Module 5.5

Grid Loss Reduction

Published in October 2016

1. INTRODUCTION AND CONTEXT

"Total System losses" is a popular indicator for measuring all losses that occur during the transmission and distribution of electricity from generating stations or points of purchase to end-use customers. Total system losses equal the difference between the power (GWh) supplied for consumption within the country and the power (GWh) billed to end users.

The main components of system losses are "Technical Losses" (e.g. heat or copper losses, magnetic losses, or transformation losses) and "Non-technical Losses" (e.g. meter failure, meter tampering or fraud, un-metered or illegal connections, or data encryption losses in billing, in other words, commercial losses, metering failures and theft).

Electricity has to be transmitted from large power plants to the consumers via extensive networks. The transmission of electricity over long distances creates power losses. The major part of electricity losses comes from "Joule effect" in transformers and power lines. Electricity losses occurs at each stage of the transmission and distribution system, starting with the step-up transformer that connects the power plant to the transmission system, and ending at the end-user.

Considering the main parts of a typical Transmission and Distribution Grid (Refer to Figure below), the average values of power losses at the different steps in normal operation conditions are as follows[1]:

- Step up transformer from generator to transmission line: 1-2%
- Transmission line: 2-4%
- Step down transformer from transmission line to distribution network: 1-2%
- Distribution network transformers and cables: 4-6%

"Optimal" range of system losses varies from system to system, but Total System Losses typically range between 7% - 10% in developed countries while they are about 30%-50% in Sub-Saharan Africa[2]. The most efficient utilities in the region report Total System Losses below 20%. System Losses remain a key issue in developing countries with a substantial amount of generated electricity not reaching intended locations.

Grid losses represent a major cost in the delivery of electrical energy. They have to be carefully managed.

Based on the above explanations, the "Grid Losses Reduction" Module presents the main technical factors of the grid losses in Transmission and Distribution networks by explaining the concept of grid Technical Losses, and identifying the actions to be taken to reduce them.

[1] Reference International Electrotechnical Commission (IEC) Document "Efficient Electrical Energy Transmission & Distribution" (http://www.iec.ch/about/brochures/pdf/technology/transmission.pdf).
[2] Monitoring Performance of Electric Utilities - Indicators and Benchmarking in Sub-Saharan Africa – World Bank 2009.

2. ELECTRICITY NETWORK ORGANISATION

The figure below (Figure) shows the organisation of typical Transmission and Distribution networks.

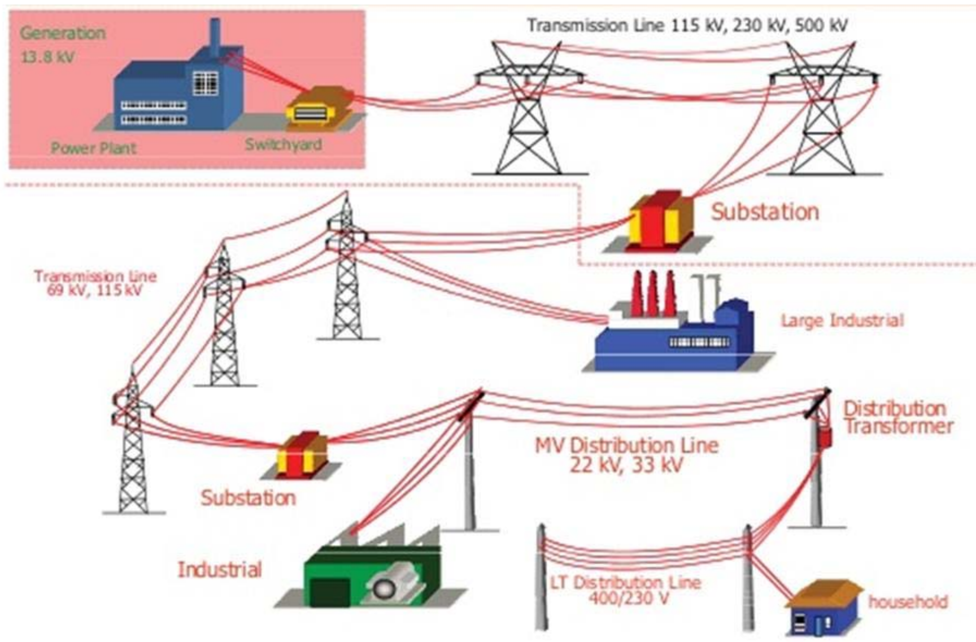

Figure 1 - Transmission and Distribution Networks Organisation

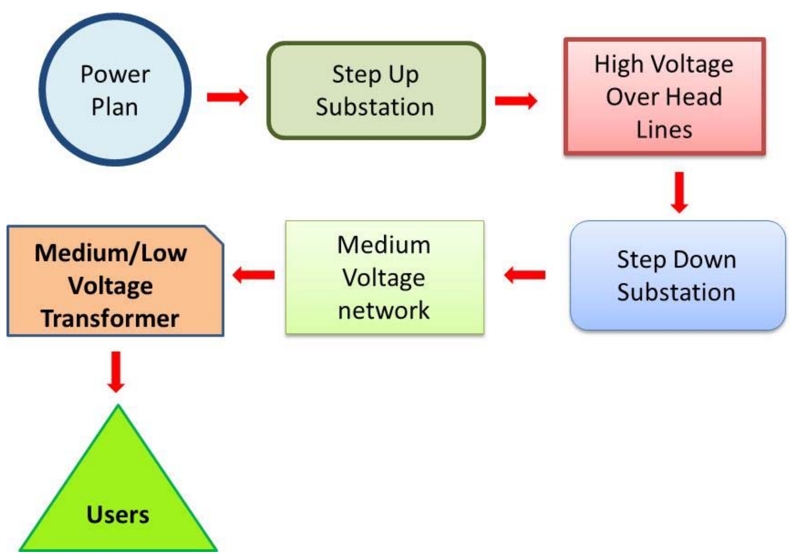

Figure 2 - Transmission and Distribution Networks Organisation

For transmission and distribution of electric power, standardized voltages according to IEC[3] 60038[4] are used world-wide. For three phase alternating current (AC) applications, four voltage levels prevail:

Level of voltage	Range of voltage	Size of the wire (mm²)[5]
Extra High Voltage	above 245 kV	1195 AGS[6] or - 2 x 570 ACSR or - 2 x 851 ACSR
High Voltage:	above 35 kV - up to 230 kV inclusive	63 and 90 kV: - 228 ACSR or - 288 ACSR or - 366 ACSR or 225 kV: - 570 ACSR or - 851 ACSR or - 2 x 570 ACSR or - 2 x 851 ACSR or - 1144 ACSR 400 kV: - 1195 ACSR or - 2 x 570 ACSR or - 2 x 851 ACSR or
Medium Voltage	from 1 kV - up to 35 kV inclusive	Medium Voltage (MT): - 120 to 200 AAAC[7] -
Low Voltage	from 100 V - up to 1 kV inclusive	Low Voltage (LV) – Insulated Cables: - 3(1x50) + 1x50 mm² - 3(1x120) + 1x120 mm²

Table 1- Level of voltage and size of wires

As shown on Figure 1 above, the Electric system consists of several key components:

- Extra high voltage (EHV) transmission lines, (Over 245 kV)
- Step down transformers (EHV/HV) at the main substation,
- HV sub-transmission lines,
- HV/MV substations,
- Medium Voltage (MV) distribution lines,
- MV/LV transformers,
- Low Voltage lines, and
- Service connection to individual consumers.

The HV lines up to 145 kV serve for subtransmission of the electric power at the regional level, and feed the medium voltage distribution networks. They constitute the connection between the interconnected HV - EHV networks and the local distribution networks.

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[3] International Electrotechnical Commission (IEC).
[4] Refer to https://webstore.iec.ch/preview/info_iec60038%7Bed7.0%7Db.pdf.
[5] Reference Electricité de France.
[6] ACSR: Aluminium Conductor Steel Reinforced.
[7] AAAC: All Aluminium Alloy Conductor

Medium voltage lines supply power to small settlements, individual industrial plants and large consumers. Their transmission capacity is typically less than 10 MVA per circuit.

Low voltage lines serve households and small business consumers.

However, when considering bulk power transmission over long distances, a more economical solution is the High Voltage Direct Current (HVDC) technology, but it is costly (due to the high cost of the conversion stations). This technology is mainly used for the transmission of large quantity of power (1'000 & 2'500 MW).

3. KEY PARAMETERS AND UNITS OF MEASUREMENT

The Table below ((*): Reactance *at frequency f=50Hz*, used in equivalent circuit for transmission lines.

Table 2) presents the main units of measurement to be used for power loss calculations.

Parameter	Measurement Unit	Symbol
Voltage	Volts (V) – kilovolts (kV)	U
Current	Amps (A) – kilo Amps (kA)	I
Active Power	Watts (W) – kilo Watts (kW) Mega Watt (MW) – Giga Watt (GW)	P
Apparent Power	Volt Amps (VA) – kilo Volts Amps (kVA)	P
Reactive Power	Volt Amps Reactive (VAR)	Q
Energy	Watt/hour (Wh) – kilowatt/h (kW/h)	E
Frequency	Cycle per second (Herz - Hz)	f
Time	Second (s)	t
Resistance	Ohm (Ω)	R
Inductance	Henry or milli Henry/meter (H/m or mH/m)	L
Inductive Reactance (*)	Ohm (Ω)	2∏f.L
Capacitance	μFarad or ρFarad/meter (μF/m or ρF/m)	C
Capacitive Reactance (*)	Ohm (Ω)	1/2∏f.C

(*): Reactance *at frequency f=50Hz*, used in equivalent circuit for transmission lines.

Table 2 – Measurement Units

4. THE MAIN GRID POWER LOSSES

Electricity has to be transmitted from large power plants to the consumers via extensive networks (see Figure).

Grid losses are defined as the energy lost in the Transmission and Distribution networks, i.e. the difference between the total energy generated at the power plants and the total energy sold and paid by the end-users.

Transmission & Distribution Losses (%) = (Energy Input at Power Plants (kWh) – Billed Energy to Consumer (kWh)) / Energy Input (kWh) x 100

System losses have two main components: technical losses and non-technical losses.

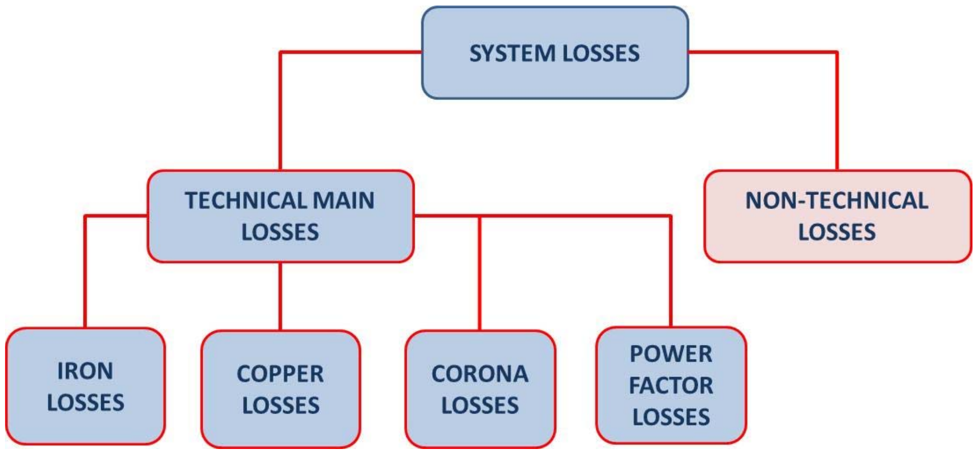


Figure 1 - Grid Losses Typology

Technical losses concern the energy dissipation from the generators to the end-users in the conductors, equipment used for transmission lines, transformers, sub-transmission lines and distribution lines and magnetic losses in transformers.

Non–technical or commercial losses are caused by external actions and consist primarily of electricity pilferage, non-payment by consumers, and errors in accounting and record keeping.

Technical losses occur naturally and are due to the main following effects:

- Joule or Copper heating effect (in line conductors, cables and transformer copper winding);
- Corona effect on transmission lines;
- Iron loss or Core loss in wound components like transformers (magnetic circuit), due to magnetic friction in the core ("hysteresis") and electric currents induced in the core ("Eddy currents" also called "Foucault currents");
- Load factor effect.

4.1 JOULE LOSSES IN TRANSMISSION AND DISTRIBUTION OVERHEAD LINES (OHL)

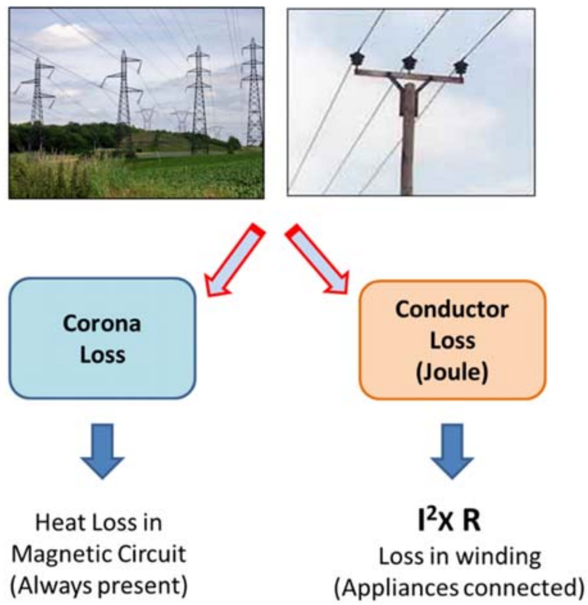


Figure 2 – Main Losses in T&D Overhead Lines

Line losses, also called "Joule losses" refer to the ohmic resistance of the conductor during transmission and distribution of the power.

For a Three Phase System, the amount of power (P) transmitted by a power line is measured in Watts (W) or kilo Watts (kW), which also correspond to current intensity (I) expressed in amperes multiplied by the Voltage (U) between Phases expressed in Volts or kilo Volts. The Voltage (U) is equal to the resistance multiplied by the intensity.

$$P \text{ (Watts)} = \sqrt{3} \times U \text{ (Volts)} \times I \text{ (Amps)} = 3 \times R \text{ (Ohms)} \times I^2 \text{ (Amps)}$$

Current (I) represents a flow rate of charge and is measured in amperes or amps. This flow of electric charge is typically carried out by moving electrons in a conductor such as wire.

The technical losses under the form of heat dissipation are due to the circulation of current (I) in the conductors, called "Joule or Copper Losses".

It concerns transmission and distribution lines and power transformers.

The main factors generating Joule losses are:

- The electrical resistance (R) of the line conductor or copper wire of the power transformer (winding);
- The current (I) flowing in the conductor or copper wire; and
- The power transiting in the line.

Voltage Level (kV)	Conductor Cross-section (mm^2)	Max current carrying capacity (Amps)	Max Transmission Capacity (MW) (**)	Average Cost per kilometre (USD (*)
66	228	600	68	165,000
	288	700	80	
	570	1100	125	
132	228	600	137	220,000
	288	700	160	
	570	1100	251	
225	412	850	331	385,000
	570	1100	429	
	2 x 570	2200	857	
400	2 x 570	2200	1524	550,000
	2 x 851	2700	1870	
	1144	1650	1143	

(*): Due to difficulties in getting the right-of-way, Transmission OHL are now most of the time built as Double Circuit OHL. The costs indicated here are for only one (1) circuit equipped. You must add 15% when both circuits are equipped.

(**): $\cos \varphi = 1$.

Table 3 - Optimum Transmitted Capacity of Overhead Lines

4.1.1 Electrical Resistance

The electrical resistance of the conductor depends on the resistivity of the conductor material (Aluminium, copper) and the temperature of the conductor (temperature coefficient).

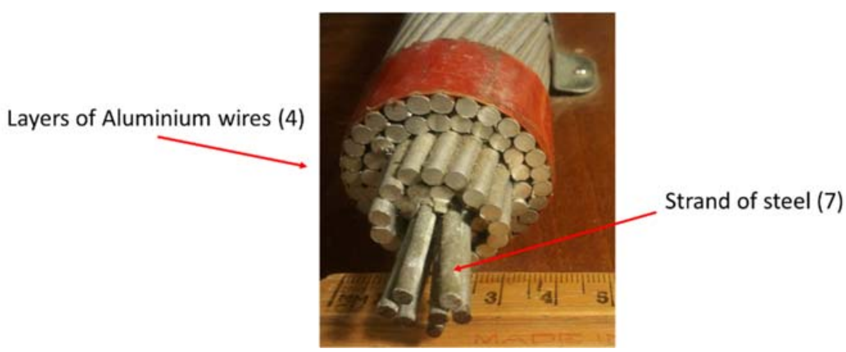


Figure 3 - Aluminium Conductor Steel Reinforced Type used for Transmission lines

a) Conductor Resistivity

The conductor resistivity is an intrinsic property of a material that is measured as its resistance to current per unit length for a uniform cross section. The symbol is ρ.

Material	Resistivity **ρ** (Ω.m) at 20°C		Temperature coefficient **α** per °C
Silver	1.59	$x10^{-8}$	0,0038
Copper	1.68	$x10^{-8}$	0,00386
Copper annealed	1.72	$x10^{-8}$	0,00393
Aluminium	2.65	$x10^{-8}$	0,00429
Tungsten	5.6	$x10^{-8}$	0,0045
Iron	9.71	$x10^{-8}$	0,00651

Figure 4 - Resistivity of some common conductors

b) Conductor Resistance

The electrical resistance of an electrical conductor depends on:

- The length of the conductor,
- The material of the conductor (copper or aluminium),
- The temperature of the conductor, and
- The cross sectional area of the conductor.

It is calculated as following:

$$R = \frac{\rho L}{S}$$

L= Length of the conductor (m)

S= Cross section area (m^2)

R= Resistance of the conductor (Ω Ohm)

ρ Conductor Resistivity (Ω.m)

$$1\ \text{Ohm}\ (\Omega) = \frac{1\ \text{Volt (V)}}{1\ \text{Amp (A)}}$$

c) Conductor Temperature

The temperature coefficient of resistivity describes the change in resistivity as a function of temperature:

Resistivity (T) = (Resistivity T0 x (1 + a (T - T0)

a = Temperature coefficient of resistivity

T0 = Reference temperature (20°C)

The coefficients of resistivity (a) for the main materials are presented in the Table below.

Material	Coefficient of resistivity (20°C)	-10°C (10^{-8})	0°C (10^{-8})	20°C (10^{-8})	40°c (10^{-8})	60°C (10^{-8})	80°C (10^{-8})
Silver	0.0038	1.41	1.47	1.59	1.71	1.83	1.95
Copper	0.00386	1.48	1.55	1.68	1.81	1.94	2.07
Copper annealed	0.00393	1.52	1.58	1.72	1.86	1.99	2.13
Aluminium	0.00429	2.31	2.42	2.65	2.88	3.10	3.33
Tungsten	0.0045	4.84	5.1	5.6	6.10	6.60	7.11
Iron	0.00651	7.81	8.45	9.71	10.9	12.23	13.5

Table 4 - Resistivity calculation for the main materials at different temperatures in Ωm

Example 1: Resistance calculation of a three phase overhead line with an aluminium conductor at 20° C:

a) Line voltage: 380 V/220 V
b) Maximum Current (I): 100 A per phase
c) Cross section of the conductor: 54 mm^2
d) Length of the line: 300 meters
e) Resistivity of aluminium: 2.65 x 10^{-8} Ωm at 20°C

Total Resistance of the line: R (Ω) = (2.65 10^{-8} x 3 x 300)/ 54 10^{-6}
R= 0.44 Ω

P_{Loss} (Joule loss) = 3 x 0.44 x 100^2 = 13 200 W

The charts presented in Annex 1 allow how to calculate the level of Joule losses and distribution and transmission lines per kilometre (kW/km) for different voltage levels, transited loads and length of the lines. Power losses in medium voltage distribution feeders are essentially a function of three main variables: peak demand, feeder length and load distribution profile along the feeder.

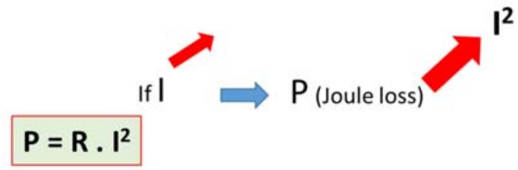
4.1.2 Current in the line

The electrical resistance of a circuit is defined as the ratio of the voltage applied to the electric current, which flows through it (Ohms' Law):

$$I = \frac{U}{R} \longleftrightarrow R = \frac{U}{I} \longleftrightarrow U = R \cdot I$$

The current (I) is inversely proportional to the Voltage (U) i.e. higher the voltage is, lower is the value of the current and the Joule losses.

From this equation, we can observe that the line losses are directly proportional to the square of the current (I2).



Note: P shall be multiplied by 3 for a three phase circuit.

The power transmitted for any size of conductor depends on its current carrying capacity which is directly linked to its power factor[8]. This can be calculated from the following formula:

Power in W:	$\sqrt{3}$.U.I cos φ
Power in kW:	$\sqrt{3}$.U.I cos φ /1000
Cos φ:	Power Factor
V :	Voltage
I :	Current in Amp

<u>Example 2</u>:

Assuming Power Factor of 0.8 lagging, power transmitted at various voltages can be calculated approximately as follows:

a) At 132 kV:

Power in MW $= \sqrt{3} \times 132 \times I \times 0.8/1000$
$= 0.183 \times I$

b) At 220 kV:

Power in MW $= \sqrt{3} \times 220 \times I \times 0.8/1000$
$= 0.305 \times I$

c) At 400 kV:

Power in MW $= \sqrt{3} \times 400 \times I \times 0.8/1000$
$= 0.554 \times I$

Thus, the value of the transmitted power can easily be calculated at 132 kV, 200kV or 400 kV for a given value of the current.

4.1.3 Corona losses

Corona is a phenomenon associated with all energized transmission line under certain conditions. The localized electric field near an energized conductor can be sufficiently concentrated to produce a tiny electric discharge that can ionize air close to the conductor.

[8] The electrical power factor is explained and presented in Section 4.4 of the present document.

Corona discharge or Corona effect is a partial discharge of electrical energy. Several factors including conductor voltage, shape, diameter and surface irregularities such as scratches, nicks, dust or water drops can affect a conductor's electrical surface gradient and its corona performance. Corona is a physical manifestation of energy loss that can transform discharge energy into very small amounts of sound, radio noise, heat and chemical reaction of the air component (ozone).

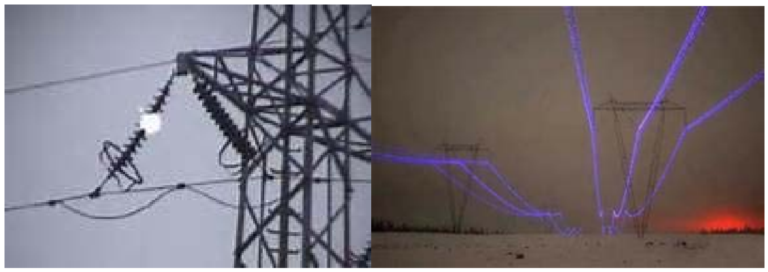


Figure 5 - Corona Effect

Figure 8 below shows the effect of conductor diameter in corona losses in kW/cm.

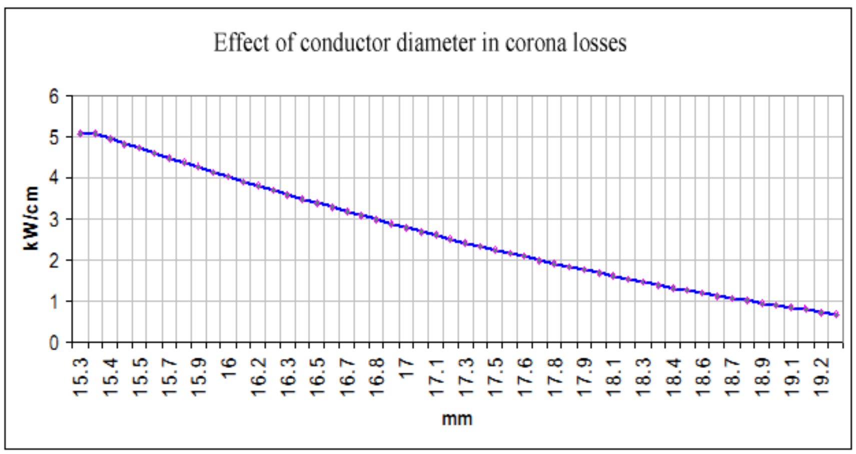


Figure 6 - Corona losses in 400kV transmission line depend of the conductor diameter

To reduce corona loss on the transmission lines, we install more conductors per phase (2, 3 and 4) to increase the apparent conductor radius.

4.2 HIGH VOLTAGE UNDERGROUND CABLES LOSSES

High voltage cables are used when underground transmission is required. These cables are laid in ducts or may be buried in the ground. Unlike in overhead lines, air does not form part of the insulation, and the conductor must be completely insulated. Thus, cables are much more costly than overhead lines. Also, unlike for overhead lines where tapings can easily be done, cables must be connected through cable boxes, which provide necessary insulation for the joint.

Figure 7 – HV Underground Cables

Cables have much lower inductive reactance than overhead lines due to the lower spacing between conductor and earth, but have correspondingly higher capacitive reactance and hence a much higher charging current. High voltage cables are generally single cored, and hence have their separate insulation and mechanical protection by sheaths.

The presence of the sheath introduces certain difficulties as currents are induced in the sheath as well. This is due to fact that the sheaths of the conductors cross the magnetic fields set up by the conductor currents. At all points along the cable, the magnetic field is not the same. Hence different voltages are induced at different points on the sheath. This causes **Eddy current** to flow in the sheaths. These eddy currents depend mainly on:

a) The Frequency of operation,
b) The distance between cables,
c) The mean radius of the sheath, and
d) The resistivity of the sheath material.

Power loss in the cable can occur due to a variety of reasons, voltage and current. Three main losses occur as depicted on the following Figure (- Types of Cable LossesFigure 8):

- Conductor loss (P1),
- Dielectric loss (P2), and
- Sheath and intersheath loss (P3).

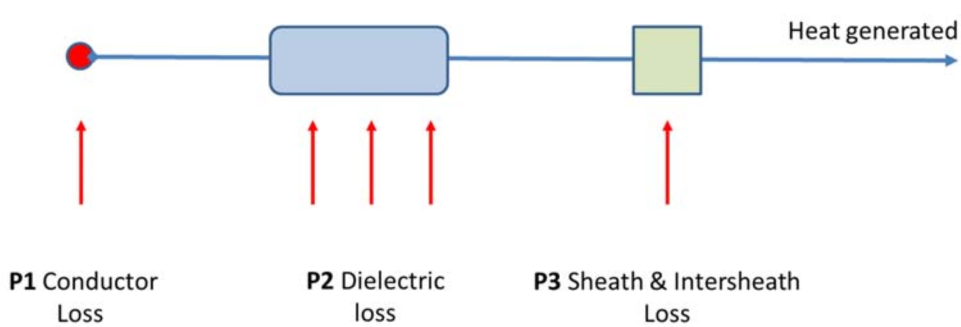


Figure 8 - Types of Cable Losses

Total Cable Losses = P1 + P2 + P3

4.2.1. Conductor loss

Conductor loss is also sometimes called "Joule Loss" or "Copper Loss" on account of the fact that conductors were mainly made out of copper.

The power loss is given by:

$$Pc = I^2 . Rc \text{ (watt)}$$

Where: **Rc** is the resistance of the conductor, and
I is the current in the cable.

4.2.2. Dielectric loss

Dielectric loss is caused by the voltage across the insulation.

For a perfect dielectric, the power factor is zero. Since the cable is not a perfect dielectric, the power factor is not zero. The current leads the voltage by angle of less than 90° (phase angle) and there is power loss.

Sheath loss

Sheath loss is caused by the induced current in the sheath.

The sheath loss is usually about 2% to 5% of the conductor loss.

Intersheath loss

Intersheath loss is caused by circulating current in loops formed between sheaths of different phases.

The intersheath loss is larger than sheath loss and may range from 10% to 50% of the copper loss.

The dielectric loss is voltage dependant while the rest is current dependant.

Conductor cross section mm²	Conductor resistance (Ω/km)		Capacitance μF/km	Carrier current capacity (Amp)
	20°C DC	90°C AC		
240	0.0754	0.0961	0.135	543
300	0.0601	0.0766	0.146	597
400	0.0470	0.0599	0.165	657
500	0.0366	0.0467	0.182	718
630	0.0283	0.0361	0.201	779
800	0.0221	0.0224	0.246	914
1000	0.0176	0.0193	0.266	972
Note: current carrier is made up by laying in soil abreast. The axial distance between cable are 200 mm. Soil temperature is 25°C. The working temperature of cable is 90°C. The coefficient of soil heat-resistance is 1.2km/W.				

Table 5 - 110kV / 220kV XLPE Copper Cables

4.3 TRANSFORMER LOSSES

Transformer losses are produced by the electrical current flowing in the coils and the magnetic field alternating in the core. Load losses are the losses associated with the coils (copper loss) while the no-load losses are the ones produced in the core (iron loss) are called no-load losses.

Load losses vary according to the load on the transformer. They include heat losses and eddy current losses in the primary and secondary windings of the transformer.

The main transformer losses consist of electrical losses as iron losses and copper losses (Joule loss) are shown in the Figure below (Figure 11).

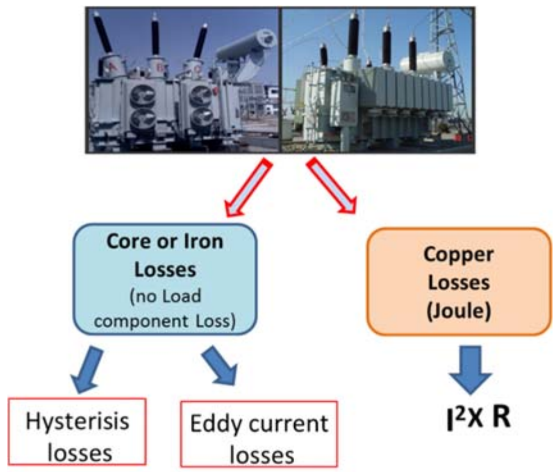


Figure 9 – Main Transformer Losses

Hysteresis losses and Eddy current losses contributes over 99% of the no-load losses, while the other losses due to no-load current are small and consequently often neglected.

a) Hysteresis loss:

The biggest contributor to Iron losses is the Hysteresis losses. Hysteresis losses come from the molecules in the core laminations being magnetized and demagnetized by alternating magnetic field. This resistance by the molecules causes frictions that result on eat.

Choice of size and type of core material reduces Hysteresis losses.

b) Eddy Current Loss:

In transformer, AC current is supplied to the primary winding, which sets up alternating magnetizing flux. When this flux links with the secondary winding, its produces induced emf (electro-magnetic forces) in it. But some part of this flux also gets linked with other conducting parts like steel core or iron body. This current is called as Eddy current. Due to these currents, some energy will be dissipated in the form of heat.

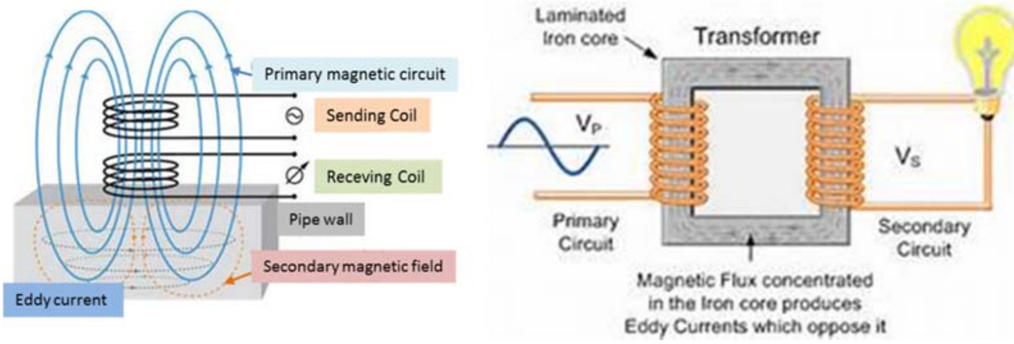


Figure 10 - Eddy Current Principle

Note: The iron losses are independent of the transformer load (depend only of the frequency and primary voltage). It is a permanent loss.

c) <u>Load loss (copper loss):</u>

Copper loss is due to ohmic resistance of the transformer windings.

Heat losses or $R.I^2$ losses, in the winding materials contribute to the largest part of load losses. They are created by resistance of the conductor to the flow of current.

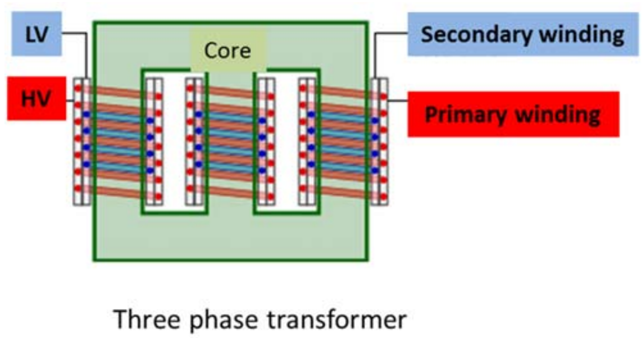


Figure 11 - Primary and Secondary Winding

Copper loss for the primary winding is $R_1.I_1^2$ and for the secondary winding is $R_2.I_2^2$. Where I_1 and I_2 are current in primary and secondary winding respectively, R_1 and R_2 are the resistances of primary and secondary winding respectively. It is clear that the copper loss is proportional to square of the current, and depends on the load.

d) <u>Total transformer losses calculation</u>

$$W = W_{fe} + W_{co} \times (S/S_n)^2$$

W : Total transformer losses (W)
Wfe : Iron losses (permanent loss) (W)
Wco : Copper losses at nominal power (W)
Sn : Nominal Power of the Transformer (VA)
S : Transformer load

<u>Example:</u>

Nominal power of the Transformer: 500 kVA
Cos φ: 0.9
Wfe: 730 W
Wco: 4550 W
Transformer load: 300 kW

<u>**Total losses**</u> = 730W+4550W x [(300 kW/0.9) / 500 (kVA)]² = **2 752 W**

An "ideal transformer" have no energy losses, i.e. zero losses and 100% efficiency, but in real transformers, energy is dissipated in the windings, core and surrounding structures.

Larger transformers are generally more efficient, and those of distribution transformers usually perform better than 98%.

4.4 ELECTRICAL POWER FACTOR

In the electrical domain, electrical power is the amount of electrical energy that can be transferred under some other form (driving force, heat, light, etc.) per unit of time (second). Mathematically, it is the product of voltage across the element by the current flowing through it.

Considering first **Direct Current (DC)** circuits having only DC voltage sources, the inductors and capacitors behave respectively as short circuit and open circuit in steady state conditions. Hence, the entire circuit behaves as resistive circuit and the entire power is dissipated in the form of heat. Here the voltage and current are in phase and the electrical power is given by:

In **alternative current (AC)** circuits, there is some phase difference between the source voltage (UR, UL and UC) and the current (IR, IL and IC). The cosine of this phase difference (φ1 or φ2) is called "Electrical power factor" as shown in the following phase diagram below.

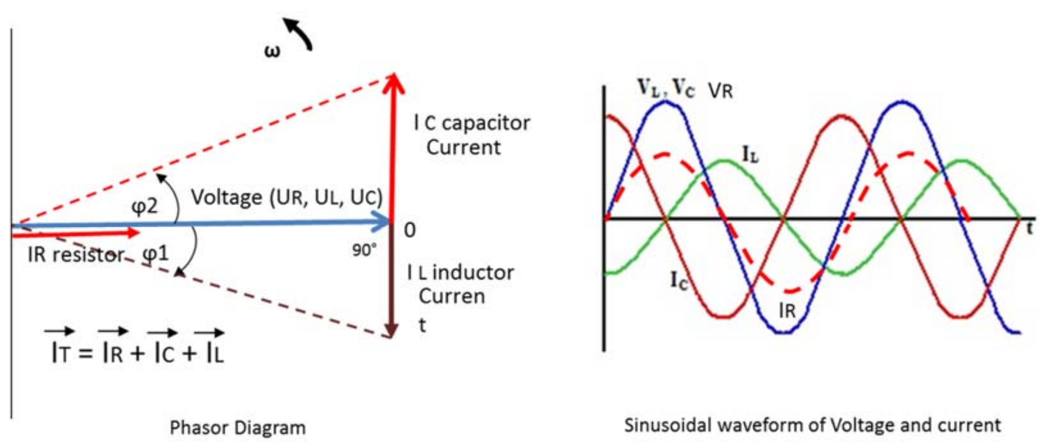


Figure 12 - Phase Diagram and Waveform of R, L, C Circuits

This factor cosine φ1 or φ2 (-1< Cos φ < 1) represents the fraction of total power that is used to do the useful work.

The other fraction of electrical power is stored in the form of magnetic energy or electrostatic energy in inductor and capacitor respectively.

The power in this case is:

Total electric power in one component of the grid = Voltage across the element x current through the element. It is called "Apparent Power" and its unit is VA (Volt Amp) or kVA and noted "S".

A fraction of this total electrical power, which actually does our useful work, is called "Active Power". It is noted as "P".

P = Active Power **=** Electrical Power x cos φ and its unit is Watt (W)

The other fraction of power is called "Reactive Power". It is not useful for work, but is required for the active work to be done. It is noted by "Q" and mathematically is given by:

Q = Reactive Power = Electrical power x sin φ and its unit is VAR (Volt Amp Reactive).

This reactive power oscillates between source and load.

To understand this better, the power is represented by the form of a triangle as shown by the Figure below (Figure 13 - Power Triangle:

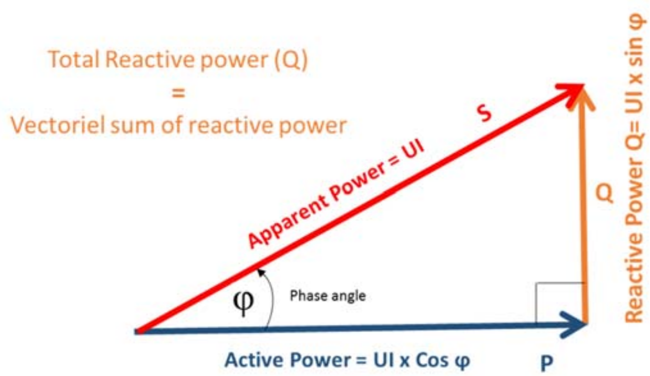


Figure 13 - Power Triangle

Mathematically, $S2 = P2 + Q2$ and electrical Power Factor (cos φ) is Active Power (P) divided by Apparent Power (S):

$$\text{Cos}\,\varphi = \frac{\text{Active power (P)}}{\text{Apparent power (S)}}$$

This formula needs to improve the power factor.

Active power is given by: $P = U.I. \cos\varphi$ for a single conductor, and

$P = \sqrt{3}\, U.I. \cos\varphi$ for a three phase circuit.

To transfer a given amount of power at a certain voltage, the electrical current is inversely proportional to cos φ. Hence, higher the power factor PF is, lower will be the current flowing in the conductors. A small current flow requires less cross sectional area of the conductor and thus saves conductor and money.

From the above relation, we can deduct that having poor power factor increases the current flowing in conductor and thus Copper Losses increase. Further, large voltage drop occurs in alternator, electrical transformer and transmission and distribution lines, which gives very poor voltage regulation.

Further, the kVA rating of machines is also reduced by having poor power factor:

$$S\,(KVA) = \frac{P\,(kW)}{\mathbf{Cos}\ \varphi}$$

Hence the size and cost of machine is also reduced. So the electrical power factor should be maintained close to (1). See the below phase diagram improvement (Figure 16).

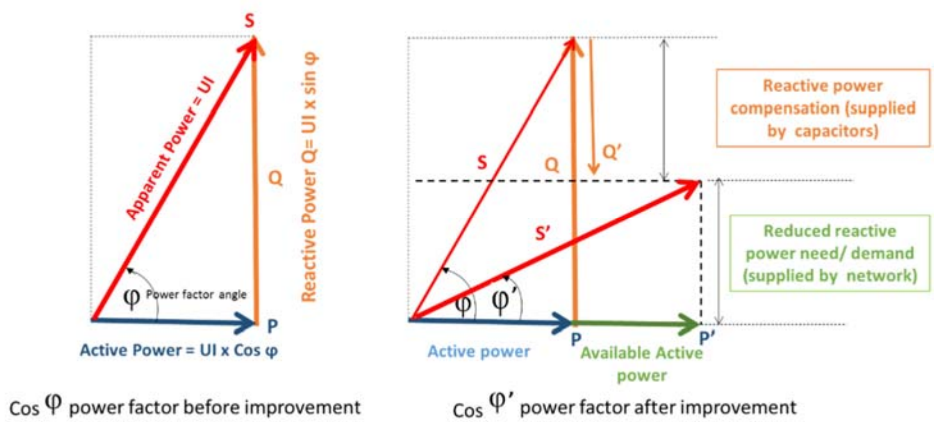
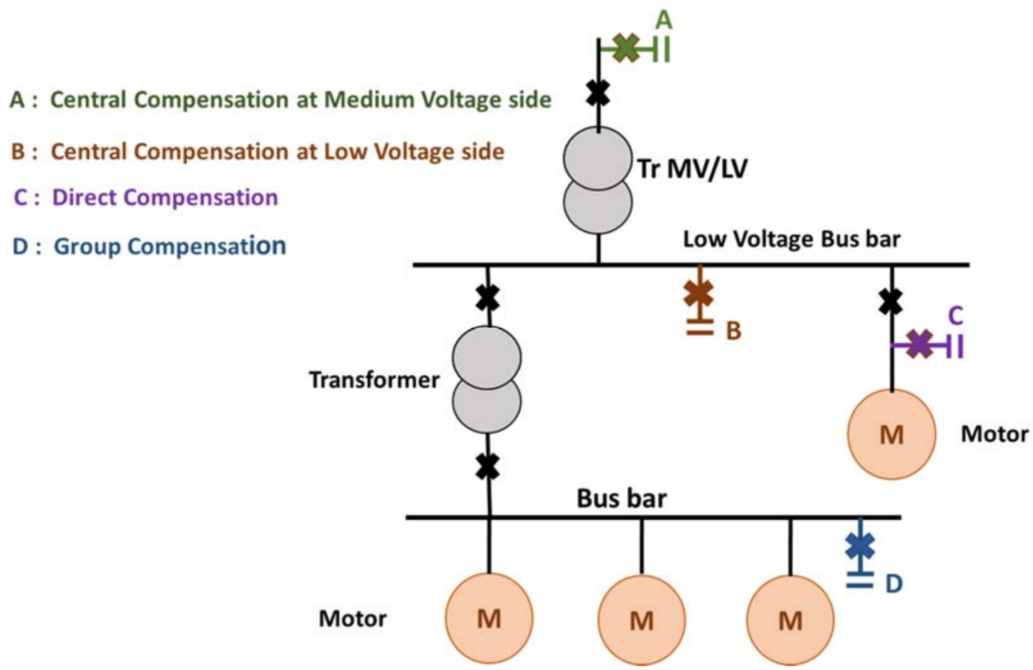


Figure 14 - Phase Diagram of Power Factor

4.5 REACTIVE POWER – IMPLEMENTING THE COMPENSATION IN THE NETWORK WITH CAPACITOR BANKS

Shunt compensation of reactive power can be employed either at load level, substation level or at transmission level. Compensation should be provided as close as possible to the consumption point to avoid having to distribute this power in the other parts of the network. Location is primarily determined by the reason for compensation. See drawing below (Figure 17).



With:

- MV: Medium Voltage
- LV: Low Voltage
- M: Motor
- C: Capacitor Bank
- Tr: Transformer

Figure 15 - Power Factor Compensation

Compensation is done with the installation of capacitor banks in the grid.

5. MAIN REASONS FOR TECHNICAL LOSSES

5.1 LENGTHY DISTRIBUTION LINES AND INADEQUATE SIZE OF CONDUCTORS OF DISTRIBUTION LINES

- HV/MV and LV lines in rural areas are extended over long distances to feed loads scattered over large areas. Thus, the primary and secondary distribution lines are largely radial laid and usually extend over long distances.
- This results in high line resistance and therefore high Joule losses in the line.
- Anarchic growths of sub-transmission and distribution system into new areas.
- Large scale rural electrification through long HV/MV and LV lines.
- The size of the conductors should be selected on the basis of kVA x km capacity of standard conductor for a required voltage regulation, but rural loads are usually scattered and generally fed by radial feeders. The conductor size of these feeders should be adequate.

5.2 INSTALLATION OF DISTRIBUTION TRANSFORMERS AWAY FROM LOAD CENTRES

- In most of the cases, distribution transformers are not located centrally with respect to the consumers. Consequently, the farthest consumers obtain an extremity low voltage, even though a good voltage level is maintained at the transformers' secondary. This again leads to higher line losses as a result of decreased voltage at the consumers end. Therefore, in order to reduce voltage drop in the line to the farthest consumers, the distribution transformer should be located at the load centre to keep voltage drop within permissible limits.

5.3 LOW POWER FACTOR OF PRIMARY AND SECONDARY DISTRIBUTION SYSTEMS DUE TO HIGH IMPEDANCE

- In most LV distribution circuits, normally the Power Factor (PF) may range from 0.65 to 0.75. A low Power Factor contributes towards high distribution losses. Line losses can be reduced by improving the Power Factor of the circuits with shunt capacitors. Shunt capacitors can be connected either in secondary side of the HV/MV power transformers or at various points of MV Distribution Line.
- The optimum rating of capacitor banks for a distribution system is 2/3 of the average kVAR requirement of that distribution system.
- The vantage point is at 2/3rd the length of the main distributor from the transformer.
- A more appropriate manner of improving PF of the distribution system is to connect capacitors across the terminals of the consumers having inductive loads.

5.4 LOW QUALITY OF WORKS

- Joints are a source of power loss. Therefore the number of joints should be kept to a minimum. Proper jointing techniques should be used to ensure firm connections.
- Connections to the transformer bushing-stems, drop out fuses, isolators and LV switches, etc. should be periodically inspected and proper pressure maintained to avoid sparking and heating of contacts.
- Replacement of deteriorated wires and services should also be made timely to avoid any cause of leaking and loss of power.

5.5 TRANSFORMER SIZING AND SELECTION

- Distribution transformers use copper conductor windings to induce a magnetic field into a grain-oriented silicon steel core. Therefore, transformers have both low load losses and no-load core losses.
- Transformer copper losses vary with load, based on the resistive power loss equation (P loss = I2.R). For some utilities, economic transformer loading means loading distribution transformers to capacity - or slightly above capacity for a short time - in an effort to minimize capital costs and still maintain long transformer life.
- However, since peak generation is usually the most expensive, total cost of ownership studies should take into account the cost of peak transformer losses. Increasing distribution transformer capacity during peak by one size will often result in lower total peak power dissipation - more so if it is overloaded.
- Transformer no-load excitation loss (iron loss) occurs from a changing magnetic field in the transformer core whenever it is energized. Core loss varies slightly with voltage but is

essentially considered constant. Fixed iron loss depends on transformer core design and steel lamination molecular structure. Improved manufacturing of steel cores and introducing amorphous metals (such as metallic glass) have reduced core losses.

5.6 SWITCHING OFF TRANSFORMERS

- One method of reducing fixed losses is to switch off transformers in periods of low demand. If two transformers of a certain size are required at a substation during peak periods for "N-1" or contingency situation, only one might be required during times of low demand so that the other transformer might be switched off in order to reduce fixed losses.

6. HOW TO REDUCE TECHNICAL LOSSES

6.1 BALANCING 3 PHASE LOADS

- One of the easiest loss savings of the distribution system is balancing current along three-phase circuits.
- Feeder phase balancing also tends to balance voltage drop among phases giving three-phase customers less voltage unbalance. Amperage magnitude at the substation doesn't guarantee load is balanced throughout the feeder length. Feeder phase unbalance may vary during the day and with different seasons. Feeders are usually considered "balanced" when phase current magnitudes are within 10%. Similarly, balancing load among distribution feeders will also lower losses assuming similar conductor resistance. This may require installing additional switches between feeders to allow for appropriate load transfer.
- Bifurcation of feeders according to voltage regulation and load.
- Balancing 3-phase loads periodically throughout a network can reduce losses significantly. It can be done relatively easily on overhead networks and consequently offers considerable scope for cost effective loss reduction, given suitable incentives.

6.2 IMPROVING DEMAND MANAGEMENT

- Because variable losses are proportional to the square of the current intensity, utilities can structure their tariffs (e.g. "time-of-use" rates) in a way that encourages customers to consume less during the peaks on the distribution network.
- With financial incentives, some electric customers are also allowing utilities to interrupt large electric loads remotely through radio frequency or power line carrier during periods of peak use. Utilities can try to design in higher load factors by running the same feeders through residential and commercial areas.

6.3 REBALANCING LENGTH OF LV LINE AND HV LINE

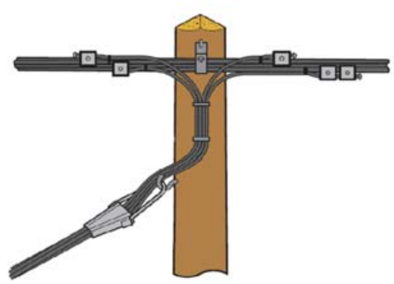
- Design the distribution network system in such a way that it is possible that large consumer gets direct power line from feeder.
- Many distribution pockets of low voltage (430V) in town are surrounded by higher voltage feeders. At this lower voltage, more conductor current flows for the same power delivered, resulting in higher I2.R losses.

- Converting old LV (430V) feeders to higher voltage, the investment cost is high and often not economically justifiable, but if parts of the LV (430V) primary feeders are in relatively good condition, installing multiple step-down power transformers at the periphery of the 430 Volts area will reduce copper losses by injecting load current at more points (i.e. reducing overall conductor current and the distance travelled by the current to serve the load).

6.4 ADOPTING HIGH VOLTAGE DISTRIBUTION SERVICE (HV-DS) FOR RURAL PRODUCTIVE CUSTOMERS.

- In high voltage direct service (HVDS), using MV lines to directly feed clusters of 2 to 3 rural productive customers with agricultural pump sets and small distribution transformers (15kVA) for given these 2 to 3 customers through smallest (almost negligible) LV distribution lines.
- In HVDS there is less distribution losses due to minimum length of distribution line, high quality of power supply with no voltage drop, less burn out of motor due to less voltage fluctuation and good quality of power, to avoid overloading of transformer.

6.5 ADOPTING AERIAL BUNDLED CONDUCTOR (ABC) FOR LOW VOLTAGE DISTRIBUTION OHL



- Where LV lines are not totally avoidable, the use of Aerial Bundled Conductors (bundled isolated conductors – 3 phases + 1 neutral / 220-400 V) will minimize faults in lines and avoid direct theft from line (tampering of line).

6.6 IMPROVING TRANSFORMERS EFFICIENCY AND USING FEEDER IN AVERAGE AT LESS THAN 30% OF ITS MAXIMUM CAPACITY

- Transformers are responsible for almost half of network losses. High efficiency distribution transformers can make a large impact on reduction of distribution losses.
- By overloading of distribution feeders, distribution losses will increase. The higher the load on a power line, the higher its variable losses. It has been suggested that the optimal average utilization rate of distribution network cables should be as low as 30% of its maximum capacity if the cost of losses is taken into account.

6.7 FEEDER RENOVATION / IMPROVEMENT PROGRAMME

Typical investments will consist in:

- Revision of transmission and distribution line according to load.
- Identification of the weakest areas in the distribution system and strengthening / improving them.
- Reducing the length of LV lines by relocation of distribution substations or installations of additional new distribution transformers.
- Installation of lower capacity distribution transformers at each consumer premises instead of cluster formation and substitution of distribution transformers with those having lower no load losses such as amorphous core transformers.
- Installation of shunt capacitors for improvement of power factor.
- Installation of single-phase transformers to feed domestic and non-domestic load in rural areas.
- Providing of small 25kVA distribution transformers with a distribution box attached to its body, having provision for installation of meters, MCCB[9] and capacitor.
- Lying of direct insulated service line to each rural productive load from distribution transformers
- Due to feeder renovation program T&D loss may be reduced from 60-70 % to 15-20 %.

6.8 INDUSTRIAL / URBAN FOCUS PROGRAM

- Separation of rural feeders from industrial feeders.
- Instantly release of new industrial or HV connections.
- Identify and replacement of slow and sluggish meters, which can be easily tampered, by electronics type meters. Today, many power companies are installing remote-reporting meters which are capable of detect any tampering in electric meters, and discover energy theft. These smart power meters are particularly helpful in preventing energy theft and encouraging security in electric meters.
- Adopting the approach "One Consumer - one Transformer" scheme with meter should be introduced with industrial and agricultural consumer.
- Change of old service line by armoured cable.
- Due to feeder renovation program T&D loss may be reduced from 60-70 % to 15-20 %.

7. SOME KEY QUESTIONS

1) ***Strategy and planning analysis***

- Is a multi- annual investment plan in grid development (extension and losses reduction) available?
- Is this plan realistic and comprehensive?

2) ***Economic analysis***

[9] A molded case circuit breaker, abbreviated MCCB, is a type of electrical protection device that can be used for a wide range of voltages, and frequencies of both 50 Hz and 60 Hz. The main distinctions between molded-case and miniature circuit breaker are that the MCCB can have current ratings of up to 2,500 amperes, and its trip settings are normally adjustable. An additional difference is that MCCBs tend to be much larger than MCBs.

- Is there a metrics for losses assessment?
- Which factors drive losses? What is the scope for reducing losses associated to each factor?
- What is the cost of losses?
- To what extent are losses considered in making operating and investment decisions?
- Are losses at an optimal level?

3) ***Technical loss reduction***

- Does technical standards target efficient transformers (low losses)?
- Are transformers operated at efficiency-maximising utilisation rates?
- Are the cables and wires of the network at the right size?
- Is the network configuration (resulting from continuous expansion and densifying connections) at optimal level?
- What is the scope for power factor improvement?
- Are the transmission and distribution networks properly maintained?

4) ***Regulatory incentive mechanism***

- Does the current regulatory regime encourage low-loss options?
- Is the current incentive for low loss option adequate?

8. SOME USEFUL REFERENCES

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9. ANNEX

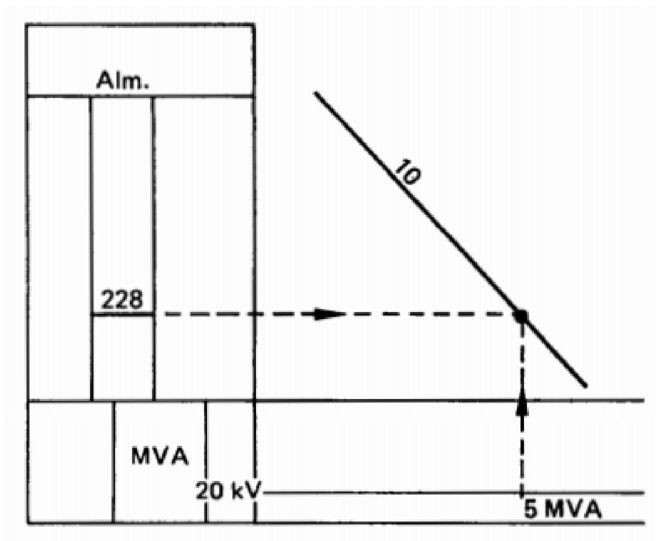
Chart providing the Joule Losses on Distribution Overhead Lines (OHL) 220V to 33kV in kW/km

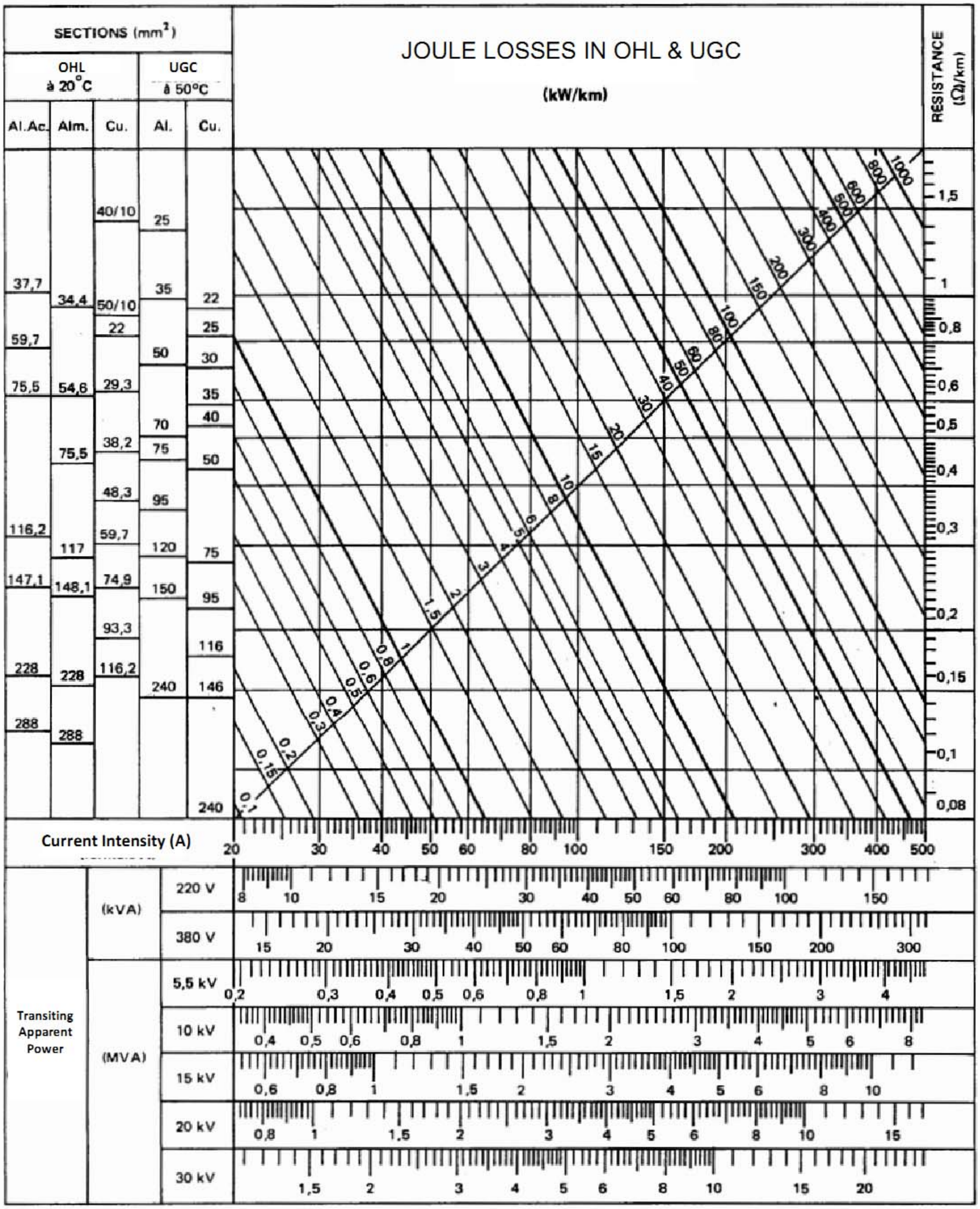
Instruction for Use:

A 20 kV distribution overhead line (section 228mm² Almelec), 10 km, carries 5 MVA. What are the losses?

- The Joule losses per km of line are estimated using the chart below
  - For that, we need to locate the point on the chart having the following ordinates:
    - 228 on the y-axis (cross-section in mm²) and 5 on the x-axis (power in MVA).
  - This point is located on the oblique setting 10 (length of the line).
  - 10 is the number of kW/km of Joule losses.

Total amount of Joule Losses: 10 kW/km x 10 km = 100 kW.

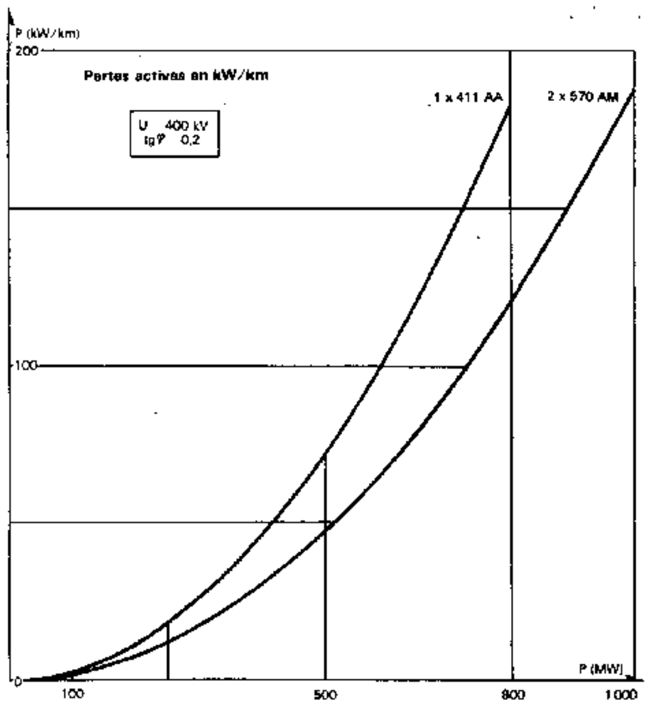


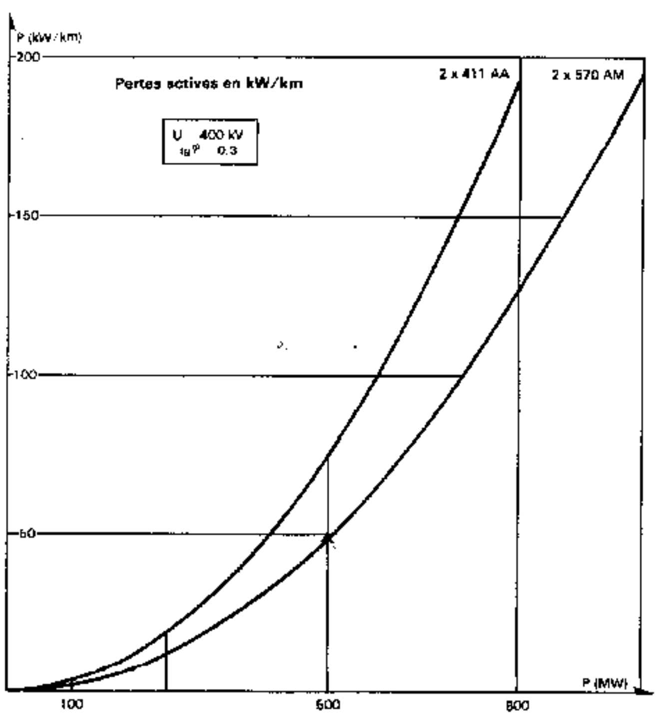


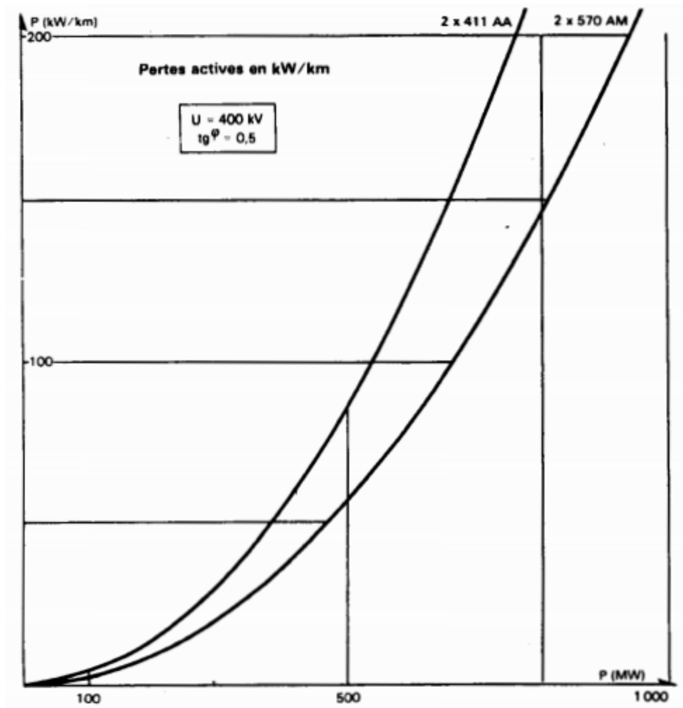
Source: Planning Guide – Electricité de France (1977)

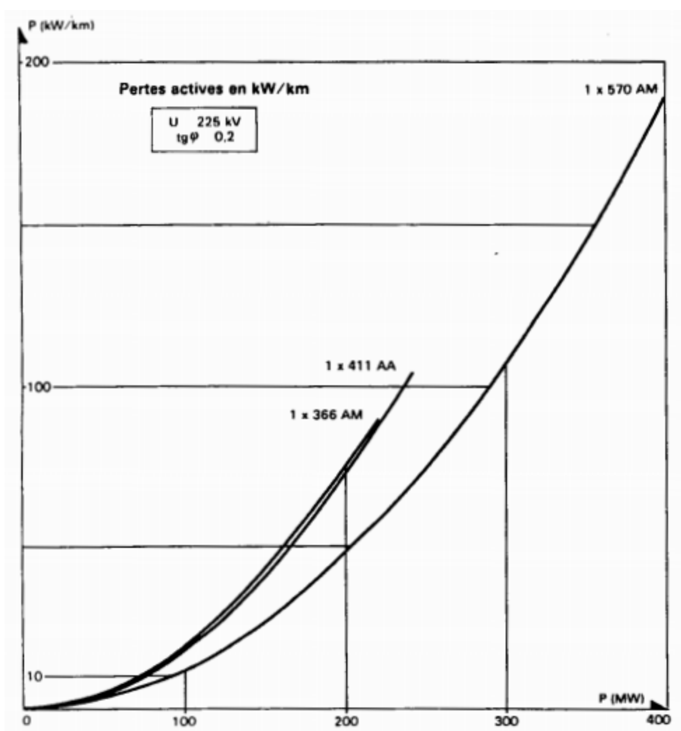
For the calculation of Joule losses in Overhead Transmission Lines (from 63kV to 400kV), the following charts can be used.

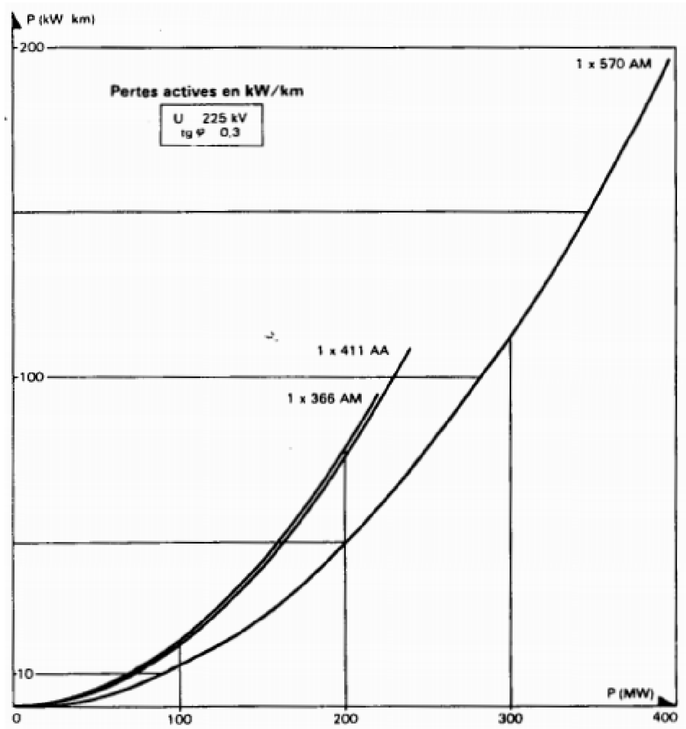
On the following charts, the value of Joule losses in kW (p) created by a power P in MW transiting in a kilometre of line can be read, this for the most commonly used standard cross-sections and for several values of tg φ (0.2 ; 0.3; 0.5), equivalent to cos φ (0.98 ; 0.96; 0.89). Losses are then obtained by multiplying this result by the length in kilometres of the line.

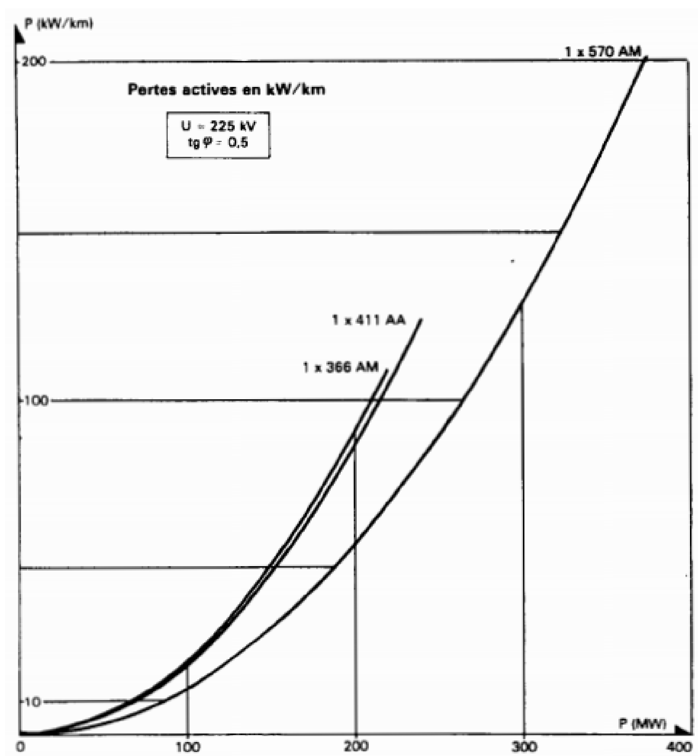


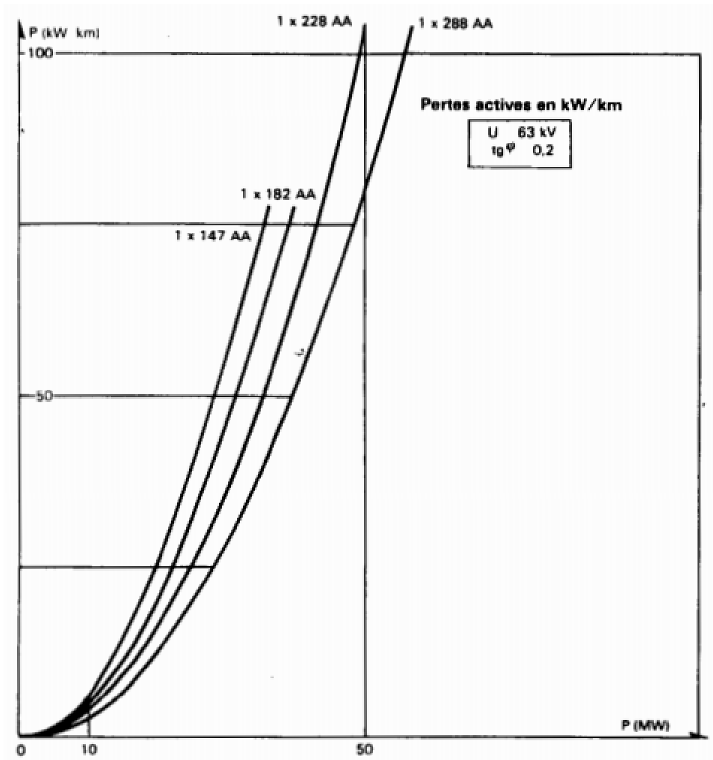


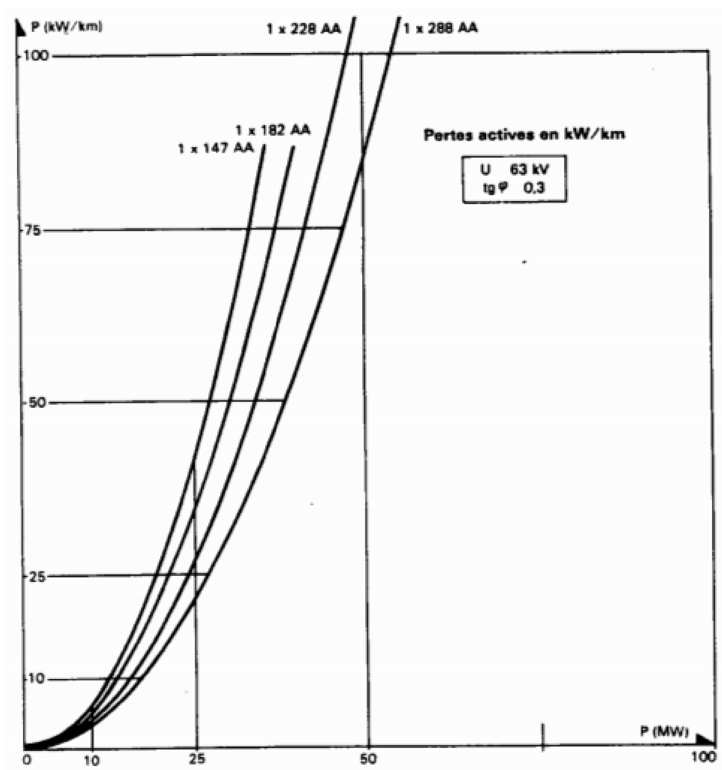

P (kW/km)
200
Pertes actives en kW/km
U = 400 kV
tgφ = 0,5
2 x 411 AA
2 x 570 AM
100
P (MW)
100
500
1 000

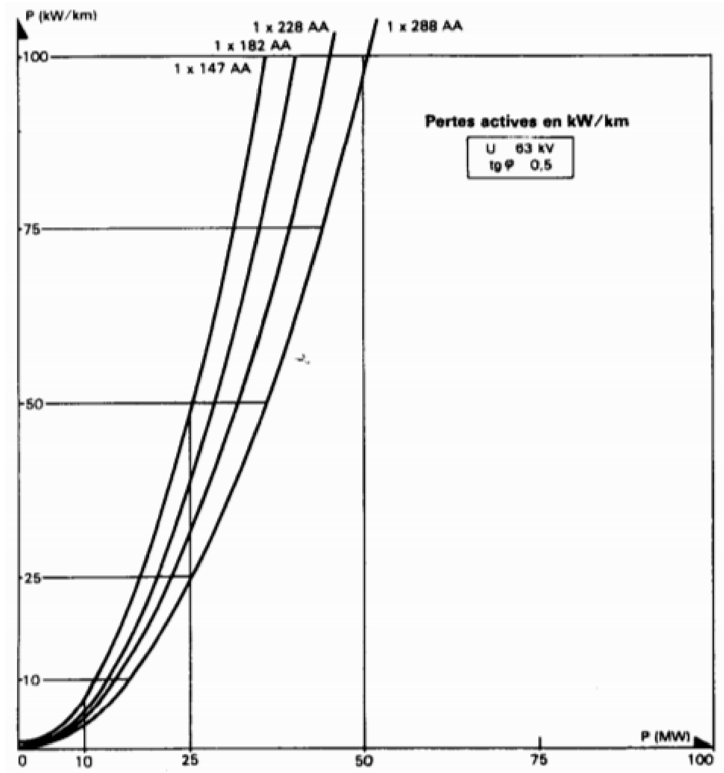

P (kW/km)
200
Pertes actives en kW/km
U 225 kV
tgφ 0,2
1 x 570 AM
1 x 411 AA
1 x 366 AM
100
10
P (MW)
0
100
200
300
400


P (kW km)
200
Pertes actives en kW/km
U 225 kV
tg φ 0,3
1 x 570 AM
1 x 411 AA
1 x 366 AM
100
10
0
100
200
300
400
P (MW)


P (kW/km)
200
Pertes actives en kW/km
U = 225 kV
tg φ = 0,5
1 x 570 AM
1 x 411 AA
1 x 366 AM
100
10
0
100
200
300
400
P (MW)


P (kW km)
100
50
0
10
50
P (MW)
1 x 228 AA
1 x 288 AA
1 x 182 AA
1 x 147 AA
Pertes actives en kW/km
U 63 kV
tg φ 0,2


P (kW/km)
100
75
50
25
10
0
10
25
50
100
P (MW)
1 x 228 AA
1 x 288 AA
1 x 182 AA
1 x 147 AA
Pertes actives en kW/km
U 63 kV
tg φ 0,3


P (kW/km)
1 x 228 AA
1 x 182 AA
1 x 147 AA
1 x 288 AA
Pertes actives en kW/km
U 63 kV
tg φ 0,5
P (MW)
100
75
50
25
10
0
10
25
50
75
100