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TESI DI LAUREA MAGISTRALE

DESIGN OF A POWER TRANSFORMER AND HVDC TRANSMISSION SYSTEM

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SOMMARIO

Nella rete elettrica i trasformatori hanno una notevole importanza, poiché con tale macchina è possibile variare principalmente i valori della tensione e della corrente. Questo permette di trasmettere l'energia dal punto di generazione fino all'utenza finale riducendo il più possibile le perdite, tenendo conto anche dell'aspetto economico in quanto non conviene avere un sistema con pochissime perdite se per realizzarlo sono necessarie molte risorse di denaro.

I trasformatori di potenza vengono progettati su commessa; questo significa che la macchina è pensata e costruita rispetto a delle specifiche caratteristiche richieste dal Cliente stesso. Durante la progettazione di una macchina elettrica non bisogna considerare solamente gli aspetti ingegneristici che mirano a costruire una macchina che si avvicini il più possibile ad una ideale, ma si deve tenere ben presente l'aspetto economico. In relazione a questi due aspetti il progettista deve essere in grado di progettare un trasformatore che rappresenti la soluzione tecnico - economica migliore. I parametri principali che il Cliente solitamente richiede sono la potenza nominale della macchina, la tensione nominale, il numero delle fasi, il tipo di connessione e il gruppo delle fasi, la frequenza nominale alla quale la macchina andrà ad operare, il tipo e il numero dei passi di regolazione del regolatore di tensione, l'impedenza percentuale e il limite delle perdite. Il Cliente deve inoltre fornire ai progettisti alcune informazioni riguardanti il sito in cui il trasformatore andrà ad operare come ad esempio l'altitudine, la temperatura ambiente media nel periodo estivo e quella nel periodo invernale, ecc. Un'altra informazione molto importante che i progettisti richiedono al Cliente riguarda gli standard di riferimento secondo i quali la macchina deve essere progettata e inoltre se esistono delle limitazioni dimensionali relative al trasporto del trasformatore e al suo posizionamento in sito.

Il punto di partenza per la progettazione di un trasformatore di potenza, in seguito alle caratteristiche che la macchina deve presentare una volta realizzata, è la determinazione della sezione del nucleo. Questo può essere fatto in relazione alla taglia della macchina, cioè alla sua potenza nominale. Già in questo primo step si deve tenere presente la relazione tra le perdite nel ferro e le perdite nel rame, così si può scegliere una sezione un po' più grande o più piccola in modo che vada a favorire una o l'altra situazione. Per quanto riguarda le altezze delle colonne vengono determinate in seguito, in relazione all'altezza degli avvolgimenti e al livello di isolamento necessario.

Successivamente deve essere determinato il livello d'induzione e qui si deve tener conto che un suo valore elevato va a ridurre il peso del rame e le sue perdite e inoltre riduce il peso del nucleo. A questo punto non si deve comunque dimenticare che una elevata induzione ha lo svantaggio che aumentano le perdite nel ferro.

In seguito si va a determinare in maniera molto semplice la tensione per spira, il numero di spire dell'avvolgimento e la corrente di fase. Per quanto

riguarda il numero di spire dell'avvolgimento che presenta la regolazione si devono calcolare anche il numero di spire massime, minime e intermedie relative ai vari gradini della regolazione della tensione. Solitamente il commutatore sotto carico viene inserito sul lato "alta tensione" della macchina perché con questo tipo di inserzione è più facile effettuare la commutazione. La commutazione risulta più semplice da effettuare in quanto la corrente nell'avvolgimento "alta tensione" è minore rispetto a quella del lato "bassa tensione", quindi l'arco elettrico che si crea durante la commutazione è più semplice da estinguere.

Ora devono essere determinati gli avvolgimenti e questo rappresenta uno dei passi più importanti durante la progettazione del trasformatore, poiché in relazione alla loro geometria dipendono molti fattori quali ad esempio i flussi dispersi della macchina, la caduta di tensione reattiva percentuale, ecc. Scegliere l'altezza dell'avvolgimento, cioè se questo deve essere più alto oppure più schiacciato, non è una cosa semplice. Infatti questo tipo di scelta dipende dalla densità di corrente che si sceglie per i conduttori, dal livello di tensione del lato "alta tensione", dal volt-spira che è stato determinato, ecc. Gli aspetti ambientali del sito in cui andrà ad operare il trasformatore, le sovratemperature ammesse e il sistema di raffreddamento che si andrà ad adottare per la macchina, giocano un ruolo fondamentale nella scelta della densità di corrente. Infatti questo parametro è strettamente legato alle perdite che poi dovranno essere dissipate per far si che la macchina non vada ad operare in condizioni di sovratemperature non ammissibili. Gli avvolgimenti possono essere ad elica oppure a disco e questo rappresenta la principale suddivisione sul tipo di avvolgimenti dei trasformatori. In queste due differenti categorie poi troviamo molte diverse soluzioni che vengono adottate in relazione a certe caratteristiche della macchina. Tra i principali fattori che influenzano l'utilizzo di un tipo di avvolgimento rispetto ad un altro sono il livello di tensione dell'avvolgimento, il livello di flusso disperso che si vuole avere, le perdite e il tipo di raffreddamento.

Determinato il tipo di avvolgimento, il quale normalmente non è lo stesso per l'avvolgimento di bassa tensione, per quello di alta tensione e nemmeno per quello di regolazione, si passa a determinare il tipo di conduttore che deve essere utilizzato. Per questo tipo di scelta un ruolo fondamentale è sicuramente rappresentato dal limite delle perdite nel rame che si possono avere e dalla sovratemperatura alla quale il conduttore andrà ad operare. A questo punto si può stabilire l'ingombro geometrico degli avvolgimenti ed in seguito si possono determinare le dimensioni della finestra del nucleo.

A questo punto si possono determinare il peso del nucleo e degli avvolgimenti e poi proseguire con la determinazione delle dimensioni della cassa.

Il passo successivo è rappresentato dal calcolo delle perdite da dissipare in modo tale che la macchina operi in condizioni garantite al Cliente senza eccedere nei livelli imposti dalle norme. Questo tipo di calcolo è fondamentale poiché va a determinare il tipo di raffreddamento che deve essere realizzato sul trasformatore.

Un ultimo passo nel processo è quello della scelta dei vari accessori e componenti presenti sulla macchina. Viene effettuato anche il calcolo del peso del trasformatore completamente montato e anche smontato e pronto per il trasporto per verificare che non si siano superati i limiti imposti.

La progettazione di un trasformatore di potenza è sicuramente molto complicata in quanto bisogna tenere in considerazioni un numero notevole di parametri. Inoltre tale processo non è lineare ma deve essere fatto in maniera "iterativa", cioè ad ogni passo bisogna tornare a quello precedente e verificare che non si siano modificati alcuni parametri che non rispettino più le richieste del Cliente e gli standard delle normative. Per un progettista è sicuramente molto importante avere molta esperienza in tale settore poiché questo lo aiuta nelle varie scelte tecnico – economiche che devono essere fatte per riuscire ad ottenere la soluzione migliore, la quale deve soddisfare le esigenze e richieste del Cliente, e inoltre il profitto dell'azienda per cui lavora.

Per quanto riguarda la trasmissione di energia elettrica in questi ultimi anni ha preso sempre più importanza il sistema di trasmissione di energia in alta tensione a corrente continua. Analizzando la situazione a livello globale, al giorno d'oggi assistiamo all'urbanizzazione, cioè grandi masse di popolazione si stanno spostando verso le città per creare delle "mega città". Gli esperti dicono che nei prossimi 20 anni la richiesta di energia elettrica aumenterà del 70% rispetto al valore attuale. Per riuscire a soddisfare questa richiesta è necessario lo sviluppo di nuove tecnologie e trovare delle soluzioni di trasmissione che permettano di ridurre il più possibile le perdite. Ciò significa che sarà necessario produrre energia anche in luoghi molto distanti rispetto al consumatore finale, ma il trasporto di tale energia deve essere fatto con dei valori di perdite che siano le più contenute possibile. Una soluzione che soddisfa queste richieste e che ha sempre una maggiore importanza è la trasmissione in alta tensione in corrente continua.

Un sistema HVDC (High Voltage Direct Current) può presentare tre diverse strutture. La prima struttura è rappresentata dalla HVDC long distance line che serve per la trasmissione di energia elettrica per lunghe distanze. La seconda struttura è rappresentata dalla HVDC cable line che viene principalmente utilizzata via mare. Queste due strutture sono caratterizzate da una stazione di conversione AC/DC all'inizio della linea, poi dalla linea elettrica e infine da un'altra stazione di conversione ma questa volta DC/AC. La terza struttura invece è la stazione HVDC back - to - back, che rappresenta l'unica soluzione per interconnettere sistemi che operano a frequenze diverse. Questa struttura è caratterizzata dal fatto che la conversione AC/DC e DC/AC sono fatte nella stessa stazione e la distanza tra le loro valvole è la più piccola possibile.

I trasformatori HVDC vengono così chiamato solamente per indicare in maniera specifica in quale sistema vengono utilizzati, ma nella pratica sono dei trasformatori che funzionano in corrente alternata. Un trasformatore HVDC è quindi un trasformatore "tradizionale" per il quale però devono essere fatte alcune considerazioni che dipendono dal particolare sistema nel quale viene utilizzato.

Solitamente queste macchine elettriche sono costituite da unità monofasi che poi vengono opportunamente connesse tra di loro per andare a formare un sistema trifase. Non vengono progettate delle macchine trifase di grandi potenza poiché queste andrebbero ad avere delle dimensioni enormi e sarebbe quindi molto difficoltoso il trasporto (se non impossibile); inoltre anche dal punto di vista ingegneristico e di costruzione non sarebbe conveniente.

Il nucleo dei trasformatori HVDC è formato solitamente da due colonne principali e due colonne di ritorno. Per quanto riguarda gli avvolgimenti bisogna considerare molti parametri i quali sono principalmente legati al livello di isolamento in quanto queste macchine vanno a lavorare con tensioni molto elevate, quindi le distanze tra parti attive per garantire l'isolamento sono maggiori rispetto a trasformatori di potenza che generalmente operano con tensioni minori. I trasformatori HVDC hanno due avvolgimenti secondari che vanno collegati ai convertitori per la conversione ed essi sono montati uso su una colonna principale e uno sull'altra. Bisogna tenere presente che uno di questi due avvolgimenti viene collegato a stella mentre l'altro viene collegato a triangolo. Questo particolare collegamento va a favorire la tensione in uscita dal convertitore che così risulta essere prossima ad un valore ideale. Per quanto riguarda invece l'avvolgimento primario, esso è "diviso" in due parti uguali, ognuna delle quali è montata su una colonna principale. Un'altra particolarità che presenta questo tipo di macchina riguarda la cassa che non è di tipo convenzionale. Questo dipende dal particolare posizionamento degli isolatori sul lato dove ci si collega poi ai convertitori da una parte, mentre il sistema di raffreddamento è posto sul lato opposto per facilitare lo scambio di calore.

In conclusione quando si deve costruire una nuova linea di trasmissione si deve valutare se conviene realizzarla in corrente alternata oppure in corrente continua. Per quanto riguarda i sistemi in corrente continua presentano sicuramente degli investimenti economici iniziali maggiori. Si è visto che se la linea di trasmissione è molto lunga (al di sopra di circa 700 km) è conveniente utilizzare il sistema in corrente continua.

INTRODUCTION

The term transformer defines a static electrical machine, that is without moving parts, which allows transferring active and reactive power between two alternating current power systems, among them not directly related but magnetically coupled and at different operating voltages. The transformers are a key component in the process of generation, transmission and distribution of electricity.

The policy of Siemens A.G. and also of Siemens LTDA is to know customers, understand and anticipate their needs and satisfy those explicit and implicit ones by providing competitive products. In order to achieve these objectives one need to be pro-active, offer visible results, motivate all staff to recognize and reward superior performance, propose solutions and do not find excuses. Regarding the technical aspect must develop and maintain primary technology, have introduced innovative products and solutions and continuous improvements in processes.

The main points of Siemens LTDA history will be illustrated from the beginning until to arrive to be the biggest industrial area in the energy sector of the South America. Some information will be also provided about their products like, for example, the size of the machines, the quantity that are produced, the main areas of business, the number of the persons that work inside the factory and so on.

After will be proposed a guideline for to design a power transformer. In this part will be possible to find some considerations with an electric and mechanic aspect about the different choices that can be possible to do during the process design of the machine.

In another part of this report, it will be explained the structure of the HVDC system in the transmission of energy and its advantages. There will be an overview on the main part of this system and an explanation of the aim of the most important components. There will be particular attention on the HVDC transformers where it will be possible to find the most information about the structure and the main points during the design process.

Some advice will be related about the tests that the transformers should pass to respect the standards and also some particular specifications that the customer require for the machine. All these information will be explained in the thesis.

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1. History

Regarding the energy sector, Siemens is the market leader in offshore wind farms, it is producer of gas turbines larger and more efficient, it is leading supplier of systems high voltage direct current HVDC and it offers a full range of efficient solutions for energy saving in buildings.

The reinforcing business success and social commitment is the object for Siemens in Brazil and also around the world. The vision and mission of the group, identify with the global efforts and global guideline of the organization, for developing, executing and maintaining policies that add value to the company and increase its contribution to sustainable development.

The Jundiaì site was founded in the 1970s, when the TUSA transformer plant was inaugurated. Now the site gathers factories that manufacture all the following products: power transformers up to 1000 MVA/800 kV, HVDC converter transformers, SVC transformers, shunt reactors up to 120 MVAr/800 kV, special transformers for rectifier and furnace applications, GEAFOL® cast-resin transformers, voltage regulators, oil-immersed distribution transformer, digital monitoring system. There are also retrofits and repair units.

The Jundiaì site represent the largest Generation, Transmission & Distribution equipment manufacturing site in Latin America and it counts on 61.000 m^2 of constructed area on 188.000 m^2 property and the unit generates around 2000 workstations. The milestones of its history are the following:

1973: start-up of Siemens' activities at the Jundiai transformer plant.

1978: inauguration of Latin America's largest transformer plant of up to 400 MVA, equipped with a state of the art high voltage test field and an internal pneumatic transportation system.

1998: Siemens produces for New Zealand the biggest three phase transformer ever built in Latin America

2000: installation of the 510 km long 440 kV Taquaruçu-Assis-Sumaré (SP) transmission line, with three substation.

2003: acquisition of Alstom's gas and steam turbine division, which already had an industrial turbine plant in Taubaté (SP), Brazil.

2005: construction start-up of the new industrial steam turbine plant in Jundiaì.

2006: transfer from Tuabaté to Jundiaì of the entire industrial steam turbine production. Delivery of the first 500 MVA 800 kV transformer repaired by Siemens in Brazil and the first power transformer immersed in vegetable oil produced by Siemens in Brazil.

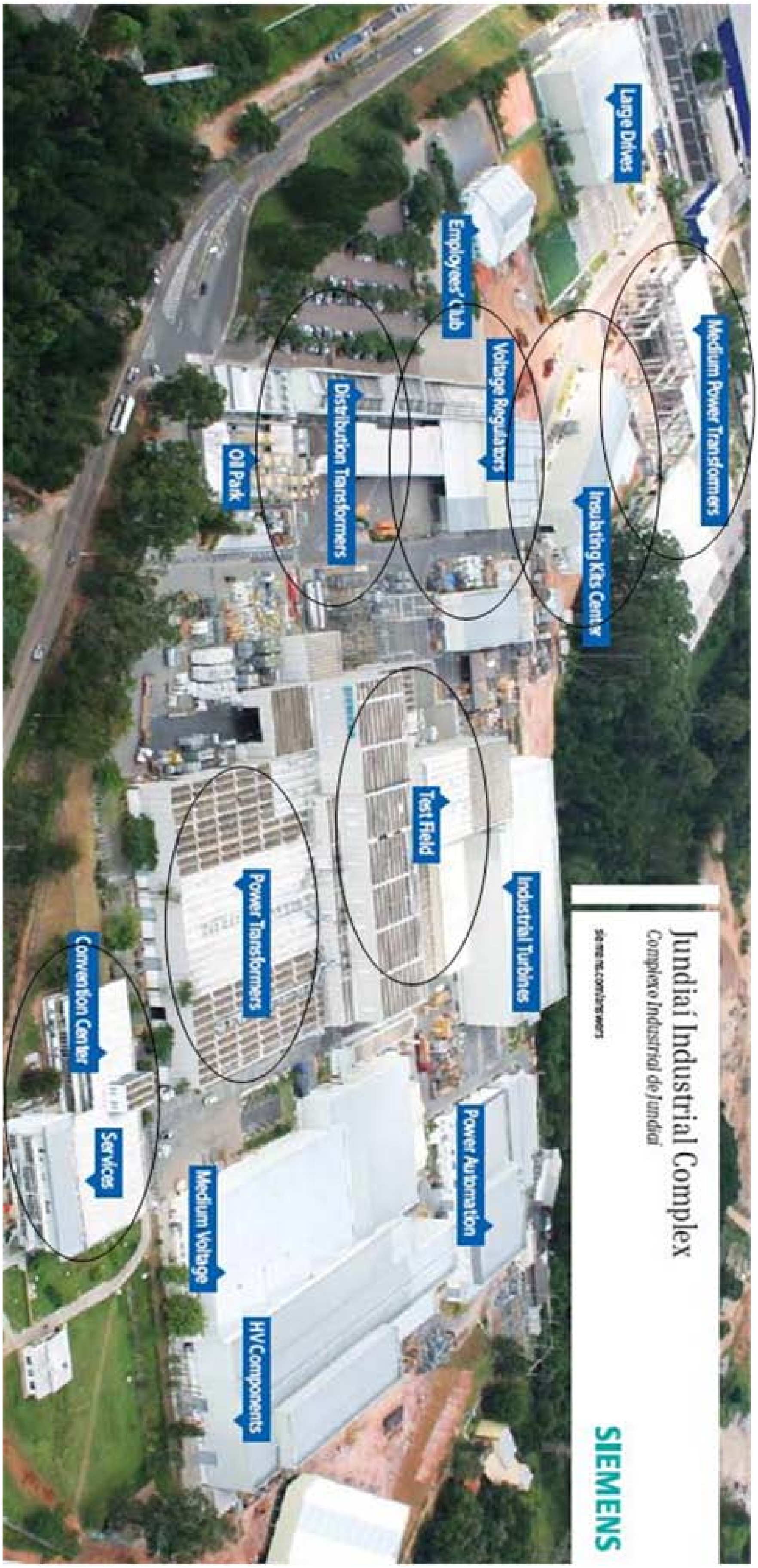
2007: inauguration of the Jundiaì site expansion with the insulation material factory, which now houses in a single location all of Siemens' power equipment plants in Brazil.

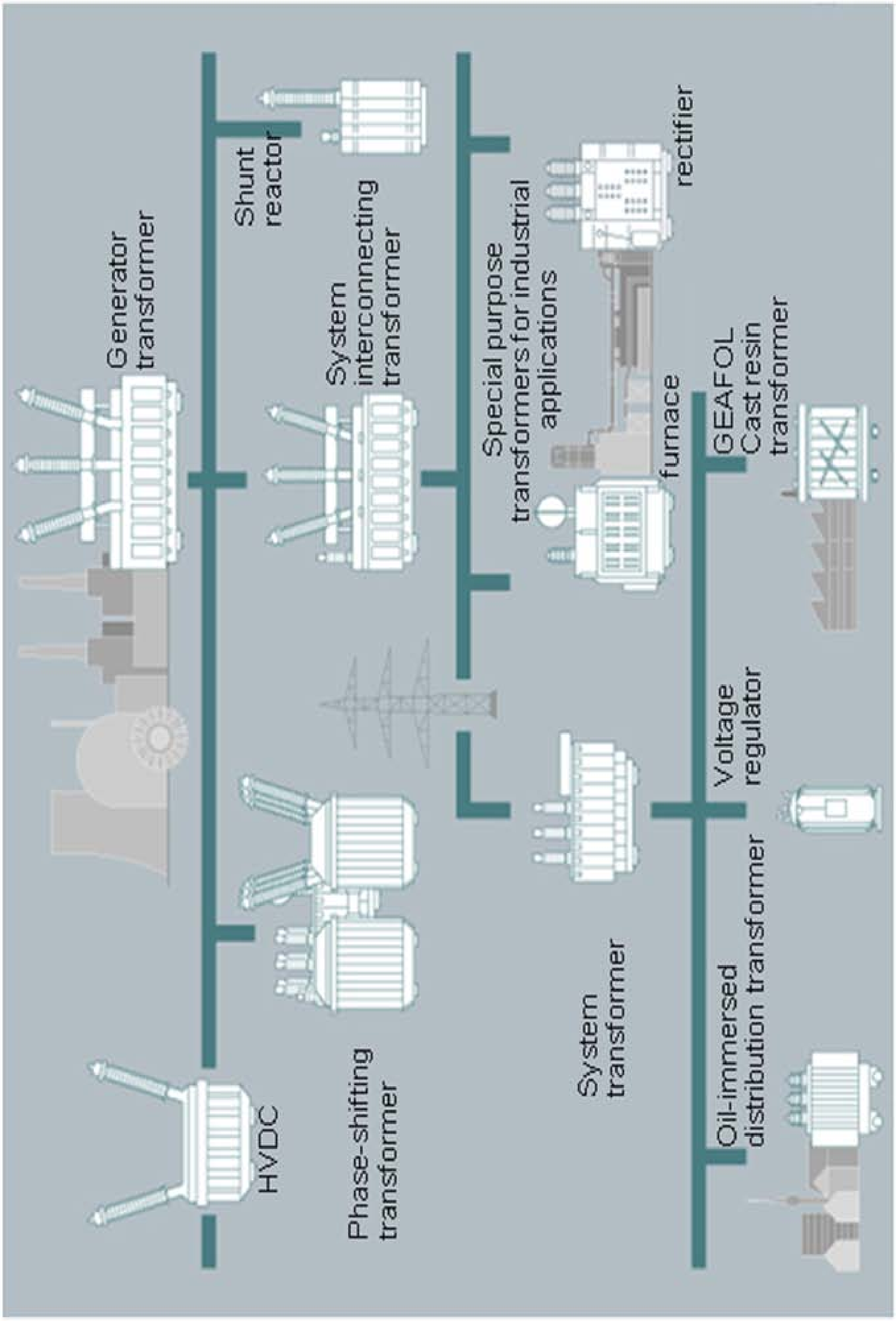
2008: inauguration of the voltage regulator and large drives plants.

2009: expansion of insulating kit centre and construction of medium power transformer plants.

2010: *inauguration of the "new" MPT factory – transformers up to 100 MVA and 230 kV*

Below there are two pictures. The first one is on the Jundiaì site where it is possible to see all the factories that compose it. In the image are highlighted parts of the site that they are destined for the transformers. The second one is on the transformers that they are designed in the site. It is possible to see that they are designed machine for all level of generation, transmission and distribution.


Jundiaí Industrial Complex
Complexo Industrial de Jundiaí
SIEMENS
Large Drives
Employees' Club
Medium Power Transformers
Voltage Regulators
Distribution Transformers
Oil Park
Insulating Kits Center
Test Field
Industrial Turbines
Power Transformers
Convention Center
Services
Medium Voltage
Power Automation
HV Components


Generator transformer
Shunt reactor
System interconnecting transformer
Special purpose transformers for industrial applications
rectifier
furnace
GEAFOL Cast resin transformer
Voltage regulator
HVDC
Phase-shifting transformer
System transformer
Oil-immersed distribution transformer

2. Design of a power transformer

2.1 Common characteristics required

Siemens LTDA produce the power transformers on job order, it is mean that the machine does not have only some default size but the transformers are designed on the specific request and features that the customer want.

Usually the main data that the customer require and explain in his document where there are all the parameters that should be respect on the machine are:

- Rated power
- Rated voltage
- Number of phases
- Windings connection and connection group
- Frequency
- Number of steps in voltage regulation and percentage value for each step
- Technical characteristics like impedance in percent, possible earthed neutral, etc...
- Particular prescriptions like on the tank, on the cooling system, etc...
- Limits of the losses
- Standard of design which are referred the tests voltage for each winding and the maximum over temperature
- Size limitation for the transport
- Ambient temperature
- Altitude

2.2 Choice of the core cross-section

Power transformers are usually built in three-phase unit and in this case it is possible to define the cross-section of the core with the following formula:

$$F = K \cdot \sqrt{\frac{P}{f}}$$

where:

F is the effective cross-section of the core [cm^2]
P is the rated power [kVA]
f is the frequency [Hz]
K is a coefficient

The coefficient K depends from the level of the losses in the iron and in the copper. It is also depends from rated power level and from the percentage voltage drop. For example, if the valuations of iron losses are much higher than the copper losses, it is better to take a small value of K and in this way it is possible to reduce the weight and the cross-section of the core. Another situation can be when the iron and copper losses have a similar value. In this case for the value of K is preferred a choice that increase a little bit the cross-section of the core but reduce the quantity of copper and also the number of turns in the windings. This choice is done for an economical reason. In other similar case the research of value K is common done with search for to find the best economical solution. Understand the relation between the coefficient K and the rated power, we can consider the following reasoning: if we regard a fixed value of K and increase the rated power, it is necessary to increase the height of the windings but on this parameters there are some restrictions for the transport.

If the required percentage reactive voltage drop is small and the level of voltage in AT side of the machine is high, it is necessary to have as big as possible cross-section of the core.

The other dimensions of the core are defined after the determination of the height of windings, but it is necessary to consider the following aspect:

- if the core has only three limbs, the cross-section of the core is constant on its parts
- if the core has the return limbs, the joke and the return limbs have a cross-section that it is about 0,58 times the value of the main limbs cross-section
- in both case it is necessary consider the minimum value for the isolation between the windings and the core

2.3 Assignment of flux density

The value of flux density depends on different factors like rated power, limits of iron losses, impedance. Normally it is necessary to choose it with a value between 1,7 and 1,95 Tesla in relation also with the sheet quality of iron that it will be use for built the core. The main advantages on a high level of flux density are:

- Minor weight of the copper
- Minor copper losses
- Minor iron weight because the limb are shorter and also the windings encumbrance is smaller

The main disadvantage on a high level of flux density is that the iron losses increase. In the choice of the value of the flux density it is necessary look if the best solution is reduce the weight and losses in the copper or reduce the iron losses. Determinate the best solution is not very easy. The experience and also some similar old projects can help to find the settlement.

2.4 Define the voltage per turn

Define the voltage per turn is one important step during the design of a power transformer. Its value can be calculated using the following formula:

$$E_t = \sqrt{2} \cdot \pi \cdot f \cdot 10^{-4} \cdot F \cdot B = 4{,}44 \cdot f \cdot 10^{-4} \cdot F \cdot B$$

where:

B is the flux density [Wb/m^2]

E_t is the voltage per turn [V/turn]

2.5 Determination of number of turns in the windings

In the determination of the turns number in the windings is very important consider that it is necessary to use the phase voltage. During this step of the design, the kind of winding connection is fundamental. In fact with a delta connection the line voltage is equal than the phase voltage. In the star connection it is essential take into account that the phase voltage is the result of the division between line voltage and the square root of 3. The number of turns in the winding under examination is defined in the following way:

$$N = \frac{E}{E_t}$$

where:

N is the number of turns

E is the phase voltage [V]

If in the design of the transformer is required the voltage regulation, it is necessary to define the number of turns that must be added or subtracted for each voltage regulation step in the winding. Do it is fairly easy because the voltage per turn is defined, so it must be narrow the output that will be connected with the tap changer. It is possible calculate the number of turns in the maximum and minimum position of the tap changer with the following formulas:

$$N_{MAX} = \left(1 + N_{step} \cdot E_{\%reg}\right) \cdot N$$
$$N_{\min} = \left(1 - N_{step} \cdot E_{\%reg}\right) \cdot N$$

where:

N_{max} is the number of turns in the maximum position of the tap changer

N_{min} is the number of turns in the minimum position of the tap changer

N_{step} is the number of step that the customer require in the regulation

$E_{\%reg}$ is the percentage value of the voltage for each step in the regulation

Usually the on-load tap changer is installed on the high voltage side. This kind of solution is very convenient because in the high voltage side the current is smaller than in the low voltage side. For this reason it is more easy extinguish the arc that it is formed during the switching time and also it is possible reduce the risks of damage.

2.6 Phase current determination

In the process for calculate the phase current it is necessary go through the line current in the following way:

$$I_{line} = \frac{P \cdot 10^3}{\sqrt{3} \cdot U}$$

where:

I_{line} is the line current [A]
U is the line voltage [V]

If there is the tap changer, the current reported to the maximum and minimum position of the tap changer must be calculated. For to do that, it is used the same formula where only the voltage is changed and its value is referred with the position of the regulation. It is show below:

$$I_{line\_MAX} = \frac{P \cdot 10^3}{\sqrt{3} \cdot U_{MAX}}$$

$$I_{line\_\min} = \frac{P \cdot 10^3}{\sqrt{3} \cdot U_{\min}}$$

where:

I_{line_MAX} is the line current with the tap changer in the maximum position [A]
I_{line_min} is the line current with the tap changer in the minimum position [A]
U_{MAX} is the line voltage with the tap changer in the maximum position [V]
U_{min} is the line voltage with the tap changer in the minimum position [V]

The phase currents are easily obtained considering the connection of windings if it is in star or delta configuration.

- In star connection: $I_{phase} = I_{line}$
- In delta connection: $I_{phase} = \frac{I_{line}}{\sqrt{3}}$

Obviously also for this current it is necessary to consider the phase current in the maximum, rated and minimum position of the tap changer using the line current obtained before. It is require only on the side where the tap changer is installed.

At the end of all this calculations for all windings it is heartily recommend do a verification multiplying the number of turns for each position of the tap changer with the relative currents at that position, because the result of the product have to be the same for all the windings. Generally it applies the following relation:

$$N_{HV} \cdot I_{phase\_HV} = N_{LV} \cdot I_{phase\_LV}$$

where:

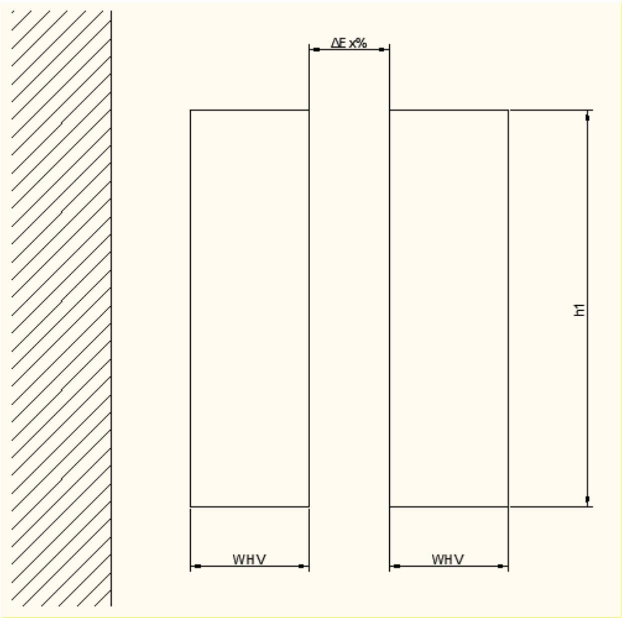
N_{HV} is the number of turns in high voltage windings
N_{LV} is the number of turns in low voltage windings
I_{phase_HV} is the phase current in high voltage windings [A]
I_{phase_LV} is the phase current in high voltage windings [A]

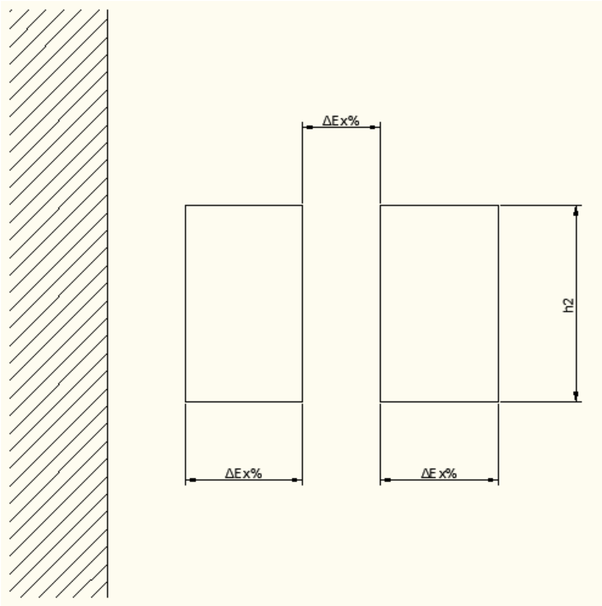
2.7 Sizing of windings

This part is very important because from the geometrical dimension of the windings depends the flux leakage and accordingly the percentage voltage drop for the reactive part. In the design of sizing windings is necessary go through the following process.

2.7.1 Predetermination of windings height

It is possible have two main dispositions for the windings if the same number of turns is considered and the same volume of copper and they are showed in the pictures below:





where:

LV is the low voltage winding
HV is the high voltage winding
W_{LV} is the width of low voltage winding
W_{HV} is the width of the high voltage winding
Δ is the width between the LV and HV
h is the height of the winding

In the first picture it is possible to see that the windings height h_1 is bigger that the height h_2 of the second situation. The main difference is that if it is used a high value for the height of winding it is possible to reduce the percentage reactive voltage drop because in this case the leakage flux is smaller. The leakage flux is smaller in this situation because the distance from the ends of windings with limb and joke of the core is smaller respect the other illustrated case. Obviously, if it is choice a small value of winding height the percentage reactive voltage drop is bigger because the resultant flux leakage is bigger.

The choice is done on the configuration that respect the customer requires on the percentage reactive voltage drop. Anyhow, the choice of windings height depends also from the following characteristics:

- ***Current density:*** if the values of currents density are lower, the windings height will be high. In the opposite situation if the values of currents density are big, the windings height will be small.

- ***Voltage level of HV side:*** if the HV voltage level is high, to respect the percentage reactive voltage drop required, the height of windings must be big because in this case the dimension of wire isolation and the distance between the LV and HV windings is bigger. If the width of isolation increase and also increase the distance between the LV and HV side, it mean that the flux leakage is bigger and respect the percentage reactive voltage drop is necessary the choice of a big value for windings height.

- ***Voltage per turn:*** if the value of voltage per turn is big, consequently the number of turns is smaller and it mean that the value of windings height can be decreased. Otherwise, if the voltage per turn is small the number of turns is bigger and the windings height is increased. It means that the flux leakage depends also from the widths of the windings areas (W_{HV} and W_{LV}).

First indicative values for calculate the windings height can be defined from the formula below but after it is possible adjust its value considering the concepts explained above.

$$h = \frac{N \cdot I_{phase}}{C \cdot \sqrt{F \cdot B}}$$

where:
h is the windings height [mm]
C is a coefficient that it is defined using some similar machine

2.7.2 Choice of current density

Another important aspect during the process of windings design, it is the choice of the current density. Its value depends from some different parameters:

- ***Evaluation of copper losses:*** if its value is high, it is recommended use a small value for the current density to reduce the losses.

- ***Cooling system:*** if, for example, the cooling system is ONAN (circulation of natural oil and natural air) the current density must be small than in the case with a cooling system ODWF (circulation canalized and forced for the oil and forced water) because the efficiency of ONAN system is lower than ODWF system. This means that the ODWF cooling system is able to dissipate more heat than the ONAN system, so it is possible to use a higher value of current density in the case ODWF.

- ***Limit of rise temperature:*** its values are fixed from the standards. It is possible that some customer has some particular request on it, but it is unusual. If the over temperatures have a high value, it is possible to use a high current density. Otherwise, if the over temperatures are small the current density must be small. The over temperature depends from the ambient temperature of the place where the transformer will be installed. It is clear understand the importance of know the temperature of the location where the machine will work.

- ***Weight:*** this parameter is important if there is some limitation in the transportation weight. In this case it is fundamental increase the current density, but probably it will be necessary increase the power of the cooling system.

- ***Eventual overload requested:*** it is easy understand that if in the design of the machine is required some special overload, the current density must be lower. The reason of this choice is that in the overload situation the over temperature have to be respected for have not some problem with the insulation and does not go over the guaranteed value in the losses. There are some standards that define the permitted over temperature for the overload. Their values are related also with the kind of overload, like for a short time or for a long time. Obviously their values are different in the both case.

Naturally there are some advantages and also some disadvantages in the choice of a low value for the current density.
The main advantages are:

- ***Low level of copper losses:*** it depends from the multiplication between the resistance of the copper and the square of the current. With a low current density the resistance of the wire is lower.

- ***Lower over temperature:*** the average temperature of winding is smaller because the current that go through the winding is smaller, so if there is an overload the temperature in the winding increase slowly.

- ***Reduction of cooling system:*** the quantity of heat that must be dissipated is lower and so the power of cooling system can be lower.

The main disadvantages are:

- ***Higher copper weight:*** the cross-section of the wire is bigger and the weight of the windings is higher.

- ***Higher losses due to the Foucault's current:*** in this case the wire has a big cross-section. This kind of losses increase because they depend from the lateral cross-section of the wire that it is invested from the flux.

- ***Small increase in weight of iron:*** it is necessary for "compensate" the more quantity of copper.

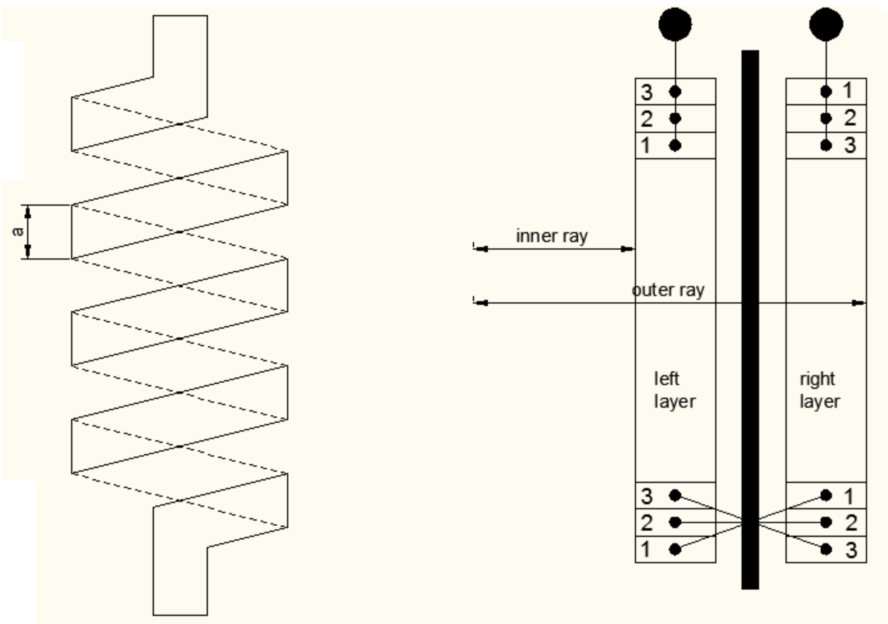
- ***Consequence increase of iron losses:*** it due to of a major quantity of iron.

- ***Increase weight of transformer and oil:*** it is necessary more quantity of iron and copper. The tank, consequently also the weight of oil, must to be bigger in dimension to guarantee the insulation level.

2.7.3 Choice in the kind of windings

In the construction of a winding there are not only one model, but it is possible to build it with different kinds of structure. Below it is possible find the most used structures for the windings in the power transformers.

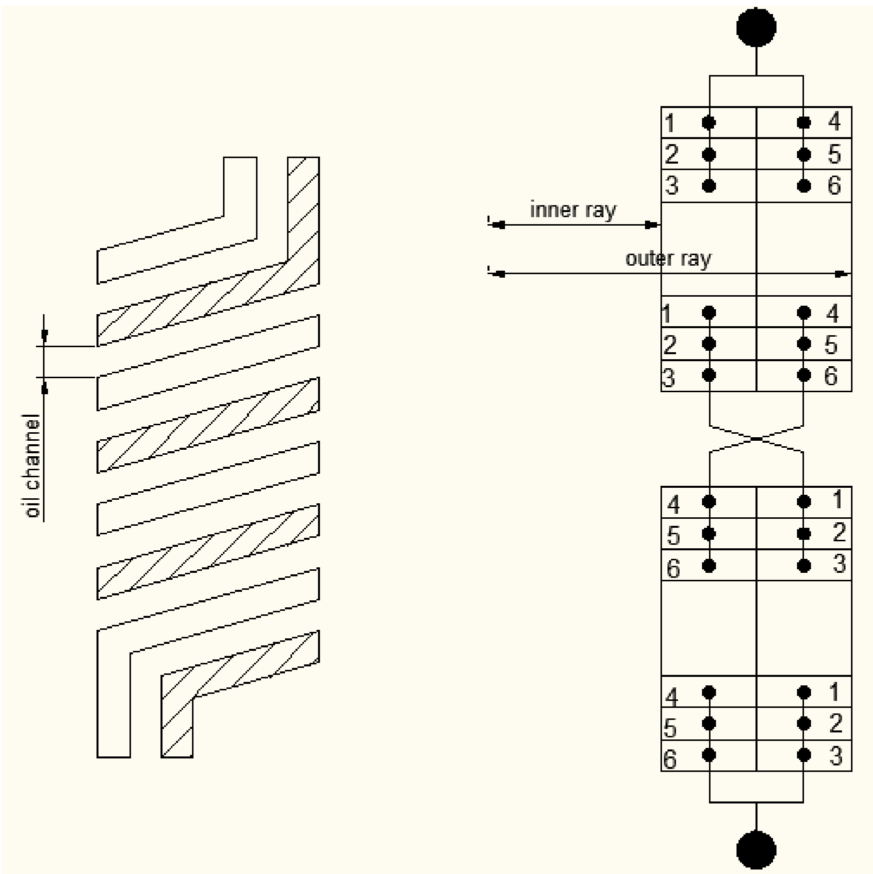
1. ***Simple layer winding:*** this kind of winding is used for the LV side where the number of turns is small and the current in the winding is high. It is possible use more than one layer and they are classified in right layer and left layer. The distinction between those two name is not for technical reason, but it is done only for distinguish them. It can built with one or more conductors in parallel, but only in axial direction. If there are conductors in parallel, the transposition of them is very important, because in this way each conductor is subject at the same induced voltage and the current is uniformed distributed in the wires. The relatively capacity is low and this kind of winding is used until 36 kV. Below there is a schematic representation of this kind of winding.



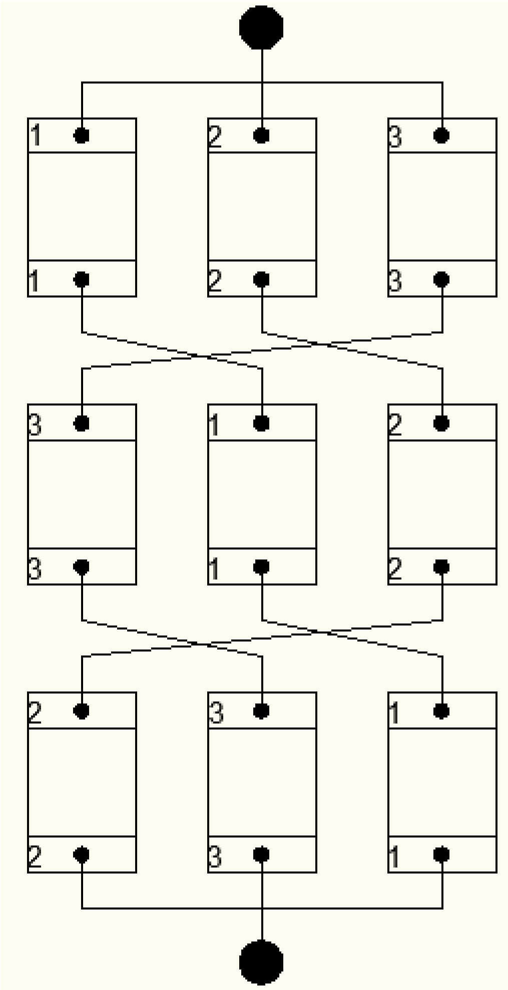
where:

a is the height of the wire

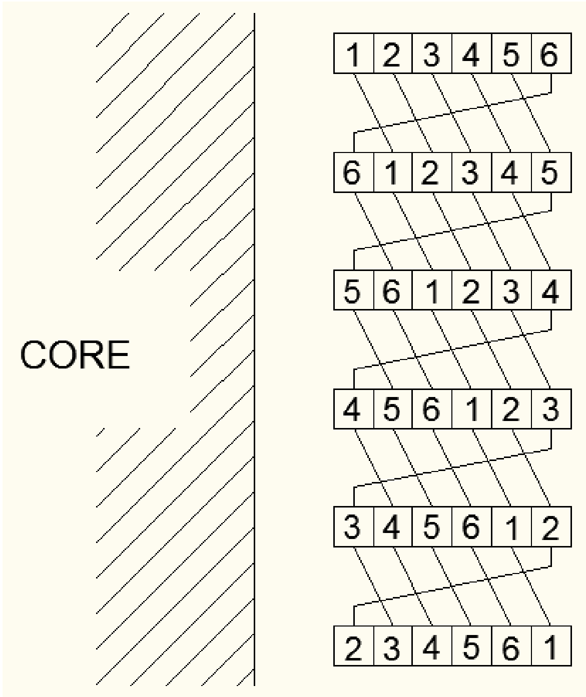
2. ***Double layer winding:*** also this kind of winding is used for the LV side with small number of turns and high current. It is possible use more than one layer. It is built with more than one conductors in parallel. There are always 2 conductors in parallel in radial direction and in axial direction they can be one or more. The transposition of wire is very important for the same reason explained above. Radial and axial channels can be utilized or not in this solution. This configuration permit to reduce the losses in the winding. Below there is a schematic representation of it.



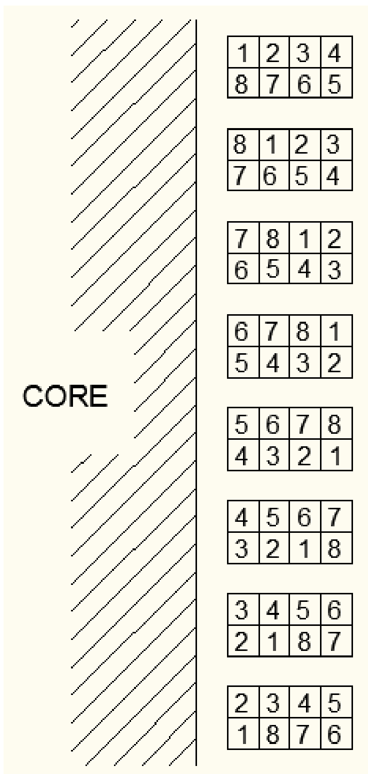
3. ***Cross cylinder:*** in this kind of winding there is only one layer with more than two conductors in parallel in radial direction and with axial channels between them. This structure is done for cooling and dielectric reasons. Also in this situation, the transpositions are needed for the same concept explain before. Transposed cable are normally used also. This solution is take into account until 230 kV when the single or double layer are not enough.



4. **Simple helix:** this kind of winding is used for thermal reason and it presents radial channels. The conductors are disposed in parallel in radial direction and there are radial channels. Of course the transposition is necessary. This solution is used until 36 kV with an high current. It can be built using layer winding with transposed cable.



5. ***Double and multiple helix:*** in this configuration there are also 2 or 4 conductors in parallel in axial direction, moreover the wires in parallel in radial direction. It is used until 36 kV with an high current that the simple helix cannot support.



6. ***Disk winding:*** with this configuration it can be used single conductor, twin conductor or more and transposed cable. Obviously they are built with the transpositions and on these parts it is necessary to increase the isolation. The windings can present only radial channels, or only axial channels or a combination of radial and axial channels. The input and the output of the winding can be positioned on the same side but for to do that, the number of all disks must be even. Below there is a representation of it. One very important concept is represented from the following formula:

$$N_{disk} \cdot N_{turns\_disk} > N$$

where:

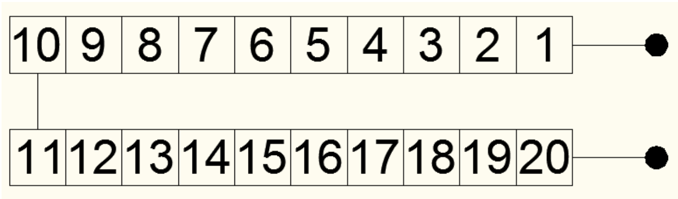
N_{disk} is the number of disks in the winding
N_{turns_disk} is the number of turns per disk

This equation has to be respected because during the pass from one section to the following one, there is a part of the turn that it is lost. In this way the encumbrance of the winding results uniform.

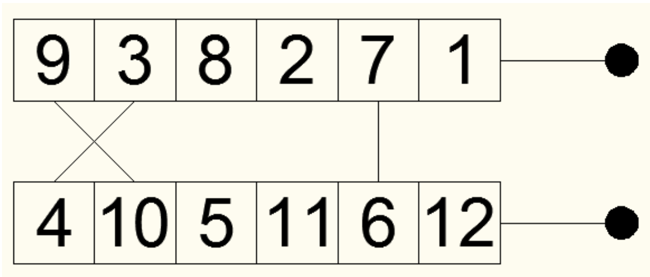
This solution is used usually on the HV side in a machine with a big rated power and where there is a high voltage. It is also used on the LV side when the helix winding is not enough.

In the disk winding there is a classification in "continuous disk" and "interleaved disk". In the "continuous disk" every section is connected with the following one without soldering, how it is showed in the picture above. The "interleaved disk" is used for increase the capacity series of the winding and so it reduces the concentration of impulse between turns. The concept is to stabilize, through soldering between wire of consecutive sections, the difference of potential at half turn rather than one turn. Considering this important aspect, for the same impulse level, the interleaved disk requires less insulation than the continuous disk and also less encumbrance. Usually if the BIL (Basic Impulse Level) is bigger than 750 kV, it is necessary to use the interleaved disk. Below it is represented a continuous disk with ten turns for disk and an interleaved disk of two sections with six turns per disk.

- <u>Continuous disk</u>

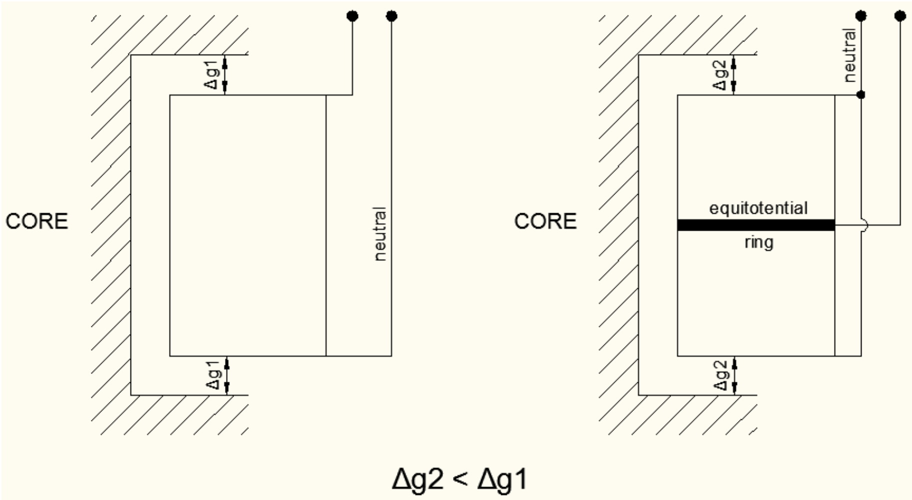


- <u>Interleaved disk</u>



The winding can be built with two part in parallel and the input is in the middle. This configuration for the winding reduce the number of conductors in parallel connection. This solution is used when the neutral wire has reduction insulation or if the neutral wire is grounded. The two options use the same quantity of copper, but when it is possible, it is preferred adopt the solution with the input in the middle of the winding because there are the following advantages:

- half of parallel conductors because the windings are realized physically with two part in parallel
- possibility to reduce the distance between the winding and joke when the neutral is earthed



where:

Δ_{g1} is the distance between the joke and the winding with the terminals at its ends

Δ_{g2} is the distance between the joke and the winding with the input in the middle

After the explanation on the main common types of windings, it is possible to go on and understand how it can be possible to define which are the best choices on the windings in relation with the characteristics of transformer.

In the LV windings the starting point is determine if it is possible to use the simple layer calculating the available height of the conductor for each turn with this formula:

$$a = \frac{h}{N_{LV} + K_e + K_t} - c_a - i$$

where:

a is the effective height of conductor

K_e is a number that take into account the effective encumbrance of layer

K_t is a number that take into account the transposition of wire in the layer

c_a is the height of oil channel

i is the insulation of the wire (must be considered the insulation on both side of wire)

In relation with the result of "a" there are some internal standards in the factory that assign which is the solution on the configuration winding choice.

Sometimes in some machines on the LV side there is a very big current and the relative heat that it is necessary dissipate is very big. A solution for this case is use a Netting tape CTC, that it is composed with a transpose cable without isolation. The exchange of heat between the wires and the oil is very high in comparison with a cable with the paper isolation.

In the HV winding are done the same considerations explained above for the LV windings. Usually the HV winding is built with a disk configuration, and also it is common that in it there is a combination of continuous disk and interleaved disk.

2.7.4 Determination of wire dimension and encumbrance of windings

Now it is possible define the effective cross-section of the wire and after that it will be necessary choose a corresponding standard wire with the effective equivalent cross-section that it is a little bit bigger. The cross-section of the conductor is calculated with the formula:

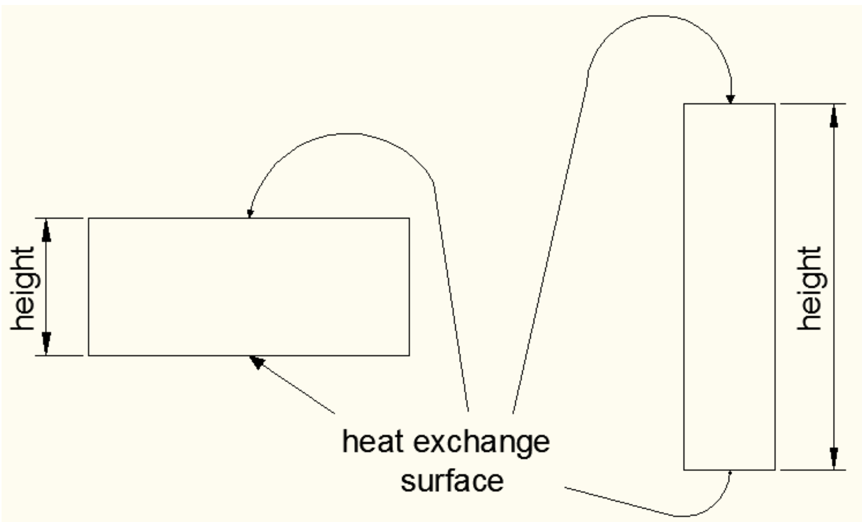
$$S = \frac{I_{phase}}{\sigma}$$

where:

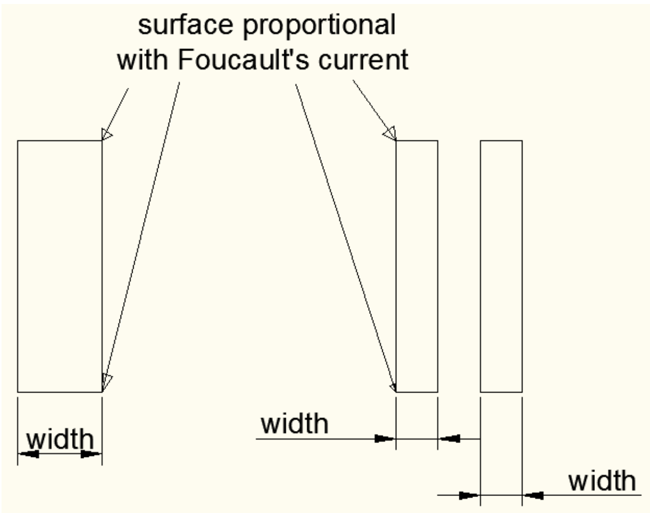
S is the effective cross-section of the wire [mm^2]
σ is the current density [A/mm^2]

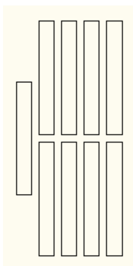
The formula above is general and it is necessary to apply it for each winding of the transformer utilizing the corresponding phase currents and current density. Now the minimum value of the cross-section for the conductor is known. It is necessary consider the following aspects in the choice of the conductor type that it will be use for to make the winding:

- Considering two different conductors with the same cross-section but with different dimension for height and width, the conductor with a high height is subject to a higher over temperature, because the heat exchange surface oil - wire is smaller. This concept is shown in the picture below.



- Considering two different conductors with the same cross-section but with different dimension for height and width, the conductor with a high width has higher additional losses due to the Foucault's current, because these losses are proportional with the lateral surface of the wire. A solution for reduce this losses is use a cable with the same equivalent cross-section but it is split in more conductors in parallel. In this case, if the number of conductors is big, it is used a transpose cable. On this kind of cable there is also a better distribution of the current in the winding because the wires that formed the cable have the same average length. This concept is shown in the picture below.





Regarding the axial dimension, in the simple layer and in the double layer, it is necessary consider some mechanical turns more. Those more mechanical turns take into account the characteristic of winding construction and for the transpositions.

In the determination of the total radial dimension of winding installed around the limb, it must be take into account a big number of elements. The elements that must be considered are:

- Ray of core limb.
- Thickness of the cylinders insulation that there are between the limb and the winding and also between different layers of winding
- Width of LV winding
- Distance between LV and HV windings
- Distance between HV and regulation windings
- Distance between large and fine regulation windings
- Width of fine regulation winding

The real radial dimension after the manufacture of the winding is usually a little bit bigger than the theoretical value and it is due to for the tolerance in the construction and also for the tolerance of the materials. During the design of the machine this factor must be considered.

2.8 Approximate determination of percentage reactive voltage drop

The encumbrance of the windings is known and so it is possible to define the percentage reactive voltage drop. It will be the result of the following steps.

$$\Delta E_{x\%} = \Delta E_{x\%teor} \cdot R$$

$$\Delta E_{x\%teor} = \frac{4{,}96 \cdot f \cdot N \cdot I_{phase}}{E_t \cdot h \cdot 10^6} \cdot F_R$$

where:

$\Delta E_{x\%}$ is the approximate percentage reactive voltage drop
$\Delta E_{x\%teor}$ is the percentage reactive voltage drop
R is the corrective Rogowsky's factor
F_R is the reactance factor
N and I_{phase} are referred on the same winding

Define the reactance factor is difficult and its value depends on the configurations of windings. Moreover its value takes into account of the fringing leakage flux.

If the obtained value for the percentage relative voltage drop does not respect the requested data, it is compulsory to repeat the determination of sizing windings but it is necessary choose a new value for the height of windings. The new value of winding height is calculated with the formula below.

$$h_{new} = \left(\frac{\Delta E_{x\%old}}{\Delta E_{x\%required}} \right) \cdot \frac{1}{2} \cdot h_{old}$$

where:

h_{new} is the new height of windings
h_{old} is the old height of winding
$\Delta E_{x\%old}$ is the old percentage reactive voltage drop
$\Delta E_{x\%required}$ is the required percentage reactive voltage drop

2.9 Heating

One important step during the design of a power transformer is the heating because, in relation with this value, it will be planned the cooling system. Heating is defined through the following process.

2.9.1 Calculation of specific losses in the copper

The specific losses in the copper are split in two different kinds of losses: ohm losses and additional losses. The ohm losses must be calculated, usually, referred with the temperature of 75°C in according with the standards. Its value is defined with the formula below but its value can be determinate with standards tables.

$$w_{ohm} = 2{,}37 \cdot \sigma^2$$

where:

w_{ohm} is the specific ohm losses [W/kg]

Regarding the specific additional losses in the copper, their value is obtained in the following way.

$$w_{add} = K_e \cdot K_f \cdot b^2$$

$$K_e = \left(\frac{0{,}167 \cdot f \cdot N \cdot I_{phase}}{h \cdot 10^3} \right)^2$$

where:

w_{add} is the specific additional losses
b is the width of wire

The K_f coefficient depends mainly from the number of windings and its value is defined in standards tables. It is not so simple. The eddy losses in the winding are calculated considering the axial and radial leakage flux in each conductor along the winding. This value is calculated with specific computer programs.

2.9.2 Calculation of specific load

In the determination of the specific load is necessary consider the kind of windings. In the disk or layer windings is possible proceed in this following way.

$$W_S = 0{,}105 \cdot \sigma^2 \cdot a \cdot n \cdot \left(\frac{b}{b+1} \right) \cdot \left(1 + \frac{W_{Fucault}}{100} \right) \cdot K_P \cdot K_F$$

$$W_S = \frac{w_{add}}{w_{ohm}} \cdot 100$$

$$K_F = \frac{W_{LV}}{W_{LV} + (a+1)}$$ in disk and simple layer winding

$$K_F = \frac{W_{LV}}{W_{LV} + 2 \cdot (a+1)}$$ in double layer winding

where:

W_S is the specific load [W/dm^2]

n is the number of wire per coil in parallel with the heat flux (n=1 in disk and layer windings, n=2 in double layer windings)

$W_{Foucault}$ is the Foucault losses expressed in percentage of ohm losses

W_{LV} is the width of the LV winding (in the calculation for the HV side is required to use the width of the HV winding W_{HV})

K_P is a coefficient that takes into account the surface of wire covered from the spacers

K_F is a coefficient that takes into account the exchange radial surface of wire

The formula above is used for the winding on one layer. The formula that is used for calculate the specific load it is the following one, if the windings have more than one layer.

$$W_S = 0{,}105 \cdot \sigma^2 \cdot b \cdot n \cdot \left(\frac{a}{a+1} \right) \cdot \left(1 + \frac{W_{Fucault}}{100} \right) \cdot K_P \cdot X$$

where:

n is number of wires included between two following oil channels

K_P is a factor that takes into account the covered surface from the spacers in each oil channel

X is a coefficient that depends from the kind of winding

<u>2.9.3 Determination of average over temperature in the copper on the average temperature of oil</u>

During the process design of a transformer, one important aspect is represented from the temperature and the over temperature. It is very significant because from its value depends the time life of the machine. In fact, for example, if the machine goes to work with an over temperature bigger than the value defined from the standard, the life of transformer can be reduce noticeably. The determination of average over temperature in the copper on the temperature of oil is calculated in the following way.

$$\Delta T_{Cu} = \Delta T + K_i + K_c$$

$$\Delta T = 3{,}3 \cdot (W_S)^{0{,}71}$$

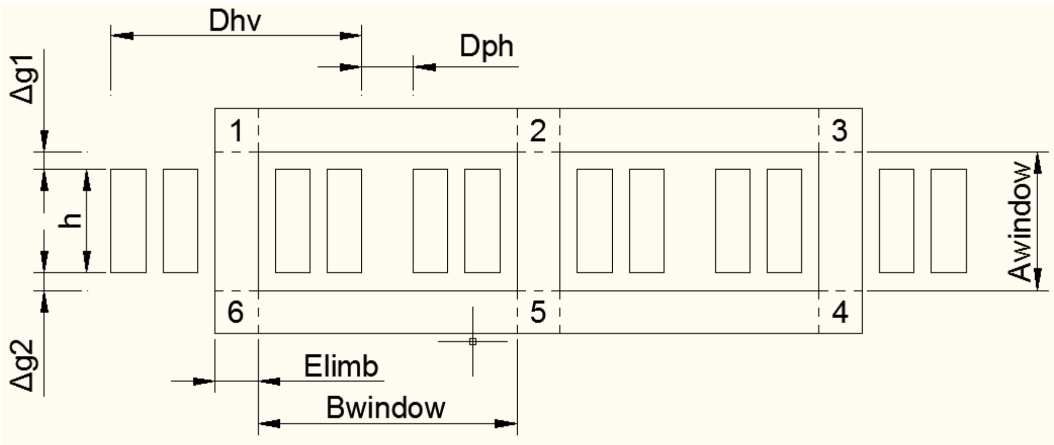
where:

ΔT_{Cu} is the average over temperature in the copper on the temperature of oil [°C]

ΔT over temperature caused from the specific load [°C]
K_i is a coefficient that takes into account the isolation
K_c is a coefficient that depends on which kind of oil channel there is in the windings

2.10 Determination of the windows in the core

At this point of the process design it is possible define the dimension of window in the core. In this case it is considered a core with 3 main limbs, one for each phase, because it is the most common used configuration for the power transformer. This structure is shown in the picture below.



$$A_{window} = h + h_{eq.ring} + \Delta_{g1} + \Delta_{g2}$$
$$B_{window} = D_{HV} + D_{ph} - E_{\lim b}$$

where:

A_{window} is the height of the core window [mm]
B_{window} is the width of the core window [mm]
$h_{eq.ring}$ is the height of the equipotential rings [mm]
D_{HV} is the outer diameter of the HV winding [mm]
D_{ph} is the distance between the phases [mm]

2.11 Determination of iron weight

Now all the dimensions of the core are known and so it is possible to define the iron weight. This value is important because it is in relation with the losses in the core. It must be compared if its value is above the maximum value available for the transportation or close to this value because after it should be added also the weight of the copper, of the oil and of all equipments.

$$P_{iron} = \left(3 \cdot A_{window} + 4 \cdot B_{window} + 6 \cdot E_{\lim b}\right) \cdot p + M$$

where:

P_{iron} is the weight of the core [kg]
p is the weight per linear dimension [kg/dm]

M is the weight increase [kg]
A_{window}, B_{window} and E_{limb} are expressed in [dm]

2.12 Determination of copper weight

The first formula below is general and it must be used for the LV windings and also for the HV windings. The total weight is the sum of results obtained from the LV and HV side. The result of the first formula is for the effective weight of the copper without isolation. For this reason, in the second formula, it is used a coefficient 1,05 because in this way the weight of isolation is taken into account.

$$P_{Cu} = n_{phases} \cdot N_{MAX} \cdot S \cdot l_m \cdot w_{Cu}$$
$$P_{CuTOT} = 1{,}05 \cdot \left(P_{CuLV} + P_{CuHV}\right)$$

where:

P_{Cu} is the weight of windings [kg]
n_{phases} is the number of phases in the machine
l_m is the average length of turns [m]
w_{Cu} is the specific weight of copper [kg/dm^3]
P_{CuTOT} is the total copper weight [kg]

2.13 Determination of iron losses

The iron losses are very important. They are due to the magnetization of the core and they produce heating. This kind of losses there are in no-load and on load condition of the transformer and they are constant. The no load losses are determined in specific curves which relate the flux density with the W/kg. There are specific curves for each type of silicon steel and core type. The machine is connected with a network that it has voltage waveform that it is almost constant for to respect the standard. It means that it is possible to consider the losses in the core constant for every kind of working condition, both no-load and on load situation. The main point for this kind of losses is reduce its value because they are constant for each kind of working condition.

Their value depends also from the quality of the iron sheet. In fact to reduce this kind of losses for the transformer are used iron - silicon sheet with crystal orientated. Moreover it is used a step-lap construction for the core because in this way the air gap is distributed and the flux encounter less resistance. They are calculated in the following way.

$$W_{iron} = P_{iron} \cdot w_{iron} \cdot 10^3$$

where:

W_{iron} is the iron losses [kW]
w_{iron} is the specific losses [W/kg]

2.14 Determination of copper losses

The value of the copper losses is not constant but its value depends on the load condition of the machine. Its value is due to the sum of three different kinds of losses and they are:

- ***Ohm losses:*** its value must be calculated for each winding. All the results have to sum together. Its value is gotten from the following formula.

  $$W_{ohm} = \rho \cdot V \cdot \sigma^2$$

  where:

  W_{ohm} is the ohm losses [W]
  ρ is the electrical resistivity of the copper [Ω m]
  V is the volume of the copper [m^2]

- ***Foucault losses:*** this kind of losses are determinate multiplying the specific additional losses for the volume of copper for each winding. The specific additional losses are defined for the request load condition and it is very important consider this aspect.

- ***Leakage losses:*** this kind of losses are defined in the following way.

  $$W_{leakage} = k_{leakage} \cdot \Delta E_{x\%} \cdot P \cdot \frac{f}{50}$$

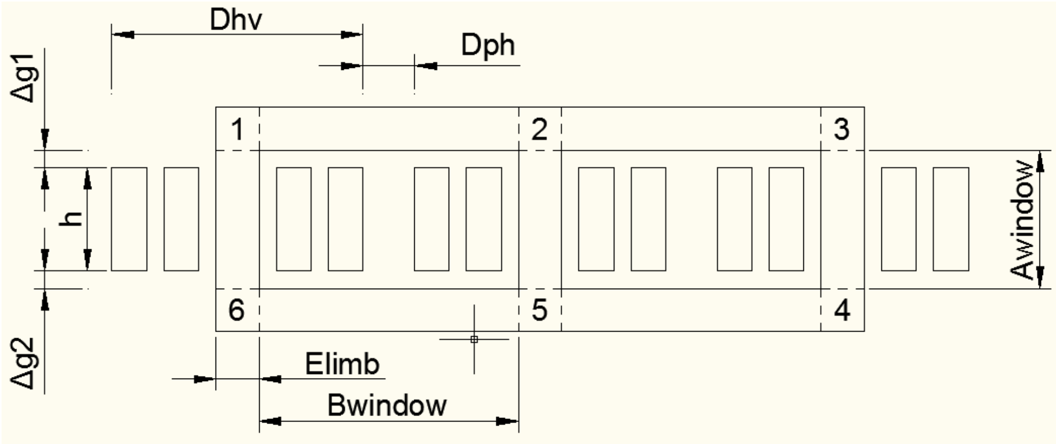
  where:

  $W_{leakage}$ is the leakage losses [W]
  $k_{leakage}$ is the leakage coefficient

The determination of the total copper losses cannot be very accurate and it depends mainly from the calculation of the leakage coefficient. The difference between the theoretical value and real value of it can have a range of around 5%.

2.15 Determination of internal tank dimension

Now it is the time for define the minimum internal dimension of the tank because all the dimensions of the active part of the machine are defined. At the beginning it is necessary calculate the external dimension of the structure core - winding and after that, with the help of standards, it is possible to arrive at the internal dimension of the tank. The standards stabilize the minimum distance between the active part of the transformer and the walls of the tank for guarantee the isolation. Those dimension and also the formulas for calculate them are shown below.



$$h_{act.part} = h + h_{eq.ring} + \Delta g_1 + \Delta g_2 + 2 \cdot h_{joke}$$
$$l_{act.part} = 3 \cdot D_{HV} + 2 \cdot D_{ph}$$
$$w_{act.part} = D_{HV}$$

where:

$h_{act.part}$ is the height of the active part [mm]
$l_{act.part}$ is the length of the active part [mm]
$w_{act.part}$ is the width of the active part [mm]

$$h_{\tan k} = h_{act.part} + h_{s\tan dard1} + h_{s\tan dard2}$$
$$l_{\tan k} = l_{act.part} + 2 \cdot l_{s\tan dard}$$
$$w_{\tan k} = w_{act.part} + w_{s\tan dard1} + w_{s\tan dard2}$$
$$V_{\tan k} = h_{\tan k} \cdot l_{\tan k} \cdot w_{\tan k}$$

where:

h_{tank} is the height of the tank [mm]
l_{tank} is the length of the tank [mm]
w_{tank} is the width of the tank [mm]
V_{tank} is the volume of the tank [m^3]
$h_{standard1}$ is the distance between the active part and the ceiling of the tank [mm]
$h_{standard2}$ is the distance between the active part and the bottom of the tank [mm]
$l_{standard}$ is the distance between the active part and the lateral wall (in length) of the tank [mm]
$w_{standard1}$ is the distance between the active part and the lateral wall (in width) of the tank [mm]
$h_{standard1}$ is the distance between the active part and the lateral wall (in width) of the tank and it take into account the space for the connections of the windings [mm]

2.16 Determination of losses by dissipate

The losses, that they are necessary to dissipate, are the sum of the copper losses with the iron losses and additional losses due to the leakage flux in the frame active part and tank, leads and flux generated by high current in the leads. Regarding the copper losses, the losses relatively with the minimum position of the tap changer must be take into account, because in this condition the current in the windings is bigger, so there are more losses. Their value depends also from the level of excitation. The worst case is with the under excitation and it is necessary also consider this situation. The copper losses in the under excitation can be calculate with the following formula.

$$W_{under.ex} = W_{Cu.rated} \cdot \left(\frac{I_{phase}}{L_{excitation}} \right)^2$$

where:

$W_{under.ex}$ is the copper losses in condition of under excitation [W]
$W_{Cu.rated}$ is the copper losses in rated condition [W]
$L_{excitation}$ is the level of excitation [%]

The losses in the iron in the condition of under excitation will be smaller because the flux density will be smaller. Usually the sum of the copper and iron losses on the case of under excitation is bigger than the value calculated in rated condition.

2.17 Determination of cooling system

Define a correct cooling system that dissipates all the losses necessary is very important for a good work in normal condition of the machine with a long duration of its life. The temperature and the over temperature of all the parts and components that compose the transformer can be divided in the following way:

- average temperature of the copper admissible: its value depends from the standards that it is request
- rise temperature of average copper against average oil: its value is calculated in relation with the specific load of the windings
- average temperature of oil: its value is calculated like the difference between the average admissible copper temperature and the over temperature of copper against the oil
- over temperature between oil and ambient
- ambient temperature

There are some different kinds of cooling system and they are classified with different names. The differences depended on the circulating type of oil in the tank and the substance utilized for the cooling system outside the tank with their flux that it can be natural, forced or forced and wizard. The main used cooling systems for the transformers are take into account below.

1. ***Cooling system ONAN (natural circulating of oil and air)***
   The height of the radiator must be defined in relation with the difference of temperature between the oil in the top and in the low part of the tank and with the characteristic and efficiency of the radiator elements. This calculation is not so easy and to determine it require the utilization of specific software.
   The number of radiator must be even because they are coupled in pair. Usually the number of elements for each radiator should not be upper than 30. One important check is compare the number of radiators and their size with the dimension of the tank, where it is necessary take into account that normally 1/4 of the external perimeter of the tank should be assigned for the command's panel and for some other instrument for measure.

2. ***Cooling system ONAF (natural circulating of oil and air forced on the radiator)***
   In this case, all the considerations done for the cooling system ONAN are valid. The height of the radiator should be change because here there are the ventilators mounted on the radiators. The ventilator can be positioned on the lateral side or under the radiators. This choice is done in relation with the heating that it is necessary dissipate and also from the available space in the installation.
   The height of the radiator in the cooling system ONAF is done in the same way shown for the ONAN system. These two solutions are built on the same machine because the solution ONAF requires only the installation of funs. The advantages with the fun is that the speed of air that exchange heat with the radiator is higher, so the equivalent exchange surface is bigger and it is possible to dissipate more losses.

3. ***Cooling system ODWF (forced and wizard circulating of oil and water forced circulating around the radiator):***
   This is the best solution for the cooling system and it has the highest efficiency. In this case there are not the radiators but the exchange of heat is done in a heat exchanger. Define the input and the output temperature of oil and water is quite difficult, so it require the utilization of software. The ODWF is used mainly in the industry area where the transformer is installed inside of a room and there is not a lot of space.
   There is also another solution for the cooling system in comparison with the ODWF. The other type is the cooling system OFWF (forced circulating of oil and forced circulating of water) but it is advised against because the efficiency of the cooling system is

lower. The average temperature of copper and oil increases respect also the ONAN configuration. It depends mainly from the speeds difference between oil and water. It means that the two liquid does not have time enough to exchange a good quantity of heat.

2.18 Determination of volume and weight of oil

The number of radiators utilized in the cooling system is known now, so it is possible define the volume of oil and also its weight. It can be calculated with the following formula.

$$V_{oil} = V_{\tan k} + V_{rad} + V_{cons} - V_{act.part}$$

where:

V_{oil} is the volume of oil in the machine [m^3]
V_{tank} is the internal volume of the tank [m^3]
V_{rad} is the internal volume of all radiators [m^3]
V_{cons} is the volume of oil in the conservator [m^3]
$V_{act.part}$ is the volume of the active part [m^3]

In the conservator is contained a quantity of oil equal to the 5 - 8 % of the total volume of oil normally. When the total volume of oil is known, it is quite easy find the weight of it. It is the result of the formula below.

$$W_{oil} = \delta_{oil} \cdot V_{oil}$$

where:
W_{oil} is the weight of total oil [kg]
δ_{oil} Is the density of the oil [kg/m^3]

2.19 Choice of the bushings

The choice of bushing is not so difficult but there are some aspects that it is necessary to consider. Every supplier has a catalogue where there are reported all the information on their products. The main points that must be observed are:

- the test voltage must be equal or bigger than the customer request
- the rated voltage must be equal or bigger than the rated voltage of the transformer
- the rated current of the bushing is equal or bigger than the rated line current of the transformer

These are the mainly characteristics of the bushings, but there are others, like: cantilever, ambient conditions (pollution, wind , etc), earthquake requirements, installation position, etc.

2.20 Choice of the tap changer

The choice of tap changer is not so difficult but there are some aspects that are necessary to consider. Every supplier has a catalogue where there are reported all the information on their products. The main choice is on the kind of the tap changer. It can be a no-load tap changer or an on-load tap changer. Usually the customer requires one or other kind of configuration. After this decision it is necessary to take into account the rated voltage and rated current of the machine, step-voltage, voltage to ground, dielectric tests, etc.

2.21 Total weight of transformer

The calculation of the total weight of the transformer is easy because it is necessary sum all the parts of the machine. The principal parts that have a major weight and their weight has a major influence on the final result are:

- iron of the core
- copper of the windings
- tank
- oil
- conservator
- tap changer
- bushing
- radiator
- ventilator
- other parts

2.22 Main points of the mechanical process design

The main software that the mechanical area use for design a power transformer is a 3D CAD. In the past was utilized a 2D CAD program but the design was more difficult and it was more easy to find some problem during the manufacture process. Solve them were not always simple. A 3D CAD software permit to understand and find some mechanical and isolation problem in a easy way. In this situation it is possible reduce the errors that they can be find during the manufacture process. The time built of the transformer result more fast and it is another important advantages.

The starting point of the mechanical design process is defined from the output documents of the electric design. In the electric design are defined all the dimension of the core and winding as shown in the precedent pages.

The main concept in the mechanical design is begun from the heart of the machine for to arrive at the most external part. The “heart” of the power transformer is represented from the assemblage of iron core and copper windings. With the term "external parts" are considered all the components and elements that they are installed outside of tank. In practical terms, the mechanical process design can be represented in order from the following points:

- windings and core
- pressboard and support of windings
- support of core
- tap changer
- connections
- tank
- bushings, measurement elements and their support
- radiator
- control cabin and its connections

Now, in the section below, there are illustrated some aspects and concepts that they are considered or that they does not affect during the mechanical process design.

The temperature level is considered only in the design of two elements. The first element where is require to know the temperature it is the cooling system. Understand the reason is very clear. In relation with the temperature of the machine and the maximum temperature permitted, it is necessary define the number of radiators and the number of elements per radiator. During this calculation must be taken into account that the efficiency of the elements is not the same for each element and also it depends from the paint of radiator. The second part, where the temperature is very important, is the design of the conservator. In this part it is necessary consider that the volume of the oil changes with the temperature. In the conservator must be defined a minimum and maximum level of oil. The maximum level of oil does not coincide with the full conservator because usually inside the conservator there is an "atmoseal bag". It is better to take a certain value of tolerance also. The "atmoseal bag" is a component that reduces the possibility of penetration for the humidity inside the machine.

Another important element in the mechanical design is the tank. The stress and the forces that are take into account in its design. They are generally the forces due to the weight of oil and of other components installed on the cover of the machine. Sometimes it is possible that they are considered also the forces produced during the failure for short circuit in the network where the machine will be installed. In this case usually a disk with a membrane is mounted on the wall of the tank. If the pressure inside the tank is bigger than a certain value, the membrane will break and the oil will go in another conservator installed for the emergency. Another important aspect, that it is necessary take into account, during the process design of a tank, it is the stress that there is in the condition where inside the tank there is vacuum. If the transformer present an high height for the tank, probably the biggest stress on it is caused from the over pressure. In the majority cases for the transformers, its height is not so big and usually the main critical stress for the tank is represented from the condition where inside of it there is vacuum.

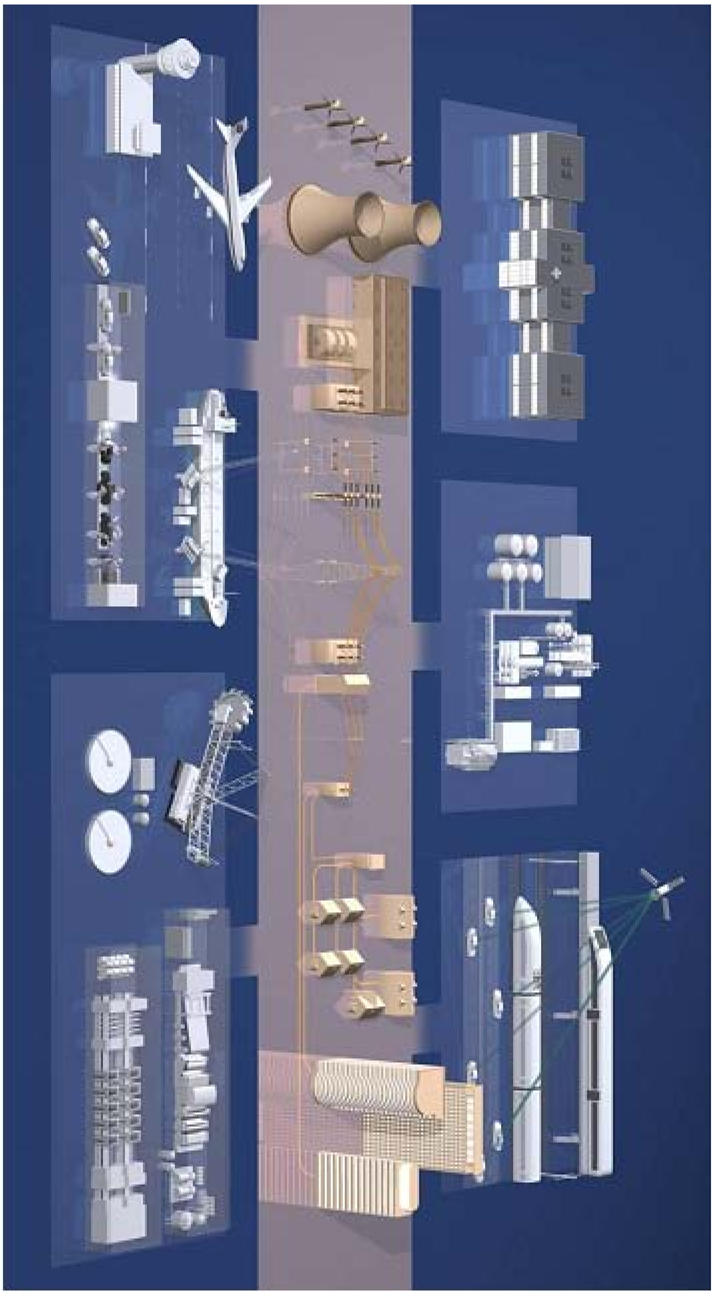
A very important test is done on every transformer. It is the oil pressure test. When the machine is ready for the testing area and it has already the oil inside. An over pressure is applied inside the tank from the oil in the conservator. In this way the overpressure is distributed in all the mass of oil. With this measure is possible to see if there are some losses of oil in the ambient due to some capillaries in the tank.

In the mechanical design is very important to consider the standard relative with the transportation. In relation with the kind of transport that will be used for lead the transformer in site, it must be take into account some different parameters. For example, the transport on road or on railway are not the same because the machine during the transport on railway is more subject at vibration. Every market and every Country have their standards. In relation with these standards, for example, the transformers during the lead does not present oil inside for reduce the weight. In place of oil there is a gas and it is used to reduce the chance for the humidity to go inside the machine.

3. HVDC transmission and HVDC transformer

3.1 Overview and consideration on the Energy system

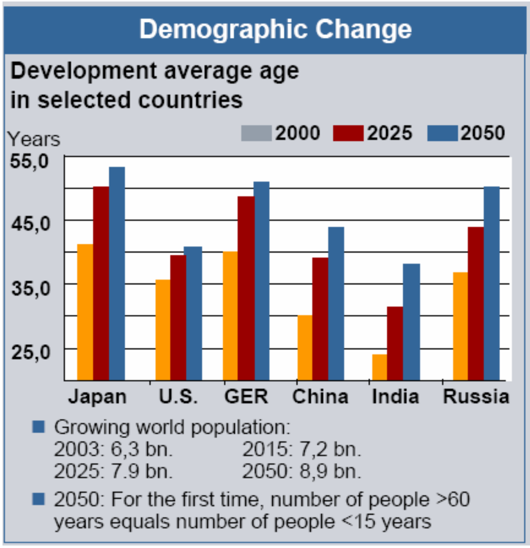
In recent decades, demand for energy by the utilities is always growing. In relation to this factor, the production, transmission and distribution of electricity have become increasingly important and the investments have been and they are increased. On this sector are invested more resources to improve the whole system for find new technologies and more efficient solutions. The electrical energy system can be considered the backbone of the today's and tomorrow's society. The offices, the industries, the manufacture factories, the transports, etc., they need of electrical energy and an idea of its importance can be represented thanks to the picture below.

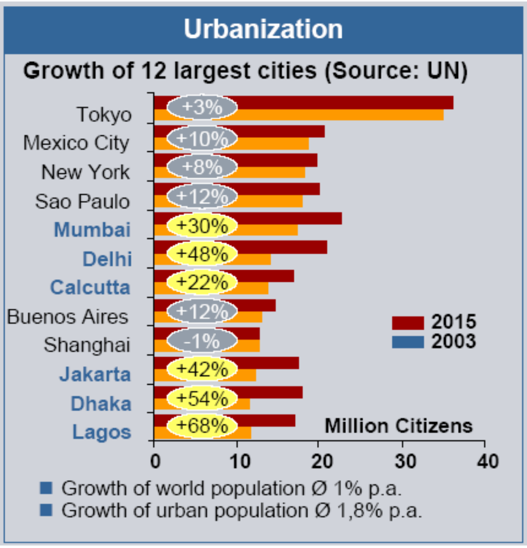


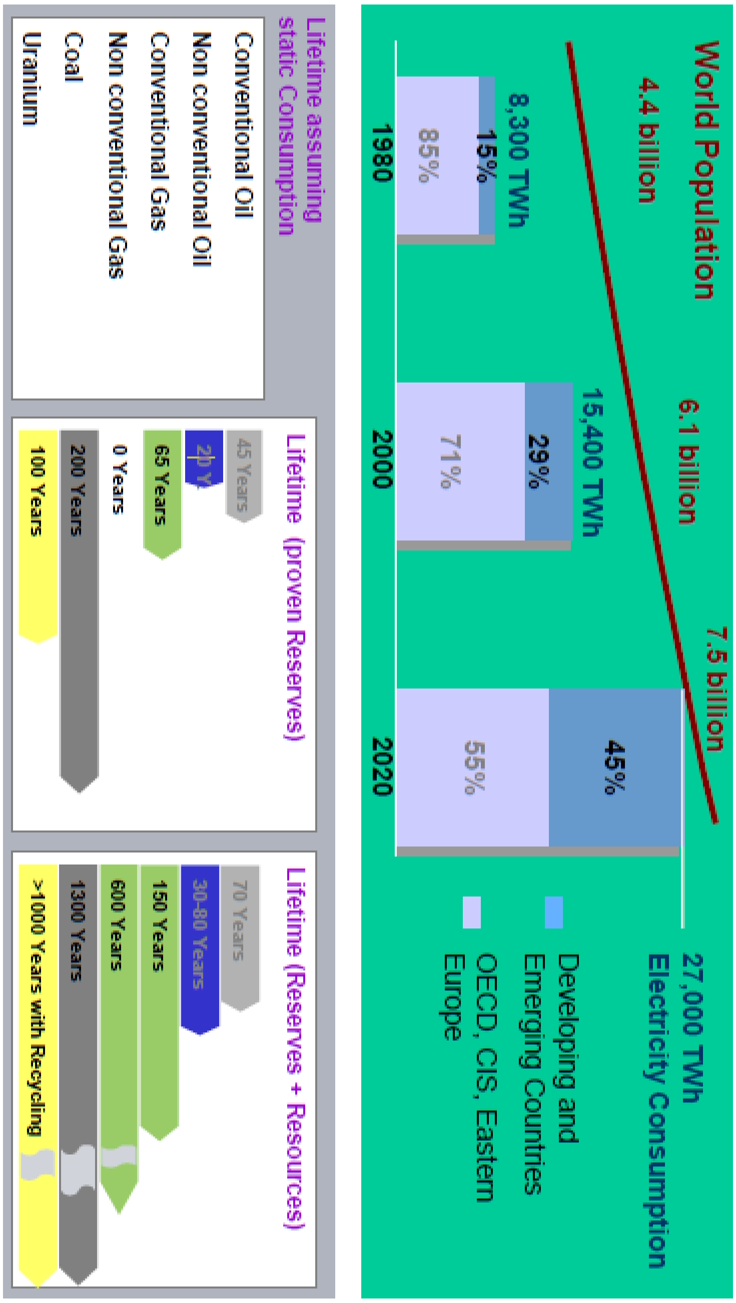
On this moment all the companies around the world are trying to work in the same direction. An indicative percentage value of the investments in the different field of power industry can be the following one:

- ≈ 40% in generation
- ≈ 20% in transmission
- ≈ 40% in distribution

The request of electric energy from the customer is in continuous grow and it depends from the number of people in the world that increase every year. Another aspect for which the demand for energy continues to increase is the urbanization and the begin of development that occur in developing countries. The increase of the number of people in the world mean that the total energy required for each day is bigger so it is necessary to produce more of it and, at the same time, try to reduce the losses. The problem with the urbanization is that the cities are beginning to be very big and for supply energy at the customers, the network should be intelligent. With the term intelligent network is considered a network with a loop structure and with distributed points of generation. In this way the quality of the energy and also its flow is better. A very important problem related on this grow is the necessity to find some new way for produce energy and reduce the pollution. The develop of new processes that use renewable sources is fundamental because the mainly sources that they are used now, they are very pollutions and also their quantity is limited. After those consideration it is very easy to understand the problem from the following graphs shown below.





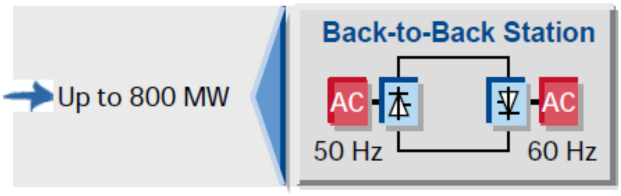


The main challenges for electrical power transmission and distribution are: increased use of distributed and renewable energy resources, capacity increase and bulk power transmission over long distances, distribution within congested areas / megacities. The goal of it is design a network that can be reliable, flexible, safe and secure grids.

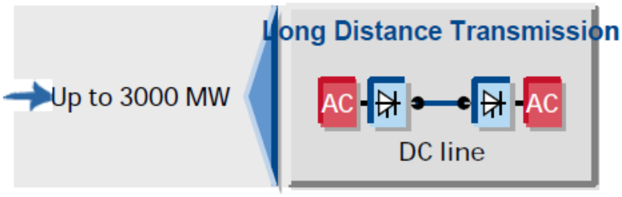
About the world wide electrical power consumption is projected to increase by over 70% during the next 20 years, implying enormous investments in power generation. To built new generation station is required but it is necessary take into account that the distances between the power plant and consumption centers are separated by long distances. This tendency demand a global energy market with the consequence that the national grids must be interconnected with the grids of other countries for built an international grid. With this international system the stability and the quality of the power are better respect a single national grid that operates alone.

The HVDC system is a very interesting solution and it is developed in the last decades, mainly in the last one. In this network configuration there are some advantages related with the minor losses in compare with the AC system, but the main disadvantages is the high cost of the power plan. All those aspects will show after. The HVDC technology is used in three different configuration and they are:

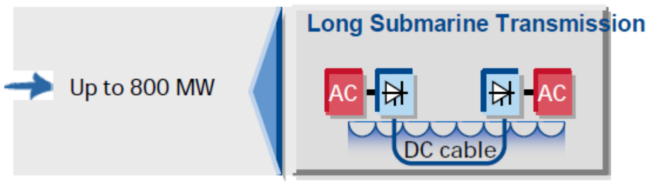
- ***HVDC back-to-back:*** is the unique solution to interconnect asynchronous systems with different grid frequencies



- ***HVDC long distance line:*** represents the most economical solution for distances greater than approx. 600 km / 400miles



- ***HVDC cable line:*** is an alternative for submarine transmission. It is economical even for shorter distances such as a few 10km/miles



3.2 Milestone of HVDC history

Electrical energy system for transmission and distribution started with direct current. In Germany between Miesbach and Munich was built in 1882 a 50 km 2 kV DC transmission line. At that period, conversion between reasonable consumer voltages and higher DC transmission voltages could only be realized by means of rotating DC machines. Voltage conversion is simple if it is used an AC system. If it is require a high power levels, high insulation levels and also with low losses within one machine, it is necessary to use a power transformer in AC system. Moreover, a three-phase synchronous generator is superior to a DC generator in every respect. The AC technology was introduced in the development of electrical power systems for these reasons. This solution was soon taken as the only feasible technology for generation, transmission and distribution of electrical energy.

In the high voltage AC transmission line there are also some disadvantages that they may think about the use of DC system, which they can be better. The main disadvantages in the AC line are:

- the transmission capacity and the transmission distance depends on inductive and capacitive elements that they put some limits
- for an AC cable the achievable distance will be in the range of 40 to 100 km because it will be limited by the charging current for some heating reason and for some losses economical evaluation
- it is not permit the directly connections between two AC system with different frequencies
- a new connection between two AC systems within a meshed grid may be impossible because of system instability, too high short-circuit levels or undesirable power flow scenarios.

The first commercial HVDC system was built in Germany on 1941: an underground cable of 115 km and 60 MW. It was built to supply the city of Berlin. The system was ready for to be energized in 1945 with ±200 kV and 150 A but it was never put into operation.

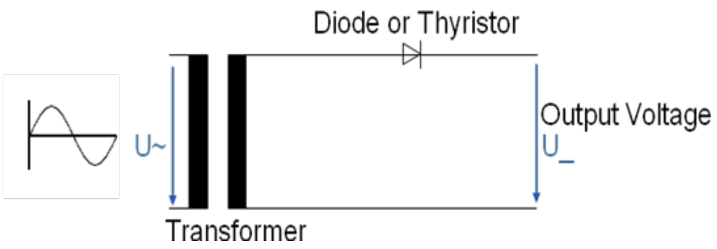
The mercury arc valves were the next major development. The first thyristor valves were put into operation in the late nineteen-seventies. The outdoor valves with oil insulated were designed with parallel and series connection of thyristors and an electromagnetic firing system. The next step of development was an air-cooled valves and the last one is the water-cooled design, which it is used in HVDC valve design. The development of thyristors characteristic has eliminated the need for parallel connection and reduced the number of series connected thyristors per valve. The reliability of this technology and innovations in almost every other area of HVDC has been grown constantly together.

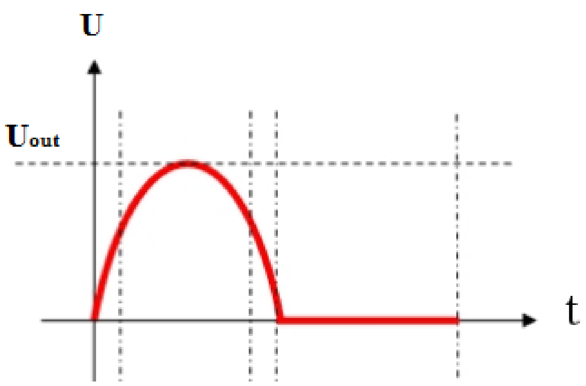
The development of IGBT (Insulated Gate Bipolar Transistors) has accelerated the development of voltage sourced converters for HVDC applications in the lower power range. The voltage sourced converters should have a compact design and four-quadrant operation capability.

3.3 How to produce DC voltage

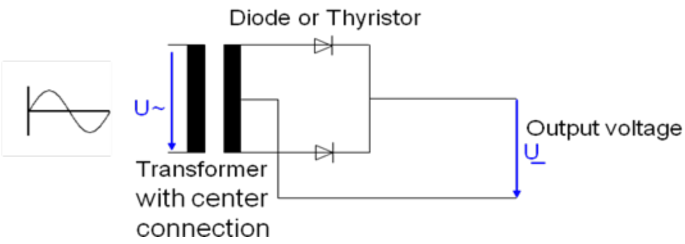
Almost all the energy is produced thanks to the asynchronous generators. It means that the produce waveform is sinusoidal. In the HVDC system, but in general in all DC system, is necessary straightening the alternative waveform in a waveform with a constant level. To do this it is essential to use a rectifier and below will be explained the basics to make this conversion.

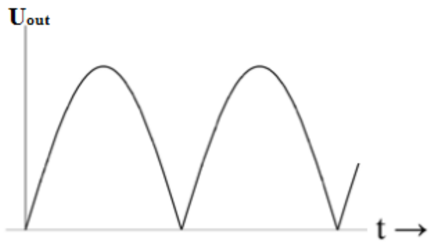
The diode is a component that works only if the voltage applied on its terminals is positive on the cathode and the current can flow from the positive terminal to the negative one. If the voltage on the cathode is lower that the voltage on the anode, the behavior of the component is like an open circuit and the current cannot flow through it. Considering a sinusoidal waveform applied on the primary winding of a transformer and on the secondary side there is a diode, and it taken into account the characteristic's work of diode, it is simple to understand that at the terminal of the secondary side is possible to have a voltage only for the positive part of the sinusoidal waveform. In this case it is a 1 pulse voltage rectifier. The system and the output voltage are shown in the pictures below.



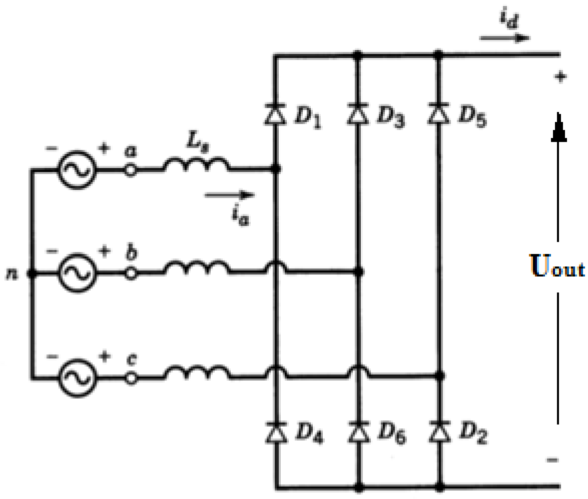


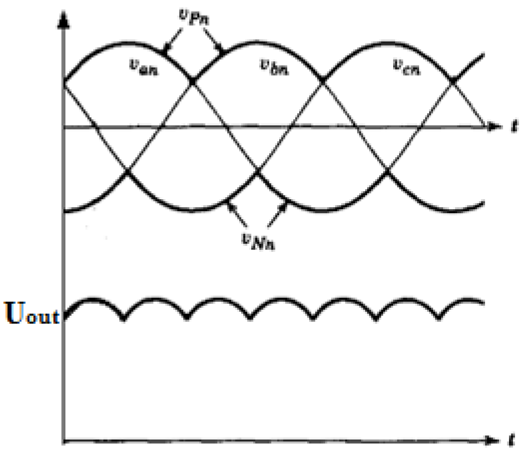
If there are two diode in the secondary side of the transformer where one is on the reference positive terminal and the other one is on the negative terminal and the transformer has a center connection like show in the figure below, the output voltage is double pulse.





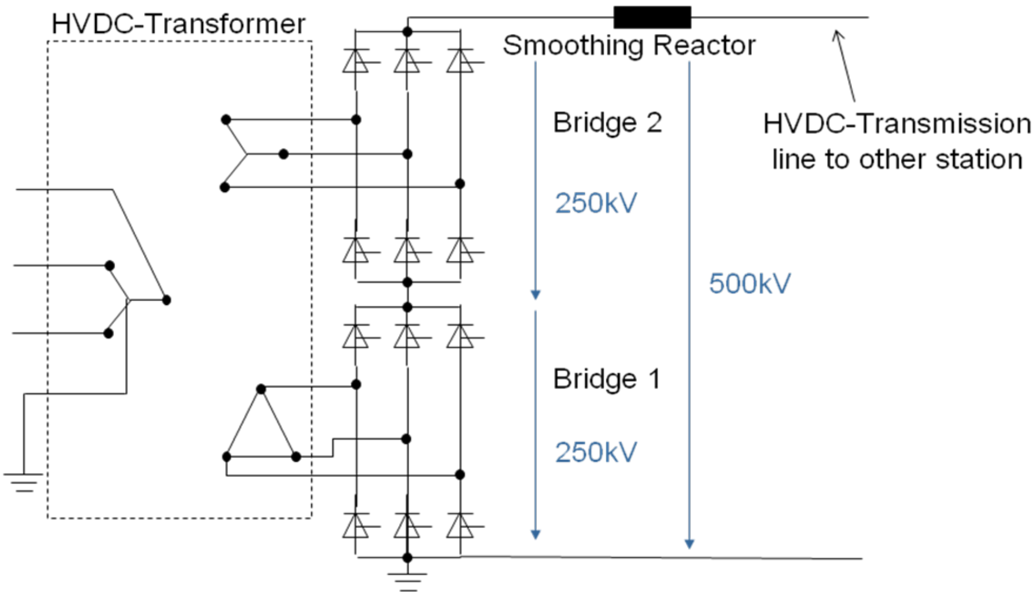
The same concepts are possible to apply for a three phase system. The resulting system is called six-pulse bridge rectifier. In the pictures below there are its schematic circuit, the phase voltages and the output voltage.





The considerations done until now can be applied also with the thyristors with the same concepts. The thyristor works like a diode but it has also a controller. In fact the current can flow through the component only during the positive part of the waveform and there is a starting impulse on the gate terminal.

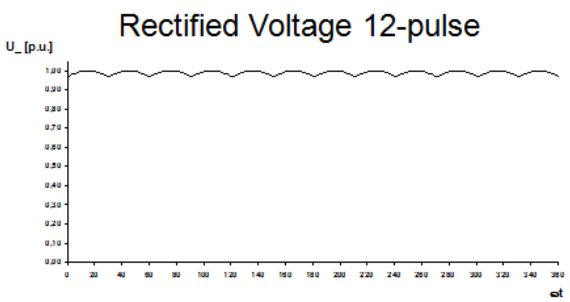
The HVDC transformers have a particular configuration. In fact they have a primary winding usually connected in star mode and two secondary windings. On the secondary side of transformer there are three windings in star connection and three windings in delta connection. Each secondary winding is connected to a six-pulse rectifier and the rectifiers are connected in series. A schematic representation of all this system is shown in the figure below.

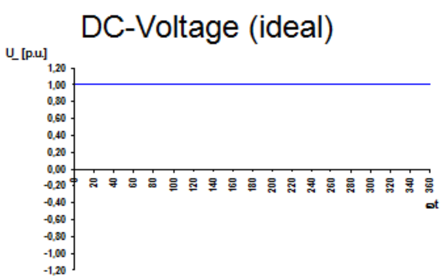


In the circuit of a 12 pulse transmission line the transformers are connected in star and delta connection at the valve side. Each system is connected to a 6 pulse bridge and the both bridges are connected in series. The star connected valve system is connected to the high voltage and the delta connected valve side is grounded. In this way each bridge gives 250 kV so in addition 500kV are available. During the design of the HVDC transformers is very important take into account that the line voltage of the secondary side in delta and star connection should be the same. In this case the total power of the system is split in two equal parts.

In the HVDC system there are two secondary windings with different connection and this solution is adopted because the total output voltage from the series of two rectifiers result with better quality because it has lower ripple. In the two secondary windings the amplitude of the voltage is the same but their waveform is shifted of 30 degree and it is due to from delta and star connection. In this way when the amplitude of each single pulse of each secondary winding in delta and star connection are summed with all the other, the resultant output voltage present a waveform that is more close to the ideal DC waveform. This result is mainly thanks to the angle difference of signals between the two secondary windings. Increasing the number of pulse is possible to obtain a better output waveform that it is almost ideal, but it is necessary to consider that if the number of pulse grows, at the same time increases the technical complexity of the rectifier. The solution of 12 pulse rectifier, with two 6-pulse bridge, is a good compromise between the quality of the output voltage and the technical complexity.

On the high voltage reference on the secondary side there is also a smoothing reactor. It is connected as series reactor and it is necessary to reduce the ripple in the output voltage. The smoothing reactor is also used to prevent the intermittent current, to limit the DC fault currents, prevent of resonance in the DC circuit and reduce the harmonic currents including the limitation of telephone interference. All these considerations will be explained in more details later. Below it is possible to see a comparison between the output voltage of a 12 pulse rectifier with the ideal DC voltage.

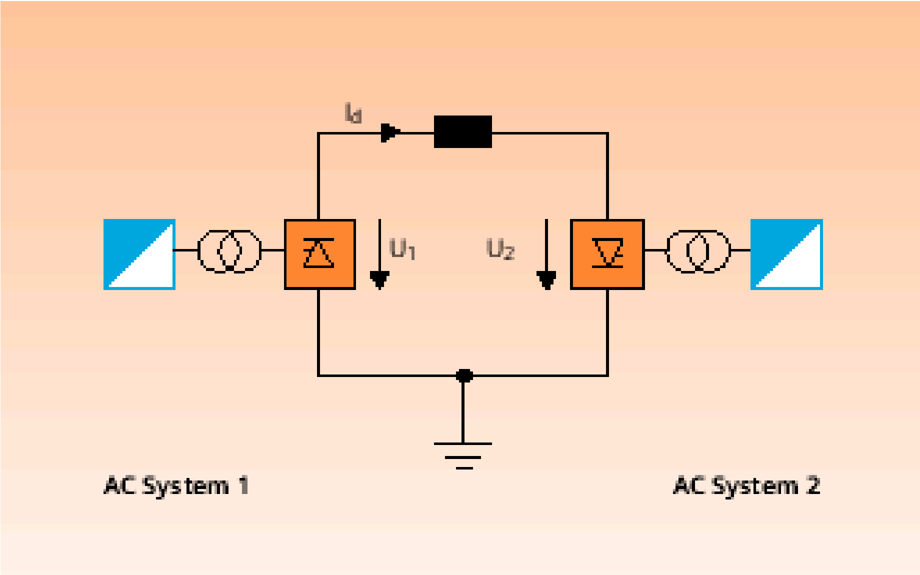




3.4 Main types of HVDC schemes

The most common configuration of an HVDC link is two inverter/rectifier stations connected by an overhead power line. Multi-terminal HVDC links, connecting more than two points, are rare. The configuration of multiple terminals can be series, parallel, or hybrid (a mixture of series and parallel). Parallel configuration tends to be used for large capacity stations, and series for lower capacity stations.

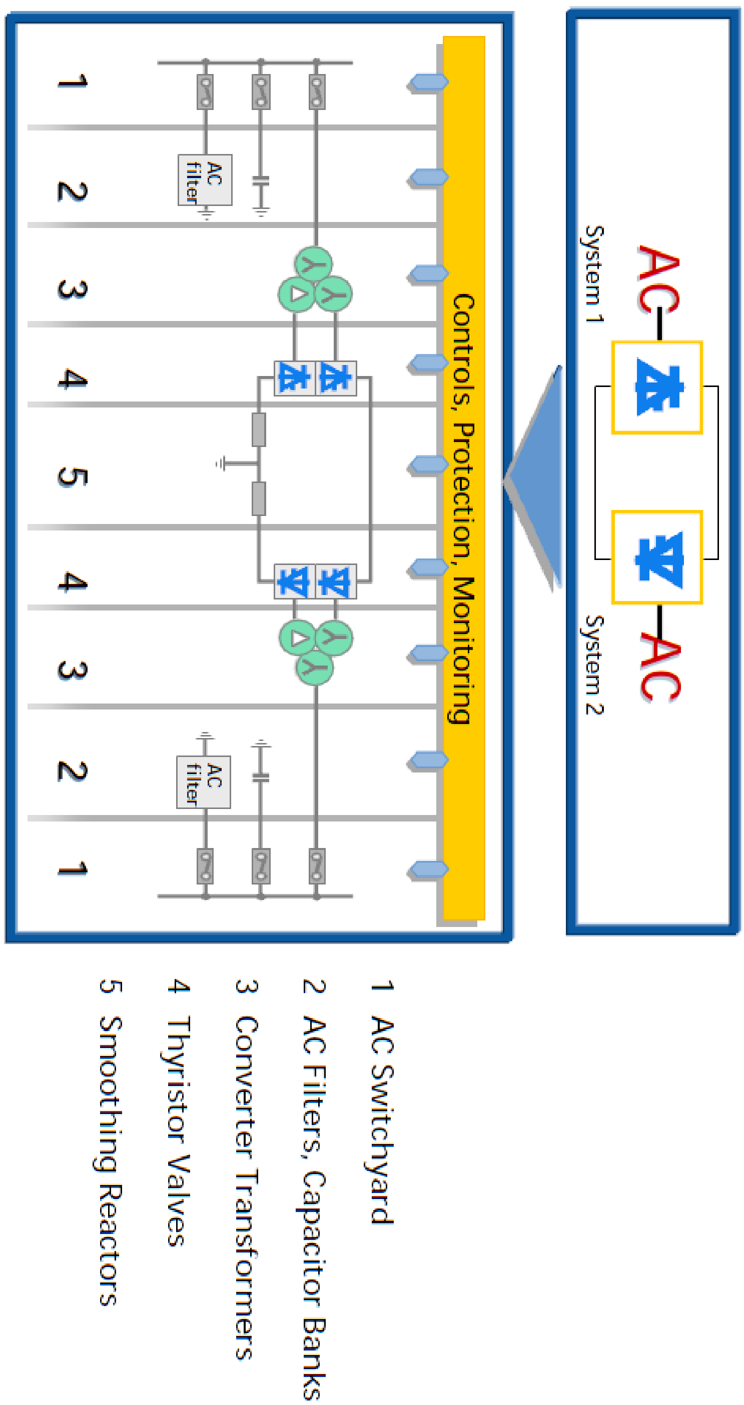
In relation with the DC circuit arrangements, the HVDC converters can be classified in different types. In the picture below there is a representation of a schematic diagram for a HVDC transmission system.



From the system 1 there is a transformer coupled with a rectifier. After that there is a smoothing reactor and the line. At the end of line there is another smoothing reactor and an inverter with a transformer connected with the system 2. The direction of the current, and a consequence the power flow, is controlled by means of the difference between the controlled voltages. In relation with the polarity voltage is possible to fix the direction of the current. In the next sections will be described the converters and also their different schemes.

3.4.1 Back-to-back converter

The expression back–to-back indicates that the rectifier and inverter are located in the same station. Back-to-back converters are mainly used for power transmission between adjacent AC grids which they cannot be synchronized. The main technical advantages of this solution are that it is possible connect two different systems that operate with different frequency and also they have a different control's and regulation's system of frequency. Normally in this station, the exchange of power is low in comparison with the size of the interconnected AC systems. The back–to-back link can also be used within a meshed grid in order to achieve a defined power flow. This configuration can be used also where there are two networks of the same nominal frequency, but there is not a fixed phase relationship. The back–to-back is adopted also where there are networks with different frequency and phase numbers, for example as a replacement for traction current converter plants. Reversal of the energy flow is frequent in the back-to-back system. Below there is a schematic representation of a HVDC back-to-back station.



In this station is very important the controls, the protections and monitoring of all components, so it is possible to define the exchange power quantity. The DC voltage in the intermediate circuit can be selected freely at HVDC back-to-back stations because of the short conductor length. The DC voltage is as low as possible, in order to build a small valve hall and to avoid series connections of valves. Valves with the highest available current rating are used for this reason in HVDC back-to-back stations. Another particular point in the design of this system is that the smoothing reactors are connected on the grounded side of the link. This choice is done because in this way the level of isolation in the reactors is lower respect the solution where reactors are installed on the unearthed side of the link. The configuration shown in the picture above is the best one because it permits to reduce the costs.

The cost of a plan with a back-to-back station is related with the quantity of exchange power that it is requested in the link. Anyway it is always the best solution for connect two system with different frequencies.

<u>3.4.2 Monopolar long distance transmission</u>

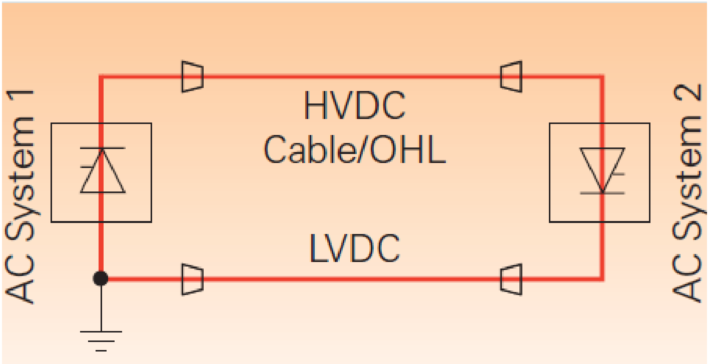
In a common configuration, called monopolar, one of the terminals of the rectifier is connected to ground. The other terminal, at a high potential above or below the earth reference value, is connected to a transmission line. For very long distances and in particular for very long sea cable transmissions, a return path with ground or sea electrodes will be the most feasible solution. In many cases, existing infrastructure or environmental constraints prevent the use of electrodes.

If no metallic conductor is installed, current flows in the ground between the earth electrodes at the two stations. Therefore it is a type of single wire earth return. The issues that can be occur regard the earth or water returns current include:

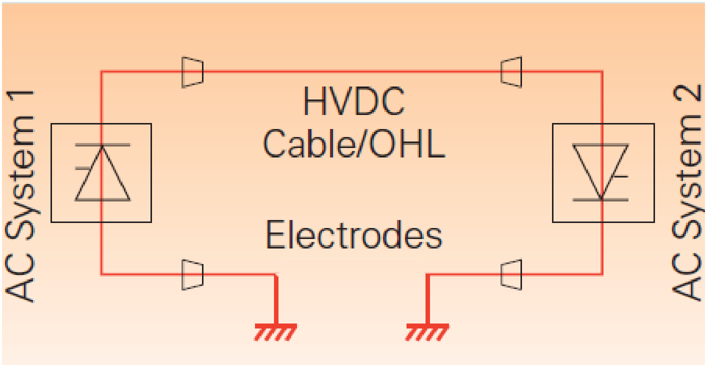
- electrochemical corrosion of long buried metal objects such as pipelines
- underwater earth-return electrodes in seawater may produce chlorine or otherwise affect water chemistry.
- an unbalanced current path may result in a net magnetic field, which can affect magnetic navigational compasses for ships passing over an underwater cable.

These effects can be eliminated with installation of a metallic return conductor between the two ends of the monopolar transmission line. Since one terminal of the converters is connected to earth, the return conductor need not be insulated for the full transmission voltage which makes it less costly than the high-voltage conductor. Use of a metallic return conductor is decided based on economic, technical and environmental factors.

The two different configuration with earth return or with metallic return are represented in the pictures below. Regard the path in the case of the underwater cable, the concept and the equivalent circuit is the same of the earth return solution. The difference is that in one case the return cable is represented by the earth and in the other case it is represented by the sea.



Monopole with metallic return path



Monopole with ground return path

Most monopolar systems are designed for future bipolar expansion. Transmission line towers may be designed to carry two conductors, even if only one is used initially for the monopole transmission system. The second conductor is either unused, it used as electrode line or connected in parallel with the other.

3.4.3 Bipolar long distance transmission

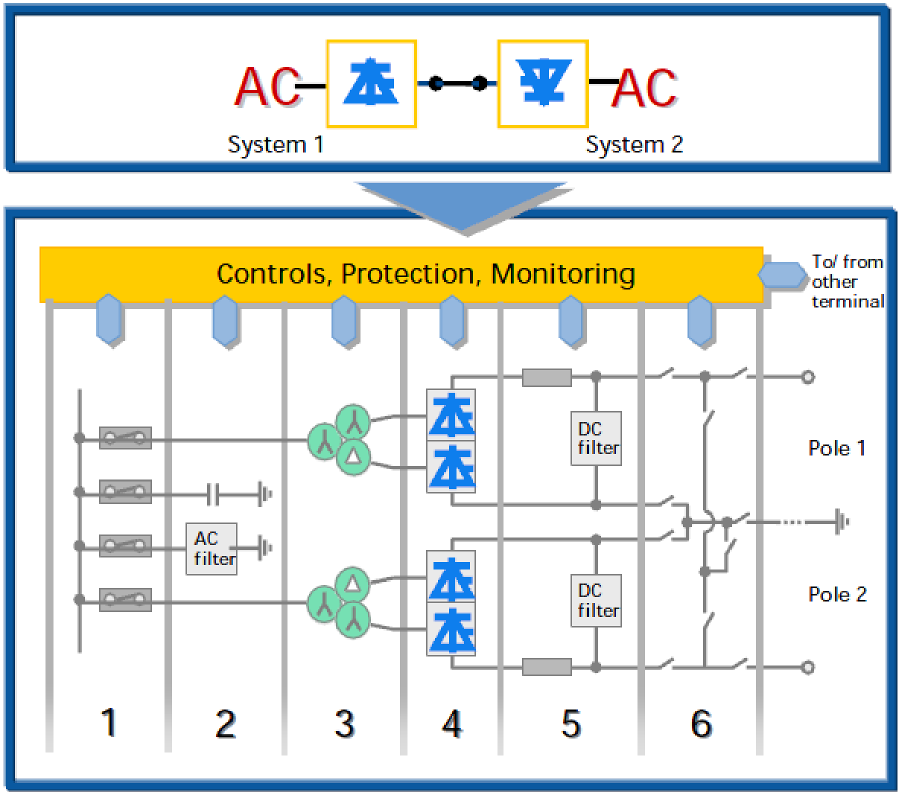
The bipolar long distance transmission is a combination of two poles where for each pole there is a common low voltage return path that, if available, it will be used for a small unbalance current during normal operation. This kind of configuration is utilized if the required transmission capacity exceeds the maximum capability of a single pole line transmission. A bipolar system may also be installed with a metallic earth return conductor. It is also used if requirement to higher energy availability or lower load rejection power makes it necessary to split the capacity on two poles.

There are a lot of advantages to bipolar transmission which can make it the attractive option and they are:

- Under normal load, negligible earth-current flows, as in the case of monopolar transmission with a metallic earth-return. This reduces earth return loss and environmental effects.
- If there is an outages or during the maintenance of one pole, it is still possible to transmit a certain quantity of the electric power. Usually the part of energy that is possible to transmit in this situation is bigger than the 50% of the rated power of the system.
- Since for a given total power rating each conductor of a bipolar line carries only half the current of monopolar lines, the cost of the second conductor is reduced compared to a monopolar line of the same rating.
- In very adverse terrain, the second conductor may be carried on an independent set of transmission towers, so that some power may continue to be transmitted even if one line is damaged.

The main disadvantage is that unavailability of the return path with adjacent components will affect both poles.

Below there is a schematic representation of a HVDC bipolar station. Moreover, there are some different kinds of condition where the bipolar system can work, in relation with an outage or a particular situation of work for the maintenance.



1 AC Switchyard

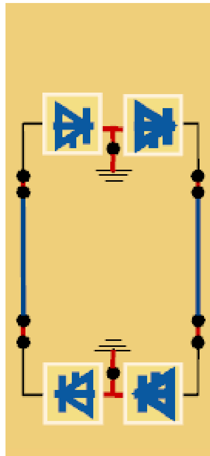
2 AC Filters, Capacitor Banks

3 Converter Transformers

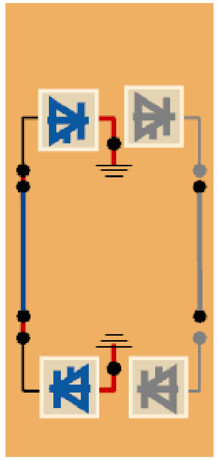
4 Thyristor Valves

5 Smoothing Reactors
and DC Filters

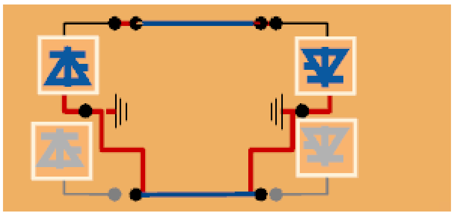
6 DC Switchyard



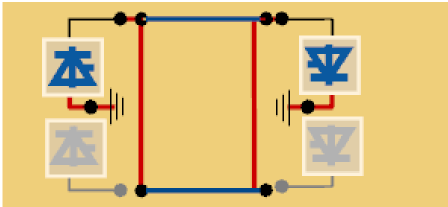
Bipolar



Monopolar, ground retur one DC line pole



Monopolar, metallic return



Monopolar, ground return two DC line poles

3.5 HVDC technology

The HVDC transmission systems are point-to-point configurations where a large amount of energy is transmitted between two regions. The traditional HVDC system is built with line commutated current source converters, based on thyristor valves. In the HVDC systems the fundamental process that occurs it is the conversion of electrical current from AC to DC (rectifier) at the terminal ends of transmission AC line, and from DC to AC (inverter) at the starting terminals of another transmission AC line. There are three different ways of achieving the needed conversion:

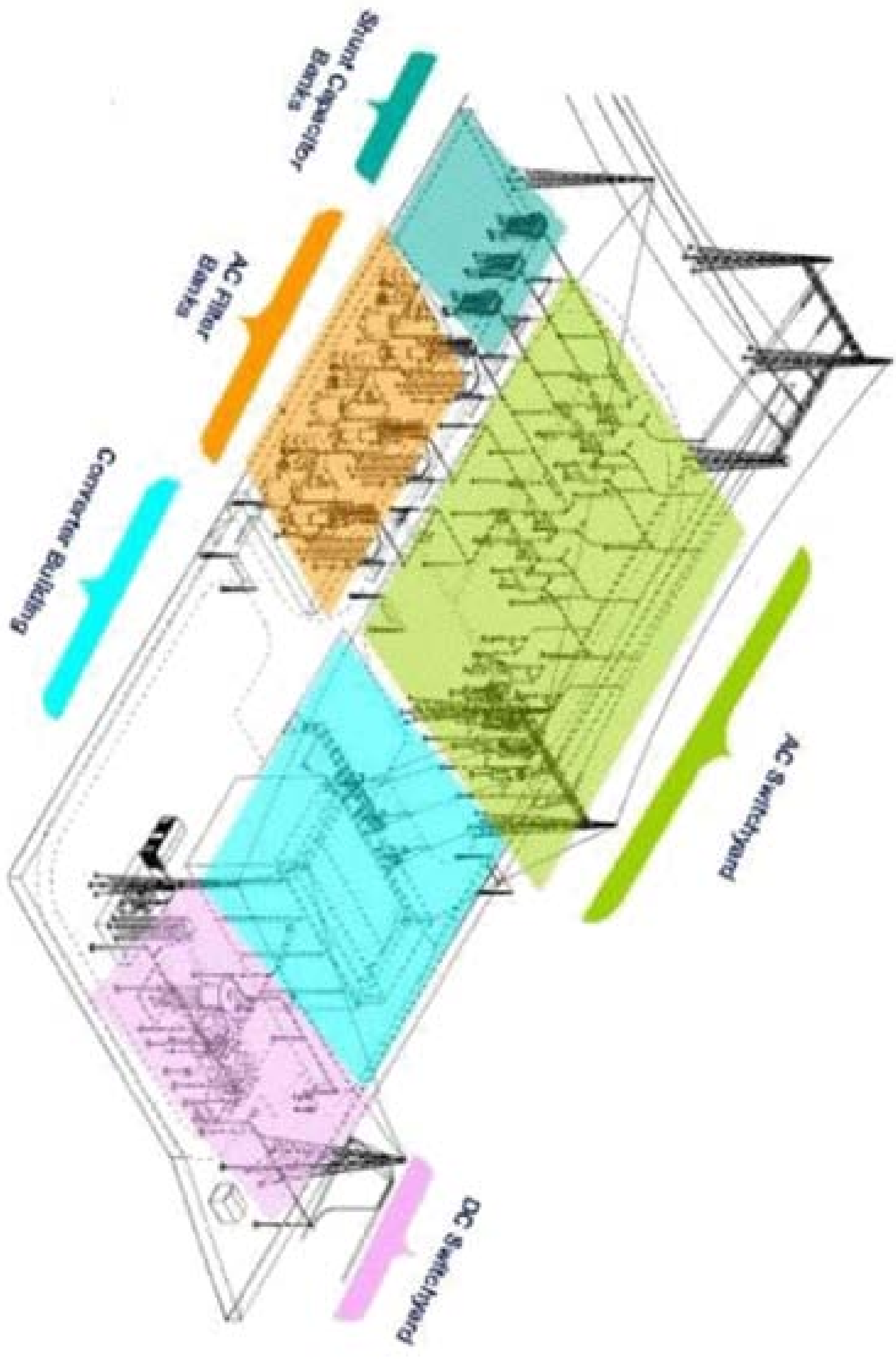
- ***Natural Commutated Converters.*** The thyristor is used in this conversion process. This component is a controllable semiconductor that can carry very high currents and it is able to block very high voltages. It is possible built a thyristor valve by means of connecting the thyristors in series. The valve can operate at very high voltages and it is operated at net frequency. It is possible to change the DC voltage level of the bridge by adjustment of the control angle. Thanks to this ability of the component, the transmitted power is controlled quickly and easily.

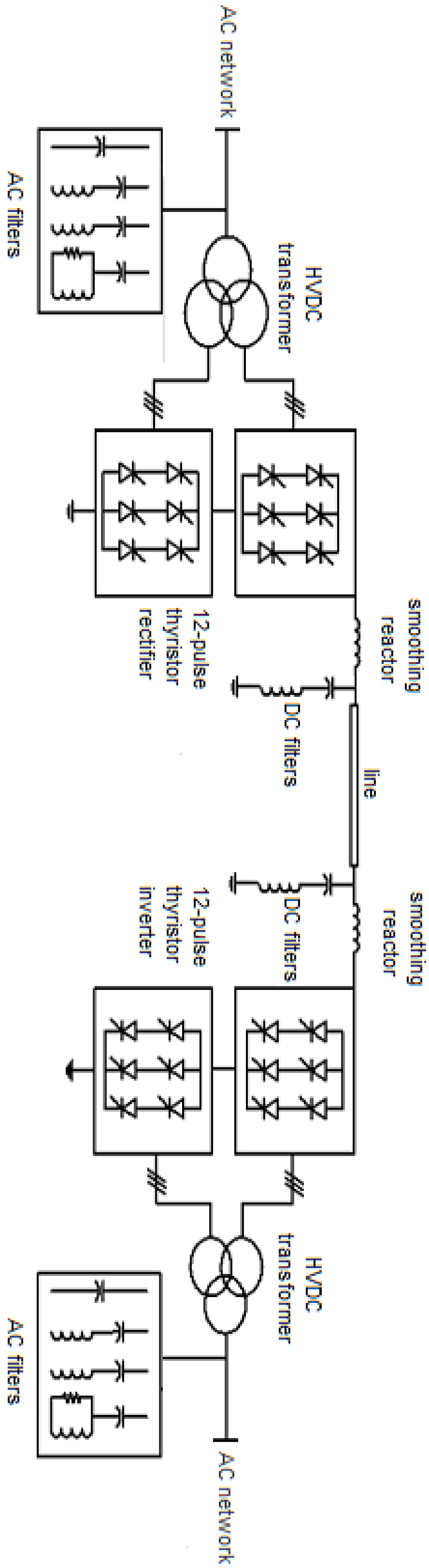
- ***Capacitor Commutated Converters (CCC).*** The CCC is an improvement in the thyristor based commutation. This configuration is characterized by the use of commutation capacitors inserted in series between the converter transformers and the thyristor valves. When the converters are connected to weak networks, their commutation failure performance is not so efficient but it is improved with the utilization of commutation capacitors.

- ***Forced Commutated Converters.*** These types of converters have some advantages. Whit this solution, for example, it can be possible feed of passive networks, that it is without generation. Another advantage is that the control of active and reactive power is independent, so therefore the power quality increases. The constituents of those valves have the ability of to turn-on and also to turn-off the elements. They are known as VSC (Voltage Source Converters). In the VSC can be used two different elements: the GTO (Gate Turn-Off Thyristor) or the IGBT (Insulated Gate Bipolar Transistor). The commutation frequency of VSC is not the net frequency but it is higher. The operations of the converters are done with PWM (Pulse Width Modulation). With PWM it is possible to create any phase 3 angle and/or amplitude (up to a certain limit) by changing the PWM pattern, which it can be done almost instantaneously. Thus, PWM offers the possibility to control both active and reactive power independently. This makes the PWM Voltage Source Converter a close to ideal component in the transmission network.

3.6 Main component in HVDC system

Below there is a representation of the HVDC station. Also a schematic representation of a HVDC system is shown in the picture below. The main component that compose this system are: AC filters, HVDC transformer, valves, smoothing reactor, DC filters and the line.


Shunt Capacitor Banks
AC Filter Banks
Converter Building
AC Switchyard
DC Switchyard


AC network
AC filters
HVDC transformer
12-pulse thyristor rectifier
smoothing reactor
DC filters
line
DC filters
smoothing reactor
12-pulse thyristor inverter
HVDC transformer
AC filters
AC network

3.6.1 AC filters

In a HVDC converter station before the HVDC transformer there are the AC filters. Those components have a good importance in the system. Their two main duties are:

- to absorb harmonic currents generated by the HVDC converter and thus reduce the impact of the harmonics on the connected AC systems. In this way the AC voltage distortion and telephone interference are reduced.
- to supply reactive power for compensating the demand of the converter station.

The active power, the transformer reactance and the control angle are the factors from which the reactive power consumption of an HVDC converter depends. It grows with increasing active power. A converter station requires the presence of a full compensation or overcompensation at rated load.

Characteristic and non-characteristic harmonic currents are generated from HVDC converter stations. The characteristic harmonics are of the order $n = (12 * k) \pm 1$ (with $k = 1, 2, 3...$) in a 12-pulse converter. The distortion level on the AC busbar depends on the grid impedance as well as the filter impedance. The third harmonic, which it is mainly caused by the negative sequence component of the AC system, will in many cases require filtering. The local conditions and regulations define the acceptance level of the harmonic distortion.

3.6.2 HVDC transformer

The HVDC transformer is mainly a normal transformer but during its design is necessary do some considerations relatively especially with the isolation and limit of transportation. In the following parts there is an overview on the main parts of the machine and their considerations. The main components are:

- ***Iron core:*** HVDC transformers are normally single phase transformers, whereby the secondary windings will be connected in star or delta configuration. In relation with the rated power and the system voltage of the machine, the most common configurations of iron core are with two main limbs and two return limbs. Another configuration can be with one main limb and two return limbs. Satisfy the requirements covering losses, noise level and over-excitation, it is necessary use a quality for core sheets adequate. Normally the core is built with the technique "step-lap". During the design of the machine must be taken a particular attention on the DC premagnetization of the core due to small asymmetries during operation and due to stray DC currents from the AC voltage network.

- ***Windings:*** The choice during the design of windings in a HVDC transformer requires significant flexibility. This suppleness depends from the large number of parameters concerning it like transport limitations, rated power, transformer ratio, short-circuit voltage, and guaranteed losses. The valve windings are mounted on the main limb of the core. If the iron core has two main limbs and two return limbs, the two valve windings are one on each main limbs and the primary winding is split in equal parts on the two main limbs.

- ***Tank:*** The tank design in HVDC transformers is not conventional and it depends from the following requirements:

    - The valve-side bushing should extend into the valve hall
    - The cooling system is mounted on the opposite side to facilitate rapid transformer exchange

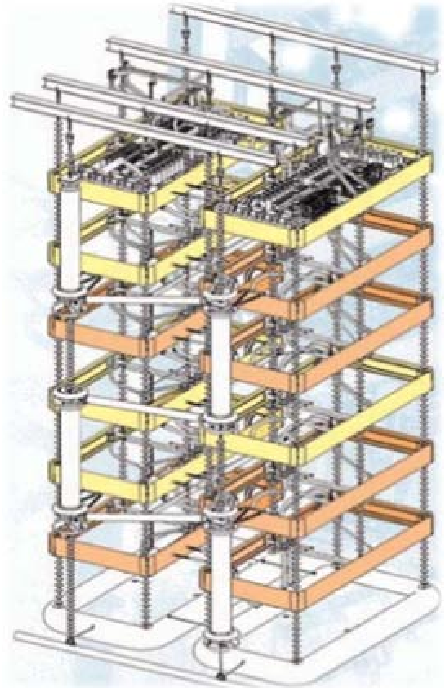
  In the HVDC transformers there are delta and star valve winding in one tank and their relative bushings must be positioned in a place that satisfies the isolation and also the geometry of the thyristor valve towers. For those reasons usually the heights of connections are very high and also the oil expansion tank is mounted at a significant height.

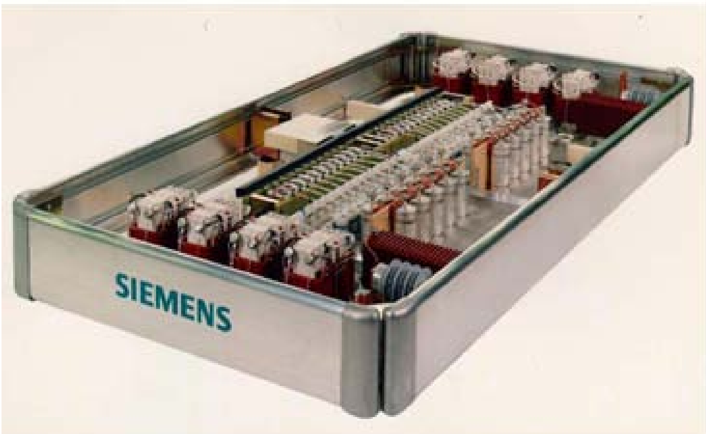
- ***Bushings:*** Compared to porcelain, composite bushings provide better protection against dust and debris. A 15% higher DC voltage testing level compared to the windings underscores the particular safety aspect of these components.

3.6.3 Valves

The central components of any HVDC converter station are the thyristor valves because they make the conversion from AC into DC. The thyristor valves can be indoor type or air-insulated type.

There are some different mechanical setups for thyristor valves and their configuration can best suit each application: single, double, quadruple valves or complete six-pulse bridges standing or suspended from the building structure. In some regions of the world there is the possibility of earthquake and it is necessary take into account this factor during the design of the valves. A solution for this problem can be to use an install of the valves where they are suspended from the ceiling of the valve hall. These kinds of insulators are projected to carry the weight and additional loads originating for example from an unbalanced weight distribution. By varying the number of thyristors per module and the number of modules per valve, the same design can be used for all transmission voltages that may be required. A schematic representation of suspended valves and a picture of a thyristor module layout are shown below.

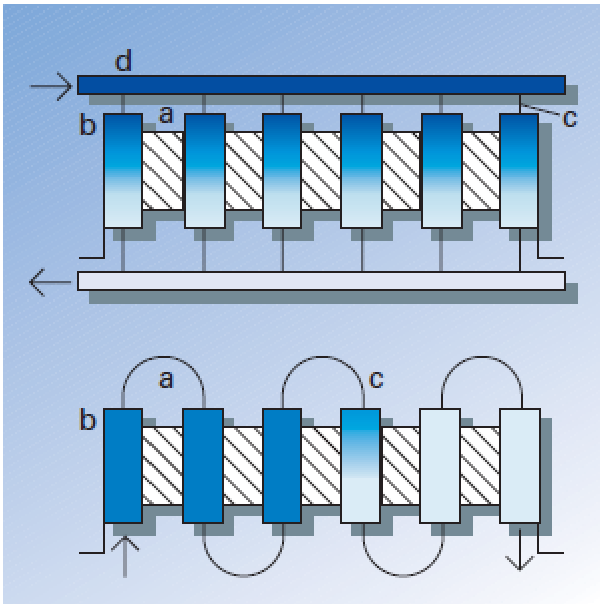




In the last years the performance of thyristors are increased a lot. In HVDC plants today are installed thyristors that they can block voltages up to 8 kV and current carrying capacities up to 4 kA DC. Considering these characteristic, the parallel connections of the thyristors for support the current are not necessary today. With a series connections of valve module are achieved the required value for the voltage.

The thyristors are stacked in the module with a heat sink on either side. About the dissipation of heat there a two different system and they are: parallel or series cooling water. These two different solutions are shown in the following picture. The best solution for the cooling system is the parallel configuration because there is the same cooling water temperature on all modules and this allows a better utilization of the thyristors capability. Another advantage with the parallel cooling system is that the construction is easier.

Parallel cooling system



Series cooling system

3.6.4 Smoothing reactor

Smoothing reactors are vital components in HVDC systems. It can be either oil or air insulated. The purpose of the reactor is to reduce the current ripple on the DC side of the system. The direct current that comes from the rectifier in the DC system has superimposed harmonic components, also called ripple. The smoothing reactor is connected in series with the rectifier and the whole load current flows through it. The purpose of the reactor is to provide high impedance to the flow of the harmonic currents, reduce their magnitude and thus making the DC current more smooth.

This component can also prevent steep-front surges from the DC line or DC yard from entering the valve hall. It is used also for decrease the incidence of commutation failures.

3.6.5 DC filters

In the DC transmission line is possible find AC currents superimposed and they are generated from harmonic voltages which they occur on the DC side of a converter station. Despite limitation by smoothing reactors, these alternating currents of higher frequencies can create interference on telephone systems. DC filter circuits are connected in parallel to the station poles. They are an effective tool for combating these problems. The configuration of the DC filters is very similar to the filters on the AC side of the HVDC station. Usually filters are not needed for pure cable transmissions as well as for the back-to-back stations. However, it is necessary to install DC filters if an overhead line is used in part or in all transmission system.

Regarding the intensity of interference currents on the telephone lines, it is strongly dependent on the operating condition of the HVDC. In fact the telephone interference is significantly stronger in monopolar operation than in bipolar operation.

3.6.6 Transmission line

For bulk power transmission the most frequent medium used it is the overhead line. Normally this overhead line is with bipolar configuration. Cables in HVDC are usually used for submarine transmission.

There are two most common types of cables that they are used and they are: the solid and the oil-filled ones.

The first type is in many cases the most economic solution. The conductor is built of stranding copper layers of segments around a central circular rod. The conductor is covered by oil and resin-impregnated papers. The inner layers are of carbon-loaded papers whereas the outer layer consists of copper-woven fabrics. The fully impregnated cable to keep the outside environment away from the insulation. The next layer is the anti-corrosion protection which consists of extruded polyethylene. There is not length limitation exists for this type and designs: today they are available for depths of about 1000 m. The capacity of mass-impregnated cables is limited by the conductor temperature which results in low overload capabilities.

The second type of cable is completely filled with low viscosity oil and always works under pressure. Oil-filled cables are suitable for both AC and DC voltages and great sea depths. Due to the required oil flow along the cable, the transmission line lengths are however limited to <100 km. During the choice of this kind of cable it is necessary take into account the risk of oil leakage into the environment.

The development of new power cable technologies has accelerated in recent years. Most of the research and development activities for new cable types are done with the insulation material. Today a new HVDC cable is available for HVDC underground or submarine power transmissions. This new HVDC cable is made of extruded polyethylene and it is used in VSC based HVDC systems.

3.7 HVDC transmission Vs. HVAC transmission

The three-phase alternating current is the system that the vast majority of electric power transmissions use all around the world. Numerous and complex reasons there are behind a choice of HVDC instead of AC to transmit power in a specific case. There are a lot of reasons justifying the choice in each project for to use the DC or AC system. Below there are the main general characteristics with the most common arguments where it is possible to see that the HVDC solution is the best choice.

1. ***Investment cost***
   If it is considered the same quantity of power that it is necessary transmit on a line from one point to another one, the solution with the DC link is cheaper. One disadvantage point of HVDC system is that the terminal stations are more expensive than the HVAC because they must perform the conversion AC to DC and vice versa. On the other hand, the costs of transmission medium (overhead lines and cables), land acquisition/right-of-way costs are lower in the HVDC case. Another aspect is that the operation and maintenance costs are lower in the HVDC case. The initial loss levels are higher in the HVDC system, but they does not vary with distance. Instead, in the AC system, the losses increase with distance. The HVDC alternative will always give the lowest cost above a certain distance.
   The price of the system depends on a lot of different parameters. Compare and have an indicative value about the cost and the possibility for design a HVDC system must be based on few data as rated power, transmission distance, type of transmission and voltage level in the AC networks where the converters are going to be connected. When the voltage is lower, for example, the price goes down, so in distribution networks the total cost is lower than in the transmission ones. It is depends from the equivalent isolation of the system that in the distribution network is lower.

2. ***Long distance water crossing.***
   In HVDC there is no distance limitation for long cable links. In a long AC cable transmission, instead, the reactive power flow due to the large cable capacitance will limit the maximum transmission distance. HVDC is the only available technical alternative.

3. ***Lower losses.***
   Considering the same power capacity in a line and optimize the link, the HVDC configuration is the best solution because the losses are smaller. The losses in the converter stations have of course to be added, but since they are only about 0.6 % of the transmitted power in each station, the total HVDC transmission losses come out lower than the AC losses in practically all cases. HVDC cables also have lower losses than AC cables.

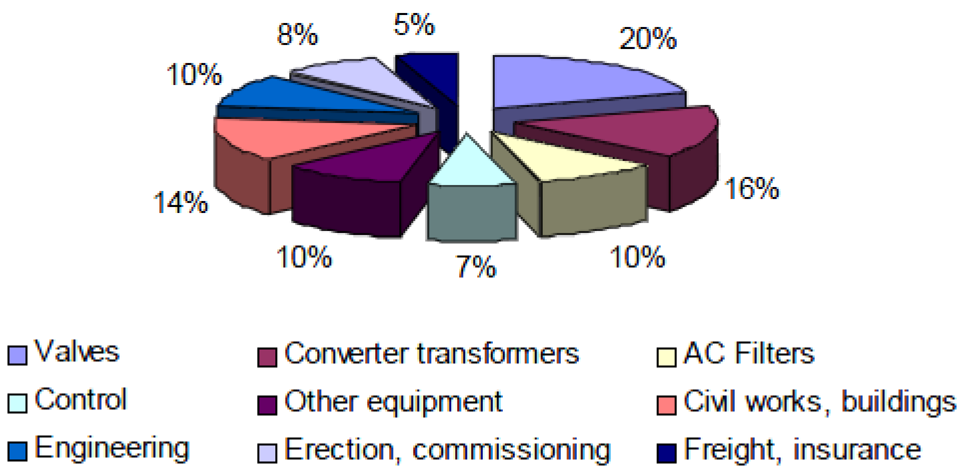
4. ***Asynchronous connection.***
   It is sometimes difficult or impossible to connect two AC networks due to stability reasons. In such cases HVDC is the only way to make an exchange of power between the two networks. There are also HVDC links between networks with different nominal frequencies and it is the only possible solution.

5. ***Controllability.***
   The control of the active power in a link HVDC is very easy and it is represent one of the fundamental advantages of this technology.

6. ***Limit short circuit currents.***
   A HVDC transmission does not contribute to the short circuit current of the interconnected AC system.

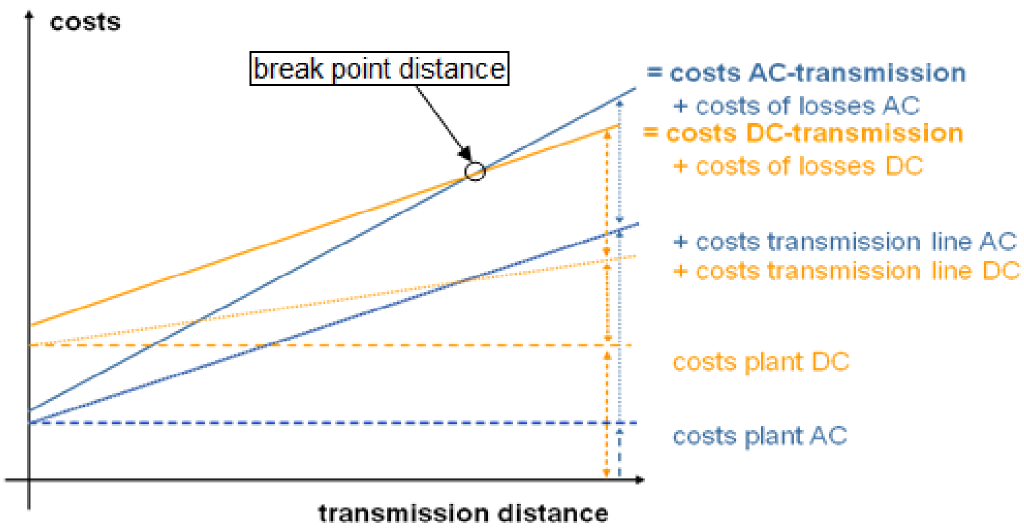
7. ***Environment.***
   A more efficient utilization of existing power plants can be improved thanks to energy transmission possibilities with higher quality. The land coverage and the associated right-of-way cost for a HVDC overhead transmission line is not as high as for an AC line. This reduces the visual impact. Regard the existing line it can be possible to increase their power transmission capability. In the HVDC system there are, however, some environmental issues which they must be considered for the converter stations, such as: audible noise, visual impact, electromagnetic compatibility and use of ground or sea return path in monopolar operation. In general, it can be said that a HVDC system is highly compatible with any environment and it can be integrated into it without the need to compromise on any environmentally important issues of today.

The point where the costs of HVAC system and the HVDC system are the same is called "break-even distance". The value of break-even-distance is much smaller for submarine cables (typically about 50 km) than for an overhead line transmission. It depends because with the submarine cable the cooling of the line is more efficient. If it is considered the same cross-section of the conductor, in the submarine cable is possible to use a bigger current density. In general this distance depends on several factors as transmission, different commutation techniques, variety of filters, transformers, etc... It is difficult to give a cost figure for a HVDC system. Nevertheless, a common and typical cost structure for the converter stations can be represented with the following picture.



Actually the HVDC system is designed for the transmission of large amounts of energy because its cost is normally high and it is due to from the necessity of filters, capacitors, valves and other auxiliary equipment

In the graph below it is possible to see a comparison between an AC system with the DC system considering the cost of the plan, of the transmission line and of the losses. A normal value where there is the break-even distance for an overheat line is about 700 km. Obviously before the break-even point it is better use the AC system, but after it is better use the DC system.



3.8 Considerations about a double circuit AC lines that it is converted to DC lines

Below it is shown the power carrying capability of AC and DC lines. Compare the transmission capacity of AC lines and DC lines is quite difficult. In AC system the actual transmission capacity is a function of reactive power requirements and also of the security of operation in relation with the stability of the network. In DC system it depends mainly on the thermal constraints of the line. Now there are some considerations about a double circuit AC lines that it is converted in DC lines.

Considering a given insulation length on a transmission link, the ratio of continuous-working withstand voltage between DC and AC is as indicated in the following equation.

$$k = \frac{U_{DC\_w}}{U_{AC\_w}}$$

where:

k is a coefficient
U_{DC_w} is the withstand DC voltage [V]
U_{AC_w} is the withstand AC voltage [V]

Various experiments on outdoor DC overhead-line insulators have demonstrated that a safe value of coefficient k is equal to 1 when they are installed in some areas where there is a high level of pollution. If a overhead line pass in a clean area the coefficient k can be the root of 2, where this value corresponding with the peak value of rms AC voltage. However for the cables the value of k can be equal at 2.

During the process design of a line, it has to be insulated for overvoltage expected during faults, switching operations, and so on. Normally the AC transmission lines are insulated against overvoltage of more than 4 times the normal rms voltage; this insulation requirement can be met by insulation corresponding to an AC voltage of 2,5 to 3 times the normal rated voltage. In the AC line a coefficient of transmission ratio can be obtained from the following equation.

$$k_1 = \frac{E_{isol\_AC}}{E_{p\_AC}}$$

where:

k_1 is a coefficient
E_{isol_AC} is the isolation voltage of AC line [V]
E_{p_AC} is the rated voltage of AC line [V]

On the other hand, considering the same principle shown for the AC line, the corresponding HVDC transmission ratio is calculated with equation below. Normally the value of k_2 is around 1,7.

$$k_2 = \frac{U_{isol\_DC}}{U_{p\_DC}}$$

where:

K_2 is a coefficient
U_{isol_DC} is the isolation voltage of DC line [V]
U_{p_DC} is the rated voltage of DC line [V]

Thus it is possible, from the formula below, define the isolation ratio between insulation length required for each pole of AC phase and insulation length required for each DC pole.

$$Isolation_{ratio} = k \cdot \frac{k_1}{k_2} \cdot \frac{E_{p\_AC}}{U_{p\_DC}}$$

Now it is possible to define the DC transmission capacity of an existing three-phase double circuit AC line. It is necessary to consider that the AC line can be converted to three DC circuits, each one having two conductors at ± V_d to earth respectively. Considering those aspects and imposing the same current for AC and DC solution, it is possible to write the following equations.

$$I_L = I_d$$
$$P_{AC} = 6 \cdot E_{p\_AC} \cdot I_L$$
$$P_{DC} = 6 \cdot U_{p\_DC} \cdot I_d$$
$$U_{p\_DC} = \left(k \cdot \frac{k_1}{k_2} \right) \cdot E_{p\_AC}$$
$$\frac{P_{DC}}{P_{AC}} = \frac{U_{p\_DC}}{E_{p\_AC}} \cdot \left(k \cdot \frac{k_1}{k_2} \right)$$

where:

I_L is the rated current in AC line [A]
I_d is the rated current in DC line [A]
P_{AC} is the power transmitted by AC line [W]
P_{DC} is the power transmitted by DC line [W]

If they are used the same values of k, k1 and k2 as above, the power transmitted by overhead lines can be increased to 147%, with the percentage line losses reduced to 68%. The corresponding figures for cables are 294 % and 34%

respectively. There are no changes on the conductors and the total rated current remains the same, which means that the transmitted power increases proportionally to the adopted new DC line to ground voltage.

The two following tables where it is possible to see the difference between transmitted power and losses of original double circuit AC lines with the converted DC lines.

AC lines

Voltage (kV)	0.7 A/mm2		1.0 A/mm2		1.4 A/mm2	
	P (MW)	Joule % of P (per 10Km)	P (MW)	Joule % of P (per 10Km)	P (MW)	Joule % of P (per 10Km)
33	26	11.0	37	16.1	52	22.6
132	130	3.5	180	4.9	262	7.1

DC lines

Voltage (kV)	0.7 A/mm2		1.0 A/mm2		1.4 A/mm2	
	P (MW)	Joule % of P (per 10Km)	P (MW)	Joule % of P (per 10Km)	P (MW)	Joule % of P (per 10Km)
66	89	3.8	127	5.4	178	7.6
264	440	1.2	636	1.7	890	2.4

4. CONCLUSION

After an accurate reading of this part of the report, it is possible to have a good overview on the principles steps of the electric design of the power transformer. It is possible understand the different solution that they can be done for respects all the requests of customer. For example now it is clear that the dimensions of the iron core and the windings are related with the losses of the machine. In relation with the losses must be done different choice in the height of the windows core, in the width of the windings, in the kind and configurations of conductors and so on. All these characteristics depend also from the necessary isolation level, the capability of support a lightning, etc. Another step very important on the design of a transformer is defined from the cooling system. It is fundamental for the life time of the machine and there are different kinds of it, how it was illustrated.

It is very important have an overview on the electric system. This is fundamental because it represents the backbone of the today's and tomorrow's society. Growth of the population, the civilization of the areas that it is developing and also the urbanization must be study. In relation with those aspects it is very clear understand the important of find new systems for generation, transmission and distribution of energy. The main advantages that these new technologies should be made to the system are increase the efficiency, increase the stability of the system and also the quality of the energy.

One solution that it has a very great importance and growing develops during the last decades it is the HVDC system. This configuration in the transmission energy has some very good advantages like reduced losses, they does not depend on the reactive power, there are not limit on distance, reduced environmental impact, and so on. The cost for this kind of energy transmission is convenient normally for very long distance because the price of the station is usually very big and for amortizes them it is necessary long distance transmission. If, in the transmission line, the return current path can be done go through the sea, the limit of distance where this solution is convenient it is not so big.

In relation mainly with the quantity of power that should be transmitted and with some environmental aspect also, there are some different solutions in the HVDC system like monopolar or bipolar system with different configurations for the return current path. According with those aspects must be choice the best solution.

The main concepts and aspects during the conversion of energy from AC system to the DC system and vice versa are clear now. The objectives and functions of all the components that compose the system were explained. They are used mainly for increase the quality of the energy, reduce the losses and interferences, and some other electric aspects.

All around the world the electric transmissions of different countries with the neighbourhood countries are connected or will be connected for increase the stability and the quality of the power. This configuration of distributed generation and transmission of global system require the connection of system that they operates with different frequency. The HVDC system is the only solution for interconnect two different systems that work with different frequency.

RINGRAZIAMENTI

Sicuramente le prime persone che devo ringraziare sono i miei genitori. Loro non mi hanno mai fatto mancare nulla e mi sono sempre stati vicino. Mi hanno sempre lasciato libera scelta su ciò che volevo fare dandomi dei preziosi consigli e sostenendomi sempre. Mi hanno appoggiato quando ho intrapreso il mio percorso di studi a Padova e sono sempre stati al mio fianco quando ho deciso di andare a studiare un anno all'estero in Finlandia e poi nell'avventura per il tirocinio in Brasile. E' stato difficile non avervi vicini fisicamente ma con il cuore non ci siamo mai lasciati e non ci lasceremo mai. Grazie a voi, che mi avete dato la possibilità di fare tutte queste esperienze, sono cresciuto molto. GRAZIE DI CUORE MAMMA E PAPA'.

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