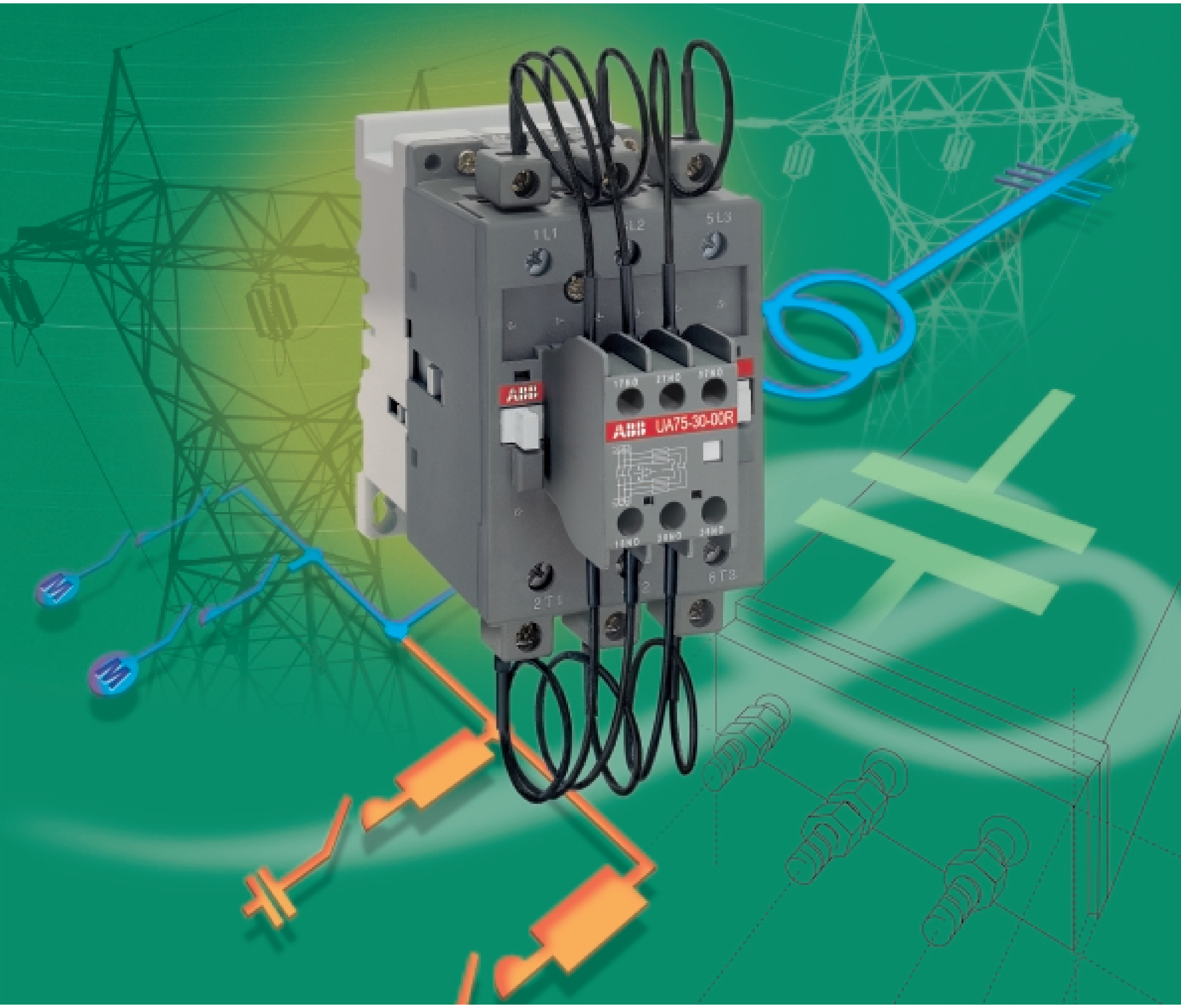
Application guide

Contactors for Capacitor Switching

1SBC 0064 99 R1002



ABB

Contactors for Capacitor Switching

Contents

Capacitor Bank Switching

General

Reminder of capacitor transient conditions

In Low Voltage industrial installations, capacitors are mainly used for reactive energy correction (raising the power factor). When these capacitors are energized, overcurrents of high amplitude (up to 180 $\mathbf{I_n}$) and high frequencies (3 to 15 kHz) occur during the transient period (1 to 2 ms).

The amplitude of these current peaks, also known as "inrush current peaks", depends on the following factors:

- The network inductances.
- The transformer power and short-circuit voltage.
- The type of power factor correction.

There are 2 types of power factor correction: fixed or automatic.

Fixed power factor correction consists of inserting, in parallel on the network, a capacitor bank whose total power is provided by the assembly of capacitors of identical or different unit powers.

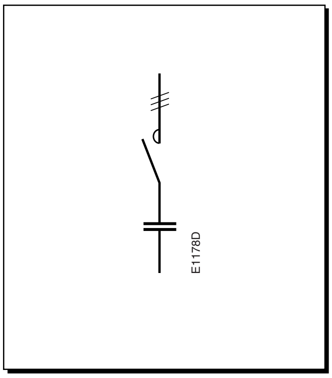
The bank is energized by a contactor that simultaneously supplies all the capacitors (a single step).

The inrush current peak, in the case of fixed correction, can reach 30 times the nominal current of the capacitor bank.

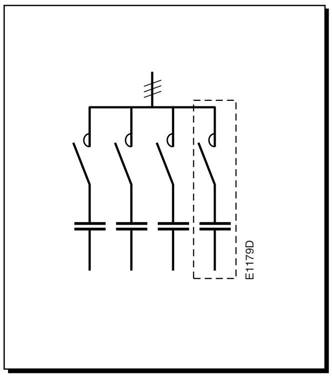
An automatic power factor correction system, on the other hand, consists of several capacitor banks of identical or different powers (several steps), energized separately according to the value of the power factor to be corrected.

An electronic device automatically determines the power of the steps to be energized and activates the relevant contactors.

The inrush current peak, in the case of automatic correction, depends on the power of the steps already on duty, and can reach 180 times the nominal current of the step to be energized.



Fixed power factor correction



Automatic power factor correction

Steady state condition data

The presence of harmonics and the network's voltage tolerance lead to a current, estimated to be 1.3 times the nominal current $\mathbf{I_n}$ of the capacitor, permanently circulating in the circuit.

Taking into account the manufacturing tolerances, the exact power of a capacitor can reach 1.15 times its nominal power.

Standard IEC 831-1 Edition 04/97 specifies that the capacitor must therefore have a maximum thermal current $\mathbf{I_T}$ of:

$$\mathbf{I_T} = 1.3 \times 1.15 \times \mathbf{I_n} = 1.5\ \mathbf{I_n}$$

Consequences for the contactors

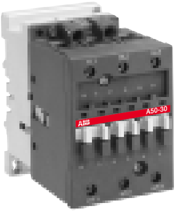
To avoid malfunctions (welding of main poles, abnormal temperature rise, etc.), contactors for capacitor bank switching must be sized to withstand:

- **A permanent current that can reach 1.5 times the nominal current of the capacitor bank**.
- **The short but high peak current on pole closing** (maximum permissible peak current $\hat{\mathbf{I}}$).

Contactors for Capacitor Switching

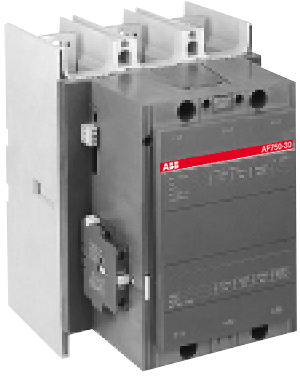
The ABB Solutions

ABB offers 3 contactor versions according to the value of the inrush current peak and the power of the capacitor bank.



SB8075S3

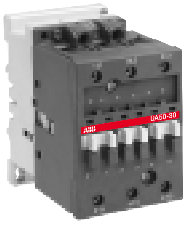
SB7324S2



SB8171S2

A.. and AF.. standard contactors (A 12 ... A 300 and AF 400 ... AF 750)
Maximum permissible peak current $\hat{I} \leq$ 30 times the nominal rms current of the switched capacitor.
Refer to the table on page 4 for the operational values.

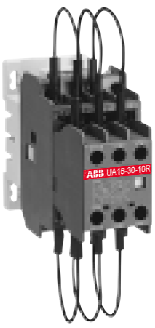
SB8009S3



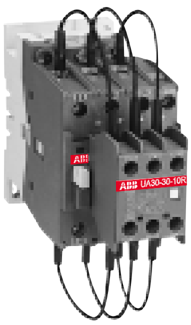
SB8078S3

SB8010S3

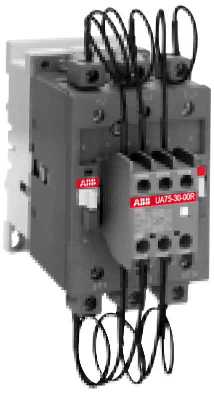
UA.. contactors for capacitor switching (UA 16 ... UA 110)
Maximum permissible peak current $\hat{I} \leq$ 100 the nominal rms current of the switched capacitor.
Refer to the table on page 5 for the operational values.



SB7822S2



SB7820S2



SB7821S2

UA...-R contactors for capacitor switching (UA 16-R ... UA 75-R)
with insertion of damping resistors.

The insertion of damping resistors rids the contactor of excessively high inrush currents.
Refer to the table on page 6 for the operational values.

● In a given application, if the user does not know the value of the inrush current peak, this value can be approximately calculated using the formulas given on pages 8 and 9.

A.. and AF.. standard contactors

The A.. and AF.. contactors are suited for capacitor bank switching for the peak current and power values in the table below.
The kvar ratings acc. to the table below are applicable to "star" connected capacitors (less current, cable savings).
The capacitors must be discharged (maximum residual voltage at terminals ≤ 50 V) before being re-energized when the contactors are making.

In these conditions, electrical durability of contactors is equal to 100 000 operating cycles.

Powers in kvar and maximum permissible peak current

Type	Powers in kvar 50/60 Hz															Max. peak current Î (kA)
	220/240 V			380/400 V			415/440 V			500/550V			660/690 V			
	40 °C	55 °C	70 °C	40 °C	55 °C	70 °C	40 °C	55 °C	70 °C	40 °C	55 °C	70 °C	40 °C	55 °C	70 °C	
A 9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A 12	7	7	6	11	11	9.5	12	12	10.5	14	14	12	19	19	16.5	0.7
A 16	7.5	7.5	6	12.5	12.5	10	14	14	10.5	15.5	15.5	12	21.5	21.5	16.5	1
A 26	11.5	11.5	9	19	19	15	20	20	16.5	23	23	19	32	32	26	1.6
A 30	13	13	11	22	22	18.5	24	24	20.5	28	28	23	38	38	32	1.9
A 40	15	15	12	26	26	20	29	29	22	35	35	25	46	46	34.5	2.1
A 50	22	22	20	38	38	34	42	42	37	48	48	42	65	65	58.5	2.3
A 63	25	25	23	43	43	39	47	47	42.5	54	54	48.5	74	74	67	2.5
A 75	28	28	24.5	48	48	41	52	52	45	60	60	51	82	82	70	2.6
A 95	35	35	33	60	60	53	63	63	58	75	75	70	80	80	75	4
A 110	40	40	35	70	70	60	75	75	65	83	83	78	90	90	85	4
A 145	50	50	42	90	90	74	93	93	80	110	110	96	110	110	110	4
A 185	60	60	45	105	105	78	115	115	85	135	135	102	135	135	135	5
A 210	75	75	57	125	125	100	135	135	110	160	160	130	160	160	160	6.5
A 260	85	85	70	140	140	130	155	155	140	180	180	165	200	200	200	8
A 300	100	100	85	160	160	150	180	180	163	210	210	196	240	240	240	8
AF 400	120	120	105	200	200	185	220	220	200	260	260	241	300	300	300	10
AF 460	140	140	120	230	230	215	260	260	230	325	325	300	325	325	325	10
AF 580	170	170	160	270	270	260	300	300	290	350	350	340	440	440	440	12
AF 750	220	220	190	390	370	332	410	410	380	490	480	435	600	600	600	12

If, in an application, the current peak is greater than the maximum peak current Î specified in the last column in the table, select a higher rating, refer to the UA contactors (see page 5) or add inductances (see page 12).

The capacitor bank will be protected by gG type fuses whose rating is equal to 1.5 ... 1.8 times nominal current.

Contactors for Capacitor Switching

Selection Table

UA.. contactors

The UA.. contactors have been specially developed for the switching of capacitor banks whose inrush current peaks are less than or equal to 100 times nominal rms current. The table below gives the permissible powers according to operational voltage and temperature close to the contactor. It also specifies the maximum peak current **Î values** accepted by the contactor.
The kvar ratings acc. to the table below are applicable to "star" connected capacitors (less current, cable savings).
The capacitors must be discharged (maximum residual voltage at terminals ≤ 50 V) before being re-energized when the contactors are making.

In these conditions, electrical durability of contactors is equal to 100 000 operating cycles.

Powers in kvar and maximum permissible peak current

Type	Powers in kvar 50/60 Hz															Max. permissible peak current Î (kA)	
	230/240 V			400/415 V			440 V			500/550 V			660/690 V			U_e	U_e
	40 °C	55 °C	70 °C	**40 °C**	55 °C	70 °C	**40 °C**	55 °C	70 °C	**40 °C**	55 °C	70 °C	**40°C**	55°C	70 °C	≤ 500 V	> 500 V
UA 16	**7.5**	6.7	6	**12.5**	11.7	10	**13.7**	13	11	**15.5**	14.7	12.5	**21.5**	20	17	**1.8**	**1.6**
UA 26	**12**	11	8.5	**20**	18.5	14.5	**22**	20	16	**22**	22	19.5	**30**	30	25	**3**	**2.7**
UA 30	**16**	16	11	**27.5**	27.5	19	**30**	30	20	**34**	34	23.5	**45**	45	32	**3.5**	**3.1**
UA 50	**20**	20	19	**33**	33	32	**36**	36	35	**40**	40	40	**55**	55	52	**5**	**4.5**
UA 63	**25**	25	21	**45**	43	37	**50**	48	41	**50**	50	45	**70**	70	60	**6.5**	**5.8**
UA 75	**30**	30	22	**50**	50	39	**55**	53	43	**62**	62	47.5	**75**	75	65	**7.5**	**6.75**
UA 95	**35**	35	29	**60/65***	60/65*	50/55*	**65**	65	55	**70**	70	60	**86**	86	70	**9.3**	**8**
UA 110	**40**	39	34	**74**	70/75*	65	**75**	75	67	**80**	80	75	**90**	90	85	**10.5**	**9**

* Use these values for U_e = 415 V

For **220 V** and **380 V**, multiply by **0.9** the rated values at 230 V and 400 V respectively.
Example: 50 kvar/400 V corresponding to 0.9 x 50 = **45 kvar/380 V**.

If, in an application, the current peak is greater than the maximum peak current Î specified in the table above, select a higher rating, refer to the UA...-R contactors (see page 6) or add inductances (see page12).

The capacitor bank will be protected by gG type fuses whose rating is equal to 1.5 ... 1.8 times nominal current.

Contactors for Capacitor Switching

Selection Table

UA…-R contactors equipped with damping resistors

The UA…-R contactors are fitted with a special front-mounted block ensuring the serial insertion in the circuit of damping resistors limiting current peak on energizing of the capacitor bank. Their connection also ensures capacitor precharging in order to limit the second current peak occurring on making of the main poles a few milliseconds later.

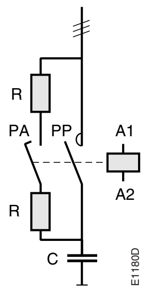
Operating principle

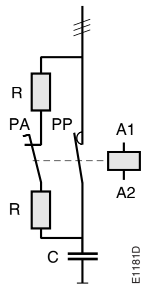
The front-mounted block mechanism of the UA…-R contactors alternately ensures early making and breaking of the auxiliary "PA" poles with respect to the main "PP" poles of the contactor.

When the coil is energized, the early making auxiliary poles connect the capacitor to the network via the set of resistors, thus attenuating the current peak. A few milliseconds later, the contactor main poles short-circuit the resistors with a new reduced inrush current.

The insertion contacts remain closed, ready to operate as early-breaking contacts for the next breaking sequence.

When the coil is de-energized, early breaking of the auxiliary poles ensures that the capacitor is disconnected via the main poles.





These contactors can be used in installations in which peak current far exceeds 100 times nominal rms current. The contactors are delivered complete with their damping resistors and must be used without additional inductances (see table below).
The kvar ratings acc. to the table below are applicable to "star" connected capacitors (less current, cable savings).
The capacitors must be discharged (maximum residual voltage at terminals ≤ 50 V) before being re-energized when the contactors are making.

Their electrical durability is 250 000 operating cycles for $\mathbf{U_e}$ < 500 V and100 000 operating cycles for $\mathbf{U_e}$ ≥ 500 V.

Powers in kvar

Type	Powers in kvar - 50/60 Hz															gG type
	220/240 V			380/400/415 V			440 V			500/550 V			660/690 V			fuses
	40 °C	55 °C	70 °C	**40 °C**	55 °C	70 °C	**40 °C**	55 °C	70 °C	**40 °C**	55 °C	70 °C	**40 °C**	55 °C	70 °C	max. (*)
UA 16-30-10-R	**8**	7.5	6	**12.5**	12.5	10	**15**	13	11	**18**	16	12.5	**22**	21	17	80
UA 26-30-10-R	**12.5**	11.5	9	**22**	20	15.5	**24**	20	17	**30**	25	20	**35**	31	26	125
UA 30-30-10-R	**16**	16	11	**30**	27.5	19.5	**32**	30	20.5	**34**	34	25	**42**	42	32	200
UA 50-30-00-R	**25**	24	20	**40**	40	35	**50**	43	37	**55**	50	46	**72**	65	60	200
UA 63-30-00-R	**30**	27	23	**50**	45	39	**55**	48	42.5	**65**	60	50	**80**	75	65	200
UA 75-30-00-R	**35**	30	25	**60**	50	41	**65**	53	45	**75**	65	55	**100**	80	70	200

(*) The fuse ratings given in this column represent the maximum ratings ensuring type 1 co-ordination according to the definition of standard IEC 947-4-1.

Contactors for Capacitor Switching

Selection examples

Application and possibilities

Description of the application

Capacitor bank:
20 kvar at **400 V, 50 Hz three-phase.**
Ambient temperature around the contactor: **40 °C**

Nominal current: $I_n = \frac{P}{\sqrt{3} \times U} = \frac{20000}{1.7 \times 400} \simeq$ **29 A**

Thermal current: $I_T = I_n \times 1.5 = 29 \times 1.5 \simeq$ **43 A**

Case no. 1 - Inrush peak current: **1700 Â**

Possibility as per table on page 4

A 30 contactor (22 kvar, 380/400 V).
This contactor accepts a maximum peak current of 1900 Â.

Case no. 2 - Inrush peak current: **2500 Â**

Possibility no. 1 as per table on page 5

UA 26 contactor (20 kvar, 400 V). **This contactor accepts a maximum peak current of 3000 Â ($U_e \leq$ 500V).**

Possibility no. 2 as per table on page 4

A 30 contactor + additional inductances limiting peak current to a **peak of 1900 Â that is acceptable for the A 30 contactor.**

Possibility no. 3 as per table on page 4

A 63 contactor (43 kvar, 400 V).
This contactor accepts a maximum peak current of 2500 Â.

Case no. 3 - Inrush peak current: **4500 Â.**

Possibility no. 1 as per table on page 6

UA 26-R contactor (22 kvar, 400 V).
This contactor can be directly used without an additional inductance.

Possibility no. 2 as per table on page 5

UA 26 contactor + additional inductances limiting peak current to a **peak of 3000 Â acceptable for the UA 26 contactor ($U_e \leq$ 500 V).**

Possibility no. 3 as per table on page 4

A 30 contactor + additional inductances limiting peak current to **a peak of 1900 Â acceptable for the A30 contactor.**

Possibility no. 4 as per table on page 4

A 185 contactor (105 kvar 400 V).
This contactor accepts a maximum peak current of 5000 Â.

i The information given on pages 8 and 9 will enable the user to calculate current peaks and to limit them to a value acceptable for the contactor. Since this calculation is never exact, capacitor bank manufacturers optimise their products by tests.

Calculation of Inrush Current Peak and Frequency

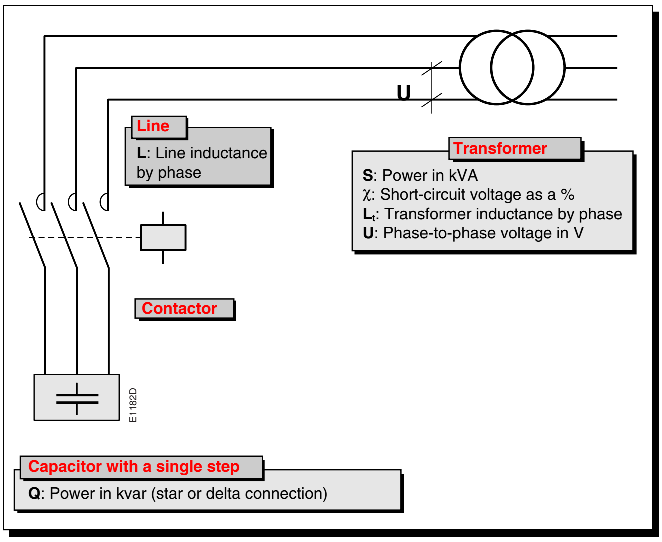
If the inrush current peak on energizing of a capacitor bank is greater than that acceptable for the switching contactor, there is a risk that power factor correction will no longer be ensured.

This is because, in this case, the contactor may remain permanently closed due to welding of its main poles.

The formulas given below are used to estimate inrush current peak as well as current frequency during the transient period. The values of the inductances used in the formulas can be determined by the methods described on pages 10 and 11.

Caution:
These formulas are applicable only if the capacitor bank is completely discharged at the time of energizing (maximum voltage at terminals $\leq$ 50 V).

Three-phase capacitor bank with a single step.



Inrush peak current Î:

$$\hat{I} = \sqrt{\frac{10^9}{3\,\pi\,f}} \times \sqrt{\frac{Q}{L + L_t}} \qquad \hat{I} = k_1 \sqrt{\frac{Q}{L + L_t}}$$

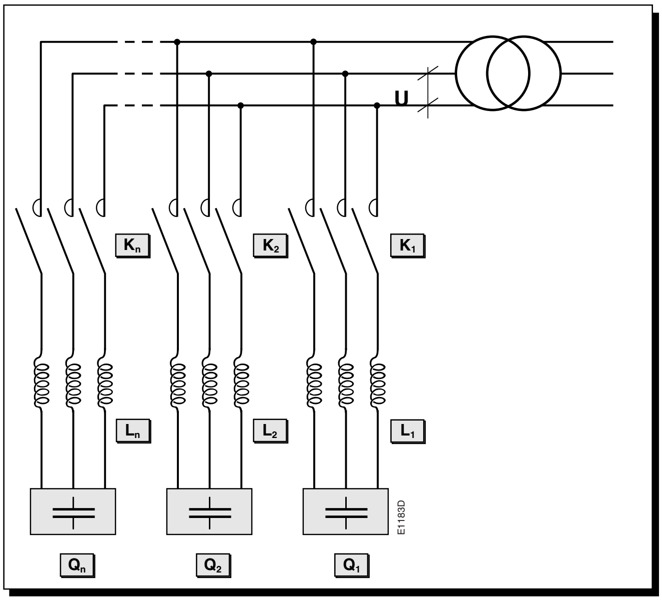
Inrush current frequency f_0:

$$f_0 = k_2\,U \sqrt{\frac{1}{Q\,(L + L_t)}}$$

Î: in Amperes
f: mains current frequency in Hz
Q: in kvar
L, **L_t** in µH
k_1 = 1457 (50 Hz) or 1330 (60 Hz)
k_2 = 89.2 (50 Hz) or 97.2 (60 Hz)

Three-phase capacitor bank with several steps of identical power.

Energizing of the capacitor **Q_n** with "**n – 1**" capacitors on duty.



Inrush peak current Î:

$$\hat{I} = k_1 \frac{n - 1}{n} \times \sqrt{\frac{Q_n}{L_n}}$$

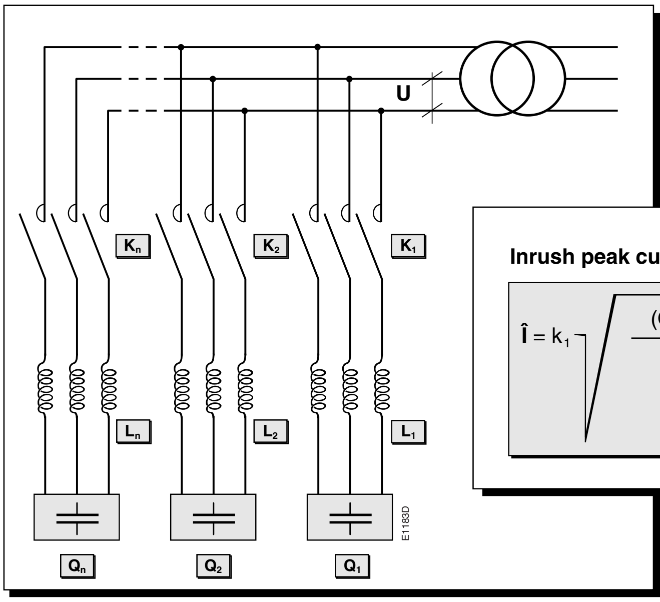
Inrush current frequency f_0:

$$f_0 = k_2\,U \sqrt{\frac{1}{L_n \times Q_n}}$$

Î: in Amperes
L_1 = **L_2** = **$L_{...}$** = **L_n**: inductance by phase of a step in µH
Q_1 = **Q_2** = **$Q_{...}$** = **Q_n**: power of a step in kvar
n: number of capacitor steps
U: phase-to-phase voltage in V
k_1 = 1457 (50 Hz) or 1330 (60 Hz)
k_2 = 89.2 (50 Hz) or 97.2 (60 Hz)

Three-phase capacitor bank with several steps of different powers

Energizing of the capacitor **Q_n** with "**n – 1**" capacitors on duty



Inrush peak current Î:

$$\hat{I} = k_1 \sqrt{\frac{(Q_1 + Q_2 + \dots + \dots + Q_{n-1})\,Q_n}{Q_1 + Q_2 + \dots + \dots + Q_n} \times \frac{1}{L_n + \dfrac{1}{\dfrac{1}{L_1} + \dfrac{1}{L_2} + \dots + \dfrac{1}{L_{n-1}}}}}$$

Energizing of Q_n

– Fictitious number of steps **n** = $\dfrac{\text{Bank total power}}{\text{Power of smallest step}}$

– The inrush current peak of **Q_n** is the same as that of a capacitor bank made up of **n** identical steps provided that the inductances **L_1**, **L_2** .... **L_n** are inversly proportional to the power of these steps.

$$L_n \text{ mini} = L_1 \frac{Q_1}{Q_n}$$

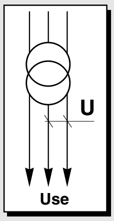
$Q_1 = a\,Q_n$	**$L_1 = L_n / a$**
$Q_2 = b\,Q_n$	**$L_2 = L_n / b$**
$Q_{..} = ..\,Q_n$	**$L_{..} = L_n / ..$**
⇣	⇣
$Q_{n-1} = z\,Q_n$	**$L_{n-1} = L_n / z$**

Determining the Transformer Inductance

The value of the inductance (L_t) of the transformer used in the various formulas above can be determined by following the method described below.

- **Reminder of the values marked on the transformer plate**

S: Power in kVA
χ: Short-circuit voltage as a %
U: Phase-to-phase operating voltage in Volts
f: Current frequency in Hertz



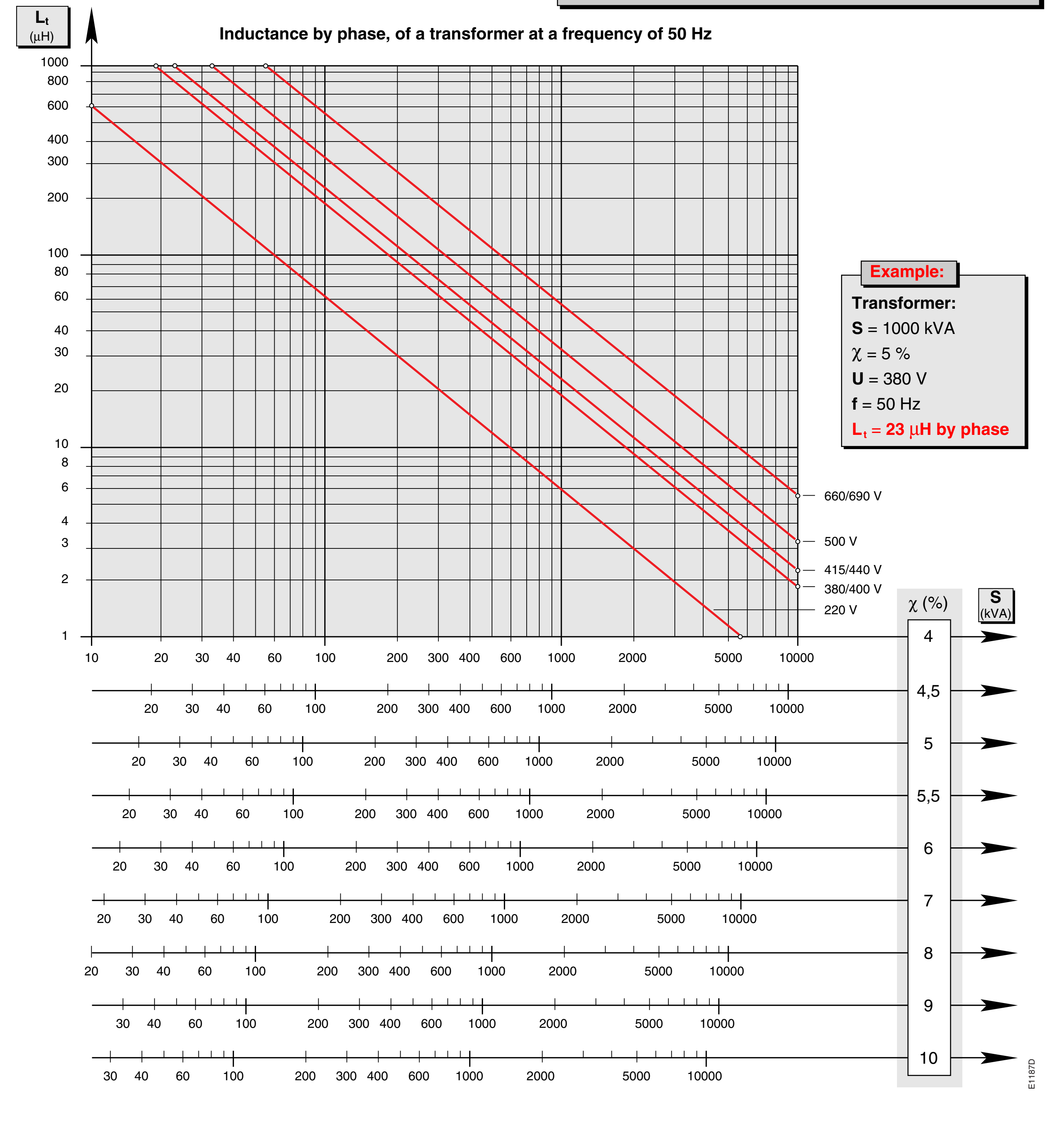
Value L_t of the inductance by phase of the transformer in **µH**:

$$L_t = \frac{1}{200\,\pi\,f} \cdot \frac{\chi U^2}{S} \cdot 10^3$$

$$L_t = \frac{\chi\,U^2}{k_3\,S}$$

k_3 = 31.4 (50 Hz) or 37.68 (60 Hz)

The following chart gives this value by direct reading



Example:

Transformer:
S = 1000 kVA
χ = 5 %
U = 380 V
f = 50 Hz
L_t = 23 µH by phase

For a symmetrical connection formed by non-magnetic conductors, the linear coefficient of apparent self-inductance is the same for all the conductors and is given by:

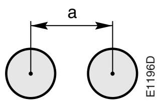
$$L = [\,0.05 + 0.46 \log_{10} \frac{2\,a_m}{d}\,]\ \mu H/m$$

d = diameter of the conductive core (mm)

a_m = geometric average of distances between the conductor axes (mm)

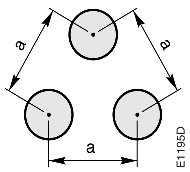
Single-phase installation

$a_m = a$



Three-phase delta installation

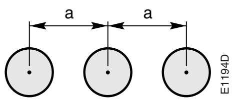
$a_m = a$

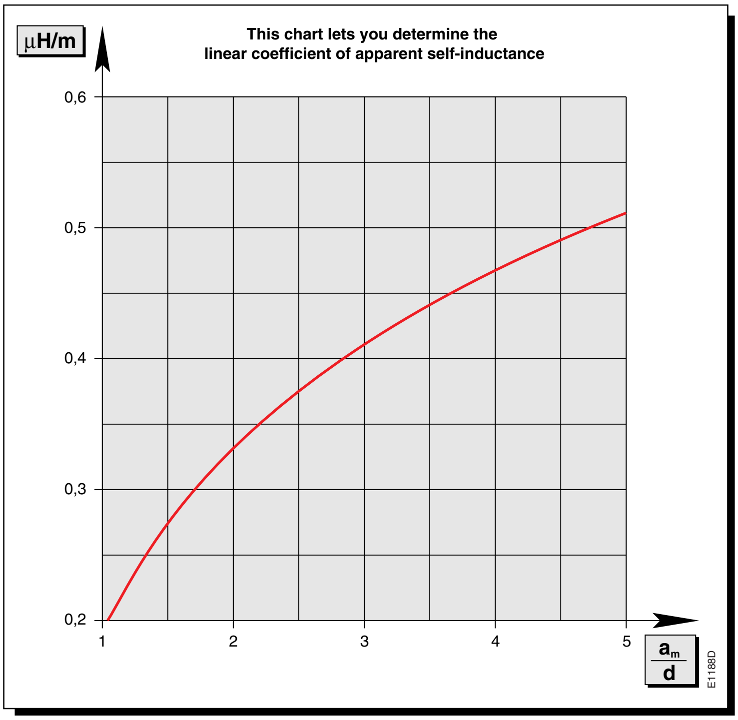


Three-phase adjacent installation

$a_m = a\sqrt[3]{2}$

$a_m = 1.26\ a$





Guideline values

Conductive cross-sectional area (mm²)	4	6	10	16	25	35	50	70	95	120
Conductive core Ø = d (mm)	2.26	2.92	3.9	4.9	6.1	7.2	8.4	10.1	11.9	13.4
Outer Ø U1000 RO2V	7.2	8.2	9.2	10.5	12.5	13.5	15	17	19	21

Attenuation of the Inrush Peak

If the electrical connection inductances are very low, the inrush current peak of the capacitor bank may not be sufficiently attenuated and thus cause welding of the main poles of the contactor.

To avoid this risk, the user must select a contactor that can withstand a higher current peak (UA or UA...-R range) or may serial-connect "additional" inductances in the circuit.

Determining electrical connection minimum inductances

The formulas given on page 8 to calculate the inrush current peak can also be used to determine the minimum value of the electrical connection inductances separating the transformer from the capacitor bank, without risk of welding the main poles of the contactor.

- **Capacitor bank with one step**

$$\hat{I} = k_1 \sqrt{\frac{Q}{L + L_t}} \quad \text{thus } L_{min} = \left(\frac{k_1^2}{\hat{I}^2} Q\right) - L_t$$

- **Capacitor bank with several identical steps**

$$\hat{I} = k_1 \frac{n-1}{n} \sqrt{\frac{Q_n}{L_n + L_t}} \quad \text{thus } L_{min} = \left(\frac{k_1^2}{\hat{I}^2} \frac{(n-1)^2}{n^2} Q_n\right) - L_t$$

L_{min}: minimum inductance of the electrical connection in µ**H**.
Î: maximum peak, acceptable for the contactor in **A** (see tables on pages 4 and 5).
Q: power of the capacitor bank in **kvar**.
Q_n: power of the n^th step in **kvar**.
L_t: inductance by phase of the transformer in µ**H**.
k_1=1457 (if f = 50 **Hz**) or = 1330 (if f = 60 **Hz**)

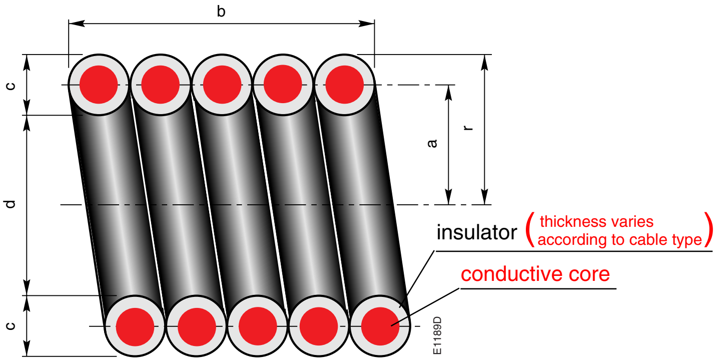
The chart on page 13 allows, by direct reading, identification of the minimum value of the inductance according to:
– the type of contactor,
– the power of the capacitor bank in kvar,
– the number of steps.

Practical method for making additional inductances

If the electrical connection inductances are too low (current peaks not sufficiently attenuated), the user can add additional inductances, simply made by winding the cables designed to be connected to the capacitor bank, onto a cylinder. The method below provides all the technical information required to make these additional inductances.

- **Theoretical reminder**

An electrical conductor wound with joining turns on a cylinder of a diameter (d), forms an inductance coil whose inductance is equal to:



$$L = 10^{-7} \frac{4\pi^2 \cdot a^2 \cdot N^2}{b + c + r} \cdot F_1 \cdot F_2$$

$$F_1 = \frac{10\,b + 12\,c + 2\,r}{10\,b + 10\,c + 1{,}4\,r}$$

$$F_2 = 0.5 \log_{10} \left(100 + \frac{14\,r}{2\,b + 3\,c}\right)$$

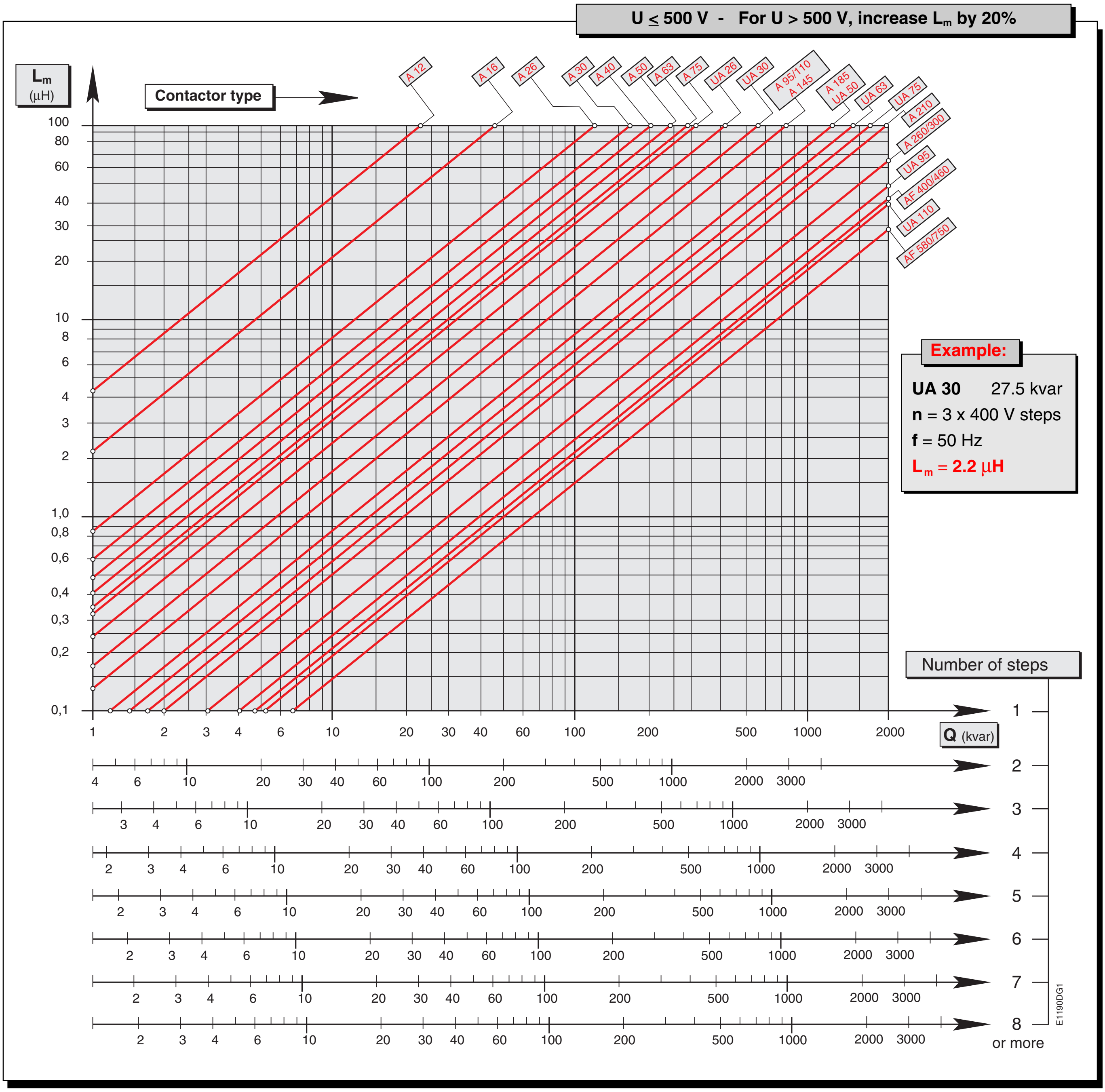
L: self-inductance in **H**
N: number of circular turns
a, **b**, **c**, **d**, **r**: dimensions in **m**

- **Charts**

The charts on pages 14 and15 allow, by direct reading, identification of the number of turns to be made according to:
– the cable cross-sectional area that will be used to connect the capacitor bank,
– the diameter of the cylinder used to make the inductance coil,
– the necessary inductance value.

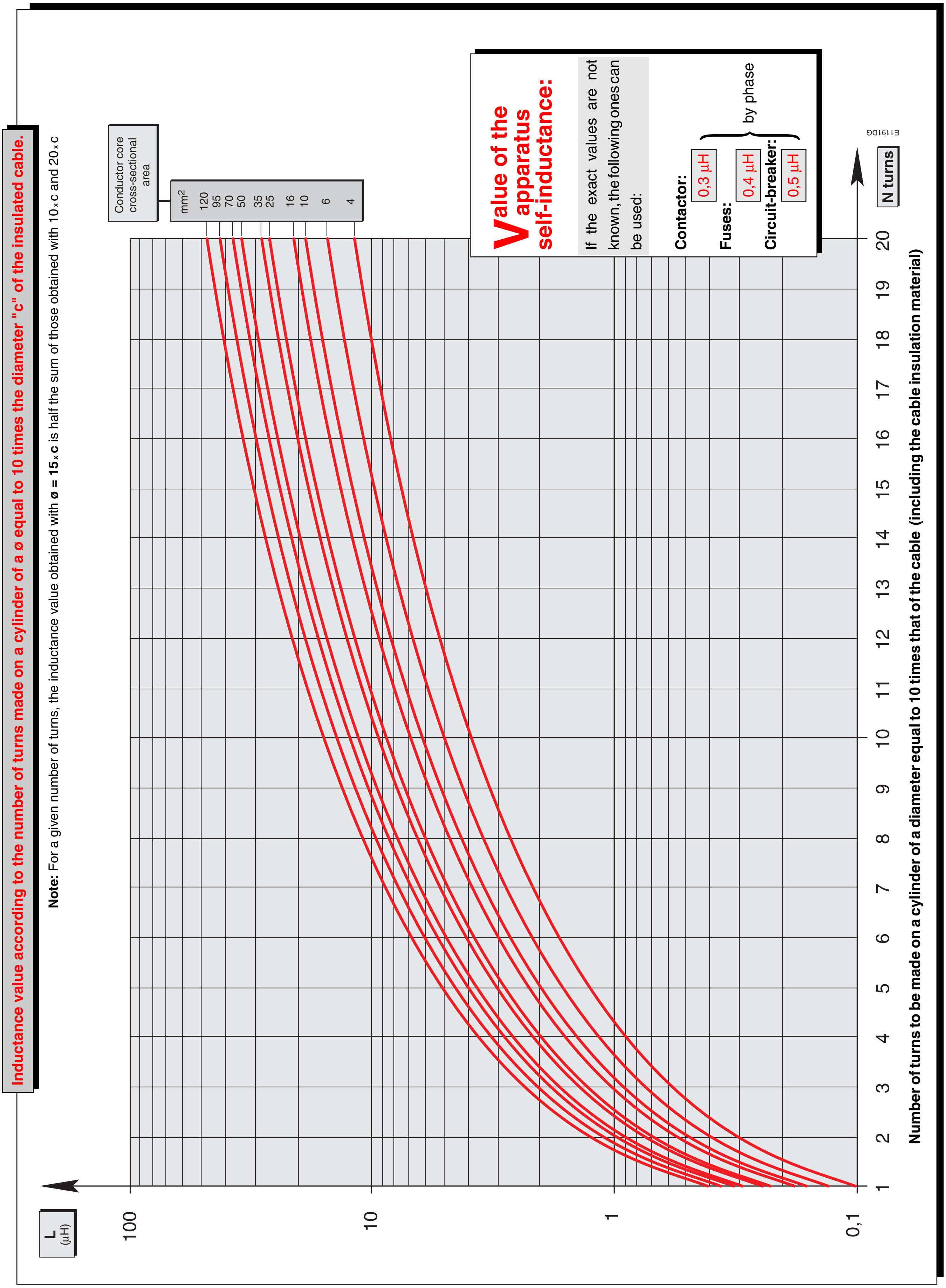
Attenuation of the Inrush Peak

Chart used to determine electrical connection minimum inductances



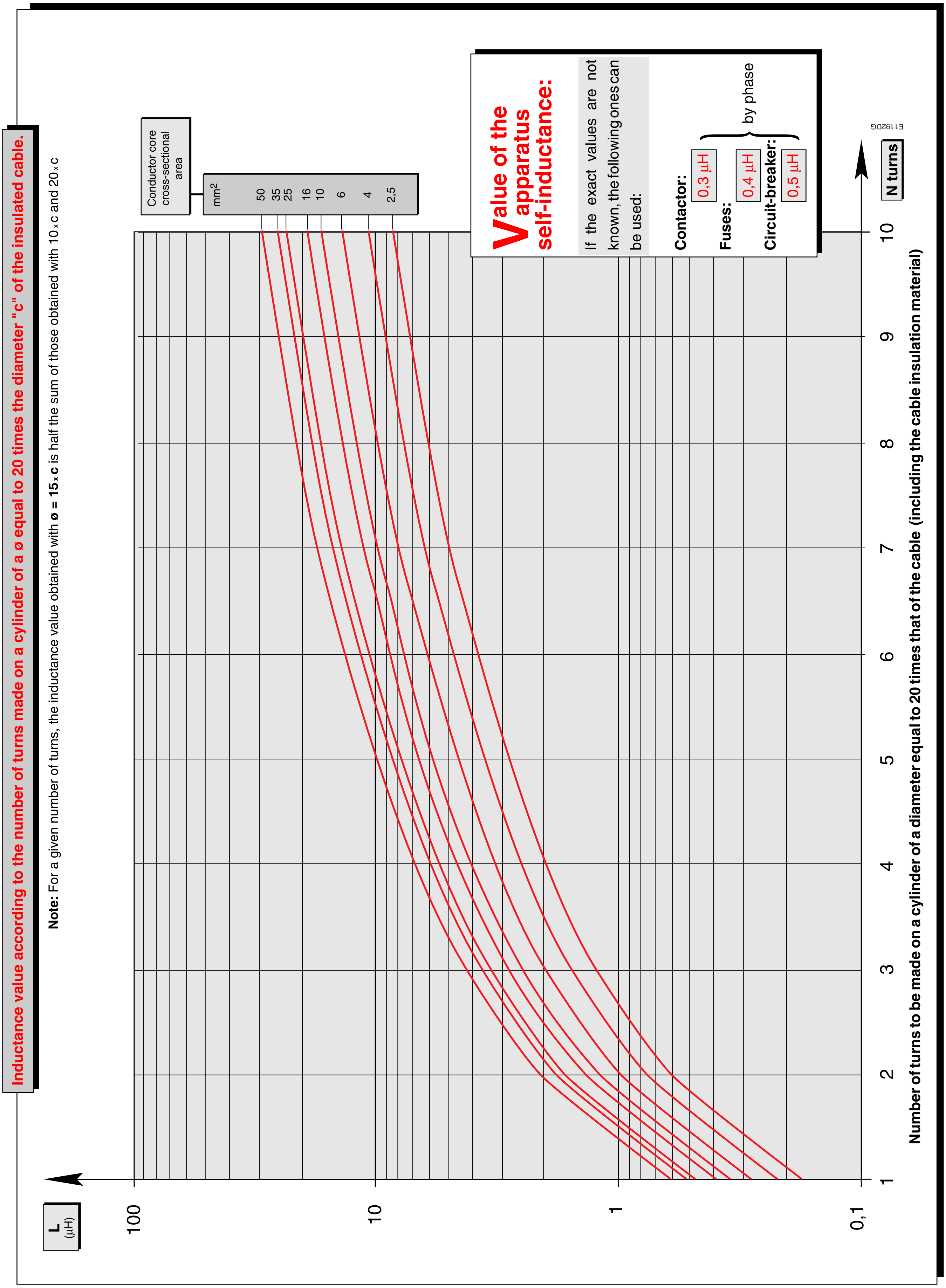
Attenuation of the Inrush Peak

Additional inductances (Ø = 10 x cable diameter)



Attenuation of the Inrush Peak

Additional inductances (Ø = 20 x cable diameter)



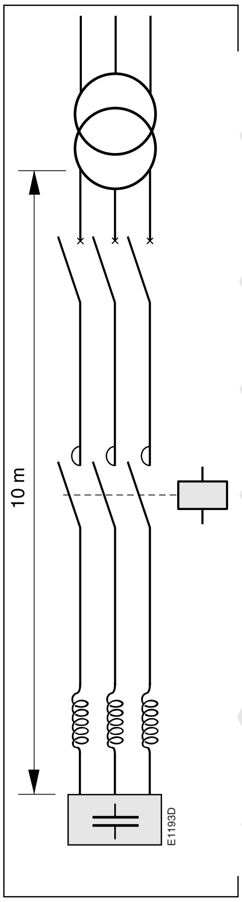
Three-phase capacitor bank with a single step

Example:

Transformer.
500 kVA 220 V 50 Hz Short-circuit voltage χ = 4 %
Capacitor = 5 kvar
Transformer/capacitor connection
10 m of adjacent cables $\mathbf{a_m}$ = 3 d (4 mm²)
Temperature: θ = 55 °C

$$\hat{I} = k_1 \sqrt{\frac{Q}{L + L_t}}$$

(see page 8)



$\mathbf{L_t}$: Transformer inductance per phase (chart on page 10) — $\mathbf{L_t}$ = 12 µH

$\mathbf{L_1}$: Circuit-breaker inductance (pages 14 and 15) — $\mathbf{L_1}$ = 0.5 µH

$\mathbf{L_2}$: Electrical connection inductance (chart on page 11) — $\mathbf{L_2}$ = 0.42 µH x 10 ⇒ $\mathbf{L_2}$ = 4.2 µH

$\mathbf{L_3}$: Contactor inductance (pages 14 and 15) — $\mathbf{L_3}$ = 0.3 µH

(L = $L_1 + L_2 + L_3$)

$\mathbf{L_t + L_1 + L_2 + L_3}$ = 17 µH

$\mathbf{L_x}$: Possible additional inductance per phase (see page 12)

Q : Capacitor power (kvar)

Selecting the contactor (pages 4-5-6)	Type (table on page 4)	**A 12**
Look for $\mathbf{L_m}$ (chart on page 13)	Network minimum inductance	$\mathbf{L_m}$ = 21 µH

If $\mathbf{L_m} \leq \mathbf{L_t + L_1 + L_2 + L_3} + \ldots$ ⇒ No additional inductance $\mathbf{L_x}$
If $\mathbf{L_m} > \mathbf{L_t + L_1 + L_2 + L_3} + \ldots$ ⇒ Add an additional inductance $\mathbf{L_x}$ such that: $\mathbf{L_x} \geq \mathbf{L_m} - (\mathbf{L_t + L_1 + L_2 + L_3} + \ldots)$

$\mathbf{L_x} \geq$ 21 µH – 17 µH thus $\mathbf{L_x} \geq$ 4 µH

$\mathbf{L_x}$ made up of 6 turns per phase of 4 mm² copper cable
(as per chart on page 15) Ø = 20 c

If you want to remove or reduce L_x you can choose a contactor with a greater making capacity

If you choose an **A 16** contactor; the chart (on page 13) gives $\mathbf{L_m}$ = 10 µH — **Thus no additional inductance as 10 < 17 µH**

Three-phase capacitor bank with several steps of identical power.

Example:

Transformer.
630 kVA 400 V 50 Hz Short-circuit voltage χ = 4 %

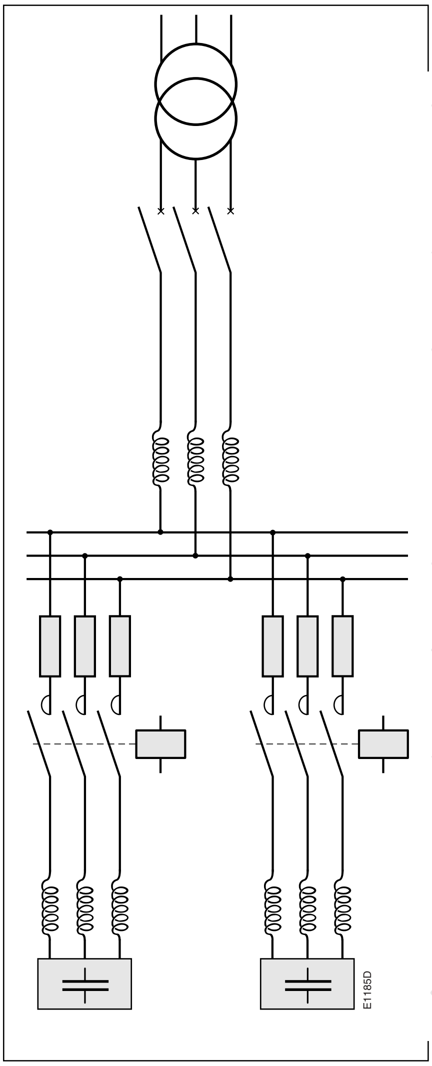
Capacitors: bank with 6 steps of 20 kvar

Connections:
transformer/ capacitors 10 m of adjacent cables a_m = 4 d
capacitors/ busbars: 0.50 m in delta 10 mm² a_m = 4 d

Temperature: θ = 40 °C

$$\hat{I} = k_1 \frac{n-1}{n} \sqrt{\frac{Q_n}{L_n}}$$

(see page 8)



L_t : Transformer inductance per phase (chart on page 10) — L_t = 30 µH

L_1 : Circuit-breaker inductance (pages 14 and 15) — L_1 = 0.5 µH

L_2 :Connection inductance: transformer/capacitor bank by phase (chart on page 11) — L_2 = 0.47 µH x 10 ⇒ L_2 = 4.7 µH

L_x : Additional inductance, if necessary, per phase (value 0 for this example). If L_x other than 0, reduce by the same amount the value of the additional inductance L_y below.

L_3 : Connection inductance: busbar/capacitor, per phase (chart on page 11) — L_3 = 0.47 µH x 0.5 ⇒ L_3 = 0.24 µH

L_4 : Fuse inductance (pages 14 and 15) — L_4 = 0.4 µH

L_5 : Contactor inductance (pages 14 and 15) — L_5 = 0.3 µH

L_n

$L_n = L_3 + L_4 + L_5$ = 0.94 µH

L_y : Additional inductance, if necessary, per phase and per step (page 12)

Q : Capacitor power (kvar) (n identical steps)

Selecting the contactor (pages 4-5-6)	Type (table page 5)	**UA 26**
Look for L_m (chart on page 13)	Network minimum inductance	L_m = 3.2 µH

If $L_m \leq L_3 + L_4 + L_5 + \ldots$ ⇒ No additional inductance L_y

If $L_m > L_3 + L_4 + L_5 + \ldots$ ⇒ Add an additional inductance L_y — L_y = 3.2 µH – 0.94 µH = 2.26 µH

L_y made up of 3 turns per phase of 10 mm² copper cable (as per chart on page 15) Ø = 20 c

If you want to eliminate or reduce L_y you can choose a contactor with a higher making capacity.

If you choose an **UA75** contactor; the chart (page 13) gives L_m = 0.85 µH **Thus no additional inductances as 0.85 < 0.94 µH**

The upstream inductance value $L_t + L_1 + L_2$ = 35.2 µH makes the addition of additional inductances L_x pointless.

Three-phase capacitor bank with several steps of different powers.

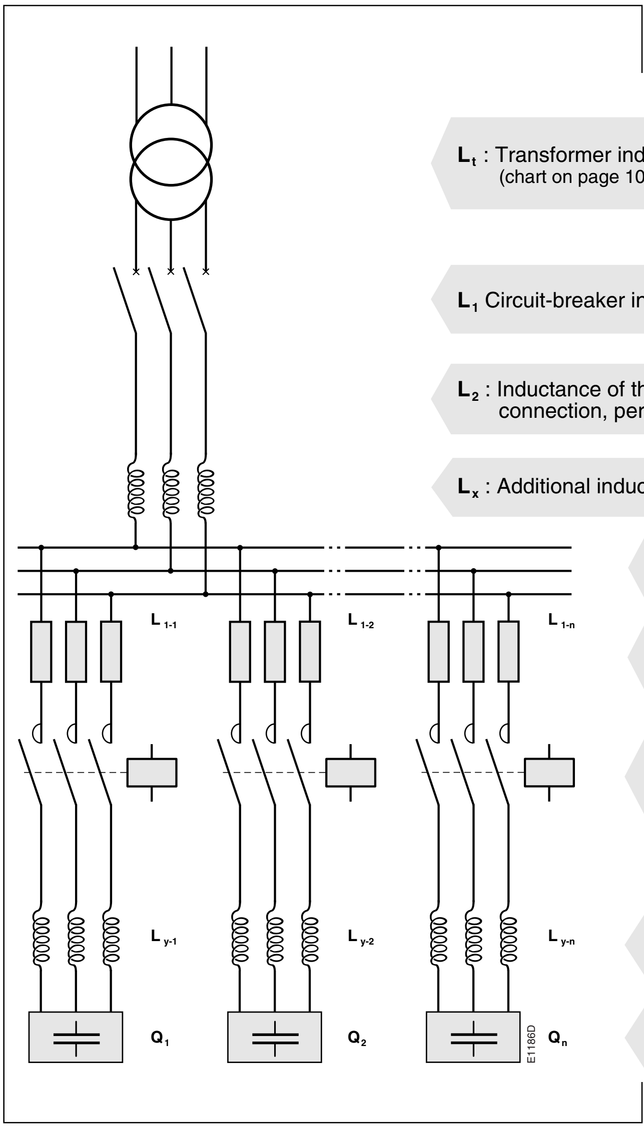
Example:

Transformer.
400 kVA 400 V 50 Hz Short-circuit voltage χ = 4 %

Capacitors: bank with 3 steps of: 20 kvar, 30 kvar, 50 kvar

Connections:
transformer/ busbars: 10 m of adjacent cables a_m = 4 d
busbars/capacitors: 1 m a_m = 4 d

Temperature: θ = 40 °C



L_t : Transformer inductance per phase (chart on page 10) — L_t = 45 µH

L_1 Circuit-breaker inductance (pages 14 and 15) — L_1 = 0.5 µH

L_2 : Inductance of the transformer/capacitor bank connection, per phase (chart on page 11) — L_2 = 0.47 µH x 10 ⇒ L_2 = 4.7 µH

L_x : Additional inductance, if necessary, per phase (page 12)

L_3 : Inductance of the busbar/ capacitor connection per phase (chart on page 11) — L_3 = 0.47 µH x 1 ⇒ L_3 = 0.47 µH

L_4 : Fuse inductance (pages 14 and 15) — L_4 = 0.4 µH

L_5 : Contactor inductance (pages 14 and 15) — L_5 = 0.3 µH

$L_n = L_3 + L_4 + L_5$ = 1.17 µH

L_{yn}: Additional inductance, if necessary, per phase (page 12)

Q : Capacitor power (kvar) (n different steps)

Preselection of contactors (tables on pages 4-5-6)

Type (table on page 5)	Smallest step: **20 kvar**	⇒	**UA 26**
	Step with intermediate power: **30 kvar**	⇒	**UA 50**
	Most powerful step: **50 kvar**	⇒	**UA 75**

Determining any self-inductances L_y.

Calculate the minimum inductance of the connection of each step,
as though the bank were made up of n_p steps of identical power Q_p to that being analysed.

$$n_p = \frac{Q_1 + Q_2 + Q_3 + Q... + Q_p + Q... + Q_n}{Q_p}$$

Example : $n_1 = \frac{\text{Bank total power}}{\text{Power of smallest step}}$

Smallest step: 20 kvar

Fictitious number of steps: $n_1 = \frac{20 + 30 + 50}{20} = 5$

Preselected **UA 26** contactor (table on page 5)

Minimum inductance for 5 steps of **20 kvar** (chart on page 13): $L_1 = 3\ \mu H$

Additional inductance $L_{y1} = L_1 - L_n$

$L_{y1} = 3 - 1.17 = 1.83$ ⇒ **Additional inductance of 1.83 µH**

The inductances of the other connections must have as their minimum value the one satisfying **the most restrictive** of the 2 requirements below:

Requirement no. 1: Be at least inversly proportional to the powers of each capacitor step, i.e. $L_n\ \text{mini} = L_1 \frac{Q_1}{Q_n}$.

Requirement no. 2: Be compatible with the contactor used (chart on page 13).

Step of intermediate power: 30 kvar

Fictitious number of steps: $n_2 = \frac{20 + 30 + 50}{30}$ # **3**

Requirement no. 1: $L_2\ \text{min.} = L_1 \frac{Q_1}{Q_2} = 3 \times \frac{20}{30} = 2\ \mu H.$

Requirement no. 2: Preselected **UA 50** contactor (table on page 5)

Minimum inductance for 3 steps of **30 kvar** (chart on page 13): **1.1 µH.**

The most restrictive requirement is L_2 min. = 2 µH.

Thus, an additional inductance is required

$L_{y2} = 2\ \mu H - 1{,}17\ \mu H = \mathbf{0{,}83\ \mu H}$

Most powerful step: 50 kvar

Fictitious number of steps: $n_3 = \frac{20 + 30 + 50}{50} = 2$

Requirement no. 1: $L_3\ \text{min.} = L_1 \frac{Q_1}{Q_3} = 3 \times \frac{20}{50} = 1{,}2\ \mu H.$

Requirement no. 2: Preselected **UA 75** contactor (table on page 5)

Minimum inductance for 2 steps of **50 kvar** (chart on page 13): **0.7 µH.**

The most restrictive requirement is L_3 min. = 1,2 µH.

The value of the connection inductance,1.17 µH, is very close to 1.2 µH, there **is thus no point providing an additional inductance: $L_{y3} = 0$**

The upstream inductance value $L_t + L_1 + L_2 = 50\ \mu H$ makes the addition of additional inductances L_x pointless.

We could choose all contactors of the same size: the largest preselected rating (UA 75 in our example).

The result would be:

20 kvar step: $n_1 = 5$ ⇒ Chart page 13: **$L_{1\ min.} = 0.8\ \mu H$** ⇒ **$L_n = 1.17\ \mu H$ is greater than L_1 thus $L_{y1} = 0$**

30 kvar step: $n_2 = 3$ ⇒ Chart on page 13 : **$L_{2\ min.} = 0.8\ \mu H$**

Checking the other requirement: $L_{2\ min.} = L1 \frac{Q_1}{Q_2} = 0{,}8 \frac{20}{30} = 0{,}53\ \mu H$

The most restrictive requirement is **$L_{2\ min.} = 0.8\ \mu H$** ⇒ **$L_n = 1.17\ \mu H$ is greater than L_2 thus $L_{y2} = 0$**

50 kvar step: $n_3 = 2$ ⇒ Chart on page 13 : **$L_{3\ min.} = 0{,}78\ \mu H$**

Checking the other requirement: $L_{2\ min.} = L1 \frac{Q_1}{Q_3} = 0{,}8 \frac{20}{50} = 0{,}32\ \mu H$

The most restrictive requirement is **$L_{2\ min.} = 0{,}78\ \mu H$** ⇒ **$L_n = 1{,}17\ \mu H$ is greater than L_3 thus $L_{y3} = 0$**

Advantage: this choice means that inductances need not be added.

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