of the production with relative costs.

THYRISTOR UNITS

- The thyristor units are more expensive than contactor.
- The payback is very short because there are no maintenance or service costs and the life of one thyristor unit can be 10 years.
- In addition is also possible to use a cycle time very short (up to 20msec ON and 20 msec OFF this firing is known as Single Cycle very useful with low interthia systems). For Burst Firing see our application note on Firing modes available on CD Automation thyristor units.

- With Thriystor units is possible to adjust the power on different zones when are controlled by one temperature control only.



The output of the controller is a power demand from the process. If above process is a furnace and heating elements A – B – C are equal, but the B is central and has a lower heating losses, we can decide to send the same signal to A and C loads and to reduce the power with a devider of input signal on zone B. This can be done in digital mode on CD3000A-M family and Multidrive