UNIVERSITÀ
DEGLI STUDI DI TRIESTE

dipartimento
di ingegneria
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Electrical systems design – part I

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Fundamentals of Modern Power Systems

Analysis, classification and grouping of loads

Load diagram

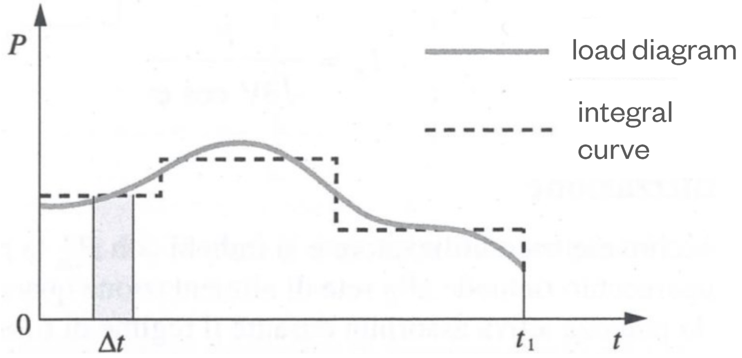
Power absorbed by a user appliance: **constant** or **variable over time**.

e.g.: lighting fixtures — e.g.: electric motors

Load diagram: representation on a Cartesian plane of the active power absorbed as a function of time.

It can refer to a single load or to an entire circuit.

Determination not simple for equipment with regimes that vary greatly over time.
It can be simplified by means of an *integral curve*, with an underlying area equivalent to that of the effective load diagram, obtained by measuring the energy absorbed by the load in the various time intervals.



Conventional power

Very high variability of the load or dependent on the use of the equipment by the user (not known).

⬇

It becomes necessary to use simplifying hypotheses and empirical coefficients (statistical criteria).

⬇

Use of *conventional load* (power or current)

Conventional power of an electrical circuit: active power for which the circuit must be sized, determined on the basis of the rated power of the powered users and *appropriate coefficients*.

The coefficients are determined statistically or on the basis of data on the operation of the users.

Extending the discussion to the complex of circuits that make up a user system, **the conventional power of the entire system** can be defined.

Operating current

Realistic hypothesis in a user system: constant voltage.

Thus, given the value of the conventional power the value of the current circulating in the circuits can be calculated.

Operating current I_b: current that can flow in a circuit in ordinary service (therefore excluding overcurrents due to overloads or short circuits).

It can be calculated as follows:

- Direct current $$I_b = \frac{P}{V}$$
- Single-phase alternating current $$I_b = \frac{P}{V \cos\varphi}$$
- Three-phase alternating current $$I_b = \frac{P}{\sqrt{3}V \cos\varphi}$$

With P active power (effective or conventional), V circuit supply voltage, $\cos\varphi$ power factor

Utilization factor

Let us consider a user appliance with P_{an} nominal absorbed active power (operation according to the rating plate data) and P active absorbed power in the specific operating regime considered.

The utilization factor (or coefficient) is defined as the ratio:

$$K_u = \frac{P}{P_{an}}$$

It is a dimensionless number, which can also be given as a percentage value ($K_{u\%}$).

Knowing P_{an} (from the rating plate data) and K_u it is possible to calculate the average power absorbed by the user:

$$P = K_u P_{an}$$

Depending on the value of the coefficient, three load conditions can be obtained:

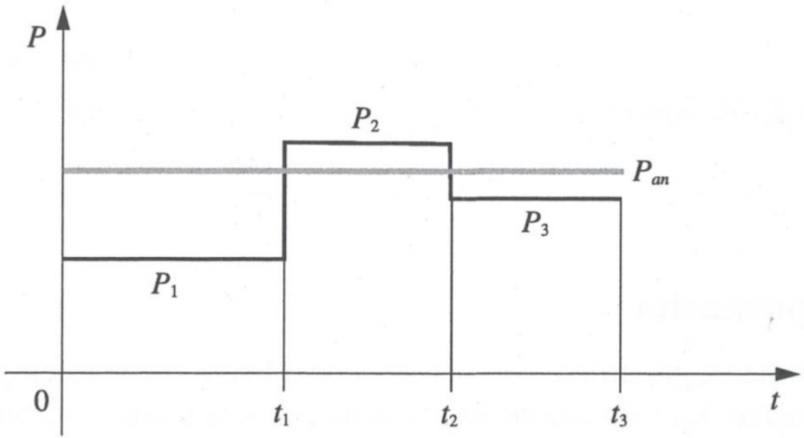
- *reduced*, if $K_u<1$ ($P<P_{an}$)
- *nominal*, if $K_u=1$ ($P=P_{an}$)
- *overload*, if $K_u>1$ ($P>P_{an}$)

Utilization factor

The values of the utilization coefficients can be determined analytically or by means of specific statistical tables.

Analytical determination → the user's load diagram must be known.

To simplify the calculations, a variable step power is assumed (integral curve, defined in previous slide).



$$K_{u1} = \frac{P_1}{P_{an}}$$

$$K_{u2} = \frac{P_2}{P_{an}}$$

$$K_{u3} = \frac{P_3}{P_{an}}$$

Having the diagram available, it would not even be necessary to calculate the coefficient, since the power *P* in the various time intervals is already known!

Utilization factor

If no data on the load operating regimes is available, generic coefficients dictated by experience can be used.

Example:
Calculating the conventional power of an electric motor

Calculate the conventional power absorbed by an electric motor with nominal power P_n = 11 kW, nominal efficiency η_n = 0,88, operating at 3/4 of the load.

The nominal (rated) power of a motor is the output one (mechanical at the shaft). Thus, the rated absorbed power is:

$$P_{an} = \frac{P_n}{\eta_n} = \frac{11}{0{,}88} = 12{,}5\ kW$$

Being K_u = 3/4 = 0,75, it follows:

$$P = K_u P_{an} = 0{,}75 * 12{,}5 = 9{,}375\ kW$$

User type	K_u
Lamps	1
Motors 0.5 ÷ 2 kW	0,7
Motors 2 ÷ 10 kW	0,75
Motors > 10 kW	0,8
Resistance and induction ovens	1
Rectifiers	1
Welders	0,7 ÷ 1
Electric heaters	1
Machine tools, conveyors	0,6 ÷ 0,8
Elevators, hoists, lifting systems	0,8 ÷ 1
Pumps, fans	1

Simultaneity factor

When an electrical circuit supplies multiple users, it must be considered that not all of them will always work simultaneously.

The exact evaluation of the total absorbed power requires knowledge of all possible load combinations. As the number and type of loads increase, it becomes very difficult to perform an analytical evaluation.

In any case, the average absorbed power will be less than (or at most equal to) the sum of the power of the individual users:

$$P_t \leq P_1 + P_2 + \cdots + P_k = \sum_{i=1}^{k} P_i$$

The total power reduction is taken into account by introducing a specific coefficient, the **simultaneity factor** (or coefficient), defined by the following dimensionless ratio :

$$K_c = \frac{P_t}{\sum_{i=1}^{k} P_i}$$

The case where all loads operate simultaneously is represented by $K_c = 1$.

Simultaneity factor

Given the value of the simultaneity coefficient, the total conventional power is determined as:

$$P_t = K_c * \sum_{i=1}^{k} P_i$$

The value of the simultaneity coefficient can be deduced in two ways:

- given the operating regime of the system and the possible combinations of the various loads, the actual values for the different groups of users can be attributed to K_c;
- In the absence of precise indications, empirical values dictated by experience are used.

User type	Numero	K_c
Ovens	<2	1
Motors 0.5 ÷ 2 kW	<10 10<n<20 20<n<50	0,6 0,5 0,4
Motors 2,5 ÷ 10 kW	<10 10<n<50	0,7 0,45
Motors 10 ÷ 30 kW	<5 5<n<10 10<n<50	0,8 0,65 0,5
Motors > 30 kW	<2 2<n<5 5<n<10	0,9 0,7 0,6
Rectifiers	<10	0,8
Welders	<10	0,4
Elevators and hoists in offices and industries	<4 4<n<10	0,75 0,6
Lighting		0,8

Conventional power of plug socket groups

In almost all systems there are sockets.

The power absorbed by the users connected to the sockets is difficult to evaluate (it depends on the number and type of loads connected).

The *maximum* power that can be transferred from a socket to the user is given by:

- $P_M = V_n I_n \cos\varphi_n$ for single-phase sockets
- $P_M = \sqrt{3} V_n I_n \cos\varphi_n$ for three-phase sockets

With V_n and I_n rated values of the plug socket.

The following can be assumed as conventional values for the power factor:

- 0,9 for single-phase users
- 0,8 for three-phase users

(except in peculiar cases of users with low power factor)

Conventional power of plug socket groups

To take into account that the sockets can operate with a lower current than the nominal one and not all at the same time, the **conventional power of the groups of plug sockets** is calculated:

$$P_c = N * P_M * K_p$$

With N number of sockets, P_M maximum power of the single socket, and K_p overall factor of use and contemporaneity of the groups of sockets.

The values of the K_p factor cannot be established precisely, as they depend on too many random factors.

Average values that can be adopted are:

- 0.05 ÷ 0.2 for single-phase sockets installed in systems for civil use;
- 0.15 ÷ 0.4 for single-phase and three-phase sockets installed in industrial or tertiary sector systems.

Please note that the variability of the coefficients provided is very high. For example, the conventional power of a circuit with 10 three-phase sockets of 16 A, 400 V (P_M = 8.8 kW) is included in a range between 13.2 and 35.2 kW.

It is clear that during the design phase it is useful to have more specific information on the use of the plug sockets.

Furthermore, the possibility of supplying P_M to at least one socket in the group must always be guaranteed.

Conventional power of electric motors

For an electric motor, the rated power is the mechanical power. The absorbed electrical power is:

$$P_{an} = \frac{P_n}{\eta_n}$$

with P_n rated power and η_n rated efficiency.

This power corresponds to an absorbed current (for a three-phase motor) equal to :

$$I_n = \frac{P_{an}}{\sqrt{3}V_n \cos\varphi_n} = \frac{P_n}{\sqrt{3}V_n \eta_n \cos\varphi_n}$$

When operating at nominal voltage, but with a power output different from the rated one, the efficiency and power factor are also different from the nominal ones. Therefore, we obtain :

$$P_a = \frac{P}{\eta} = \frac{K_u P_n}{\eta} \qquad I = \frac{P_a}{\sqrt{3}V_n \cos\varphi} = \frac{K_u P_n}{\sqrt{3}V_n \eta \cos\varphi}$$

It is necessary to know the efficiency and power factor values as the utilization coefficient varies for each motor!

This complicates the calculations and makes the exact determination of P_a and I impossible in many practical cases.

Conventional power of electric motors

It is possible to simplify the calculation if the utilization factor is known in terms of the ratio of absorbed power (and not the output power).

In this case the following formula results, in which the rated efficiency value (usually known) can be seen :

$$P_a = K_u P_{an} = \frac{K_u P_n}{\eta_n}$$

For the current, reference can instead be made to the rated current value, or the formula on the previous page can be applied in an approximate way, using the rated efficiency and power factor values..

In the case of multiple motors, the contemporaneity factor must be taken into account :

$$P = N P_{an} K_u K_c = N \frac{P_n}{\eta_n} K_u K_c$$

with N number of motors.

Conventional power of electric motors

Example: Conventional power absorbed by a group of three-phase asynchronous motors

Calculate the power absorbed by a group of 5 three-phase asynchronous motors with a nominal power of 11 kW and nominal efficiency of 0,87.

We assume:

- K_u = 0,8 (see utilization coefficient table reported above)
- K_c = 0,8 (see the contemporaneity coefficient table reported above)

It results:

$$P = N \frac{P_n}{\eta_n} K_u K_c = 5 * \frac{11}{0,87} * 0,8 * 0,8 = 40,5\ kW$$

Total conventional power of an electric power systems

To determine the total conventional power of an electric power system, there are several ways to proceed, depending on the type of system and the level of detail required by the calculation.

Sum of the conventional powers of the various circuits

The system is divided into the various circuits that compose it (lighting, plug sockets, fixed users, etc.) and for each circuit the conventional power is calculated with the methods just presented.

The total conventional power is the sum of the conventional power of the *n* circuits :

$$P_t = P_1 + P_2 + \cdots + P_n = \sum_{i=1}^{n} P_i$$

If the various circuits can operate simultaneously, no reduction factor is required. Otherwise, the most severe load condition is taken into account.

Total conventional power of an electric power systems

Application of a global reduction coefficient

This calculation method is less accurate than the previous one, but it is much faster:

- The *total installed power* is calculated as the sum of the nominal absorbed powers of all the loads of the system, without taking into account any reduction coefficient;
- The total installed power is multiplied by a *global reduction coefficient* that globally considers the utilization and simultaneity of the loads in the entire system.

The calculation is more reliable the more accurate the choice of the global reduction coefficient is.

The choice of the coefficient is made on the basis of the type of building in which the electrical power system needs to be installed.

The table shows some indicative average values.

Installation type	Coeff.
Hotels, colleges	0,6 ÷ 0,8
Hospitals	0,5 ÷ 0,75
Department stores	0,7 ÷ 0,9
Schools	0,6 ÷ 0,7
Residential buildings	0,4 ÷ 0,5
Offices	0,6 ÷ 0,8

Total conventional power of an electric power systems

Use of surface power density

The *surface apparent power density* S_{sp} (VA/m^2) of a system is the ratio between the total apparent power and the area of the building within which the system is installed.

After having fixed an appropriate value of S_{sp}, and knowing the area of the building A and the global power factor of the system, the conventional active power can be calculated as follows:

$$P_t = S_t \cos\varphi = S_{sp} A \cos\varphi$$

It is a method applicable to calculate the power to be installed in first approximation, for example when a building starts to be designed, if the loads to be installed in the system are not yet known.

Some indicative average values of the specific power are reported in the table.

Type of building		S_{sp} (VA/m^2)
Industrial	Paper mill	120
	Textile industry	100
	Electronics industry	90
	Mechanical workshop	80
	Woodworking workshop	70
Civil and tertiary	Offices	70
	Schools	50
	Hospitals	60
	Hotels	80
	Houses	40
	Shopping centers	90

Application example 1

Determination of conventional power and operating currents for an apartment

A 140 m^2 apartment is made up of the rooms, with their respective loads, shown in the table.

For the entire system, the supply voltage is 230V AC single-phase.

After dividing the system into the various circuits, we want to calculate the conventional powers and the operating currents of the circuits themselves, as well as the total conventional power of the system.

Room	Lighting			Plug sockets	
	N.	Description	P (W)	N.	Type
Entrance/corridor	2	Ceiling light points	100	1	2P+T, 10A
Living room	1 1	Ceiling light points Wall light points	300 100	4	2P+T, 10A
Bedroom 1	1	Ceiling light points	150	2	2P+T, 10A
Bedroom 2	1	Ceiling light points	150	2	2P+T, 10A
Study	1 1	Ceiling light points Wall light points	150 100	4	2P+T, 10A
Kitchen	1	Ceiling light points	150	3 2	2P+T, 16A 2P+T, 10A
Bathroom 1	1 1	Ceiling light points Wall light points	150 100	1 1	2P+T, 16A 2P+T, 10A
Bathroom 2	1 1	Ceiling light points Wall light points	150 100	1	2P+T, 10A
Closet	1	Ceiling light points	100	/	
Veranda/balcony	1	Wall light points	100	1	2P+T, 10A

Application example 1

System subdivision

A typical subdivision for this type of system is the following:

- N. 1 lighting circuit to power the lighting fixtures in all rooms;
- N. 1 circuit to power the 16 A plug sockets, the kitchens and bathroom 1, to which the higher power users will be connected (oven, dishwasher, washing machine, etc.);
- N. 1 circuit for the 10 A general purpose sockets in all rooms.

Calculation of the conventional power and operating currents of the various circuits

The following additional data are considered:

- Power factor for lighting = 0.95 considering halogen lamps, or discharge lamps already rephased;
- Power factor for sockets = 0.9 since they are single-phase sockets installed in a residential environment, generally without highly phase-shifted loads;

Application example 1

- Simultaneity factor for lighting K_c = 0,60;
- Simultaneity and utilization factor for 16 A sockets, K_p = 0,20;
- Simultaneity and utilization factor for 10 A sockets, K_p = 0,05.

From the sum of the light loads we obtain P_t = 2000 W for the lighting circuit, so:

$$P_1 = P_t K_c = 2000 * 0{,}6 = 1200\ W$$

The maximum powers P_{M2} and P_{M3}, respectively for the 16 A sockets and for the 10 A sockets, are the same for each socket to be installed:

$$P_{M2} = V_n I_n \cos\varphi = 230 * 16 * 0{,}9 \cong 3300\ W$$

$$P_{M3} = V_n I_n \cos\varphi = 230 * 10 * 0{,}9 \cong 2070\ W$$

Application example 1

Given the number of sockets, and the utilization and simultaneity factors, the result is :

$$P_2 = N_2 P_{M2} K_{p2} = 4 * 3300 * 0{,}20 \cong 2600\ W$$

$$P_3 = N_3 P_{M3} K_{p3} = 18 * 2070 * 0{,}05 \cong 1860\ W$$

To calculate the operating currents, simply apply the formula for calculating power in single-phase systems:

$$I_{b1} = \frac{P_1}{V_n \cos\varphi_1} = \frac{1200}{230 * 0{,}95} = 5{,}49\ A$$ lighting circuit

$$I_{b2} = \frac{P_2}{V_n \cos\varphi_2} = \frac{2600}{230 * 0{,}9} = 12{,}6\ A$$ 16 A socket circuit

$$I_{b3} = \frac{P_3}{V_n \cos\varphi_3} = \frac{1860}{230 * 0{,}9} = 9\ A$$ 10 A socket circuit

Application example 1

Calculation of the total conventional power of the system

Since the conventional powers of the various circuits have already been determined, taking into account the utilization and simultaneity coefficients, it is possible to calculate the total conventional power of the system as a simple sum of the conventional powers of the circuits. :

$$P_t = P_1 + P_2 + P_3 = 1200 + 2600 + 1860 = 5660\ W$$

The normalized value of the contractual power for civil users closest to the calculated one is equal to 6 kW.

This corresponds to a specific power of approximately 43 W/m^2 (close to the 40 VA/m^2 shown in previous slide).

Application example 2

Determination of conventional power and operating currents for an industrial workshop

The electrical system of an industrial workshop used for cutting and drilling metal sheets includes fixed users and plug sockets.

The characteristics of the rooms and loads (obtained from the plate data, in relation to rated supply voltage, conventional power factor, and rated absorbed power), are shown in the table.

Rooms	Dotazioni impiantistiche
Courtyard	3 outdoor lighting fixtures, 230 V, 70 W, p.f. 0,9 Electric gate, 230 V, 500 W, p.f. 0,8 Various services (intercom, etc.), 230 V, 200 W, p.f.0,9
Office	4 lighting fixtures, 230 V, 2x36 W, p.f. 0,9 3 plug sockets 2P+T, 230 V, 10 A 2 plug sockets 2P+T, 230 V, 16 A (linea computer)
Warehouse	10 lighting fixtures (split into two circuits), 230 V, 2x36 W, p.f. 0,9 2 interlocked CEE socket panels
Changing room, canteen and toilets	2 lighting fixtures, 230 V, 2x36 W, p.f. 0,9 1 lighting fixtures, 230 V, 1x36 W, p.f. 0,9 2 lighting fixtures, 230 V, 1x18 W, p.f. 0,9 5 plug sockets 2P+T, 230 V, 10 A 1 electric water heater, 230 V, 1500 W, p.f. 1
Workshop	4 lighting fixtures, 230 V, 2x36 W, p.f. 0,9 5 panels of interlocked CEE sockets, divided into two circuits of 3 and 2 panels respectively
Processing department	3 workstations (SL1, SL2, SL3), each requiring three-phase power supply with neutral, 230/400 V, maximum installed power 35 kW, p.f. 0,75 1 three-phase air compressor, 400 V, 12 kW, p.f. 0,82 12 industrial lights, 230 V, 400 W, p.f. 0,9, divided into 3 circuits of 4 lights each 4 interlocking CEE socket panels on the left wall 3 interlocking CEE socket panels on the right wall 4 hot air generators each requiring single-phase power supply, 230 V, 200 W, p.f. 0,8

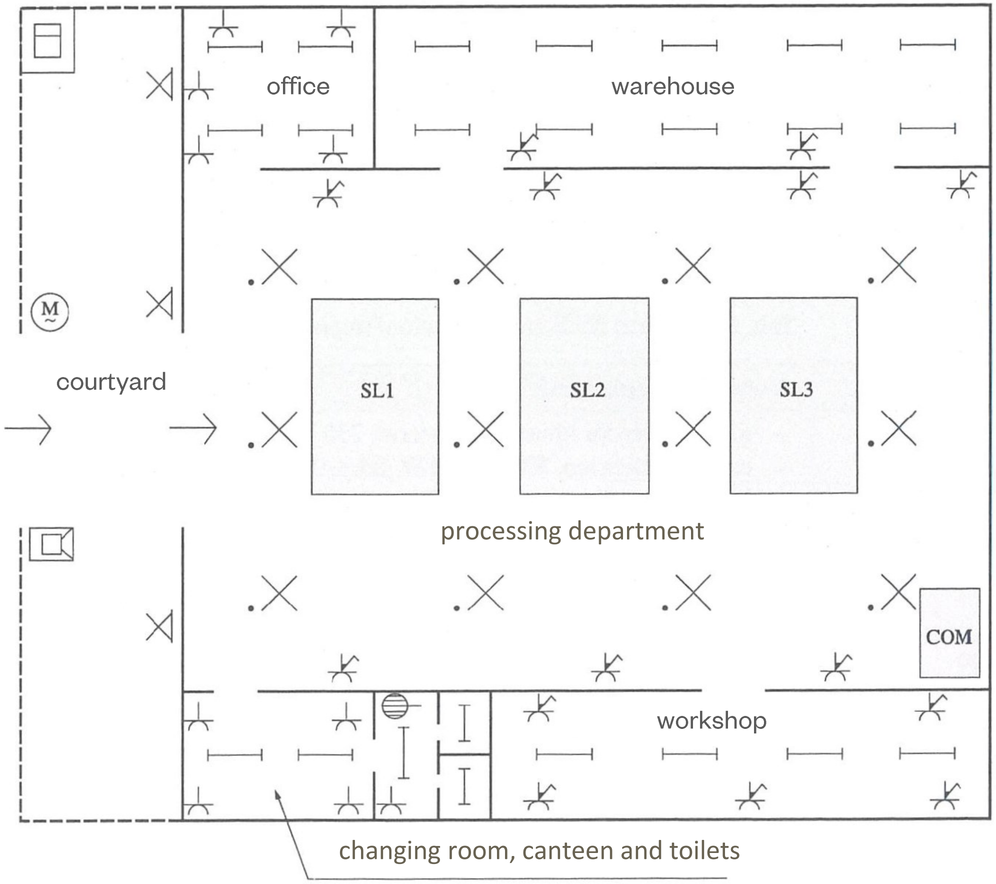
Application example 2

The figure shows the planimetric development of the rooms involved.

The system is powered in LV by the public distribution network and originates in the meter compartment in the courtyard (delivery point).

For all the rooms where their installation is planned, the interlocked CEE socket panels consist of:

- 1 three-phase socket, 3P+T, 400 V, 16 A;
- 3 single-phase sockets, 2P+T, 230 V, 16 A, each connected between a phase and the neutral.



Application example 2

It is required to determine, assuming the appropriate reduction factors:

- Conventional power and operating currents of the circuits that start from the secondary electrical panels that have to be installed;
- Conventional power and operating currents of the power lines of the secondary panels;
- Conventional power and operating currents of the circuits that start from the general electrical panel;
- Total conventional power of the system.

Application example 2

System subdivision and connection diagram of electrical panels

A possible subdivision for the system is the one made according to the rooms to be powered.

Four lines branch off from the general electrical panel that power the secondary electrical panels, each installed in a room (radial distribution), according to the diagram in the figure.

Each secondary panel powers the loads of the individual room to which it belongs.

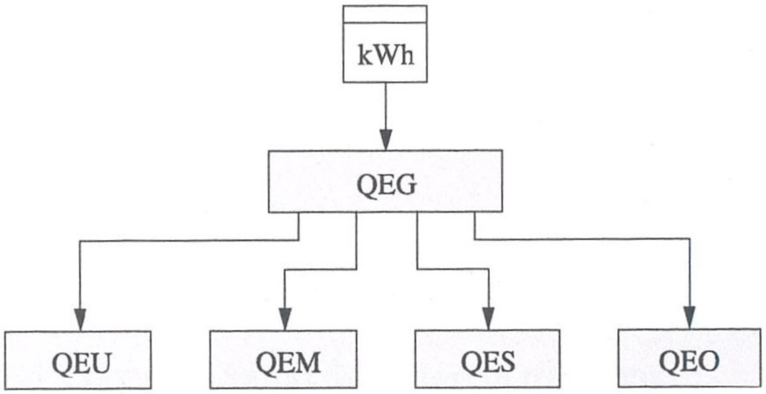
QEG: general electrical panel

QEU: office electrical panel

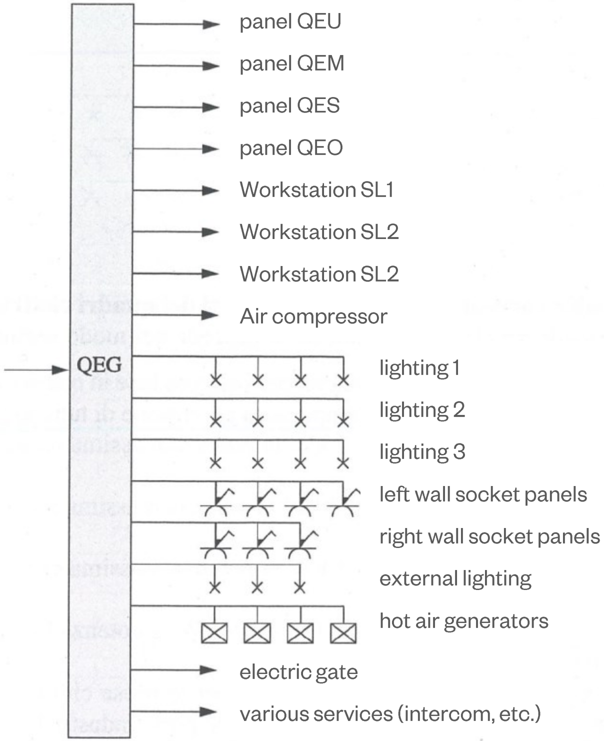
QEM: warehouse electrical panel

QES: electrical panel for changing rooms, canteen and toilets

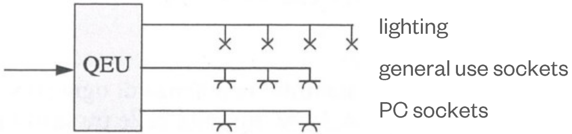
QEO: workshop electrical panel



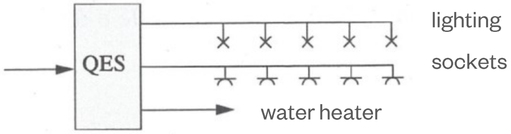
Application example 2



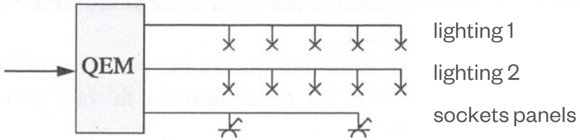
Electrical diagram of the distribution from the general electrical panel



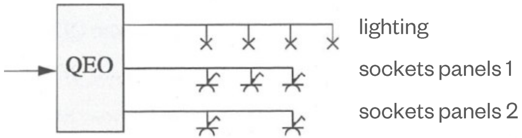
Electrical distribution diagram from the office electrical panel



Electrical diagram of the distribution from the electrical panel of the changing room



Electrical diagram of the distribution from the warehouse electrical panel



Electrical distribution diagram from the workshop electrical panel

Application example 2

Calculation of conventional power and operating currents of secondary electrical panel circuits

The calculation is done as follows:

- The simultaneity factor for the lighting circuits is assumed to be 1 since, given the small size of the rooms, it is probable that all the lamps will be turned on at the same time;
- The p.f. for socket circuits, respectively of civil and industrial (CEE) types, are assumed to be equal to 0.9 and 0.8;
- It is $P_M = 230 * 10 * 0{,}9 \cong 2\ kW$ maximum power that can be supplied by a 10 A single-phase civil socket;
- It is $P_M = 230 * 16 * 0{,}9 \cong 3{,}3\ kW$ maximum power that can be supplied by a 16 A single-phase civil socket;
- It is $P_M = 230 * 16 * 0{,}8 \cong 2\ kW$ maximum power that can be supplied by a 16 A single-phase industrial socket;
- It is $P_M = \sqrt{3} * 400 * 16 * 0{,}8 \cong 8{,}9\ kW$ maximum power that can be supplied by a 16 A three-phase industrial socket;

Application example 2

- It is assumed $K_p = 0{,}15$ as reduction factor for civil type sockets;
- It is assumed $K_p = 0{,}25$ as reduction factor for industrial type sockets;
- The contemporaneity factor for the CEE socket panels is assumed to be equal to 1, having already made the reduction with respect to the maximum power with the K_p factor;
- We proceed as previously seen with the calculation of the unit powers, the conventional ones, and the operating currents.

According to what has been established, the power of each panel of interlocked CEE sockets, distributed over the three phases, is equal to:

$$0{,}25 * (8{,}9 + 3 * 3) \cong 4{,}5kW$$

Application example 2

Calculation results of conventional power and operating currents of secondary switchboard circuits

Circuit	type	V_n (V)	Power				I_b (A)
			N.	P. single L. (W)	K_c ^ K_p	P_c (W)	
Office electrical panel circuits QEU							
Lighting	1+N	230	4	72	1	288	1,39
Sockets 10 A	1+N	230	3	2000	0,15	900	4,35
PC sockets 16 A	1+N	230	2	3300	0,15	990	4,78
Warehouse electrical panel circuits QEM							
Lighting 1	1+N	230	5	72	1	360	1,74
Lighting 2	1+N	230	5	72	1	360	1,74
CEE sockets panels	3+N	400	2	4500	1	9000	16,3
Changing room electrical panel circuits QES							
Lighting	1+N	230	5	72, 36, 18	1	216	1,04
Sockets 10 A	1+N	230	5	2000	0,15	1500	7,25
Water heater	1+N	230	1	1500	1	1500	6,52
Workshop electrical panel circuits QEO							
Lighting	1+N	230	4	72	1	288	1,39
CEE sockets panels 1	3+N	400	3	4500	1	13500	24,4
CEE sockets panels 2	3+N	400	2	4500	1	9000	16,3

Application example 2

Calculation of conventional power and operating currents of the power supply lines for secondary switchboards

Having already applied the reduction factors, the conventional powers of these circuits correspond to the sum of the powers of the circuits powered by each secondary panel.

The operating currents are calculated as a function of the load power, assuming:

- Single-phase 230 V line for the QEU panel – since it is composed only of single-phase circuits with the same p.f. for all of them, the p.f. is assumed to be 0.9;
- Three-phase 400 V line for the QEM panel – since the power of the CEE socket panels prevails over that of the lighting, the p.f. is assumed to be equal to that of the sockets, i.e., 0.8;
- Single-phase 230 V line for the QES panel – since it is composed of circuits with comparable powers, an average p.f. is assumed between those of the circuits, i.e., 0.95;
- Three-phase 400 V line for the QEO panel – since the power of the CEE socket panels is greater than that of the lighting, the p.f. is assumed to be equal to that of the sockets, i.e., 0.8.

Application example 2

Calculation results of conventional power and operating currents of secondary switchboard power supply lines

Line from QEG to ...	type	V_n (V)	*Pc* (kW)	cosφ	I_b (A)
Office electrical panel QEU	1+N	230	2,18	0,9	10,6
Warehouse electrical panel QEM	3+N	400	9,72	0,8	17,6
Changing room electrical panel QES	1+N	230	3,22	0,95	14,8
Workshop electrical panel QEO	3+N	400	22,8	0,8	41,1

Application example 2

Calculation of conventional power and operating currents of the general electrical panel circuits

The main electrical panel supplies the four distribution circuits for the secondary panels, as well as the circuits for supplying the loads of the processing department and the external courtyard.

Proceeding in a similar way to what was done previously for the secondary panels, the values of the conventional powers and the operating currents can be calculated.

For the workstations, both the utilization factor and the simultaneity factor are considered equal to 1. This because it is supposed that all the workstations can work at maximum power simultaneously.

For the air compressor, $K_u = 1$ was assumed.

Application example 2

Calculation results of conventional power and operating currents of the circuits of the general electrical panel

Circuit	type	V_n (V)	Power				I_b (A)
			N.	P. Single L. (W)	K_c ^ K_p	P_c (kW)	
Electrical panel QEU	1+N	230	1	2,18	1	2,18	10,6
Electrical panel QEM	3+N	400	1	9,72	1	9,72	17,6
Electrical panel QES	1+N	230	1	3,22	1	3,22	14,8
Electrical panel QEO	3+N	400	1	22,8	1	22,8	41,1
Workstation SL1	3+N	400	1	35	1	35	67,4
Workstation SL2	3+N	400	1	35	1	35	67,4
Workstation SL3	3+N	400	1	35	1	35	67,4
Air compressor	3	400	1	12	1	12	21,1
Lighting 1	1+N	230	4	0,4	1	1,6	7,73
Lighting 2	1+N	230	4	0,4	1	1,6	7,73
Lighting 3	1+N	230	4	0,4	1	1,6	7,73
CEE sockets panels left	3+N	400	4	4,5	1	18	32,5
CEE sockets panels right	3+N	400	3	4,5	1	13,5	24,4
External lighting	1+N	230	3	0,07	1	0,21	1,02
Hot air generators	1+N	230	4	0,2	1	0,8	4,35
Electric gate	1+N	230	1	0,5	1	0,5	2,72
Various services	1+N	230	1	0,2	1	0,2	0,97

Application example 2

Calculation of the total conventional power of the system

Having already applied the reduction coefficients on the individual loads, it is sufficient to add the powers of the individual circuits.

Assuming that a balanced derivation of the single-phase lines is carried out on the three phases from the point of view of power, it is obtained that the sum of all the active powers is equal to the total three-phase power.

In fact, if for example you had a three-phase load of 9 kW (3 kW per phase) and three single-phase loads of 2 kW each, the power for each phase would be 5 kW. That is, you would get 15 kW in total, equal to the sum of the individual powers: 9 + 2 + 2 + 2 = 15 kW.

For the system under consideration, adding the values of the P_c powers calculated previously we obtain:

$$P_t = \sum_{i=1}^{17} P_{ci} = 2{,}18 + 9{,}72 + 3{,}22 + 22{,}8 + 35 + 35 + 35 + 12 + 1{,}6 + 1{,}6 + 1{,}6 + 18 + 13{,}5 + 0{,}21 + 0{,}8 + 0{,}5 + 0{,}2 \cong 193\ kW$$

The value of P_t is quite high for an industrial warehouse of 750 m^2. This is due to the high concentration of electrical load, mostly caused by the three workstations, which results in a surface power density of about 260 W/m^2.

It is possible to reduce this value with more restrictive hypotheses on the load reduction coefficients.

Application example 2

Remarks on the operating currents of the circuits

Looking at the values of the operating currents calculated for some plug socket power circuits, you can see how they are much lower than the nominal currents of the sockets themselves. For example, in the office the operating current of the entire 10 A socket circuit is equal to 4.35 A, while for the 16 A socket circuit it is equal to 4.78 A.

This might lead you to think that it is not possible to use even one socket for the entire value of its nominal current!

It must be kept in mind that these are conventional current values, calculated based on arbitrary reduction factors, which are used to determine the power to be installed in the various panels and to be requested from the electricity distributor.

In practice, the values of the nominal current of the overcurrent protection switch and the capacity of the line must be considered, and where necessary, proper corrections must be made. In the case in question, the I_n of the breakers can be 10 and 16 A respectively, and the lines can be sized with ampacity greater than these two values.

By doing so, it will be possible to draw currents up to the nominal currents of each socket from the two circuits.

Electric lines technologies

Electric lines

Electric lines are used to distribute electrical energy in electrical systems.:

- *Overhead lines* – used for transmission and distribution, rarely in user plants;
- *Busbar trunking (or bus ducts)* – used in industrial plants when you want to exploit their modularity and reconfigurability;
- *Cable lines* – used in all utility systems.

In the course focus is mainly given to cable lines (e.g., in overcurrent protection section we referred to cable insulation protection), being them the most ubiquitous.

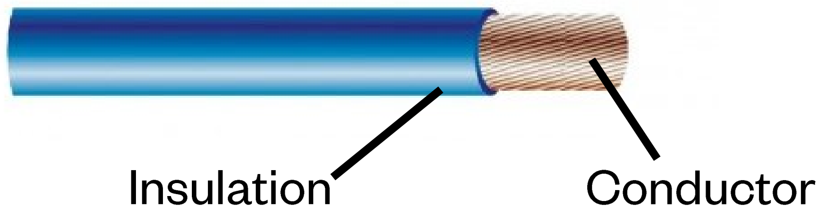
However, many of the presented considerations can easily be extended to other types of electrical lines.

Cables

Cables are the most used means of moving electrical energy in the world (and outside the world as well, as far as we know).

Cables are used at all voltage levels and in all electrical application, from high power electric power transmission (when specific motivations for avoiding building overhead lines exist), to small power appliances.

An electric cable is a single conductor (or a set of conductors joined together), insulated from other conductors and from the ground. If multiple conductors are present, each conductor with its own insulation constitutes a *core* of the cable.



Cables – classification and structure

Cables are distinguished according to the operating voltage of the system in which they can be used (*low*, *medium* and *high voltage cables*), according to the number of cores (*single-core* and *multi-core*), according to the type of insulation used, and according to compliance with CENELEC harmonization documents (*harmonized* and *non-harmonized cables*) (more info on CENELEC will be given later).

The structure of a cable varies according to the number of cores and the voltage.

Furthermore, a cable may have one or more supplementary parts in addition to the conductor and insulation alone, depending on the requirements of the cable itself.

Cables – characteristic temperatures

Depending on the type of insulation, two characteristic temperatures of the cables are defined, which are the maximum temperature values that the conductors can assume:

- *Maximum permissible temperature in steady state* (or *operating temperature*), referred to operation in ordinary conditions with constant current (no thermal transients or cyclic regimes);
- *Maximum short-circuit temperature*, referred to short-circuit conditions, i.e., intense heating but of short duration (given the protections' triggering).

Type of insulation	Operating temperature (°C)	Short circuit temperature (°C)
Impregnated paper	50-80	200
Paper impregnated with fluid oil	90	220
ethylene propylene rubber (G7, G10)	90	250
cross-linked polyethylene (E4)	90	250
polyvinyl chloride (R2)	70	160

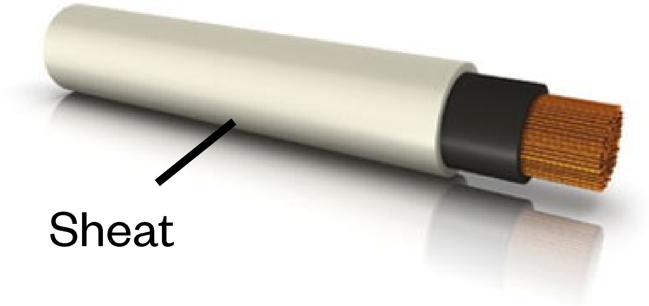
Cables – construction details – sheath

The sheath is a coating placed externally to the insulation, as mechanical protection and from environmental agents (light, chemical agents, humidity, etc.).

The sheath is colored according to a color code, recommended by the standards:

- Brown, black, gray for the phases;
- Light blue for the neutral;
- Yellow-green for the protective-earth conductor.

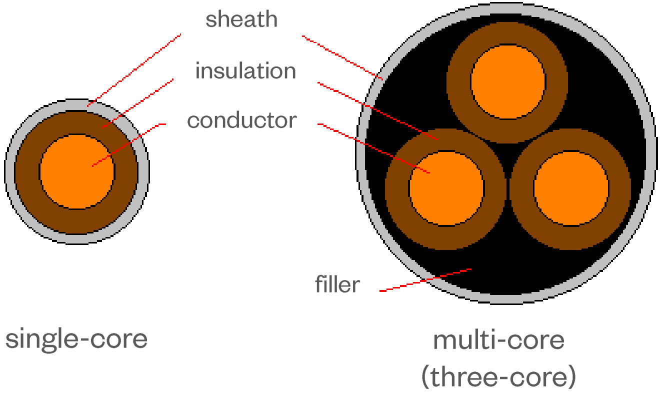
The sheaths are usually made of elastomeric or thermoplastic materials (rubber, PVC, polyethylene, etc..)



Cables – construction details – shape of conductors and number of cores

The conductors are made of copper (more rarely aluminum), single wire or rope, round or sector shaped (for large sections). They are distinguished according to their flexibility and the type of installation (fixed or mobile) for which they are suitable.

As already stated, cables can have one (single-core cables) or more (multi-core cables) conductors inside them. If the conductors are round, filling material is inserted to give the cable a round shape (easier to lay). It is also possible to make cables with a visible helix (without filler) or even flat cables.



Cables – construction details – insulating materials

Insulating materials:

- Thermoplastic resins, such as PVC and XLPE, used for low and medium voltage cables;
- Synthetic elastomers, such as EPR rubber, used for low and medium voltage cables, and silicone rubber, used when excellent heat resistance characteristics are needed;
- Mineral insulators based on magnesium oxide, used for low voltage cables when good fire resistance characteristics are needed;
- Insulating fluids, such as oil or gas.

Cables – construction details – insulating systems

Insulation system: set of components that ensure the electrical insulation of the conductor.

Classification of cables according to the type of insulation system:

- Impregnated paper cables;
- Fluid oil cables;
- Compressed gas cables;
- Extruded cables;
- Mineral insulated cables.

Cables – construction details – insulating systems

Impregnated paper cables.

Insulation system: paper-insulating mixture.

The oldest insulating system for cables, but still in use.

The paper is impregnated with an anti-migrating insulating mixture, and then wrapped around the conductor.

The paper has a mechanical function, the insulating mixture fills the air spaces and pores of the paper ensuring electrical insulation. A lead sheath is used to make the cable airtight.

Used for voltages up to 66kV, not usable in high voltage because air vacuoles remain inside the cable (insulation defects that become significant as the voltage increases).

Furthermore, they are only used for horizontal installations, as in the case of vertical installations the insulating mixture tends to migrate downwards due to the force of gravity, forming dielectrically weak points in the cable.

Maximum allowable temperature 65-70°C.

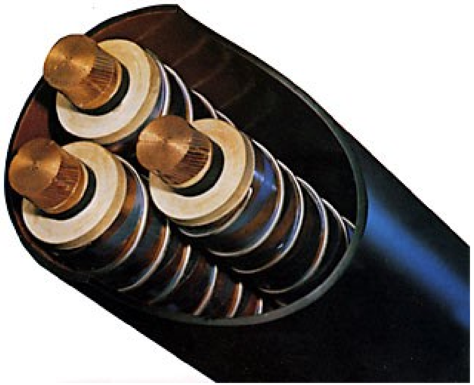
Cables – construction details – insulating systems

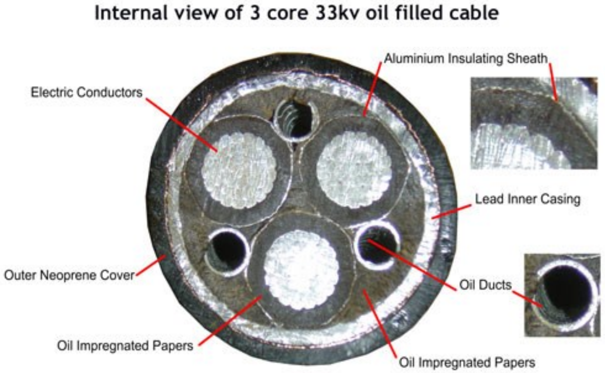
Fluid oil cables.

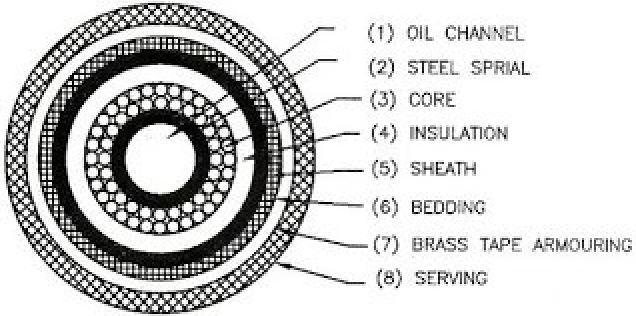
Insulation system: paper-fluid oil (they are the evolution of the previous type of cables)

The conductor is wrapped in paper tapes and immersed in fluid dielectric oil under pressure (1 – 3 atm). Various construction forms are possible with different impacts in terms of quantity of oil and construction costs.

Excellent for AT and AAT, but require oil tanks, expansion vessels, special joints, as well as being very polluting in the event of mechanical failure. Maximum allowable temperature 85-90°C.







Cables – construction details – insulating systems

Compressed gas cables.

Insulating system: paper-gas insulator.

Construction is similar to fluid oil cables, but with an insulating gas replacing the oil.

They have characteristics equivalent to fluid oil cables, but are easier to manage and less polluting in the event of mechanical failure (depending on the gas used); however, they are less widespread than oil cables.

One of the most used gases is nitrogen at 14-16 atmospheres, given its low cost and non-hazardous nature for the environment. In the past, sulfur hexafluoride (SF_6) was also used, but it is a greenhouse gas and has now been banned for all electrical applications (replaced by other synthetic gases).

Cables – construction details – insulating systems

Extruded cables.

Insulation system: solid insulation of various nature.

It is the most used insulation system thanks to its low cost, ease of production, installation and management.

The solid insulation is placed on the conductor by extrusion, and has both a mechanical and dielectric function.

Used at all voltage levels, in HV up to 150 kV (beyond this it is difficult due to problems of thermal disposal of Joule losses through the insulation).

Cables – Extruded Cable Insulators

Insulating materials for extruded cables are distinguished by an acronym, which specifies their type and quality.

In LV, the following are used:

- **E11**: natural or synthetic rubber, service temperature of 60°C and maximum short-circuit of 200°C;
- **E12**: synthetic silicone mix, service temperature of 180°C and maximum short-circuit of 350°C;
- **G7**: cross-linked synthetic rubber HEPR, service temperature of 90°C and maximum short-circuit of 250°C;
- **G9** and **G10**: cross-linked polyethylene XLPE, service temperature of 90°C and maximum short-circuit of 250°C (the only difference is the nominal voltage, 750 and 1000 V respectively);
- **R2**: PVC, service temperature of 70°C and maximum short-circuit of 160°C;
- **R3**: PVC, service temperature of 105°C and maximum short circuit of 160°C;
- **TI3**: PVC, service temperature of 90°C and maximum short circuit of 160°C.

In MV and HV, EPR or XLPE type rubbers are used, maximum allowable temperature 90°C.

Cables – construction details – insulating systems

Mineral insulated copper-clad cables.

Insulation system: solid magnesium oxide insulation.

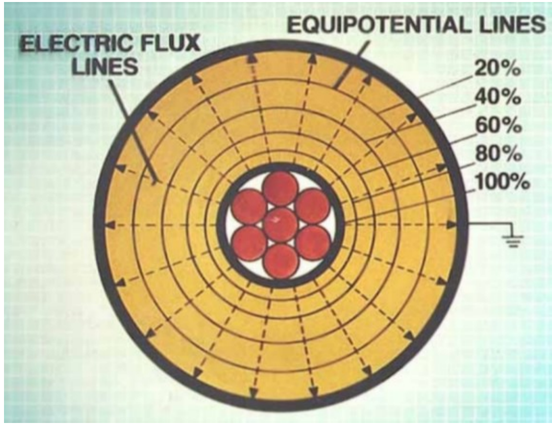
Made of solid copper conductors, magnesium oxide insulation and external copper sheath. They can be coated in PVC with low toxic fume emission in case of use in corrosive environments.

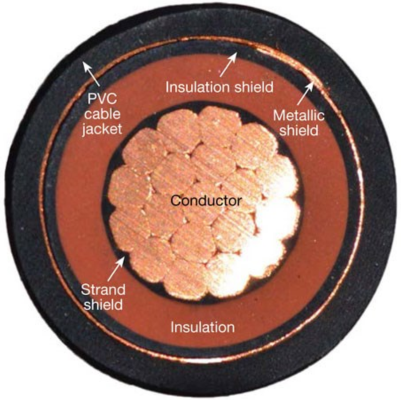
They do not propagate flame, are very robust, resist radiation and are suitable for the construction of explosion-proof electrical systems, as they do not contain oxygen inside them. Furthermore, being made of inorganic materials, they cannot burn or emit toxic gases in the event of a fire, they allow current flow even if they pass through an area where there are flames and, in the event that the fire is quickly extinguished and very high temperatures are not reached (copper melts at 1043°C and magnesium oxide at 2800°C), they do not need to be replaced after a fire.

Cables – construction details – screen

The screen is used to modify the electric field in the insulator, so as to obtain radial field lines coming out of the conductor (*radial field cables*). In this way, the dielectric stresses on the insulator are limited, making their distribution uniform and making it independent of the conditions outside the cable. The screen is useful in medium and high voltage, while in low voltage it is not used.

The screen is made with a metallized polymer tape, with a wrapped metal foil, or with a braid of conductive material. Another layer of insulation is placed outside the screen, for protection.





Cables – construction details – terminations

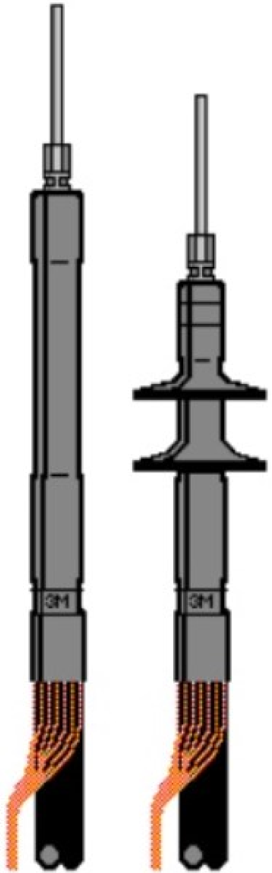
In MT and HV, special attention must be paid to cable joints and terminations.

The interruption of the sheath allows external agents to come into contact with the internal parts of the cable, degrading it more quickly. It is therefore necessary to create a seal when the cable is interrupted.

Furthermore, in these areas it is necessary to interrupt the shield, creating a localized intensification of the electric field due to the discontinuity. This can cause accelerated aging of some sections of the insulation, as well as phenomena of superficial electrical discharges.

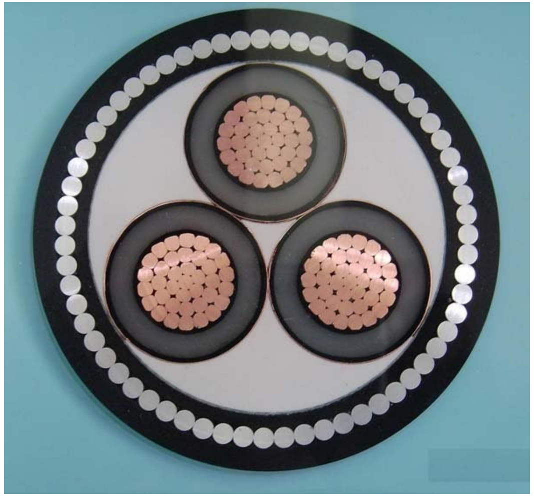
Finally, especially in high voltage applications, the interruption of the insulation creates a point where it is possible for conductive paths to originate on the surface of the material (due to external agents, or phenomena such as partial superficial discharges) which over time lead to short-circuiting the conductor to earth.

It is therefore necessary to install specifically conceived terminations at the end of the cable.



Cables – construction details – armor

In case you want to protect the cable from very intense mechanical stress (e.g. underground laying) a layer of material with high mechanical resistance is inserted. It can be made from a metal tube in lead or aluminum, or from steel wires or tapes.



Cables – ampacity

The *cable ampacity* is the *maximum current intensity that can circulate in each conductor, under certain installation and operating conditions and in permanent operation, without the temperature exceeding that admissible by the insulation*.

The capacity can be expressed in the general (approximate) form $I_z = kS^{1/2}$ with k coefficient dependent on ambient temperature, steady-state cable temperature, conductor resistivity, and thermal resistance of the insulation, and S cross section of the cable.

It is clear that the increase in ampacity as a function of the cross section is not linear, but is less than proportional. Therefore, as the cable cross section increases, it is necessary to decrease the current density.

For example, for three-core cables in air, the current density is 10÷13 A/mm^2 for sections of 1.5÷2.5 mm^2, and drops to 1.7÷1.4 A/mm^2 for sections of 400÷630 mm^2.

For this reason, to create sections greater than 630 mm^2, we resort to the use of parallel cables.

Cables – laying methods

Both cables and bare conductors can be installed in various ways, depending on the type of electrical system, the route, the operating voltage.

The choice between cables or bare conductors, and the method of installation, must be made considering various factors: the nature of the places, the nature of the parts of the building that must accommodate the elements, the possibility of access by people and animals, the stresses to which it will be subjected (in installation conditions, in service, and in failure).

There are also environmental factors to consider, the main ones of which are:

- Presence of heat sources;
- Exposure to solar rays;
- Presence of water;
- Presence of corrosive and polluting substances.

Cables – laying methods

For low voltage systems, the standards considers various types of installation, which can be grouped into the following categories:

- *Installation without fixings*, when the conductors do not have fixing systems and are installed using cavities in structures, tunnels, or by directly burying the cables;
- *Direct fixing to the wall*, when the cable is fixed using staples or other means, without mechanical protection systems (pipes, channels, etc.);
- *Installation within protective conduits*, which may be circular or not, external, embedded in the wall, buried, placed in tunnels;
- *Installation within metal or plastic channels*, fixed to the wall or ceiling or placed in false ceilings or recessed into the floor;
- *Installation on walkways or brackets*, generally external and made of metal;
- *Installation on insulators*, used for bare conductors;
- *Suspended cable* fixed to a wire or metal cord that ensures its anchoring.

Cables – laying methods –bending radius and parallel cables

To prevent cables from being damaged by mechanical stress during installation and use, the manufacturer specifies the minimum tolerable bending radius (usually as a multiple of the external diameter of the cable).

This data depends on the conductor cross-section, the type of insulation, the number of conductors, the screen and any armoring.

In systems with limited space for cable installation, it may become impossible to guarantee the minimum bending radius for cables with a large cross-section. The solution is therefore to divide the total cross-section necessary for the transport of the current into several single-core cables with a smaller diameter, characterized by a bending radius smaller than the single cable with a total cross-section.

These single-core cables are laid side by side and connected in parallel at both the starting and the arriving ends.

Cables – influence of laying conditions on ampacity – in air

The ampacity of low voltage cables insulated with elastomeric or thermoplastic material, operating in steady state and laid in air, is established by the CEI-UNEL 35024/1 standard.

For a given installation condition, the cable ampacity can be obtained with the formula:

$$I_z = I_0 K_1 K_2$$

With:

- I_0 ampacity at conventional room temperature (30 °C) for a single multi-core cable or a set of single-core cables that make up the single circuit, for the different laying conditions;
- K_1 correction factor for room temperature other than 30 °C (>1 if the temperature is lower, <1 if the temperature is higher);
- K_2 correction factor for multiple circuits installed in a bundle or layer.

A layer means a set of multiple circuits made with cables installed side by side, spaced or not, arranged horizontally or vertically; A bundle means a set of multiple circuits made with cables that are not spaced and not installed in a layer. Multiple overlapping layers = bundle.

Cables – influence of laying conditions on ampacity – buried

Buried installation is generally more inconvenient and expensive than air installation, so it is best to use it only when strictly necessary.

The ampacity of a buried cable is more uncertain to evaluate than air installation and depends on the following factors:

- *Ground temperature*, as the temperature increases, the ampacity decreases; reference standard 20 °C;
- *Number of buried cables on a plane and their distance*; due to the proximity effect, the ampacity decreases as the number increases and the distance decreases;
- *Depth of burial*; the ampacity decreases as the depth increases, as the mass of soil that the heat must pass through to reach the surface increases; deep installation is only justified if you want to reach a layer of soil with lower thermal resistivity; reference standard 0.8 m at the center of the cable;
- *Thermal resistivity of the soil*; the ampacity decreases as the thermal resistivity of the medium increases; in the case of buried installation, this is the most influential factor; in the case of underground installation in pipes, the effect becomes less influential due to the presence of stagnant air in the pipe itself, which has a much higher resistivity than the ground; regulatory reference 1.5 Km/W.

Cables – influence of laying conditions on ampacity – buried

The ampacity of low voltage cables insulated with elastomeric or thermoplastic material, operating in steady state and buried, is established by the CEI-UNEL 35026 standard.

The capacity of the cable is defined in the regulatory conditions described above, and for laying in protective pipes, while in the case of cables directly buried the capacity can be calculated using an increase coefficient that the standard defines as 1.15.

The capacity can be obtained with the formula:

$$I_z = I_0 K_1 K_2 K_3 K_4$$

With:

- I_0 ampacity relative to a certain cross section, a certain type of insulation, and a certain installation method; equal to the effective ampacity for a ground temperature of 20 °C, installation of a single circuit, installation depth of 0.8 m, thermal resistivity of the ground 1,5 Km/W;

Cables – influence of laying conditions on ampacity – buried

- K_1 correction factor for temperatures other than 20 °C (>1 if the temperature is lower, <1 if the temperature is higher);
- K_2 correction factor that takes into account the number of elementary circuits (in the case of single-core cables) and the number of three-core cables laid on the same layer of soil and their distance (<1 for a number greater than one);
- K_3 correction factor for laying depths other than 0.8 m (>1 for smaller depths, <1 for greater depths);
- K_4 correction factor that takes into account the thermal resistivity of the soil, if different from 1,5 Km/W (<1 for greater resistivity).

Cables – characteristic voltages

The insulating material is chosen by evaluating its electrical, mechanical, heat and environmental resistance characteristics, cost, lifespan, etc.

For example, the thickness of the insulation is directly proportional to the voltage at which the system must work.

For the design and selection of cables, two voltage values are usually evaluated (in rms kV), conventionally called *insulation voltages*:

- U_0: nominal reference voltage for the insulation between each insulated conductor and the earth;
- U: nominal reference voltage for the insulation between any two insulated conductors of the cable.

Two further voltage values can be defined, which may be of interest in practical applications:

- U_m: maximum phase-to-phase voltage that can occur between two conductors of different phases;
- U_p: withstand voltage to the atmospheric impulse (expressed in peak kV).

Cables – designation codes

Each cable is classified according to the regulations, assigning it a name that uniquely describes its main characteristics. They are also called designation acronyms.

The regulations provide tables to derive the identification code from the structure of the cable (typical of cable manufacturers) or vice versa (typical of installers).

Main regulation in Italy for cables unified within the EC (harmonized cables) is CEI 20-27, which is written in accordance with the CENELEC harmonization document HD361.

Examples of cable codes as per CEI 20-27:

H07V-R 3G1,5 *H05VV5-F 5G6* *H1Z2Z2-K 1x6*

In Italy is also valid the CEI UNE 35011 standard, which provides a different coding (for cables that cannot be used outside Italy)

Attached you can find the Cable designation codes tables

Cables – notes on lifespan

Insulating material is essential in a cable. Its lifespan determines the life of the cable itself, when the cable is used within its specifications. If the cable is used incorrectly, the insulation is the first component of the cable to lose its functions in almost all situations.

Environmental stresses (both thermal and chemical) and electrical stresses damage the insulating material, breaking the chemical bonds of its molecules. The process continues until the insulation becomes unable to maintain its electrical or mechanical properties.

Using a cable with currents higher than its ampacity, with excessively high ambient temperatures, or in chemically aggressive environments exponentially reduces its lifespan.

Since cables are the primary method for distributing electrical energy in power systems, it is clear that the correct choice, sizing, and use of cables is essential to ensure a long and safe lifespan for the power system.

Cables – Fire behavior of cables

All cables on the market must have reduced emission of toxic and corrosive fumes when burning.

However, when there is a risk of fire, it is necessary to pay attention to the fire behavior of the cables.

The old standards provided for 3 categories:

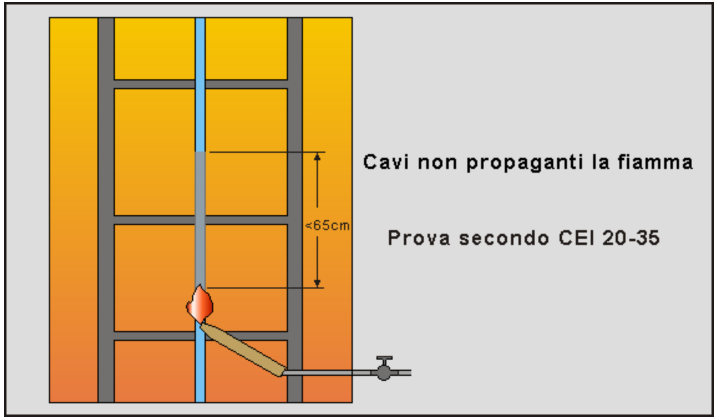
- Flame-retardant cables;
- Fire-retardant cables;
- Fire-resistant cables (for emergency services).

New standards use a different approach (shown afterwards), yet the old standards testing methods are useful for having an idea of the conditions that cables must withstand in the presence of fire) .

Cables – Fire behavior of cables

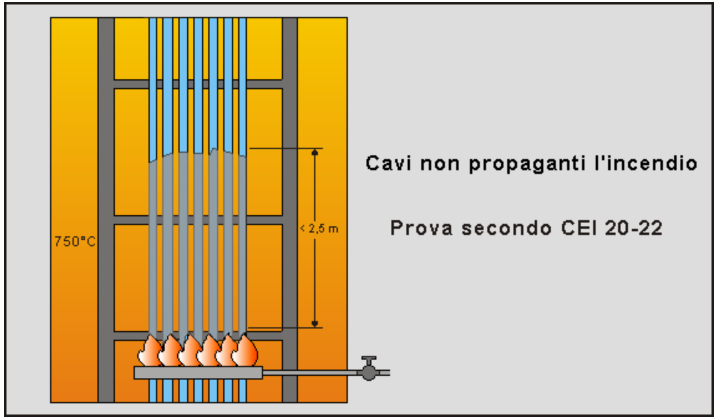
Flame retardant cables:

The individual cable must be self-extinguishing. The insulation, although it catches fire and is ruined when touched by the flame, must be able to self-extinguish within 65 cm from the point of application of the flame.



Fire-retardant cables:

The self-extinguishing capacity of a bundle of cables is required. The insulation, even if it catches fire in an environment where temperatures reach 750°C, must be able to self-extinguish within 250 cm from the application point of ignition of the fire.



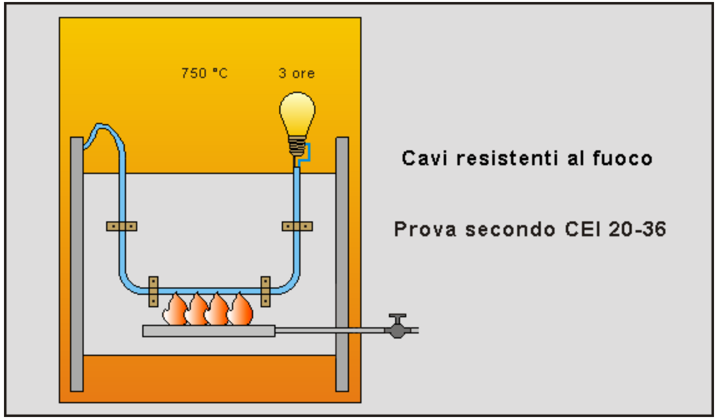
Cables – Fire behavior of cables

Fire-resistant cables:

Resistance to flame for at least 3 hours in an environment at 750°C is required, with the cable carrying current, ensuring continuous power to the emergency user connected even with the insulation completely burned.

Cables able to pass this test are usually very costly and its use is avoided as much as possible (by using different approaches).

Mineral insulated cables are typically among the best fire-resistant cables.



Cables – Fire behavior of cables

From 1 July 2017, in Italy CEI EN 50575:2014 *Power, control and communication cables – Cables for general applications in construction work subject to reaction to fire requirements* came into force as a harmonized standard pursuant to EU Regulation 305/2011 (*Construction Products Regulation - CPR*). The same standard has been introduced in all EU countries.

Therefore, cables that must be installed in a building must be CE marked in compliance with the reaction to fire requirement. Consequently, national cable standards have been amended to converge with compliance with the reaction to fire requirement.

The IEC standards for the identification of the fire behavior of electrical cables have therefore undergone several amendments in relation to the new CPR cable classification. This new classification is mandatory only for cables placed on the market and intended to be permanently installed inside buildings, as construction products pursuant to the CPR.

Cables – Fire behavior of cables

A new cable must meet more stringent requirements than in the past and therefore withstand more demanding tests than traditional cables. In this regard, the following main parameters have been introduced:

FIGRA	Fire Growth Rate Index - Indice del tasso di crescita dell'incendio, utilizzato ai fini della classificazione (W/s)
PCS	Potere calorifico superiore (MJ/Kg)
THR_{1200}	Total Heat Release – Rilascio di calore totale per 1200 s (MJ)
Peak HRR	Heat Release Rate – Valore massimo del rilascio di calore - picco (kW)
Peak SPR	Valore massimo della produzione di fumo mediato su 60 sec (m^2/S)
FS	Flame Spread – Propagazione della fiamma verticale - lunghezza danneggiata del campione (m)
H	Height - Altezza Propagazione della fiamma verticale (mm)

Cables – Fire behavior of cables

Based on the performance of the tests, the standard classifies cables into 7 classes, from *Aca* (high performance) to *Fca* (low performance). Each class provides minimum thresholds for heat release and flame propagation. The subscript *ca* indicates cables.

Aca	B1ca	B2ca	Cca	Dca	Eca	Fca

\+ high performance — low performance -

In addition to this main classification, the European authorities have also regulated the use of the following additional parameters:

- a = acidity and corrosivity (from *a1* to *a3*)
- s = opacity of the fumes (varies from *s1* to *s3*)
- d = dripping (varies from *d0* to *d2*)

Cable selection and sizing

Cables – selection criteria

Choosing the most suitable cable for an electrical installation is important, as it helps determine the safety and functionality of the latter.

There are numerous provisions in this regard, contained in various standards.

The most important factors to consider are:

- Nominal voltage of the system;
- Cross-section of the phase conductors and, if applicable, the neutral conductor;
- Presence or absence of the protective conductor;
- Place where the installation must take place;
- Cable laying method.

The selection of the correct cable is done by the designer of the electrical system, carefully evaluating all the above factors. In the following some insights are given, even if this task is the responsibility of an electrical engineer, to allow comprehending how the electrical power systems are designed.

Cables – selection criteria

The choice of cable insulation voltages depends on the nominal voltage of the system and its voltage to earth (both in normal conditions and in the event of an earth fault).

The choice of conductor cross-section derives from the electrical calculation of the line sizing and from the possible presence of minimum cross-sections imposed by the standards in relation to the installation conditions. The choice of cross-section depends not only on the current to be transmitted, but also on the admissible voltage drop and coordination with the overcurrent protection devices. More info are given in the following.

The presence or absence of the protective conductor in the cable derives from the choices made regarding the state of the neutral of the system and the presence of a grounding system. The protective conductor can however be made with a cable separate from the power cable.

The specific installation location requires the application of specific regulations, which influence the choice of all components, including cables (special cases: places with explosion hazard, etc.).

The installation conditions influence not only the cross-section of the conductor, but also the presence of sheath and other protection systems (for example armor).

Design and verification calculations

The *design calculation* of an electrical circuit means *determining the physical characteristics* (section of the conductors, type of cable, installation method, etc.) *based on the input data and in compliance with certain design constraints*, which will then be verified once the calculation is complete. *It refers to newly installed lines, or those that completely replace existing conduits*.

In the most common case of cable lines, the calculation includes the following phases:

- Choice of the type of cable and its insulation voltages based on the nominal voltage of the system and the installation method;
- Determination of the theoretical section of the conductors and choice of the standardized section;
- Verification of the ampacity of the chosen cable in relation to the operating current of the circuit.

Design and verification calculations

The *verification calculation* consists in *checking that an existing electrical line, following changes in its operating regime, continues to possess certain requirements and satisfy the pre-established constraints*.

Common case: checking that the section is adequate in the face of an increase in the operating current.

The following methods can be used both for the sizing of electrical lines and for their verification:

- Direct ampacity check → most used for sizing
- Permissible power loss method → very uncommon use (shown, being in the app. example)
- Maximum allowable temperature method → only for bare conductors
- Maximum allowable voltage drop method → most used for verification
- Unitary voltage drop method → very uncommon use (shown, being in the app. example)
- Current moments method → very uncommon use (here not shown)

Permissible power loss method

Let ρ be the electrical resistivity of the conductor at the operating temperature, l the length of the line, P the transmitted active power, V the nominal voltage (phase-to-phase for three-phase systems), $cos\phi$ the load power factor, S the conductor cross-section and $\Delta p\%$ the admissible percentage power loss.

The design cross-section of the conductors can be calculated as follows:

- Direct current $S = \frac{200\rho l P}{\Delta p\% V^2}$
- Single-phase alternating current $S = \frac{200\rho l P}{\Delta p\% V^2 (\cos\varphi)^2}$
- Three-phase alternating current $S = \frac{100\rho l P}{\Delta p\% V^2 (\cos\varphi)^2}$

Permissible power loss method

To verify the power loss corresponding to the adoption of a certain section, the following are used:

- Direct current $$\Delta p\% = \frac{200\rho l P}{S V^2}$$
- Single-phase alternating current $$\Delta p\% = \frac{200\rho l P}{S V^2 (\cos\varphi)^2}$$
- Three-phase alternating current $$\Delta p\% = \frac{100\rho l P}{S V^2 (\cos\varphi)^2}$$

The absolute power loss is: $$\Delta p = \frac{\Delta p\% P}{100}$$

To use the method as a design calculation, the value of *Δp%* must be set in advance (variable between 2 and 8%), taking into account that as it increases the section decreases (lower installation costs) but power losses increase (higher management costs).

Permissible power loss method

Example 1:

Calculate the cross-section of the conductors of a three-phase overhead line of length 2 km, operating with a nominal voltage of 6 kV, which supplies the power of 500 kW (cosφ 0.8), so that the power loss is not greater than 6%. The line is made with copper conductors with resistivity 0.0202 $\Omega mm^2/m$ (T=55 °C).

From the formulas just presented it results:

$$S = \frac{100\rho l P}{\Delta p\% V^2(\cos\varphi)^2} = \frac{100 * 0{,}0202 * 2 * 10^3 * 500 * 10^3}{6 * (6 * 10^3)^2 * 0{,}8^2} = 14{,}6\ mm^2$$

The determined section is the minimum one, corresponding to the maximum admissible limit of the power loss.

Therefore, the commercial section must be chosen with a value not less than 14,6 mm^2. For example 16 mm^2.

Permissible power loss method

Example 2:

Verify that in a single-phase line with copper conductors of 16 mm^2 section, operating with a nominal voltage of 230 V, 200 m long, which transmits the power of 6 kW (cosφ 0,85), the power loss is less than 5%. Assume the resistivity value of 0,0213 Ωmm^2/m (T=70 °C).

From the formula presented above, it results:

$$\Delta p\% = \frac{200\rho l P}{S V^2 (\cos\varphi)^2} = \frac{200 * 0{,}0213 * 200 * 6 * 10^3}{16 * 230^2 * 0{,}85^2} = 8{,}36\%$$

The verification is negative. To comply with the power loss constraint, it will therefore be necessary to increase the cross-section of the conductors or reduce the transmitted power.

Maximum allowable temperature method

This is a method that is mainly applied to bare conductors. It is based on the equation that is obtained in thermal equilibrium conditions, i.e. by equating the power produced by the Joule effect from the current flowing in the conductor (RI^2) and that dissipated by the same towards the outside ($\lambda\theta^{\Delta}A$):

$$\rho l I^2 = \lambda \theta^{\Delta} A S$$

With ρ resistivity of the material at the operating temperature θ (sum of ambient temperature θ_a and overtemperature θ^{Δ}), l length of the conductor, A area of the conductor's dispersing surface, S conductor cross-section, λ global heat transmission coefficient.

For θ^{Δ} between 30 and 90 °C we have:

- $\lambda = 12 \div 16$ W/(m^{2}K) for conductors in stagnant air;
- $\lambda = 15 \div 20$ W/(m^{2}K) for conductors in air with natural circulation.

The equation must be developed differently depending on the shape of the conductor. We will see the cases of conductors with circular and rectangular cross-sections

Maximum allowable temperature method

Circular conductor with diameter d.

The section is $S = \pi d^2/4$, while the lateral heat dissipation area is $A = \pi d l$.

We obtain: $4\rho l I^2 = \lambda \theta^{\Delta} \pi^2 d^3$

- *Design*: given θ^{Δ}, we calculate $d = \sqrt[3]{\frac{4\rho I^2}{\lambda \pi^2 \theta^{\Delta}}}$ with $\theta^{\Delta} \leq 25 \div 30$ °C, and θ_a=40 °C in the most unfavorable conditions

- *Verification of the overtemperature*: we calculate $\theta^{\Delta} = \frac{4\rho I^2}{\lambda \pi^2 d^3}$

- *Verification of the maximum admissible current*: given *d* and given θ^{Δ} we determine $I = 1{,}571\sqrt{\frac{\lambda \theta^{\Delta} d^3}{\rho}}$

Maximum allowable temperature method

Conductor with rectangular section with base *b* and height *h*.

The section is given by $S = bh$, while the lateral heat dissipation area is $A = 2(b + h)l$.

We obtain: $\rho I^2 = 2\lambda\theta^{\Delta}(b + h)bh$

- *Design*: it is necessary to determine two unknowns, *b* and *h*, for which it is necessary to fix one of the two dimensions in advance, or alternatively the ratio $k_d = h/b$ can be fixed.

  The cable sizing can then be carried out with the relations: $\begin{cases} b = \sqrt[3]{\dfrac{\rho I^2}{2\lambda\theta^{\Delta}(1+k_d)k_d}} \\ h = k_d b \end{cases}$

Maximum allowable temperature method

- *Checking for overtemperature*: calculate $\theta^{\Delta} = \frac{\rho I^2}{2\lambda(b+h)bh}$

- *Checking for the maximum permissible current*: given the dimensions *b* and *h*, and fixing θ^{Δ}, determine the maximum current that can flow in the conductor:

$$I = \sqrt{\frac{2\lambda\theta^{\Delta}(b+h)bh}{\rho}}$$

Maximum allowable temperature method

Example 3:

Calculate the diameter of a cylindrical copper conductor capable of conducting a current of 80 A with a temperature increase not exceeding 30 °C, starting from an ambient temperature of 40 °C with naturally circulating air.

Assume λ=15 W/(m^{2}K) and ρ=0,0213*10^{-6} Ωm (copper at temperature $\theta=\theta_a+\theta^{\Delta}$=30+40=70 °C).

From the formula seen previously we obtain:

$$d = \sqrt[3]{\frac{4\rho I^2}{\lambda\pi^2\theta^{\Delta}}} = \sqrt[3]{\frac{4 * 0{,}0213 * 10^{-6} * 80^2}{15\pi^2 * 30}} = 0{,}497 * 10^{-2}\ m \cong 5\ mm$$

Maximum allowable temperature method

Example 4:

Verify that an aluminum conductor, of the same diameter and in the same conditions as that of example 3, is able to conduct a current of 60 A.

The resistivity of aluminum at 70 °C is 0,034 $\Omega mm^2/m$. Apply the verification relationship seen previously:

$$I = 1{,}571\sqrt{\frac{\lambda\theta^{\Delta}d^3}{\rho}} = 1{,}571\sqrt{\frac{15 * 30 * (0{,}5 * 10^{-2})^3}{0{,}034 * 10^{-6}}} = 63{,}9\ A$$

The verification is positive since *I* >60 A.

It must be noted that, for the same section and environmental conditions of the previous example, the permissible current is lower due to the greater resistivity of aluminum compared to copper.

Maximum allowable temperature method

Example 5:

Determine the dimensions *b* and *h* and the current density of a rectangular section aluminum bar, with a dimensional ratio k_d=5, capable of conducting a current of 300 A with a temperature increase not exceeding 25 °C, starting from an ambient temperature of 45 °C. For the resistivity and the overall transmission coefficient, assume ρ=0,034 Ωmm²/m and λ=18 W/(m²K).

We obtain:

$$b = \sqrt[3]{\frac{\rho I^2}{2\lambda\theta^{\Delta}(1+k_d)k_d}} = \sqrt[3]{\frac{0{,}034 * 10^{-6} * 300^2}{2 * 18 * 25 * (1+5) * 5}} = 0{,}484 * 10^{-2}\, m = 4{,}84\, mm$$

Maximum allowable temperature method

The height and section of the bar are given by:

$$h = k_d * b = 5 * b = 5 * 4{,}84 = 24{,}2\ mm$$

$$S = b * h = 4{,}84 * 24{,}2 = 117{,}1\ mm^2$$

The current density is obtained as:

$$\delta = \frac{I}{S} = \frac{300}{117{,}1} = 2{,}56\ A/mm^2$$

Maximum allowable temperature method

Example 6:

Verify that a rectangular section aluminum bar, 5x20 mm in size, is able to conduct a current of 300 A without the overtemperature exceeding 25 °C starting from an ambient temperature of 35 °C, in an environment with naturally circulating air.

Assuming λ=15 W/(m^{2}K) and ρ=0,0329*10^{-6} Ωm (aluminum at a temperature $\theta=\theta_a+\theta^\Delta$=35+25=60 °C).

From the formula seen previously we obtain:

$$I = \sqrt{\frac{2\lambda\theta^\Delta(b+h)bh}{\rho}} = \sqrt{\frac{2*15*25(5+20)*10^{-3}*5*10^{-3}*20*10^{-3}}{0{,}0329*10^{-6}}} = 238{,}7\ A$$

The verification is negative since *I* <300 A. To respect the constraints the current in the bar must be limited to a value lower than 238,7 A.

Maximum allowable voltage drop method

For a line of length *l*, rated voltage V_n (phase-phase for three-phase lines, phase-ground for single-phase lines), load current *I*, load angle φ, and unit parameters r_l and x_l, the approximated voltage drop, in percentage referred to the rated voltage is given by:

- Direct current $$\Delta V\% = \frac{200 I l r_l}{V_n}$$
- Single-phase alternating current $$\Delta V\% = \frac{200 I l}{V_n}(r_l \cos\varphi + x_l \sin\varphi)$$
- Three-phase alternating current $$\Delta V\% = \frac{100\sqrt{3} I l}{V_n}(r_l \cos\varphi + x_l \sin\varphi)$$

Maximum allowable voltage drop method

To determine the cross-section of the conductors, the procedure is as follows:

- Assign a value to the percentage voltage drop ΔV%;
- Define a value of the unit reactance x_l (approximately 0.4 Ω/km for overhead lines and 0.1 Ω/km for cable lines);
- Calculate the unit resistance of the line r_l from the corresponding expression of *ΔV%* (see previous page);
- Determine the theoretical cross-section of the conductors with the formula $S = \rho/r_l$, assuming the value at the operating temperature for the resistivity;
- Choose the closest commercial cross-section of the conductors (in excess) and verify that the flow rate is higher than the current that must flow on them, otherwise move on to the next higher cross-section;
- In doubtful cases, verify that the actual c.d.t, calculated starting from the real parameters r_l and x_l of the chosen conduit, falls within the imposed limit.

To choose the percentage voltage drop value, it should be kept in mind that standards usually recommends (not an obligation) prospective values. E.g., the Italian standard CEI 64-8 recommends for LV systems a value not exceeding 4% between the PCC (point of common coupling with the public grid) and any user device.

Maximum allowable voltage drop method

Example 7:

A three-phase AC line at 50 Hz with a nominal voltage of 6 kV and a length of 500 m supplies a load that absorbs 80 A with cosφ=0.85. The line is made with a three-core copper cable without a screen on the individual cores, insulated in EPR (maximum temperature 90 °C) and laid in an underground pipe, without other cables nearby, with a laying depth of 0.8 m, thermal resistivity of the ground 2 Km/W and ground temperature 20 °C. Determine the cross-section of the conductors so as to have a voltage drop of no more than 4%.

The absolute voltage drop is:

$$\Delta V = \frac{\Delta V\% * V_n}{100} = \frac{4 * 6000}{100} = 240\ V$$

Maximum allowable voltage drop method

The kilometric reactance value x_l =0.1 Ω/km is established and the expression for calculating the voltage drop seen previously is applied:

$$\Delta V\% = \frac{100\sqrt{3}Il}{V_n}(r_l \cos\varphi + x_l \sin\varphi)$$

From which it is obtained : r_l= 4,015 Ω/km.

The resistivity of copper at operating temperature (90 °C) is :

$$\rho = 0{,}0178 * \frac{234{,}5 + 90}{234{,}5 + 20} = 0{,}0227\ \Omega mm^2/m = 22{,}7\, \Omega mm^2/km$$

The minimum cross-section of the conductor is therefore :

$$S = \frac{\rho}{r_l} = \frac{22{,}7}{4{,}015} = 5{,}65\, mm^2$$

Maximum allowable voltage drop method

The closest commercial section is 6 mm^2, which however does not have sufficient capacity.

Evaluating the ampacity with the coefficient coming from the standards, we obtain that the suitable section is 25 mm^2. In fact, we have:

- I_0=93 A;
- K_1=1 (laying temperature 20 °C);
- K_2=1 (one cable only);
- K_3=1 (installation at 0.8 m depth);
- K_4=0,91 (thermal resistivity of the soil 2 Km/W).

The actual ampacity is therefore: $I_z = I_0 K_1 K_2 K_3 K_4 = 93 * 1 * 1 * 1 * 0{,}81 = 84{,}6\ A$

which is higher than the operating current (80 A).

Maximum allowable voltage drop method

From datasheets about three-pole cables, it results that a 25 mm^2 cable presents the following kilometric inductance and a kilometric capacitive susceptance per phase:

$L_s = 0{,}366 * 10^{-3}\ H/km$ $\qquad$ $b_c = 60 * 10^{-6}\ S/km$

It follows that $x_l = \omega L_s = 314 * 0{,}366 * 10^{-3} = 0{,}115\ \Omega/km$

which confirms that the previously hypothesized reactance (0.1 Ω/km) is sufficiently accurate.

The capacitive current per phase is :

$$I_c = b_c l \frac{V_n}{\sqrt{3}} = 60 * 10^{-6} * 0{,}5 \frac{6 * 10^3}{\sqrt{3}} = 0{,}103\ A$$

which with its negligible value confirms the validity of the hypothesis of neglecting the transversal components of the line.

Maximum allowable voltage drop method

The kilometric resistance of the chosen 25 mm^2 conductor is equal to : $r_l = \frac{\rho}{S} = \frac{22{,}7}{25} = 0{,}908\ \Omega/km$

Therefore, the actual voltage drop is equal to :

$$\Delta V = \sqrt{3} l I (r_l \cos\varphi + x_l \sin\varphi) = \sqrt{3} * 0{,}5 * 80(0{,}908 * 0{,}85 + 0{,}115 * 0{,}527) = 57{,}7\ V$$

Which corresponds to a percentage value of :

$$\Delta V\% = \frac{\Delta V}{V_n} * 100 = \frac{57{,}7}{6000} * 100 = 0{,}962\%$$

In this case the choice of the section was determined by the ampacity of the cable. Therefore, the increase in section compared to the initial value led to a decrease in the voltage drop.

Unitary voltage drop method

This method is based on the criterion of the maximum allowable voltage drop (the previous one), but it allows to simplify the calculation by using a table in which the values of the unitary voltage drop are reported as a function of the type of cable, the type of current, and three conventional values of power factor.

In particular, the unit voltage drop is defined as:

$$u = \frac{\Delta V * 1000}{I * l}$$

is expressed in milliVolts per Ampere meter (mV/Am), and represents the voltage drop for each meter of cable caused by one Ampere of current.

Considering the expression of the approximated voltage drop for a three-phase system, it is possible to derive the following expression:

$$u = \sqrt{3}(r_l \cos\varphi + x_l \sin\varphi)$$

The formula depends only on the characteristics of the cable, and the power factor of the load.

A similar procedure can be used for the single-phase case, and for direct current.

Unitary voltage drop method

The method requires to:

- Set the value of ΔV%;
- Calculate $\Delta V = \frac{\Delta V\% * V_n}{100}$;
- Calculate *u* using its definition (formula on previous page);
- Choose from the tables a cable section having a *u* smaller than the calculated one;
- Check that the ampacity of the selected cable is sufficient.

The values of *u* are given in a table of CEI-UNEL 30023-70 standard, referring to an operating temperature of 80 °C, and therefore applicable with sufficient approximation to both PVC and EPR insulated cables. They represent the unitary voltage drop between the two conductors for direct current, between phase and neutral for single-phase alternating current, and between phase and phase for three-phase alternating current..

Once the value u_{eff} of the unitary voltage drop for the cable has been chosen, the total voltage drop is determined as: $\Delta V = \frac{u_{eff} * I * l}{1000}$

Unitary voltage drop method

Example 8:

For a single-phase line with V_n=230 V, l=100 m, I=35 A, the unitary voltage drop corresponding to a ΔV% of 4% is given by:

$$\Delta V = \frac{\Delta V\% * V_n}{100} = \frac{4 * 230}{100} = 9{,}2\ V$$

$$u = \frac{1000\Delta V}{Il} = \frac{1000 * 9{,}2}{35 * 100} = 2{,}63\ \frac{mV}{Am}$$

Considering a line made up by unipolar cables, with p.f. near to 0,8, it results that the cross section to be selected is 16 mm^2, having it u=2,39 mV/(Am) (lower than the value calculated above). For this cross section, it must be then verified that the ampacity is higher that the operating current (35 A).

It is easy to verify that with the chosen value, the actual percentage voltage drop is equal to 3.64% (< 4%).

Minimum cross-sections of electrical lines

The methods presented allow to obtain the theoretical value of the section of the line conductors, from which one must then move on to the closest commercial value.

In the case of very short lines and powering low-power loads, it may happen that the calculated theoretical section is very small (for example less than 1 mm^2). Lines of this type, although sufficient to conduct the current required by the load, may be poorly suited to withstand the mechanical stresses due to installation.

Therefore, the technical standards specifies the minimum sections to be respected.

For low voltage user systems in Italy, the CEI 64-8 standard prescribes minimum section values, distinct for the phase conductors and for the neutral conductor, and distinct for the type of conductor material.

Minimum cross-sections of electrical lines

Type of line		Use of the circuit	Conductor	
			Material	Cross section mm^2
Fixed lines	Cables	Power circuits	Cu Al	1,5 10 (note 1)
		Signal circuits and auxiliary control circuits	Cu	0,5 (note 2)
	Bare conductors	Power circuits	Cu Al	10 16 (note 4)
		Signal circuits and auxiliary control circuits	Cu	4 (note 4)
Mobile lines with flexible cables		For a specific user device	Cu	As specified in the corresponding standard
		For any other equipment		0,75 (note 3)
		Extra low voltage circuits for special applications		0,75

Minimum cross-sections of electrical lines

Notes:

1) It is recommended that the means of connection used at the ends of aluminum conductors be tested and approved for this specific use;
2) In signal circuits (signaling and control) intended for electronic equipment, a minimum cross-section of 0.1 mm^2 is permitted;
3) For multi-core flexible cables, containing seven or more cores, note 2 applies;
4) Specific requirements for very low voltage lighting circuits are being studied.

Minimum cross-sections of electrical lines

Neutral section

The cross-section of the neutral depends on the value of the current flowing through it. In a single-phase circuit, this is equal to that of the phase, while in three-phase circuits it depends on the imbalance of the three phase currents and the presence of any harmonic components.

Obviously, in the case of a balanced sinusoidal trio of phase currents, the current in the neutral is zero.

Since it can be difficult to accurately evaluate the current in the neutral during the design stage, the standards provides indications on the choice of the cross-section of the neutral S_N based on the cross-section of the phase conductors S_F.

Minimum cross-sections of electrical lines

$S_N \geq S_F$ (they are generally set equal)

- In single-phase two-wire circuits, regardless of the conductor cross-section;
- In multiphase circuits (or in three-wire single-phase circuits) with $S_F \leq 16\ mm^2$ if in copper and $S_F \leq 25\ mm^2$ if in aluminum;
- In three-phase circuits where there are between 15% and 33% of harmonic currents of order three, or odd multiples of three. For harmonic currents greater than 33% it may be necessary to increase the cross-section of the neutral with respect to the phase.

$S_N < S_F$

- In multiphase circuits with $S_F > 16\ mm^2$ if in copper and with $S_F > 25\ mm^2$ if in aluminum; provided that the load is practically balanced, the maximum current including harmonics that is expected to flow in the neutral in ordinary service is not higher than that admissible for the reduced cross-section of the neutral, and protection against overcurrents is ensured.

Application example

Sizing of the power lines for an industrial electrical system

The power system is installed in an industrial plant where plastic products are produced from the raw material (polyethylene) using electrically operated machines.

The plant has the following general characteristics:

- Environment with a higher risk of fire due to the presence of a significant quantity of combustible material;
- Plant equipped with its own transformation cabin;
- Nominal voltages on the LV side equal to 230/400 V.

The lines to be sized are used to power five machines used for production and a compressor.

Application example

The characteristics of the loads and the length of the lines are shown in the table.

Line	Type	V_n (V)	P (kW)	cosφ	l (m)
Machine 1	3 + N	400	75	0,85	50
Machine 2	3 + N	400	40	0,85	80
Machine 3	3 + N	400	90	0,85	40
Machine 4	3 + N	400	60	0,85	60
Machine 5	3 + N	400	50	0,85	45
Air compressor	3 + N	400	35	0,78	70

Application example

The lines are planned to be laid on two perforated walkways, spaced vertically by 300 mm, with cables laid in layers. Three load lines will be laid on each walkway.

The sizing of the six lines must be carried out, respecting the following constraints for each line:

- $\Delta V\% \leq 3\%$ (precautionary compared to the 4% of the standard);
- $\Delta p\% \leq 5\%$ at the operating temperature of the cables;
- Ampacity of the cables commensurate with the operating current of the conduits and such as to ensure a sufficient margin for the choice of the rated or regulation current of the overload protection devices;
- Maximum ambient temperature to be considered equal to 40 °C.

Application example

Choosing the type of cable

The following characteristics are chosen for the cable:

- Insulation voltages U_0/U = 0.6/1 kV (abundant compared to the nominal system voltages);
- Insulation in synthetic rubber EPR of G7 quality, with service temperature 90 °C, suitable for environments at greater risk in the event of fire;
- Multipolar cables (three phases plus neutral) with sheath, suitable for laying on cable trays;
- Laying in layers on perforated cable trays (see attachment on types of laying);
- Reduced neutral section compared to that of the phase (when permitted).

Application example

Cross sections definition

The unitary voltage drop design method is chosen. During the verification, the corresponding values of ampacity I_z and percentage power loss $\Delta p\%$ will be determined, adjusting the sections in the event of a negative outcome.

The calculation formulas to be used are the following:

$$I_b = \frac{P}{\sqrt{3}V_n \cos\varphi} \qquad \Delta V = \frac{\Delta V\% * V_n}{100} \qquad u = \frac{1000 * \Delta V}{I_b * l}$$

Then, based on the values of u, the cross section of the phase conductors are determined from the unitary voltage tables (three-pole cables, three-phase alternating current, cosφ =0.8 which are the values closest to the actual ones).

The results obtained are reported in the table

Application example

Line	I_b (A)	ΔV (V)	u (mV/Am)	S (mm^2)	
				Phase	Neutral
Machine 1	127,4	12	1,884	25	16
Machine 2	67,9	12	2,209	16	16
Machine 3	152,8	12	1,963	25	16
Machine 4	101,9	12	1,963	25	16
Machine 5	84,9	12	3,141	16	16
Air compressor	64,8	12	2,646	16	16

Application example

Ampacity check

The I_z currents of the six lines are determined by choosing the values of I_0, K_1 and K_2 from the tables of the standards for the currents of cables in air. The results are shown in the table.

Line	I_b (A)	Ampacity of the phase conductors				$I_z > I_b$
		I_0 (A)	K_1	K_2	I_z (A)	
Machine 1	127,4	127	0,91	0,80	92,5	NO
Machine 2	67,9	100	0,91	0,80	72,8	SI
Machine 3	152,8	127	0,91	0,80	92,5	NO
Machine 4	101,9	127	0,91	0,80	72,8	NO
Machine 5	84,9	100	0,91	0,80	72,8	NO
Air compressor	64,8	100	0,91	0,80	72,8	SI

Application example

The results show that for four lines the ampacity is not sufficient, therefore the cross sections must be increased. It is decided to also increase the sections of the lines of Machine 2 and the Air compressor, to have a greater margin between the values of I_b and I_z. The actual values of the sections and the flow rates are shown in the table.

Line	I_b (A)	S (mm^2)		Ampacity of the phase conductors			
		Phase	Neutral	I_0 (A)	K_1	K_2	I_Z (A)
Machine 1	127,4	50	25	192	0,91	0,80	139,8
Machine 2	67,9	25	16	127	0,91	0,80	92,5
Machine 3	152,8	70	35	246	0,91	0,80	179,1
Machine 4	101,9	35	25	158	0,91	0,80	115,0
Machine 5	84,9	25	16	127	0,91	0,80	92,5
Air compressor	64,8	25	16	127	0,91	0,80	92,5

Application example

Check of the permissible power loss

The absolute and percentage power loss values are calculated using the formulas:

$$\Delta p = 3R_l I_b^2 = 3r_l l I_b^2 \quad \text{e} \quad \Delta p\% = \frac{100\Delta p}{P}$$

Where r_l is the line resistance per unity of length at 90°C, given by:

$$r_l = r_{l20°}\frac{234{,}5+90}{254{,}5} = 1{,}275 * r_{l20°}$$

The $r_{l20°}$ value can be calculated as:

$$r_{l20°} = {\rho_{20°}}/{S}$$

The calculation results are shown in the table.

Application example

Line	I_b (A)	P (kW)	$r_{l20°}$ (Ω/km)	r_l (Ω/km)	l (km)	Δp (W)	Δp%
Machine 1	127,4	75	0,379	0,483	0,050	1176	1,57%
Machine 2	67,9	40	0,710	0,905	0,080	1001	2,50%
Machine 3	152,8	90	0,262	0,334	0,040	936	1,04%
Machine 4	101,9	60	0,514	0,655	0,060	1224	2,04%
Machine 5	84,9	50	0,710	0,905	0,045	881	1,76%
Air compressor	64,8	35	0,710	0,905	0,070	798	2,28%

Having obtained Δp%<5% for all lines, the verification is positive. The actual values of the phase and neutral sections are therefore those reported in the table compiled during the ampacity verification.

The design of an electrical system

What does it mean *to design*?

Design:

Verb - decide upon the look and functioning of something by making a detailed drawing of it.

Noun - purpose, planning, or intention that exists or is thought to exist behind an action, fact, or material object

to plan something, i.e., to conceive it and study how it should be and how it has to be realized

An integral part of the design is the communication of the project implementation methods, i.e., the preparation of the so-called *project documentation*.

If the idea is not good, the result is bad.

If the idea is good but poorly expressed, the result is equally bad!

Regulatory framework

The electrical systems sector is subject to the requirements of numerous technical standards issued by national and international *regulatory bodies*.

The bodies produce standardization, unification and harmonization documents:

- *Standardization* – criteria for the design, construction and testing of electrical systems, machines, equipment and materials, designed to ensure their efficiency and safety of operation → drafting of technical standards (standardization activity)
- *Unification* – definition of the characteristics of materials, machines and equipment, to restrict them to a narrow range of construction types and dimensions; it is aimed at standardizing production, reducing costs, and promoting competition
- *Harmonization* – activity of standardization of standards at an international level, to increase the compatibility of products and their field of application

Regulatory framework

In this section reference is made to Italian regulatory framework, to provide one example of the many present around the world. Although with some differences, all states in the European Union have similar frameworks.

In Italy, the regulatory body responsible for the electrical systems sector is the CEI (Italian Electrotechnical Committee), which releases technical standards.

IT Law 186/1968 has given particular importance to the CEI, defining all machines, equipment, and systems built according to CEI standards as being executed in a *workmanlike manner* (*following the rule of the art*, in Italian "*a regola d'arte*").

Do something in a workmanlike manner: do it skillfully, adequately, and following community standards.

Community standards define the set of technical rules to be followed in order to ensure a minimum standard of acceptability of the product (including the result of an intellectual activity, such as a project) in terms of usability, duration, reliability, and safety.

The concept of workmanlike manner is important because it is abundantly reproduced in numerous articles of the Civil Code, and is frequently referred to in contracts → legal implications

Regulatory framework

IT Ministerial Decree no. 37/2008, art. 5, paragraph 3, establishes that:

> [electrical and other] *systems designs are drawn up according to the rules of the art. Designs drawn up in accordance with current legislation and the indications of the guides and standards of UNI, CEI or other standardization bodies belonging to the Member States of the European Union or which are contracting parties to the agreement on the European economic area, are considered to have been drawn up according to the rules of the art.*

At an international level, the standardization body that deals with electrical systems is the IEC (International Electrotechnical Commission). The national committees of approximately 70 countries (IT included) adhere to it.

The task of IEC is to issue recommendations and technical standards, from which those specific to each country derive. *Perfect correspondence between the IEC standards and those of the individual country is not mandatory*.

At the European level, **CENELEC** (Comité Européen de Normaisation Electrotechnique) operates, with the task of preparing harmonized standards at the European level that must be accepted by all members (harmonization). *CENELEC standards must be translated and adopted in their entirety as national standards, while all national standards that conflict with them must be eliminated*.

Regulatory framework

The verification of compliance with the standards can concern individual components or the entire system.

As regards the components, in Italy the declaration of conformity is used, through marks affixed to the equipment or certificates issued by specific bodies:

- CEI mark
  self-certification applied by the manufacturer which ensures compliance with the CEI standards

- IMQ mark
  certification by the Italian Institute of the Quality Mark, which approves the prototype and periodically checks production

- Other marks, depending on the specific application
  for example, the European Ex mark for components certified for places with explosion hazard

Regulatory framework

The European Community mark (CE marking) for low voltage electrical components deserves a separate mention.

It has been mandatory in Italy since 1997, and concerns components included in the scope of application of Law no. 791/1977 (which implements CEE Directive 73/23).

It applies to components intended for systems with nominal voltages between 50 and 1000 V in alternating current, and 75 and 1500 V in direct current.

The purpose of the CE mark is: to certify the conformity of the component to the harmonized European standards relevant *for safety purposes*.

Regulatory framework

The use of certified and standard-compliant components in an electrical system does not ensure compliance with the regulations of the entire system!

Example:
Using breakers that comply with standards is useless if they are sized, calibrated or installed incorrectly.

Problems:

- In Italy there is no single public body responsible for controlling the entire electrical system during the design, installation, testing at the end of the works, and for carrying out periodic checks;
- the testing certificate is required only for some types of installation.

Law no. 46/1990 (later replaced by Ministerial Decree no. 37/2008) introduces legal responsibilities for the client of the system, for the designer, and for the installer

Regulatory framework

For systems in workplaces with employees, checks are mainly carried out by inspectors of the Local Health Authority, who draw up reports noting the irregularities found and imposing fines or reporting the owner of the system to the judicial authority if necessary.

There are other specific control bodies, relating to particular categories of electrical installations.

For example, electrical systems in public entertainment venues must be checked by a special Provincial Supervisory Commission in order to obtain the issuing or renewal of the operating license.

The Fire Brigade also has control duties for systems installed in the activities subject to their supervision.

Regulatory framework

Main IT laws that apply to the electricity sector:

- Law no. 186/1968 *Provisions concerning the production of materials, equipment, machinery, installations and electrical and electronic systems* (later repealed and replaced by Ministerial Decree no. 37/2008) Attributes the value of workmanlike workmanship to systems built according to CEI standards, but does not exclude the possibility of building systems following other criteria.

- Law no. 791/1977 *Implementation of the European Community Council Directive no. 73/23/EEC relating to the safety guarantees that electrical material intended for use within certain voltage limits must possess.* It establishes that electrical material falling within its scope of application (50-1000Vac; 75-1500Vdc) can be placed on the market only if it is built according to the rules of the art and therefore does not compromise the safety of people, pets and property when installed and maintained correctly in a system (CE marking on the equipment)

Regulatory framework

- *Law no. 46/1990 Regulations for plant safety*
- *Presidential Decree no. 447/1991 Regulation implementing Law no. 46 of 5 March 1990 on plant safety*

  Both later replaced by Ministerial Decree 37/2008, introduced a series of significant obligations, analyzed below.

- *Law no. 36/2001 Framework law on protection from exposure to electric, magnetic and electromagnetic fields*
- *Presidential Decree no. 46/2001 Regulation simplifying the procedure for reporting installations and devices for protection against atmospheric discharges, earthing devices for electrical systems and dangerous electrical systems*

Regulatory framework

- Ministerial Decree no. 37/2008 *Regulation concerning the implementation of Article 11-quaterdecies, paragraph 13, letter a) of Law no. 248 of 2 December 2005, containing the reorganization of the provisions regarding the installation of systems inside buildings.*
  It regulates the sector of the design of systems located inside buildings or their appurtenances and which are placed at the service of the buildings themselves, starting from the point of delivery of the supply. It applies to a series of technological systems, electrical ones included.
  It requires the drafting of a project for:
  - New installation;
  - Transformation;
  - Extension.

  The project is not mandatory for ordinary maintenance, installation of household appliances, and for the temporary supply of electricity to construction site systems and similar.

Regulatory framework

- Ministerial Decree no. 37/2008 ...

  Entails the obligation for a project to be carried out by *a professional registered in the professional registers* in the following cases:

  - delivery from a public distributor at a voltage > 1000 V;
  - in LV over 200 m² of surface area for systems in the commercial and industrial sectors;
  - in LV over 400 m² of surface area for domestic systems;
  - in LV with contract power over 6 kW;
  - in all cases of application of a specific standard (e.g., medical premises, or locations for which there is a risk of explosion or increased risk in the event of fire).

  In other cases, the project can be drawn up by the technical manager of the installation company.

Regulatory framework

- Ministerial Decree no. 37/2008 ...

  Recalls the obligations previously defined in Law no. 46/1990 and in Presidential Decree no. 447/1991, as it repeals and replaces them:

  - Performance of installation, transformation, expansion and extraordinary maintenance works by *authorized companies in possession of certain technical-professional requirements* (defined in the decree);
  - Construction of systems *in a workmanlike manner*, in compliance with current legislation, and attribution of responsibility for correct execution;
  - Attribution of work *in a workmanlike manner* to those carried out in compliance with CEI standards or other standardization bodies belonging to EU member states and similar;
  - Issuance of the *declaration of conformity* to the client at the end of the works;
  - Checks and tests to be carried out at the end of the works;
  - Other obligations and specific indications for systems built before 13 March 1990 (entry into force of Law 46/1990).

Regulatory framework

- Ministerial Decree no. 37/2008 ...

  Indicates the *minimum consistency of the project documentation* (art. 5, paragraph 4):

  - Plant diagrams;
  - Plan drawings;
  - Technical report on the consistency and type of installation, transformation or expansion of the plant itself, with particular attention to the type and characteristics of the materials and components to be used and the safety measures to be adopted.

- Paragraph 4 of art. 5 imposes design according to the rules of the art and refers indirectly only to the CEI 0-2 guide on the drafting of the project and not to the other CEI guides (which are instead guides for the correct application of the standards). Therefore, the CEI 0-2 guide “Guide for the definition of the project documentation of electrical systems” is the only guide with legal value.

Regulatory framework

- Legislative Decree no. 81/2008 Implementation of Article 1 of Law no. 123 of 3 August 2007 on the protection of health and safety in the workplace

  The scope of Legislative Decree 81 is broad, as it includes all sectors of activity, private and public, and all types of risk. It affects all workers, both employed and self-employed, as well as those treated as such (for example: university students) by virtue of the use of laboratories, work equipment, chemical, physical and biological agents, including the use of video terminals.

  It requires designers, manufacturers and suppliers of equipment and installers to comply with workplace safety and hygiene regulations.

  It requires measures to be taken to safeguard health and safety:

  - Risk assessment;
  - Risk elimination;
  - Prevention planning.

  The documentation must be kept and updated by the employer.

The project

An electrical system can be considered safe when:

- it has been designed in compliance with the rules of the art;
- it has been installed correctly;
- components compliant with the relevant technical standards are used;
- it is adequately maintained;
- it is used within the established performance limits.

The client is generally lacking in knowledge relating to the regulatory and safety issues of the systems!

The project can therefore be considered the fundamental means both to achieve the quality and safety of the electrical system, and to meet the client's expectations.

What is the project?

- ➢ The project is **the moment of conception of the system**, which obviously precedes the construction of the system itself;
- ➢ The project is **the set of studies and activities that**, on the basis of the performance required in the assigned environmental and operating conditions, **provide the necessary and sufficient information for the execution of the system in accordance with the rules of the art**.

In the project:

- the project data are indicated (preliminary information on which it is based);
- the electrical diagram is defined, the main qualitative and dimensional characteristics of the components are indicated;
- the requirements and methods of installation and any methods of operation and maintenance are defined.

Fundamental design criteria

- These are the criteria on the basis of which choices are made in the design.
- They are divided into two classes:

Objective: The choice is determined by the need to comply with the reference specifications established by the client, by current legislation, or by other binding requirements.

Subjective: The design choice is at the discretion of the designer and can be made by evaluating different technical, economic and safety alternatives. The result is a system that has some specific characteristics dictated by the choices made.

Example of a choice according to an objective criterion: calibration of switches in a TN system.

Example of a choice according to a subjective criterion: topology of the system (radial, ring, etc.)

Characteristics of a system and subjective design choices

- The set of design choices determined by subjective criteria contribute to determining the performance of an electrical system.
- In particular, the choices impact on different characteristics of the system:
  - Safety;
  - Reliability;
  - Flexibility;
  - Ease of operation;
  - Costs.

- **The characteristics are not independent of each other!**
- The weight to be attributed to the single characteristic depends on the needs of the client and the performance that the designer wants to obtain from the system.

Drafting the project

For the correct drafting of the project, reference must be made to the CEI 0-2 guide "Guide for the definition of the project documentation of electrical systems"

The main figures involved in the preparation and use of the project documentation are:

- The client (customer);
- The installer;
- The suppliers of the components, who receive the technical specifications for the purchase;
- The works manager;
- The tester (where applicable);
- The control and verification bodies;
- The users and operators of the system;
- The maintenance workers.

Types of documents

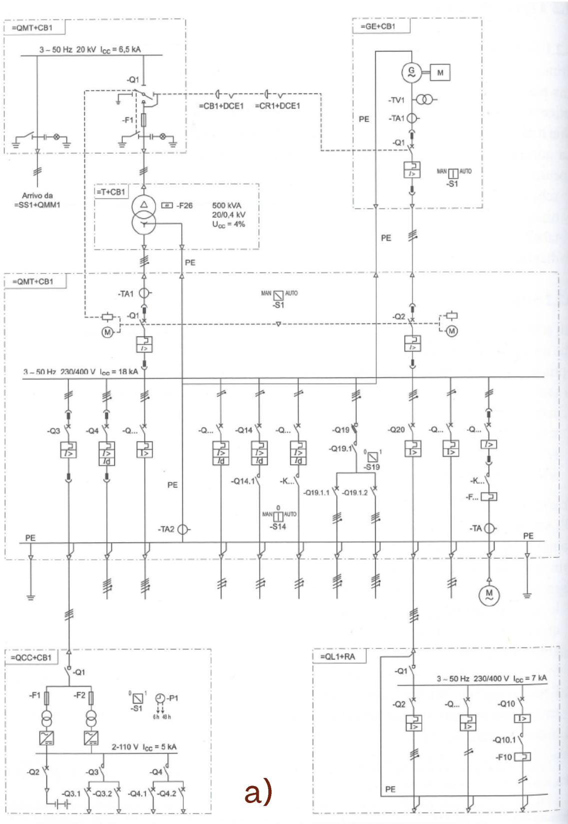
- The type of documents used in electrical engineering is defined in the EN 61082-1 (CEI 3-36) standard:
  - Schemes (or diagrams);
  - Drawings;
  - Tables;
  - Diagrams and graphs.

- Attention: the CEI 3-36 standard does not cover all the types of documents used in the electrical project!
- For example, in the electrical project there are descriptions (texts), such as the explanatory report and technical report, not mentioned in the standard.

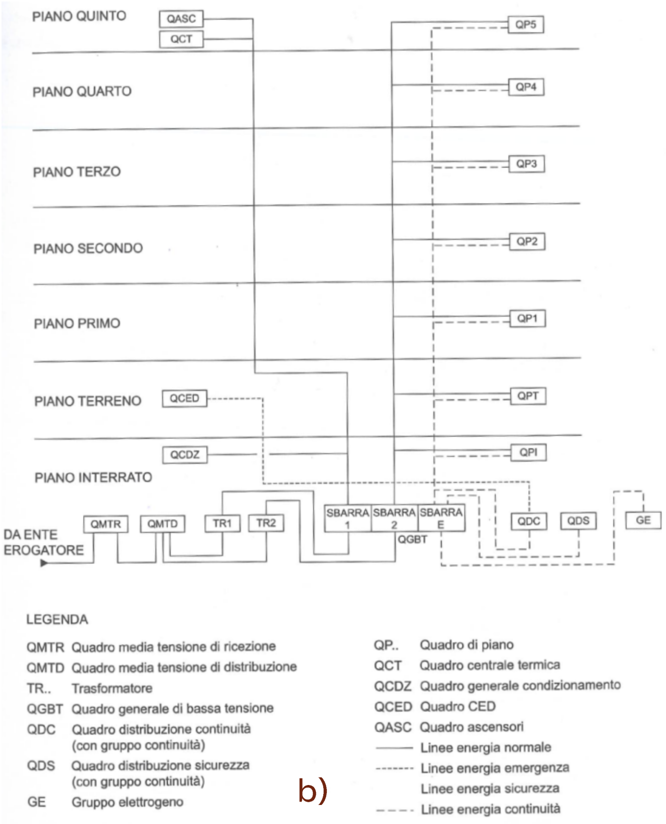
Schemes (or diagrams)

- Diagrams are graphic documents that indicate the electrical components and the relationships between them.
- The main diagrams used in the design documentation of electrical systems are:
    - *General diagrams*
      They provide a complete view of the system by indicating in low detail the main relationships between the components, even non-electrical ones
    - *Functional diagrams*
      They show in principle the details on the operation of a system by means of theoretical circuits, without taking into account the position of the components
    - *Circuit diagrams*
      They report (usually in multi-wire representation) the executive details of the circuits of a system, providing details on the interaction between the components and their connections
    - *Wiring diagrams*
      They provide the information to identify the terminals and conductors used to make the connection between systems, systems, or equipment

General schemes, examples



a)



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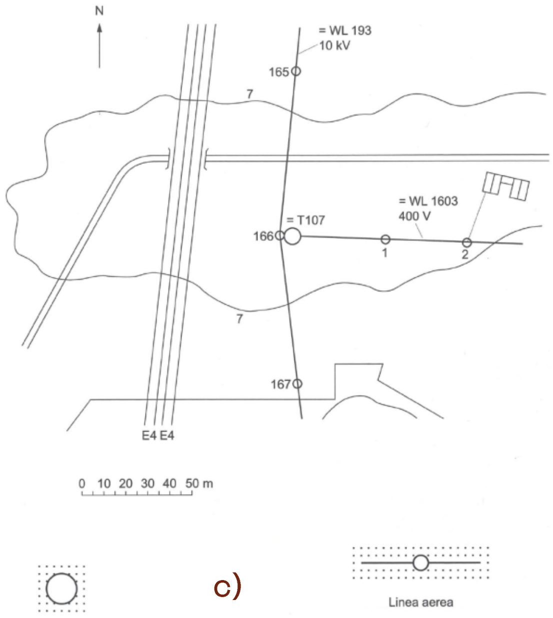
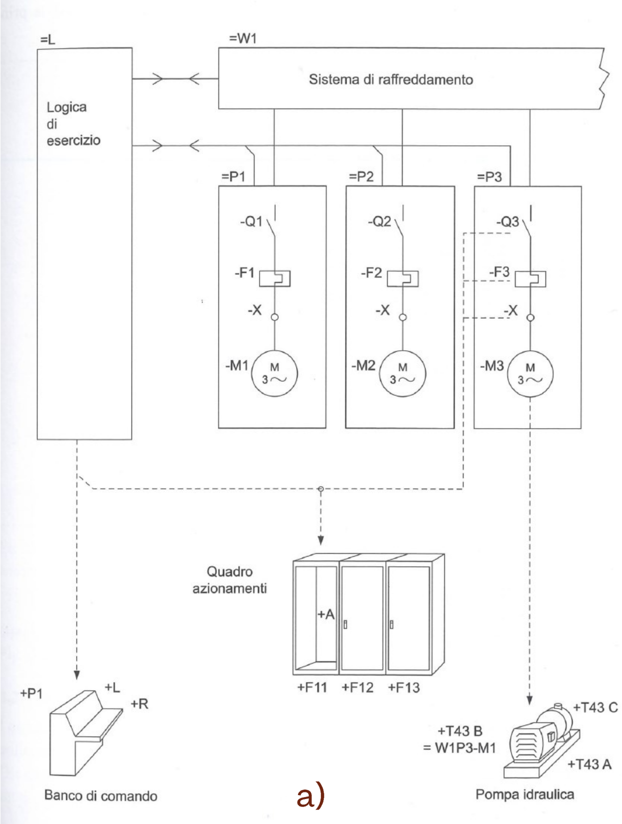


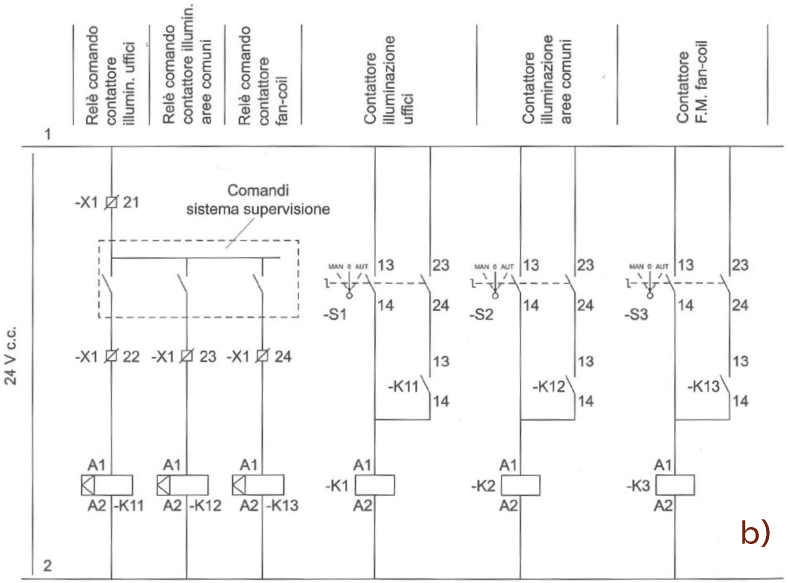
c)

a) MT/BT system diagram
b) Block diagram
c) LV distribution network map

Functional diagrams and circuit diagrams, examples



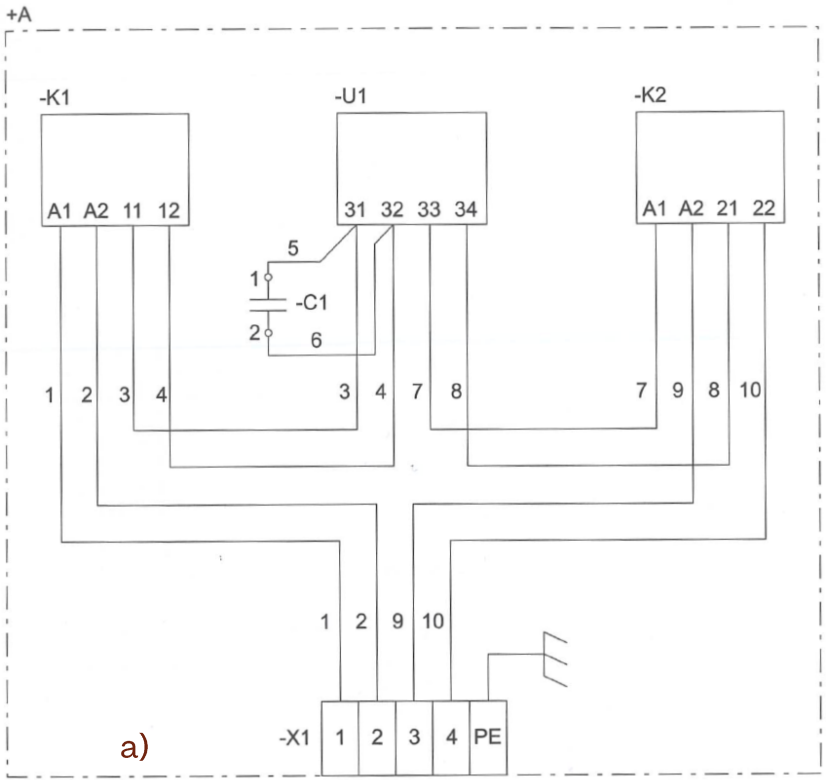
a)

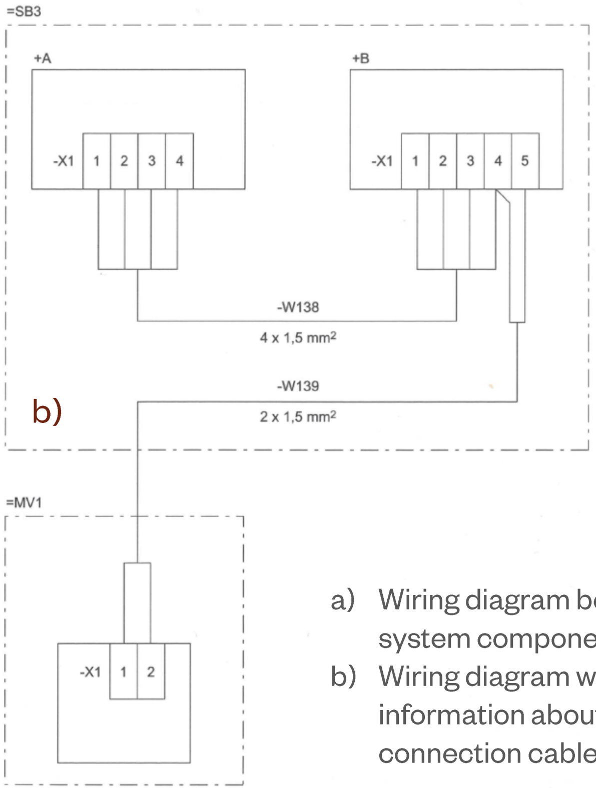


b)

a) Functional diagram of a pumping system
b) Circuit diagram of the 24V DC part of a LV panel

Wiring diagrams, examples





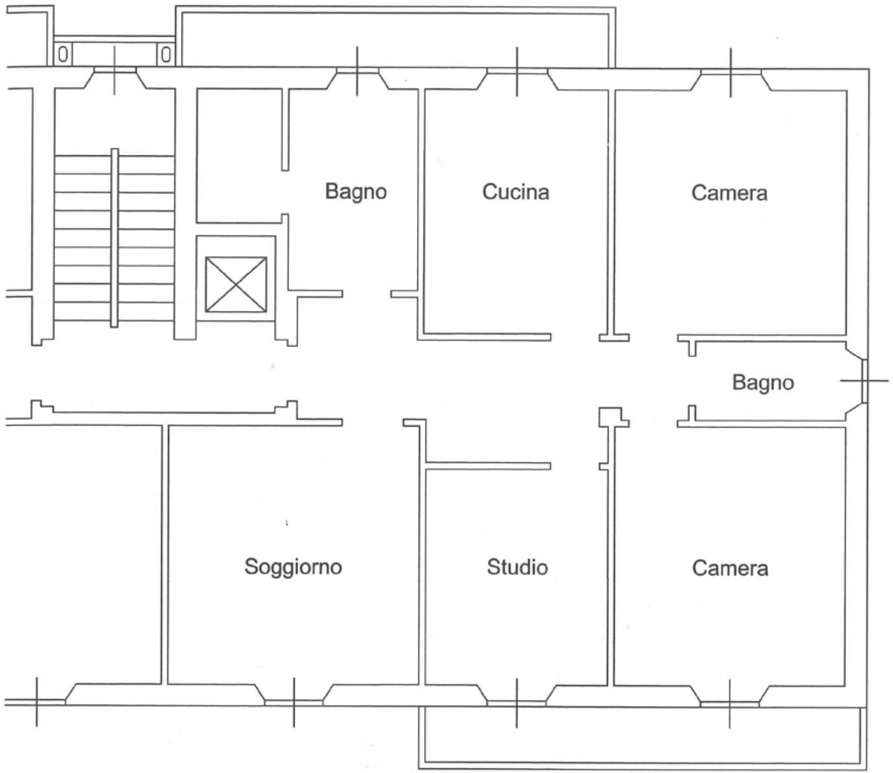
a) Wiring diagram between system components

b) Wiring diagram with information about connection cables

Drawings

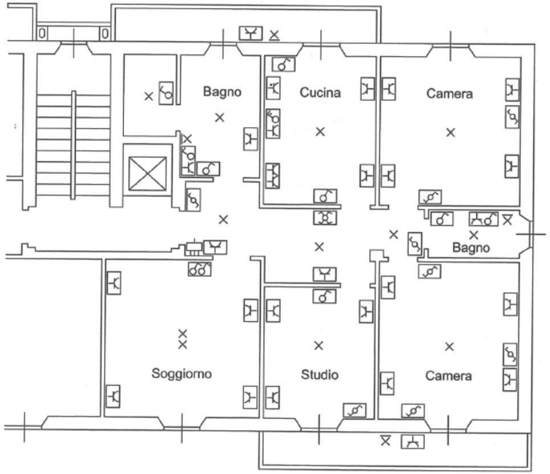
- Drawings are documents that indicate the topographical or geometric position in which the electrical system and its components are located.
- They are distinguished as:
  - *Basic documents (plans)*
    Planimetries of sites, lands, buildings, etc., generally drawn up in a non-electrical context
  - *Layout (or arrangement) drawings*
    Based on the basic documents, they show the position of the components, represented with graphic symbols or simplified shapes, corresponding to the arrangement on site. They may show the connections between the components, or they may not show them. They must show the methods of laying the components.

Basic documents (plans), example



Basic drawing of an apartment (floor plan)

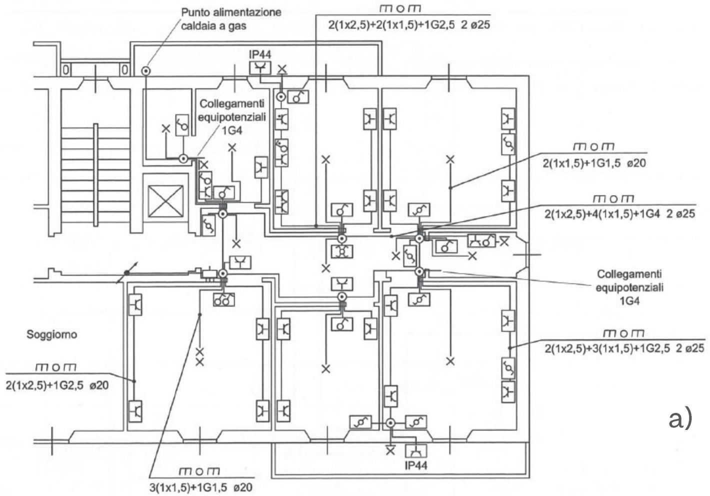
Layout (or arrangement) drawings, examples



a)

LEGENDA

- Centralino di appartamento
- Scatola portafrutti
- Punto luce a soffitto
- Punto luce a parete
- Interruttore unipolare
- Interruttore unipolare per comando presa
- Deviatore
- Invertitore
- Presa bipasso 10/16 A + T
- Presa bipasso 10/16 A + T comandata



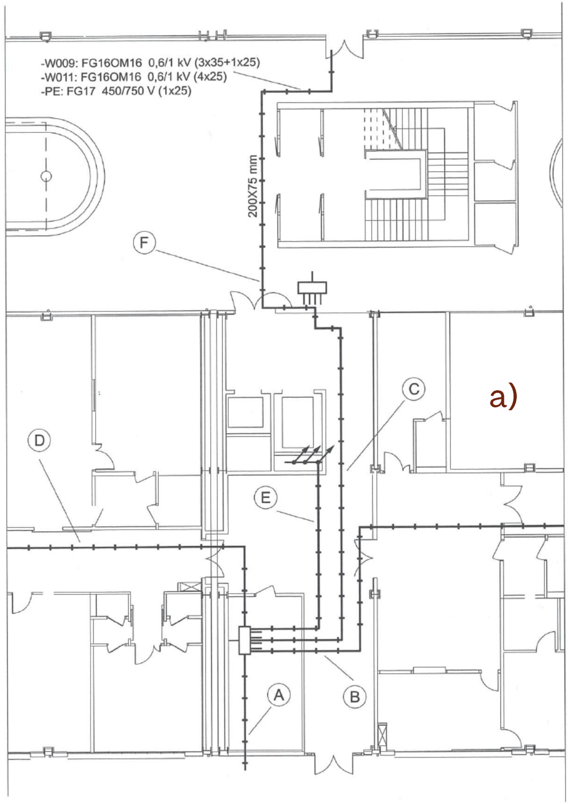
b)

LEGENDA

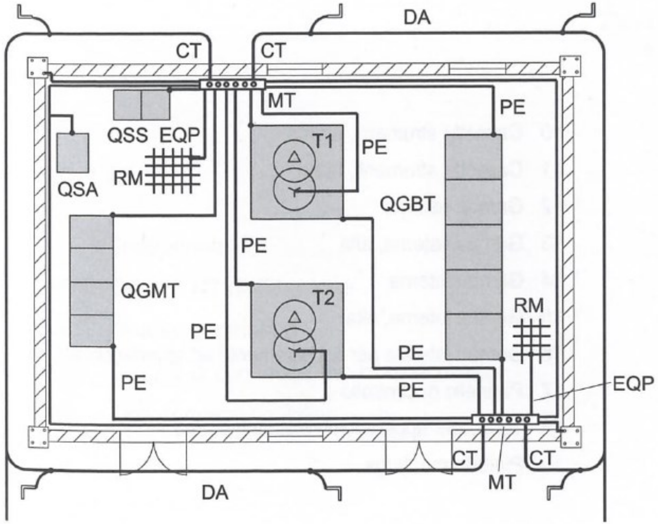
- Centralino di appartamento
- Scatola portafrutti
- Punto luce a soffitto
- Punto luce a parete
- Interruttore unipolare
- Cassetta di derivazione
- Interruttore unipolare per comando presa
- Deviatore
- Invertitore
- Presa bipasso 10/16 A + T
- Presa bipasso 10/16 A + T comandata
- Tubo in PVC incassato

a) Layout of the system components of an apartment
b) Layout of the system components of an apartment with connections

Layout (or arrangement) drawings, examples



a)



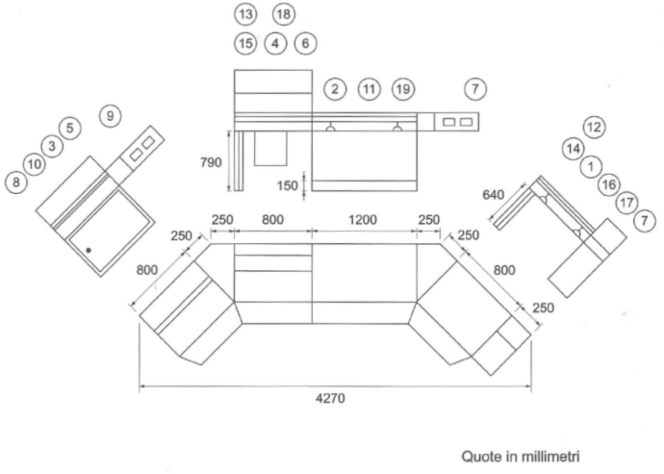
LEGENDA

QGMT: Quadro generale MT
QGBT: Quadro generale BT
QSA: Quadro servizi ausiliari
QSS: Quadro servizi sicurezza
T1 e T2: Trasformatori entro box di protezione
MT: Collettore di terra
RM: Rete metallica elettrosaldata sotto pavimento
∟ : Dispersore verticale in acciaio ramato h = 2 m
DA: Dispersore orizzontale in corda di rame interrata (profondità h= 0,7 m) sez. 25 mm^2

b)

a) Cable path of a hospital department
b) Arrangement of the earthing system of a MV/LV cabin

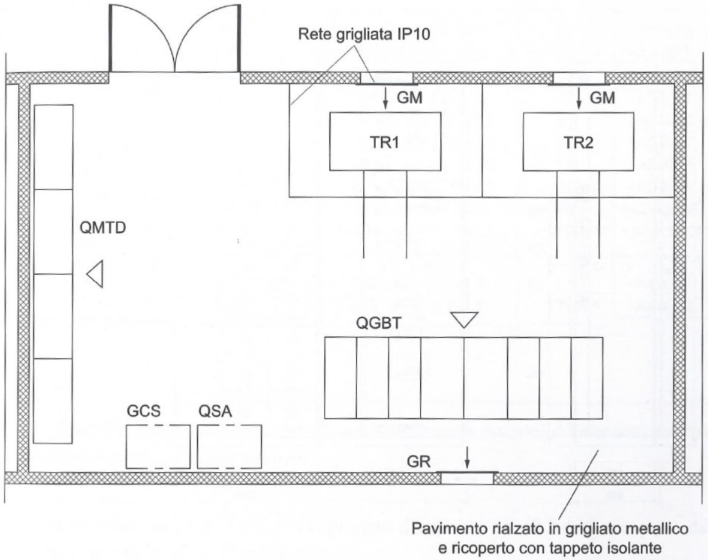
Layout (or arrangement) drawings, examples



a)

LEGENDA

1 Piano di controllo, stretto
2 Piano di controllo, largo
3 Piano di comando, basso, stretto
4 Piano di comando, alto, stretto
5 Pannello di comando, basso, stretto
6 Pannello di comando, alto, stretto
7 Spalla di chiusura destra
8 Spalla di chiusura sinistra
9 Angolo
10 Cassetta strumenti, stretta
11 Cassetta strumenti, larga
12 Gamba esterna
13 Gamba esterna, alta
14 Gamba interna
15 Gamba interna, alta
16 Gamba laterale per accostamento ad apparecchiatura
17 Pannello di controllo
18 Telaio per apparecchio elettrico, stretto
19 Piattaforma, larga



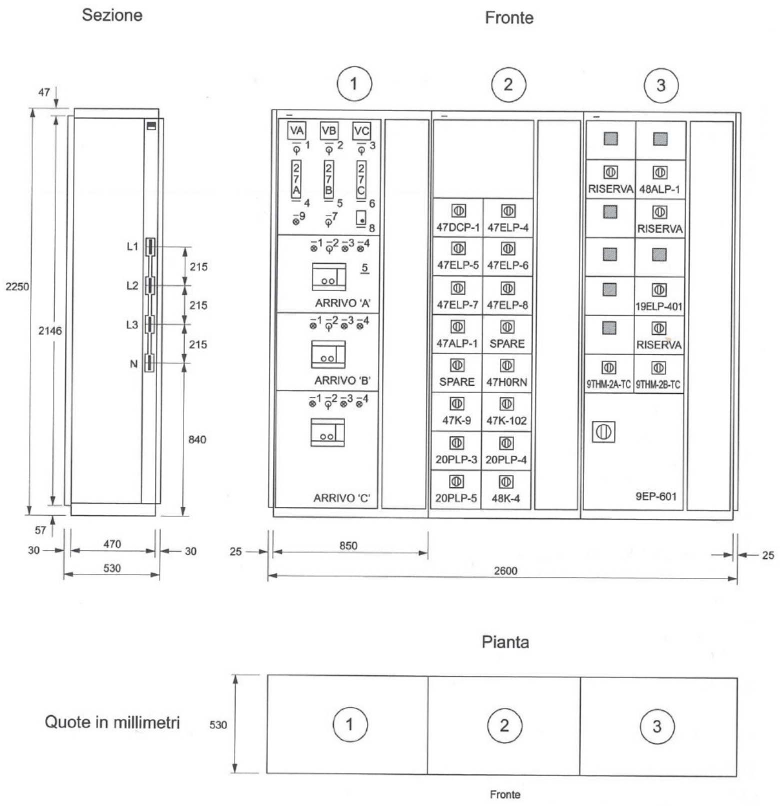
b)

LEGENDA

TR... Trasformatore
QMTD Quadro MT distribuzione
QGBT Quadro generale BT
GCS Gruppo di continuità servizi di sicurezza
QSA Quadro servizi ausiliari

a) Assembly drawing of a machine
b) Arrangement of panels and other equipment in an electrical cabin

Layout (or arrangement) drawings, examples



Arrangement of components inside a LV panel

Tables

- Used to replace or clarify diagrams.
- Connection tables are generally used in electrical system design.

Morsettiera	Morsetto	Cavo	Tipo/sezione	Conduttore	Unità remota
-X1	:1	-W01	FG16OR16 0,6/1kV 5G4	L1	+A2-X2:4
	:2	-W01	FG16OR16 0,6/1kV 5G4	L2	+A2-X2:5
	:3	-W01	FG16OR16 0,6/1kV 5G4	L3	+A2-X2:6
	:4	-W01	FG16OR16 0,6/1kV 5G4	N	+A2-X2:7
	:5	-W02	FG16OR16 0,6/1kV 5G2,5	L1	+A5-X1:1
	:6	-W02	FG16OR16 0,6/1kV 5G2,5	L2	+A5-X1:2
	:7	-W02	FG16OR16 0,6/1kV 5G2,5	L3	+A5-X1:3
	:8	-W02	FG16OR16 0,6/1kV 5G2,5	N	+A5-X1:4
	:PE	-PE	FG16OR16 0,6/1kV 5G4	PE	+A2-X2:PE
	:PE	-PE	FG16OR16 0,6/1kV 5G2,5	PE	+A5-X1:PE
-X2	:1	-W03	FG17 450/750 V 2(1x1,5)	L1	+A4-X1:1
	:2	-W03	FG17 450/750 V 2(1x1,5)	N	+A4-X1:2

Table sorted by terminals, with the characteristics of the connection cables reported

Diagrams and graphs

- They provide additional information useful for understanding the functional behavior of a component, equipment, or system.
- In electrical projects, the following are typically used:
  - *Functional diagrams*
    Describe the behavior of a system by means of operational phases
  - *Time sequence diagrams*
    Describe the succession of operational phases over time.

Additional documents

- In the design of electrical systems, other types of documents not covered by the CEI 3-36 standard are also used:
  - ➢ *Lists of electrical material*
    List of material and List of spare parts
  - ➢ *Specific documents for installation*
    They provide instructions for the supply, transport, installation, power supply and testing of components, equipment, machines, etc.
  - ➢ *Specific documents for commissioning*
    They provide instructions for the calibration, simulation mode, recommended temperature values and actions to be carried out for the commissioning of components, equipment, machines, etc.
  - ➢ *Specific documents for operation and operation*
    They provide instructions relating to the operation and operation of components, equipment, machines, etc.
  - ➢ *Specific documents for maintenance*
    They provide instructions relating to the maintenance procedures of components, equipment, machines, etc.
  - ➢ *Other documents*
    Technical reports, manuals, guides, catalogues, lists of documents, etc.

Design levels

Legislative Decree 36/2023 (new public procurement code) contains an important innovation regarding the design levels: it goes from 3 (preliminary, definitive and executive design) to the following 2 (the definitive project disappears):

- *technical-economic feasibility project*;
- *executive project*

The division of the project into levels is mandatory only in the case of public works contracts, while in other cases (service contracts and projects for private individuals) the use of only one level is permitted.

NB: in large works, the subdivision into multiple levels allows for the provision of all the information necessary for the progress of the works with the least expenditure of energy and costs. Thus, the public procurement code goes so far as to also define the contents of the design levels and the specific documentation to be presented.

The technical-economic feasibility project

a) identifies, among several possible solutions, the one that expresses the best relationship between costs and benefits for the community in relation to the specific needs to be satisfied and the services to be provided;

b) contains the necessary references to the possible use of digital information management methods and tools for construction (ref. BIM);

c) develops, in compliance with the framework of needs, all the investigations and studies necessary for the definition of the aspects referred to in the paragraph;

d) identifies the dimensional, typological, functional and technological characteristics of the works to be carried out, including the choice regarding the possible subdivision into functional lots;

e) allows, where necessary, the initiation of the expropriation procedure;

f) contains all the elements necessary for the issuing of the required authorizations and approvals;

g) contains the preliminary maintenance plan for the work and its parts.

The technical-economic feasibility project

Generally, it includes the following descriptive and graphic documents:

- a descriptive report of the system
- a detailed technical report
- a series of graphic documents (electrical diagrams, installation drawings, plans, sections, etc.),
- a report on the preliminary calculations for sizing the system,
- the descriptive and performance specifications of the technical elements
- when required, the metric calculation, the metric-estimative calculation and the economic framework

The executive project

a) develops a level of definition of the elements such as to fully identify their function, requirements, quality and list price;

b) is accompanied by the maintenance plan of the work for the entire life cycle and determines in detail the works to be carried out, their cost and their completion times;

c) if digital information management methods and tools for construction are used, develops a level of definition of the objects that meets the specifications in the information specifications accompanying the project;

d) as a rule, it is drawn up by the same person who prepared the technical-economic feasibility project. In the event that justified reasons justify separate assignment, the new designer accepts the design activity carried out previously without reservations.

The executive project

Drawn up on the basis of the technical-economic feasibility project, and integrated with any requirements that emerge during the issuing of the various administrative, building, etc. authorizations.

Generally, it includes the following descriptive and graphic documents:

- a general report describing the criteria used for the design choices,
- a specialist report on the consistency and typology of the electrical system,
- the scheme (description) of the system,
- the graphic documents (electrical, system and installation diagrams, planimetric drawings, construction details, etc.) that completely define the work to be carried out,
- a report on the executive calculations for the sizing of the system,
- the tables and diagrams for the coordination of the protections,
- the metric calculation, the metric-estimative calculation, the economic framework, the special tender specifications.

Variants during the work in progress

- The executive project may undergo changes during the works.
- All variations must be reported in the *final project documentation*.

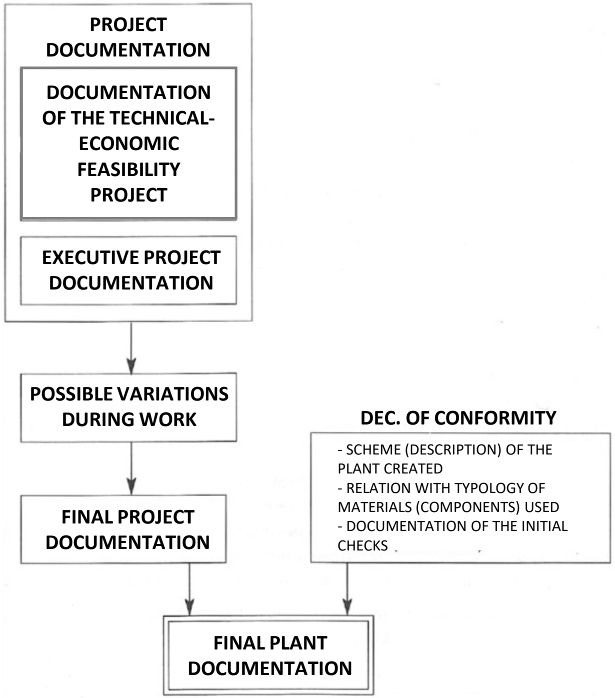
- Variations can be:
  - *Significant*, when they affect safety or quality aspects of the system, or when they involve a change in the methods of use of the electrical components to the point of requiring a verification of their performance and characteristics;
  - *non-significant*, in other cases.

- Significant variations must be authorized by the designer; they cannot be carried out only by decision of the client, the installer, and/or the works manager.
- The documents of the executive project that are the subject of the variations can only be modified by the designer who carried them out. If the variations are approved by another professional, they must be reported in an additional document, in order to unequivocally clarify the limits of liability.

Variants during the work in progress

- Non-significant variations can be made by the installer; they must also be reported in supplementary documents in order to clarify the limits of responsibility of the designer and installer.
- Examples of significant variations:
  - Change of one or more design data;
  - Modification of the geometry of the earthing system;
  - Reduction of the degree of protection of electrical components;
  - Variation in the nominal power of a user appliance;
  - Addition of circuits;
  - Replacement of protection devices.
- Examples of non-significant variations:
  - Moving a control device if it does not alter its function and does not involve its location in an unsuitable position;
  - Addition of a socket or a light point on a circuit;
  - Changing the route of a conduit, if it does not involve a change in the length or type of installation of the conduit itself (otherwise it involves checking the sizing of the cable → significant variation).

Project and plant documentation



The *project documentation* is the set of documents that constitute the system project and refers to the project level considered.

If *variations* are made during the work, the executive project documents, updated with those of the variations, constitute the *final project documentation*.

The *final plant documentation* is the set of the final project documentation, the declaration of conformity issued by the installer with the related mandatory attachments, and the documentation provided by the manufacturers of the electrical components (concerning the instructions for installation, commissioning, operation, verification and maintenance).

Design software

Design software

The following slides show some examples of software for the following areas:

- Electrical system design
- BIM (Building Information Modeling)

As for BIM, some basic explanations will also be provided on what it is.

The presentation does not claim to be complete and is not motivated by any commercial promotion purpose of the software listed below.

Electrical System Design Software

ACCA Software – Impiantus-ELETTRICO (https://www.acca.it/software-progettazione-impianti-elettrici)

Software in Italian for the design and verification of low voltage civil and industrial electrical systems with TT and TN-S distribution system according to CEI 64-8 and CEI 11-25 standards:

- Plan drawing
- Calculation and dimensioning
- Design of electrical panels and earthing system
- Drawing of single-line diagrams
- Lighting calculation
- Drafting of documents, technical reports and metric calculation

Possibility of free trial for 30 days

Electrical System Design Software

GEWISS – various software (https://www.gewiss.com/ww/en/services/software)

Gewiss provides several software suites dedicated to electrical engineers, with software modules dedicated to different applications. Some of them are listed:

- *PBT-Q Design*, dimensioning and estimating of Low Voltage systems and panels
- *CADpro* CAD for the advanced design of floor plans and electrical systems
- …

It also provides plug-ins for the most famous lighting design and calculation software, as well as specific applications for home automation.

Electrical System Design Software

Electro graphics – software vari (https://www.electrographics.it/en/solutions-electrical-systems.php)

Electro graphics produces software for electrical design of various kinds, from electrical CAD to network calculation or estimation applications:

- *CADelet* Drawing and engineering electrical system in AutoCAD
- *Ampere* software for calculating LV and MV electrical networks, in alternating and direct current, according to CEI 64-8, 11-17, 11-25, 17-1 and international standards IEC 60364, 60909, 62271-100, NF C 15-100 (French), UNE 20460 (Spanish), BS 7671 (English), NBR 5410 (Brazilian), NFPA 70: NEC (American)
- …

For its products it also provides plugins for integration with Autodesk - Revit MEP (BIM software)

Electrical System Design Software

ABB – e-Design (https://new.abb.com/low-voltage/support/software/e-design/overview)

Technical software suite for professionals in the electrical sector. Composed of 4 modules dedicated to:

- Electrical sizing
- Configuration and engineering of panels
- Economic estimate
- Selection and configuration of products and accessories

Electrical System Design Software

AUTODESK – AutoCAD Electrical (https://www.autodesk.com/eu/products/autocad/included-toolsets/autocad-electrical)

Electrical CAD with strong integration towards BIM AUTODESK Revit.

Symbolic library included, with support for all the most widespread international standards.

Large availability of plugins produced by other software houses.

Possibility of free trial for 30 days

Electrical System Design Software

HEXAGON – Intergraph Smart Electrical (https://hexagonppm.com/offerings/products/intergraph-smart-electrical)

Software strongly focused on integration with the BIM software Intergraph Smart 3D solution.

Aimed at designing electrical distribution systems for both industrial and maritime land applications, with a comprehensive approach (from load identification to system commissioning)

Electrical System Design Software

Schneider Electric – various software (https://www.se.com/it/it/work/support/technical-software/)

Software package in Italian for design, quotation and drafting of technical and economic documents (also available in English, searching on the international site):

- *i-project 6.1* integrated design for Medium Voltage, Low Voltage, Building Automation, Mechanical Regulation, Emergency Lighting, Continuity Systems and more
- *eXteem 6* technical and economic quotation of the Schneider Electric offer
- *Schneider Electric CAD Library* Schneider Electric Medium and Low Voltage component library for AutoCAD environment

The i-project 6.1 software is free upon registration as an end user / training institute

Electrical System Design Software

ETAP (https://etap.com/)

Software for the analysis, calculation, simulation and design of electrical systems.

Performs calculations in compliance with various technical standards, so the results can be used in the sizing and design of electrical systems.

Various software and suites are available.

ProfiCAD (https://www.proficad.com/)

ProfiCAD is designed for drawing electrical and electronic diagrams, schematics, and control circuit diagrams.

Its free for non commercial use, with some significant limitations: only 3 pages, no bill of materials, no list of cables, no reference grid, etc.

QElectroTech (https://qelectrotech.org/)

Building Information Modeling

Building Information Modeling (BIM) is a method for optimizing the planning, construction and management processes of buildings, based on the use of software, which takes advantage of the modern calculation capabilities of computers.

It is a "building information container" (something like a database) that collects, combines and connects all the relevant data of a building. The data can be graphical (drawings, plans, diagrams, etc.), but also parameters relating to the various components and systems (for example the thickness of a reinforcing bar, the power of a user, the thermal resistance of an insulating wall, etc.). The container can be filled with objects created from scratch, or with pre-existing models that are then combined to create the specific construction.

The virtual construction can be viewed as a three-dimensional geometric model, which contains all the components of interest and can provide the data.

While CAD design allows the development of a project through 2D or 3D drawings, BIM design is not limited to visual information or rendering but specifies the functionality and performance of each BIM object present in the project or of the entire building being developed.

Building Information Modeling

A fairly complete version of the definition of BIM is the following: "*use of shared digital representation of a built object (including buildings, bridges, roads, process plants, etc.) to facilitate design, construction and operation processes to form a reliable basis for decisions*".

BIM was born from the desire to ensure greater collaboration between designers, software interoperability, process integration and sustainability. The ability to access at any time the most up-to-date and complete information possible regarding what is being designed allows the entire design process to be speeded up and made more efficient. At the same time, it ensures that this information is not lost in communication to other studios and in the conversion to other software platforms. Furthermore, the 3D model can be used to evaluate, and if necessary, show the client the results of the design choices in advance, thus allowing an informed choice between various design solutions.

Finally, BIM also becomes useful in the post-construction phase, as it allows for better evaluation of maintenance needs, and to implement improvements to the project in the future in a much simpler way.

Building Information Modeling

The BIM method is becoming increasingly widespread in the world, even if it requires greater investment and work in the initial phase of the project (in which all the information is entered), as it subsequently greatly simplifies the work, if you want to obtain energy certification, structural calculations, etc. from the three-dimensional model.

There are many commercial software aimed at providing the container to be used for BIM-type design. This has raised the problem of standardizing the saving and output formats of these programs.

As for the individual BIM object objects, these are generally saved in the IFC (Industry Foundation Class) format, with the *.ifc* extension. These IFC files are classified as 3D image files, which also contain other technical information, and are compatible with all software that uses BIM technology.

The IFC file format has been only recently standardized (ISO 16739-1:2024).

Building Information Modeling

BIM will become the standard process for all buildings and is being integrated into public procurement legislation across Europe. In fact, Directive 2014/24/EU on Public Procurement clearly expresses the indication to introduce Building Information Modeling into the Procurement procedures of Member States. The adoption of the directive requires the 28 member states to encourage the use of BIM in their respective countries for projects financed with public funds in the European Union starting from 2016. It is important to underline that the text of the directive does not explicitly refer to the use of a particular software, but rather to the creation of methodologies for managing and verifying the data that make up the entire building process.

The adoption of BIM is a gradual path, in which we move from a process divided into phases to a process in which all the subjects involved in the construction of the model work in sync, collaborating on the same virtualization of the construction through the same data container.

Building Information Modeling

The BIM maturity level defines the position reached on a scale that goes from traditional design to complete BIM:

- *Level 0 - Standardized CAD*: requires the organization of traditional work around a system of standards.
- *Level 1 - Lonely BIM or non-collaborative BIM*: the BIM method is used within the single design process, but there is no collaboration with other professionals. The work follows standards, internal or international, especially with regard to the naming of the elements.
- *Level 2 - Collaborative BIM*: all the subjects involved in the design work in BIM, collaborating on the final result. Each subject works separately on their own model, and there is a subject whose task is to bring together the various models produced by each subject into a single overall model.
- *Level 3 - Shared BIM*: all subjects work simultaneously on the same BIM model, thus having real-time awareness of model updates and the choices of others.

Building Information Modeling

To define the quantity and detail of the information contained in the BIM model, the so-called LODs (*Level Of Detail*) are used. These represent the reference point, defined by the client, which allows all the subjects involved to build the model with the same level of definition of the contents, throughout all the project phases.

The specifications of the characteristics of each individual LOD are contained in two American and Italian regulatory references.

Building Information Modeling

As for the American Institute of Architects (AIA), a Level Of Detail framework for the AIA G202-2013 Building Information Modeling Protocol has been published. The approach adopted is to refer to the "level of development" of the model elements, rather than their graphic "level of detail":

- LOD 100: the element is represented in a generic, schematic, symbolic way. All information is still approximate.
- LOD 200: A generic placeholder with a recognizable shape, but which contains a reference to a series of accurate information.
- LOD 300: The quantity, shape, size, positioning and orientation of the element can be deduced and measured directly by interrogating the model, without having to consult additional documentary material.
- LOD 350: In addition to what is specified for LOD 300, those parts of the element necessary for coordination, such as supports and connectors, are also modeled.
- LOD 400: The element is modelled and specified with sufficient detail to allow its fabrication.
- LOD 500: The modelling of an existing construction, therefore not linked to the previous levels.

Building Information Modeling

The Italian standard UNI 11337-4:2017 refers to Levels Of Detail, distinguishing between LOD, LOG and LOI. In this perspective, the LOD (level of development of digital objects) is composed of the LOG (level of development of objects - geometric attributes) and the LOI (level of development of objects - information attributes). As regards the definition of individual LODs, the standard adopts the following general scale:

- LOD A: symbolic representation;
- LOD B: generic representation;
- LOD C: defined geometric system;
- LOD D: detailed geometric system;
- LOD E: specific object;
- LOD F: executed object;
- LOD G: updated object.

Building Information Modeling

There is currently an international association dedicated to the regulation of BIM. This is *buildingSMART international*, an association of industrial partners that provides guidelines and standards for the implementation, certification and interoperability of BIM software.

The association's website also contains a list of currently certified software and supported formats for data exchange.

Address: https://www.buildingsmart.org/compliance/software-certification/certified-software/

Some examples will be provided below.

Building Information Modeling Software

ACCA Software – Edificius (https://www.acca.it/bim-modeling-software)

Software in Italian

- 2D and 3D architectural design
- redevelopment of historic buildings
- filters for hand sketches
- BIM object library
- photo insertion and photo editing
- video editing
- rendering
- real-time rendering
- VRi (immersive virtual reality)
- BIM voyager (online sharing of models)

Building Information Modeling Software

AUTODESK – Revit (https://www.autodesk.it/products/revit/mep)

- Parametric Components
- Worksharing
- Architectural Design
- Structural Design & Fabrication
- MEP Engineering & Fabrication
- Construction

Free 30-day trial

Building Information Modeling Software

BRICSYS – BricsCAD BIM (https://www.bricsys.com/bricscad/bim)

BIM software that includes artificial intelligence algorithms to simplify the transition of professionals to a BIM approach.

Possibility of free trial for 30 days

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Electrical systems design – part I

Fundamentals of Modern Power Systems

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