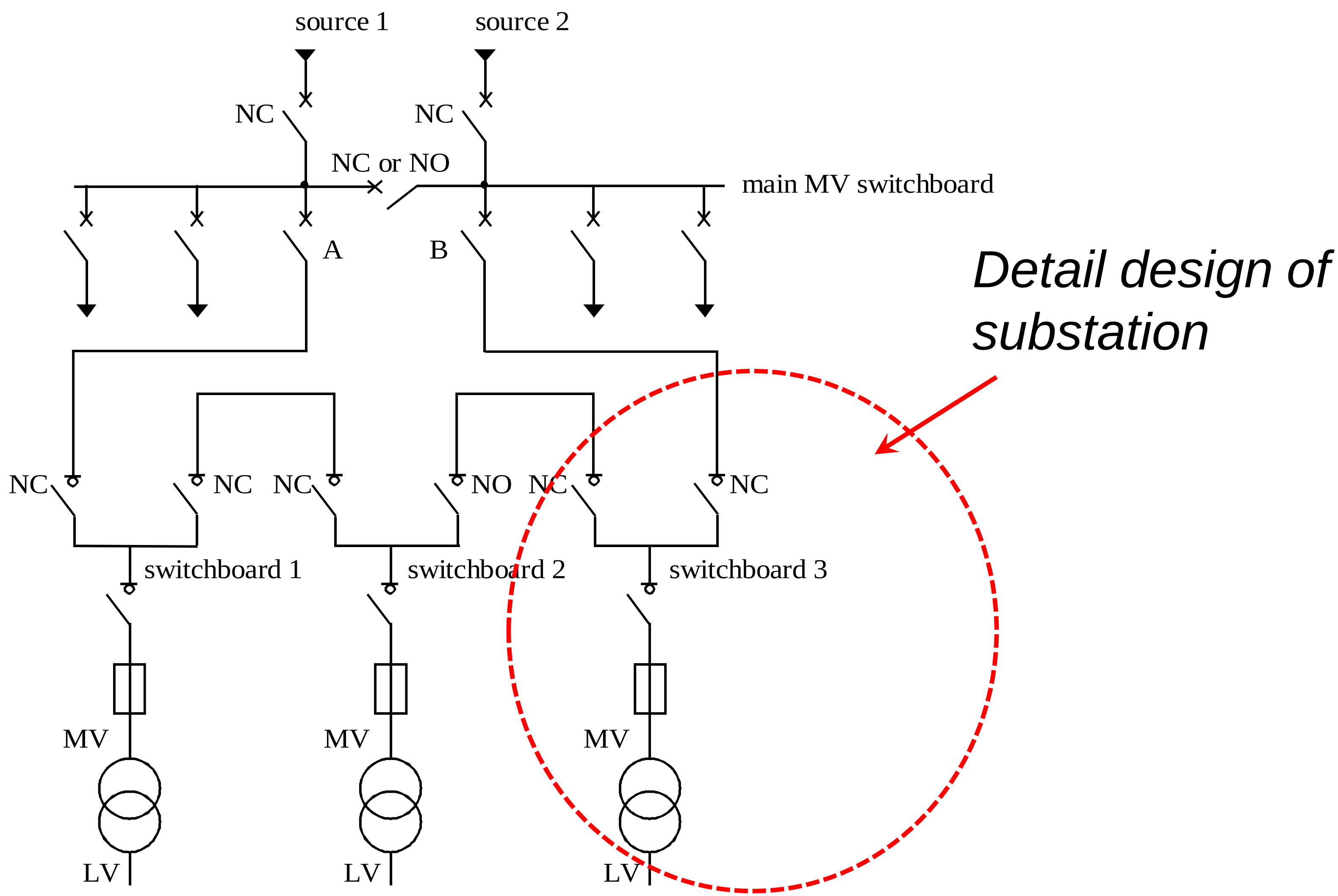
Substation Design

Consider open loop MV network as an example



Substation Design

The rating of substation equipment as well as the connections must be decided.

Selection of substation equipment

Selection of transformers

Switchgear
- Ratings of Circuit Breakers
- Ratings of Switch Disconnecters (Load-break switches)
- Ratings of Isolators (Disconnecters)

Measurement
- Characteristics of Voltage Transformers
- Characteristics of Current Transformers

Substation Design

Selection of Transformers:

- ✓ Transformer size/s must be selected according to the <u>maximum expected load and possibility of future expensions</u>.
- ✓ The size of transformer may be selected from power ratings given below to supply present and future loads.

Commonly Available Ratings for Substation Transformers

Powers:

25 kVA, 50 kVA, 100 kVA, 250 kVA, 400 kVA, 630 kVA, 800 kVA, 1000 kVA, 1250 kVA, 1600 kVA, 2000 kVA

Primary Voltages (line-to-line**):**

6 kV, 7.2 kV, 10 kV, 12 kV, 22 kV, 24 kV, 31.5 kV, 33 kV, 34.5 kV, 35 kV, 36 kV

Secondary Voltages (line-to-line**):**

380 V, 400 V

Substation Design

***Example*:**

Consider that you would like to choose a transformer to supply power to a factory which requires maximum of 270 kVA of power at 400 V on the LV side and no expension is considered for near future. The power will be provided by connecting the factory to 33 kV MV voltage level. Choose the transformer.

***Solution*:**

Powers:

25 kVA, 50 kVA, 100 kVA, 250 kVA, **400 kVA**, 630 kVA,
800 kVA, 1000 kVA, 1250 kVA, 1600 kVA, 2000 kVA

Primary Voltages (line-to-line**):**

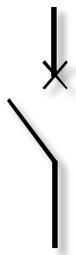
6 kV, 7.2 kV, 10 kV, 12 kV, 22 kV, 24 kV, 31.5 kV, **33 kV**,
34.5 kV, 35 kV, 36 kV

Secondary Voltages (line-to-line**):**

380 V, **400 V**

Selected Transformer Size for the Factory**: 400 kVA, 33 kV/400 V**

Substation Design



Ratings of Circuit Breaker:

- ✓ Rated voltage, rated current, and rated short-circuit breaking (interrupting) capacity of circuit breaker must be determined.

- ✓ Short circuit capacity of the circuit breaker must be above the maximum short circuit current exists in the location.

Ratings of Switchgears in Medium Voltage

Short circuit breaking currents:

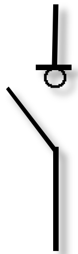
8 kA, 12.5 kA, 16 kA, 20 kA, 25 kA

Rated nominal currents:

630 A, 800 A, 1250 A, 1600 A, 2000 A, 2500 A

Rated nominal voltages (line-to-line**):**

6 kV, 7.2 kV, 12 kV, 24 kV, 36 kV



Ratings of Switch Disconnecters (Load-break switches):

- ✓ Rated voltage, rated current, and allowed short-circuit current must be determined.
- ✓ Switch disconnecters must withstand thermally and mechanically against the short circuits

Ratings of Switchgears in Medium Voltage

Short circuit currents:

8 kA, 12.5 kA, 16 kA, 20 kA, 25 kA

Rated nominal currents:

630 A, 800 A, 1250 A, 1600 A, 2000 A, 2500 A

Rated nominal voltages (line-to-line**):**

6 kV, 7.2 kV, 12 kV, 24 kV, 36 kV

Substation Design

Ratings of Isolators (Disconnectors):

- ✓ Rated voltage, rated current, and allowed short-circuit current must be determined.

- ✓ Switch disconnecters must withstand thermally and mechanically against the short circuits

Ratings of Switchgears in Medium Voltage

Short circuit currents:

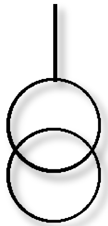
8 kA, 12.5 kA, 16 kA, 20 kA, 25 kA

Rated nominal currents:

630 A, 800 A, 1250 A, 1600 A, 2000 A, 2500 A

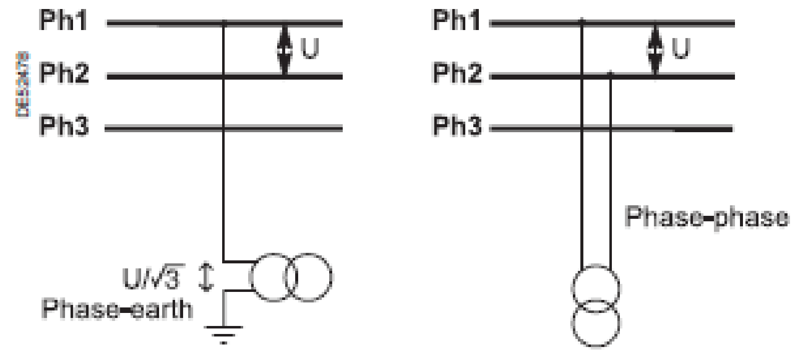
Rated nominal voltages (line-to-line**):**

6 kV, 7.2 kV, 12 kV, 24 kV, 36 kV

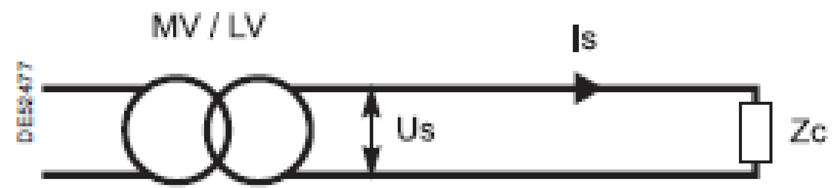


Characteristics of Voltage Transformers:

- ✓ Lowers operating voltage to the levels that can be used for measurements and protections.



Connection of a VT.



Simplified schematic diagram of a voltage transformer
IS: secondary current
Us: secondary voltage
Zc: load imped

Accuracy Powers:

10 VA, 15 VA, 20 VA, 30 VA, 60 VA

Accuracy Class:

0.1, 0.2, 0.5, 1, 3

Primary voltages (line-to-line):

6 kV, 7.2 kV, 10 kV, 12 kV, 22 kV, 24 kV, 31.5 kV, 33 kV, 34.5 kV, 35 kV, 36 kV

Secondary voltages (line-to-line):

100 V, 110 V, 220 V

a brand of Schneider Electric

Substation Design

Characteristics of Voltage Transformers:

Voltage transformer for metering:

Accuracy Class: Defines the error limits guaranteed relative to the transformation ratio and the phase shift under specified conditions of power and voltage.
The accuracy class determines the permissible error in the phase and in the magnitude for the accuracy load range.
The accuracy is valid for all loads between 25 and 100% of the rated accuracy power with an inductive power factor of 0.8.

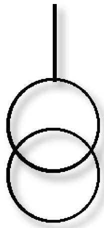
Accuracy Power: Apparent power (VA) that the VT can supply the load connected to secondary for the rated secondary voltage for which the accuracy is guaranteed.

Error limits according to the accuracy class

Accuracy class	Voltage error (ratio) ± %	Phase-shift error ± mn
0.2	0.2	10
0.5	0.5	20
1	1.0	40

Application	Class
Accurate laboratory metering applications (calibration devices)	0.2
Billing metering industrial measurements	0.2
Statistical switchboard metering indicators	0.5 - 1

Substation Design



Characteristics of Voltage Transformers:

Voltage transformer for metering:

***Example**:* Consider that a voltage transformer will be used for measurement purposes in a substation. The rated voltage of substation is 20 kV. Select the voltage transformer.

***Solution**:* The closest primary voltage is 22 kV in the previous slides. The secondary voltage can be chosed as 100 V. Therefore rated primary/ rated secondary voltage will be $\frac{22}{\sqrt{3}}$kV/$\frac{100}{\sqrt{3}}$V. For measurement Class 0.5 can be chosen and accuracy power 30 VA would be approprate.

If

- ❑ the voltage is between 80% (17.6 kV) and 120% (26.4 kV) of the rated primary voltage, and
- ❑ the load is between 20% (6 VA) and 100% (30 VA) with inductive power factor of 0.8,

the measured voltage magnitude will be within $\pm$0.5% error and phase angle within $\pm$20 minutes error.

<u>*Result*</u> : Transformer characteritics **$\frac{22}{\sqrt{3}}$kV/$\frac{100}{\sqrt{3}}$V, 30 VA, cl. 0.5**

Characteristics of Voltage Transformers:

Voltage transformer for protection:

Accuracy Class: These devices are used to show voltage measurements as accurate as possible in case of voltage drops (faults) or overvoltages for protection purposes.
In practice, the accuracy class 3P is used for all applications.
Accuracy is guaranteed for all loads of between 25 and 100% of the accuracy power with an inductive power factor of 0.8.

Error limits for each accuracy class

Accuracy class	Voltage error (± %) between		Phase shift error (minutes) between	
	5% Upn and KT	2% Upn and Kt	5% Upn and KT	2 % Upn and Kt
3P	3	6	120	240
6P	6	12	240	480

KT over-voltage coefficient.
Upn rated primary voltage.

Characteristics of Voltage Transformers:

Voltage transformer for protection:

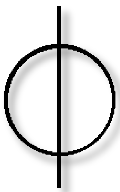
Example: Consider the following characteristics for a voltage transformer and explain the meaning of the values given.

$$\frac{22}{\sqrt{3}}\text{kV}/\frac{100}{\sqrt{3}}\text{V, 60 VA, 3P, KT=1.9}$$

Solution:

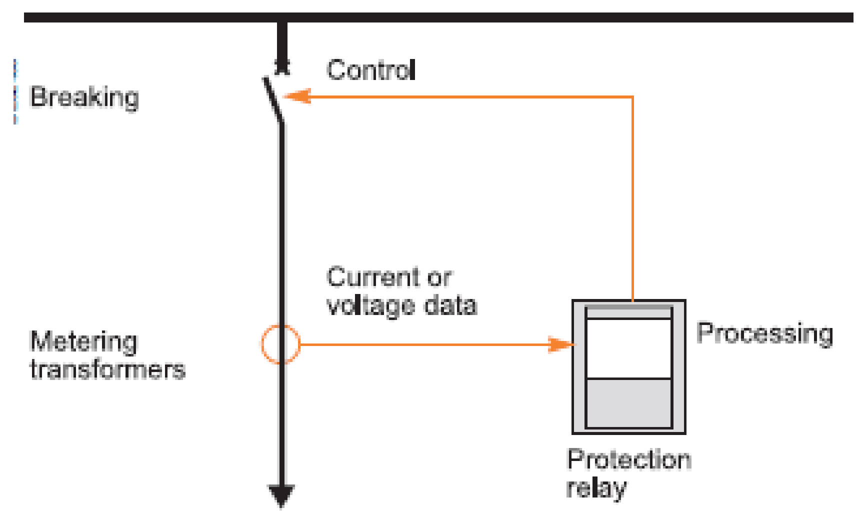
- Protection voltage transformer
- The rated primary voltage $22/\sqrt{3}$ kV, the rated secondary voltage $100/\sqrt{3}$ V
- Accuracy power 60 VA.
- Accuracy class 3P. The table of limit values shows that for:
    - A primary voltage of 5% of the rated voltage :1100 V, and KT times the rated voltage: 41800 V, and
    - the load is between 20% (6 VA) and 100% (30 VA) with inductive power factor of 0.8,

the measured voltage magnitude will be within $\pm 3\%$ error and phase angle within $\pm$120 minutes error.



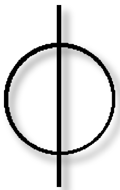
Characteristics of Current Transformers:

- ✓ One of the most important device in substation.
- ✓ Lowers operating current to the levels that can be used for measurements and protections.
- ✓ Secondary winding of current transformers must not be kept open.
- ✓ There are two types
  - CT : Current transformer
  - LPCT (Low power current transformer): Electronic current transformer



Example of a metering transformer application in a protection system.

Characteristics of Current Transformers:

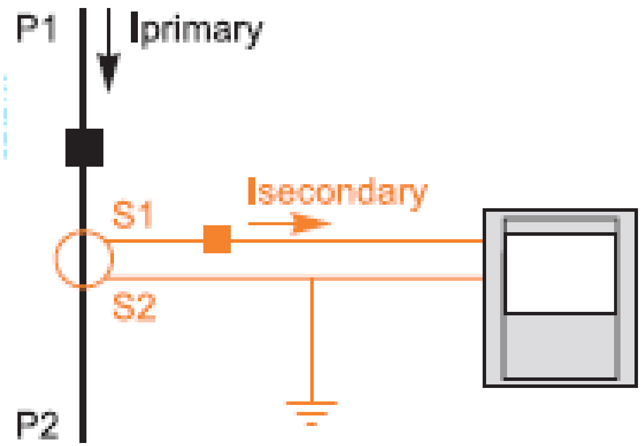


CT operation:

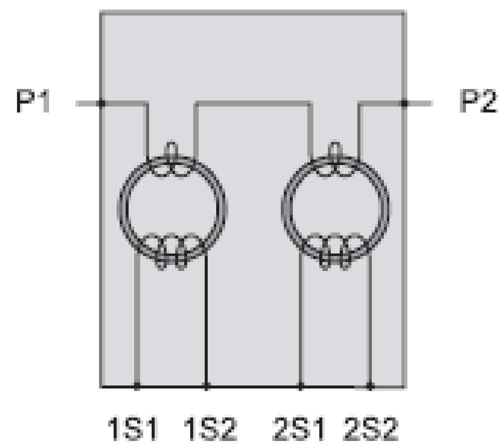
Terminal marking

CT connection is made to the terminals identified according to the IEC:

- P1 and P2 on the MV side
- S1 and S2 on the corresponding secondary. In the case of a double output, the first output is identified by 1S1 and 1S2, the second by 2S1 and 2S2.

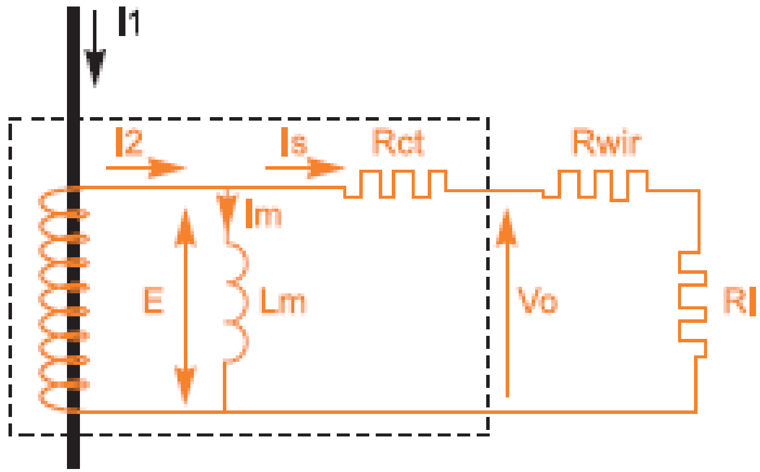


Current transformer shwing the terminals.



Characteristics of Current Transformers:

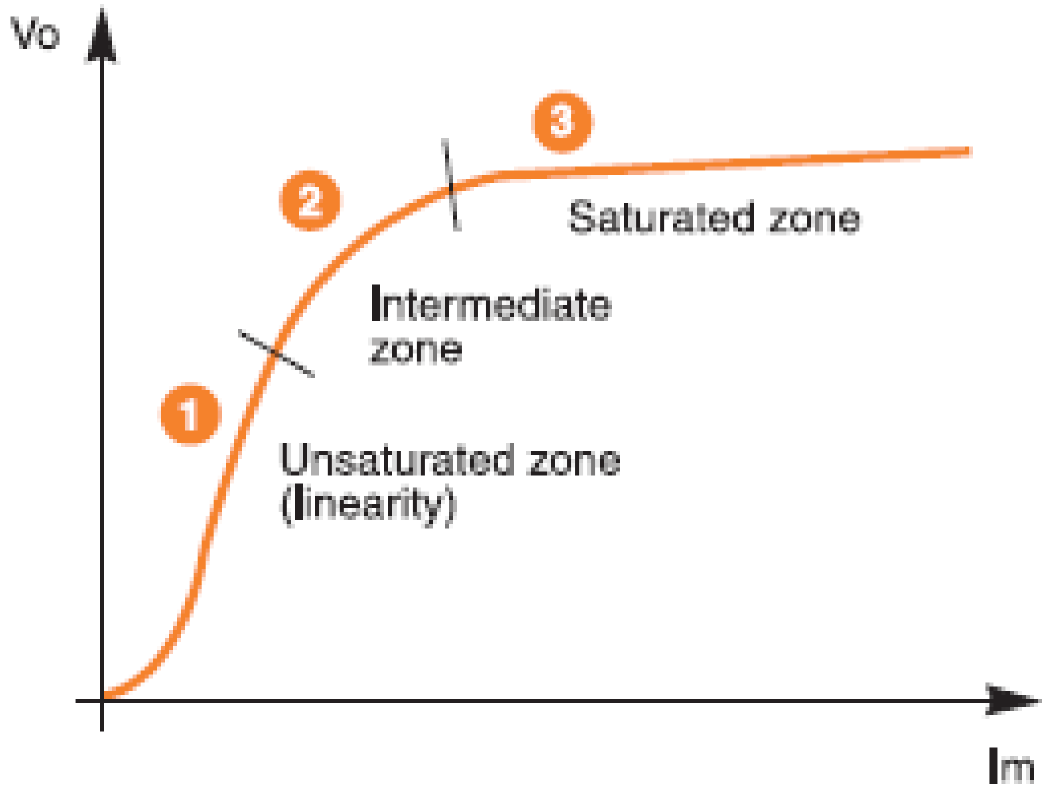
CT operation:



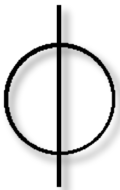
I1: primary current.
I2 = Kn I1: secondary current for a perfect CT.
Is: secondary current actually flowing through the circuit.
Im: magnetizing current.
E: induced electromotive force.
Vo: output voltage.
Lm: magnetization inductance (saturable) equivalent to the CT.
Rtc: resistance at the CT secondary.
Rfil: resistance of the connection wiring.
Rc: load resistance.

Characteristics of Current Transformers:

CT operation:



Magnetization curve (excitation) for a CT.
Output voltage as a function of the magnetizing current.
Vs = f (Im)



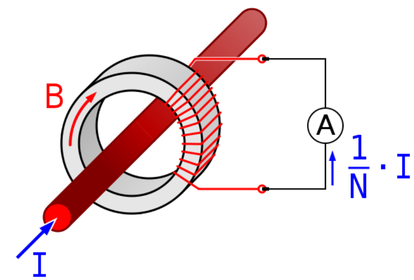
Characteristics of Current Transformers:

Rated primary currents (I_{pn}):

5 A, 10 A, 15 A, 20 A, 25 A, 30 A, 40 A, 50 A, 75 A,100 A, 150 A, 200 A, 250 A, 300 A, 350 A, 400 A, 450 A, 500 A, 600 A, 700 A, 800 A, 900 A, 1000 A, 1250 A, 1500 A

Rated secondary current:

1 A, 5 A



Accuracy powers:

10 VA, 15 VA, 20 VA, 30 VA

Short time thermal current (I_{th}):

Shows thermal witstand capability of transformer under short circuit conditions for 1 second. It is expressed as kA or in multiple of rated primary currents. (Examples: 100xI_{pn}, 150xI_{pn}, 200xI_{pn}, 250xI_{pn}, 350xI_{pn}, 400xI_{pn}, 450xI_{pn}, 500xI_{pn}, 600xI_{pn}, 700xI_{pn}, 800xI_{pn}, 900xI_{pn}, 1000xI_{pn})

The value of thermal withstand current for a different duration can be found by

$$I'_{th} = I_{th}/\sqrt{t}$$

Example: 16 kA at 1 second is equivalent to $\frac{16kA}{\sqrt{2}} = \mathbf{11.3\ kA}$ at 2 seconds.

Characteristics of Current Transformers:

Accuracy class:

Defines the limits of error quaranteed on the transformation ration and on the phase shift under the specified conditions of power and current. Classes **0.5** and **1** are used for metering and class P for protection.

Metering CT or protection CT:

Metering CT:

Requires good accuracy (linearity zone) in an area close to the normal service current. It must also protect metering devices from high currents by saturating earlier.

Protection CT:

Requires good accuracy at high currents and will have a higher precision limit (linearity zone) to detect the protection thresholds that they are meant to be monitoring.

Characteristics of Current Transformers:

Current transformer for metering:

Accuracy class:

- ✓ A metering CT is designed to measure the current accurately below 120% of the rated primary current.
- ✓ IEC 60044-1 determines the maximum error in the accuracy class for the phase and the magnitude according to the indicated operation range as follows.

Error limits according to the accuracy class

Accuracy class	% rated primary current	Current error ± %		Phase shift error ± mn	
			for S		for S
0.2 / 0.2S	1 (0.2S alone)		0.75		30
	5	0.75	0.35	30	15
	20	0.35	0.2	15	10
	100	0.2	0.2	10	10
	120	0.2	0.2	10	10
0.5 / 0.5S	1 (0.5S alone)		1.5		90
	5	1.5	0.75	90	45
	20	0.75	0.5	45	30
	100	0.5	0.5	30	30
	120	0.5	0.5	30	30
1	5	3		180	
	20	1.5		90	
	100	1		60	
	120	1		60	

Accuracy class according to application

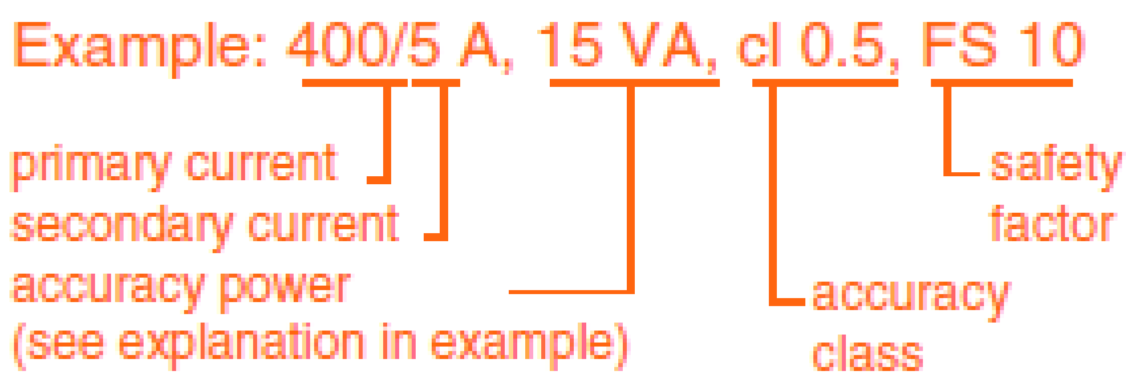
Application	Class
Laboratory measurement	0.1 - 0.2
Accurate metering (calibration devices)	
Industrial metering	0.5 - 1
Billing metering	0.2 - 0.5 - 0.2S - 0.5S
Switchboard indicators statistical metering	0.5 - 1

Characteristics of Current Transformers:

Current transformer for metering:

Safety factor:

- ✓ In order to protect the metering devices connected to the CT from high currents on MV side, transformers must have early saturation characteristics.
- ✓ The limit primary current (I_{pl}) is defined for which the current error in the secondary is equal to 10%. The standard then defines the Safety Factor (FS) as $FS = \frac{I_{pl}}{I_{pn}}$. Preferred value for FA is 10. This is multiple of the rated primary current from which the error becomes greater than 10% for a load equal to the accuracy power.



Characteristics of Current Transformers:

Current transformer for metering:

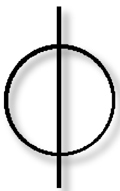
Example **: Explain the following information**

CT 200/5 A, 100xIn, 15 VA, cl. 0.5, FS 10

Solution **:**

- ✓ Current transformer for metering
- ✓ The nominal primary current 200 A and the nominal secondary current is 5 A.
- ✓ Thermal withstanding current 20 kA (100xIn)
- ✓ Accuracy power 15 VA.
- ✓ Accuracy class 0.5. Between 200 A and 240 A, current error will be within 0.5%. At 20% current (40 A), error will be equal or less than 0.75% according to the table before.
- ✓ Safety factor 10. When primary current exceeds 10 times of rated current (2000 A) error will be more than 10% if the load is equal to the accuracy load (Load between 20% to 100%)..

Characteristics of Current Transformers:



Current transformer for protection:

Accuracy class:

- ✓ A metering CT is designed to measure the current with approprate accuracy for a high currents such as overload or short circuit.
- ✓ IEC 60044-1 determines the maximum error in the accuracy class for the phase and the magnitude according to the indicated operation range as follows.

Error limits according to the accuracy class

Accuracy class	Combined error for the accuracy limit current	Current error between Ipn and 2Ipn	Phase shift error for the rated current
5P	5 %	±1 %	±60 mn
10P	10 %	±3 %	no limit

For example for class 5P the maximum error is ⩽ ±5 % at the accuracy limit current and ⩽ ±1 % at the rated current.

Standardized classes are 5P and 10P. The choice depends on the application. The accuracy class is always followed by the accuracy limit factor.

Characteristics of Current Transformers:

Current transformer for protection:

Accuracy limit factor (FLP):

- ✓ A metering CT is designed to measure the current with approprate accuracy for a high currents such as overload or short circuit.
- ✓ IEC 60044-1 determines the maximum error in the accuracy class for the phase and the magnitude according to the indicated operation range as follows.

- ✓ A protection CT must saturate at sufficiently high currents to enable sufficient accuracy in the measurements of fault currents by the protection device whose operating threshod can be very high.
- ✓ The limit primary current (I_{pl}) for which current errors and phase shift errors in the secondary do not exceed values in the table.
- ✓ The standad then defines the accurach limit factor FLP as $FLP = \frac{I_{pl}}{I_{pn}}$.

  Standard values are 5, 10, 15, 20, 30.

Characteristics of Current Transformers:

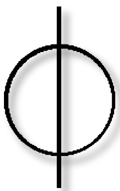
Current transformer for protection:

Example **: Explain the following information**

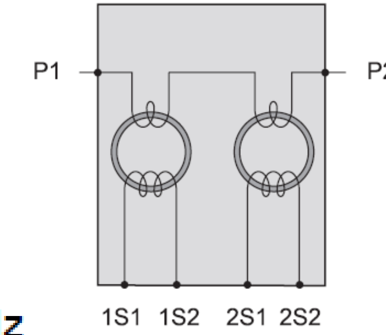
CT 100/5 A, 200xIn, 7.5 VA, 5P20

Solution **:**

- ✓ Current transformer for protection
- ✓ The rated primary current 100 A and the rated secondary current is 5 A.
- ✓ Accuracy power 7.5 VA.
- ✓ Accuracy class 5P. Under the load corresponding to the accuracy power of 7.5 VA, the error limit table gives an error equal or less than $\pm$1% and $\pm$60 mn at 100 A.
- ✓ Accuracy limit factor 20. At a load corresponding to the accuracy power, the error is equal or less than $\pm$5%.
- ✓ **Thermal withstanding is 20 kA (200x100=20 kA)**



Characteristics of Current Transformers:



Nameplate of a current transformer manufactured by Merlin Gerin:

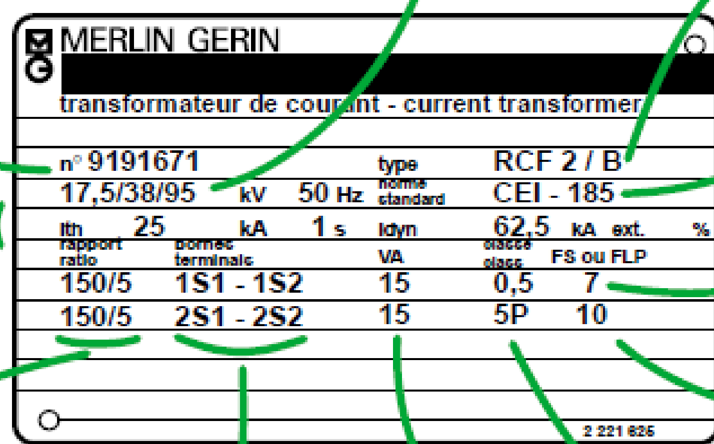
Network voltage characteristics
Rated insulation voltage: 17.5 kV
Power frequency withstand voltage: 38 kV 1 mn 50Hz
Impulse withstand voltage: 95 kV peak

CT serial number with year of manufacture

CT type

Applicable CT standard

Network current characteristic
I_{th} : 25 kA/1 s
I_{dyn} : 62.5 kA peak



Safety factor (SF)

Accuracy limit factor (ALF)

Ratio

1 primary circuit
1 secondary circuit 1S1 - 1S2
1 secondary circuit 2S1 - 2S2

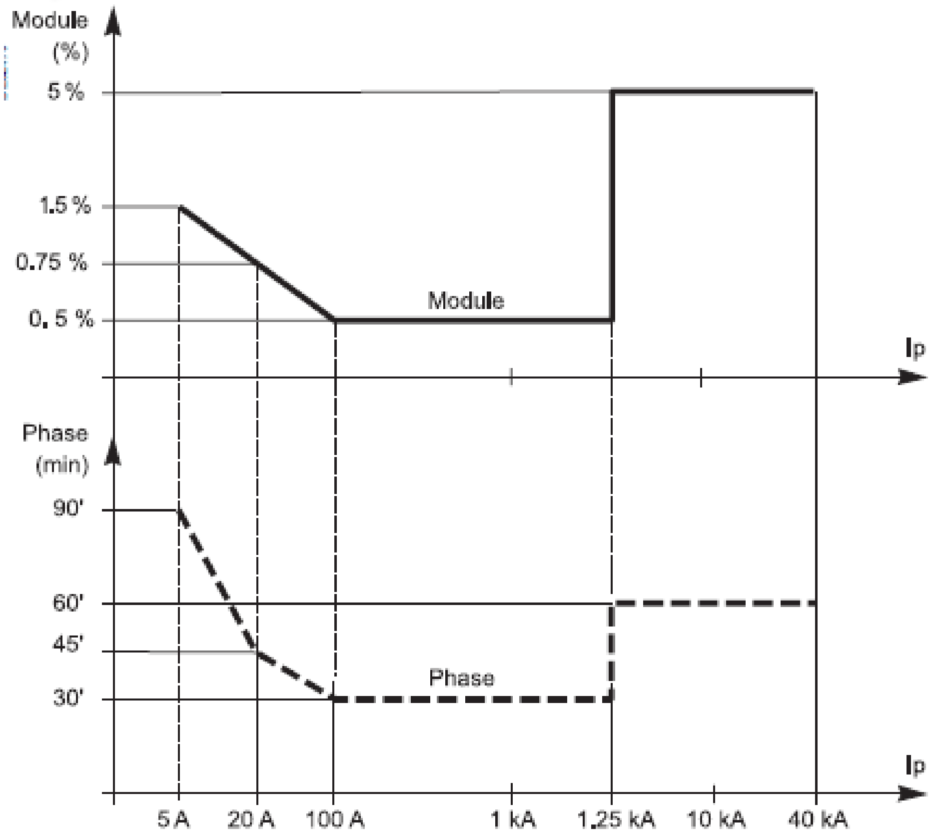
Accuracy power

Accuracy class

Characteristics of Low Power Current Transformers (LPCT):

- ✓ They are specific current sensors with a direct voltage output in conformity with standard IEC 60044-8.
- ✓ LPTC's provide metering and protection functions.
- ✓ They are defined by
  - The rated primary current.
  - The extended primary current.
  - The accuracy limit primary current or the accuracy limit factor.
- ✓ LPTC's have linear response over a large current range and do not saturate.

Characteristics of Low Power Current Transformers (LPCT):



Accuracy characteristics of a LPCT (example of Merlin Gerin's CLP1): the accuracy classes are given for extended current ranges (here class 0.5 for metering from 100 to 1250 A and protection class 5P from 1.25 to 40 kA).

Example for metering class 0.5

- ■ rated primary current Ipn = 100 A
- ■ extended primary current Ipe = 1250 A
- ■ secondary voltage Vsn = 22.5 mV (for 100 A on the secondary)
- ■ class 0.5:
- □ accuracy (see definitions on page 6.11) on:
- - the primary current module 0.5 % (error ≤ ±0.5 %)
- - the primary current phase 60 (error ≤ 30 minutes)

over a range of 100 A to 1250 A

- □ accuracy 0.75 % and 45 at 20 A
- □ accuracy 1.5 % and 90 at 5 A

which are two metering points specified by the standard.

Example for class 5P protection

- ■ primary current Ipn = 100 A
- ■ secondary voltage Vsn = 22.5 mV
- ■ class 5P:
- □ accuracy (see definitions page 6.11) on:
- - the primary current module 5 % (error ≤ ±5 %)
- - the primary current phase 60 (error ≤ 60 minutes) on a range of 1.25 kA to 40 kA.

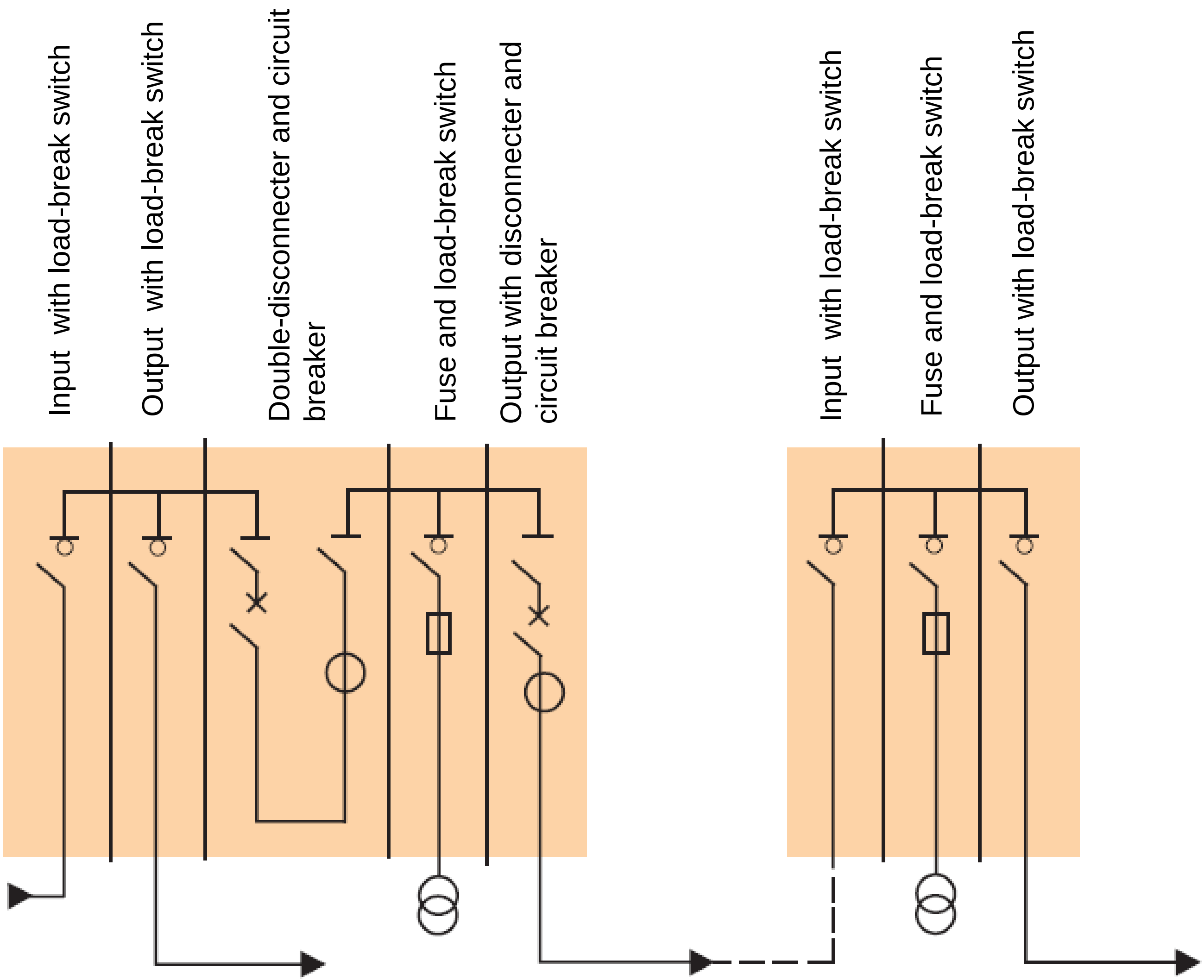
Characteristics of Low Power Current Transformers (LPCT):

Primary current		Secondary voltage (mV)	Accuracy class	Accuracy limit factor FLP	Short-time thermal current (kA - 1 s)	Rated insulation (kV)
rated (A)	extended (A)					
100	1250	22.5	0.5 – 5P	500	50	17.5
100	1250	22.5	0.5 – 5P	400	40	24
100	2500	22.5	0.5 – 5P	400	40	24
100	2500	22.5	0.5 – 5P	400	40	0.72
100	2500	22.5	0.5 – 5P	400	40	0.72

a brand of Schneider Electric

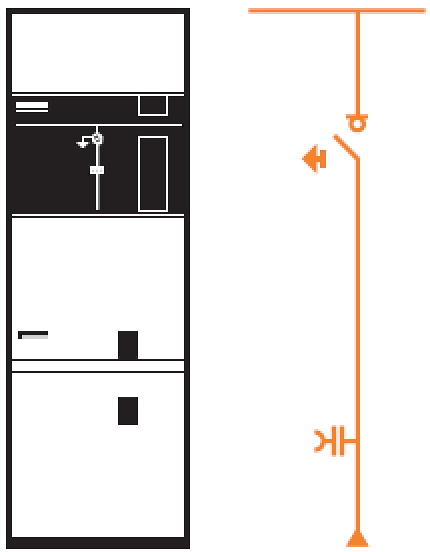
Substation Design

Cubicals and substation example:

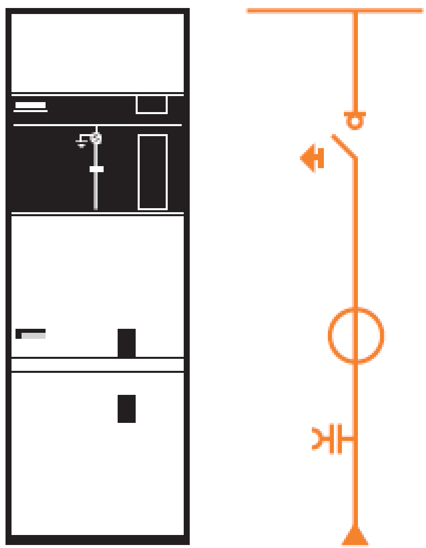


Substation Design

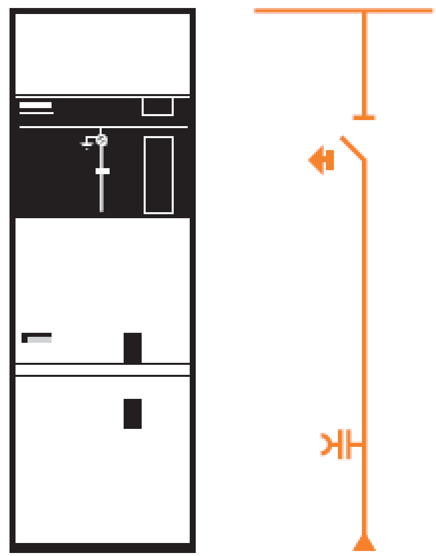
Cubicals: Connection to main (incoming) power supply



Load-break switch

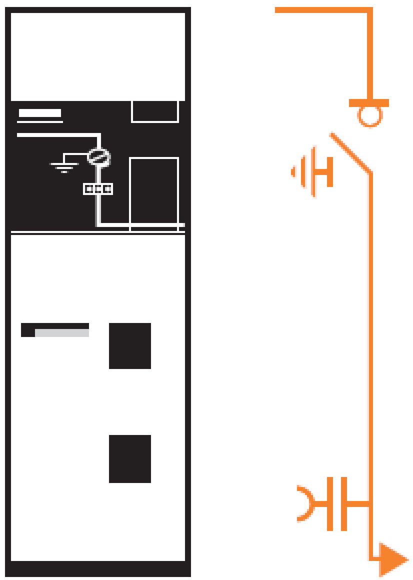


Load-break switch and current transformer

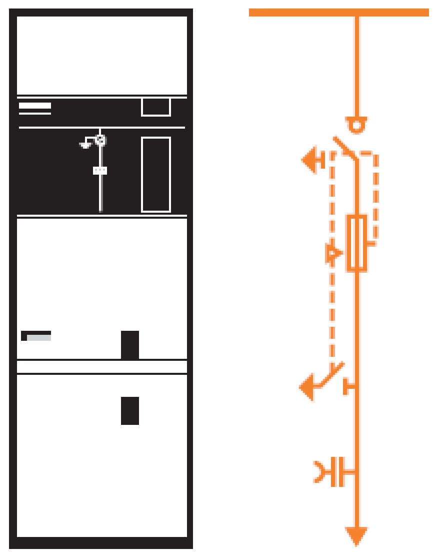


Disconnector (isolator)

Cubicals: Connection to downstream and protection



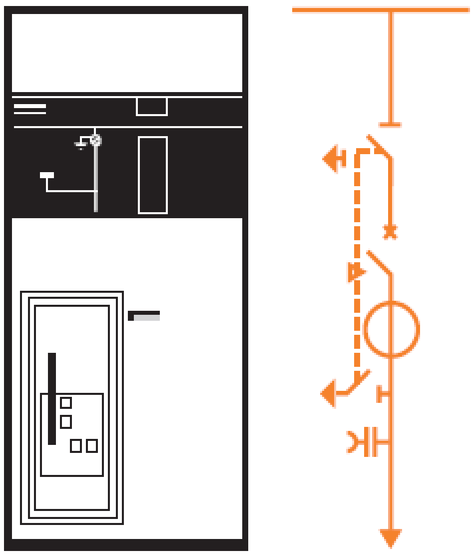
Load-break switch
(output from right)



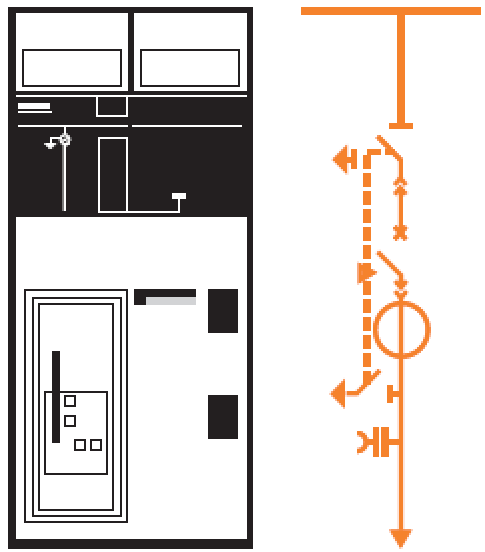
Fuse and load-
break switch

Substation Design

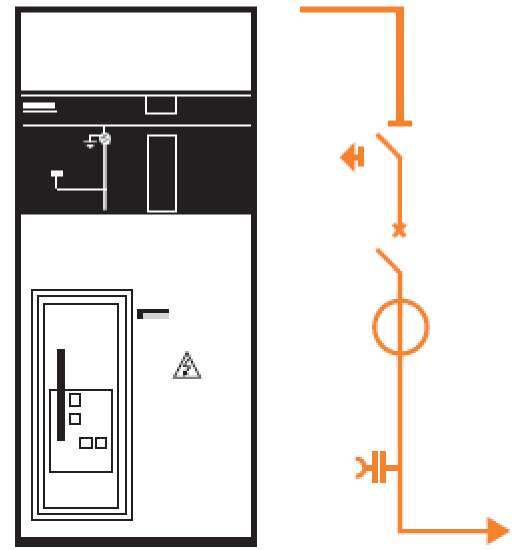
Cubicals: Protection with SF6



Circuit breaker



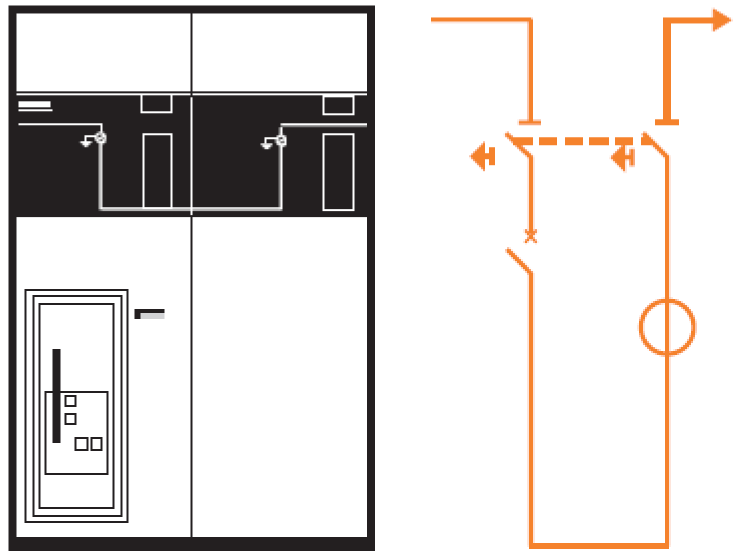
Drawout circuit breaker



Circuit breaker (output from right)

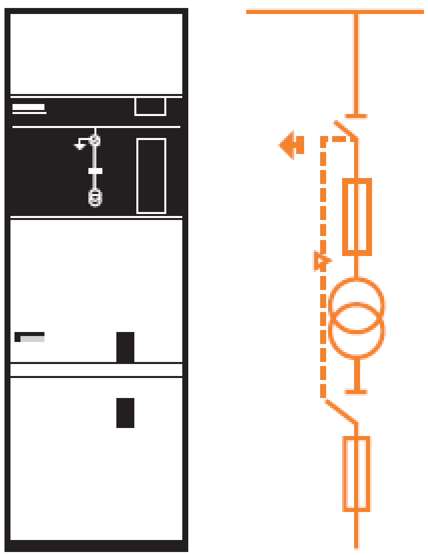
Substation Design

Cubicals: Protection with SF6

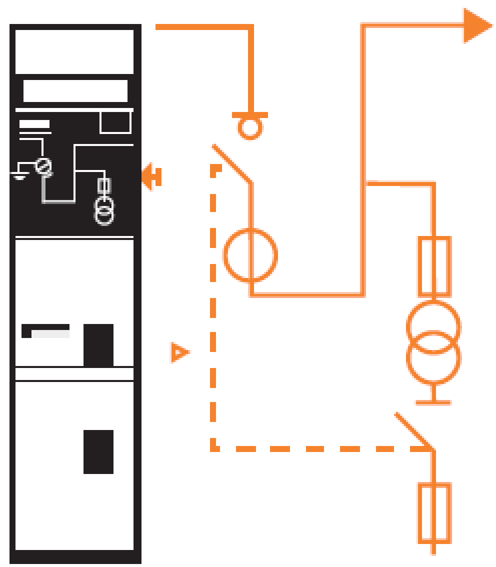


Double-disconnecter and
circuit breaker

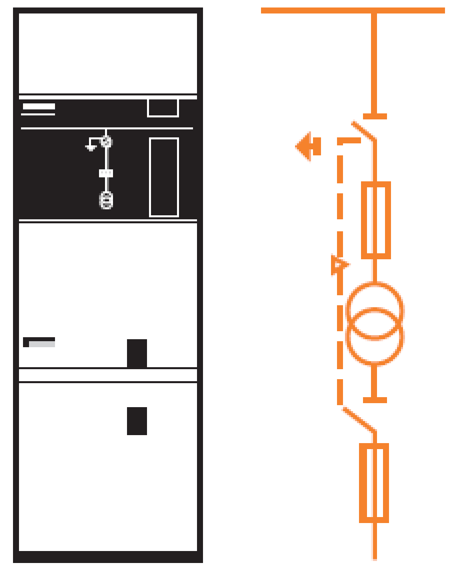
Cubicals: Measurements



Voltage
measurement unit
(phase-ground VT)



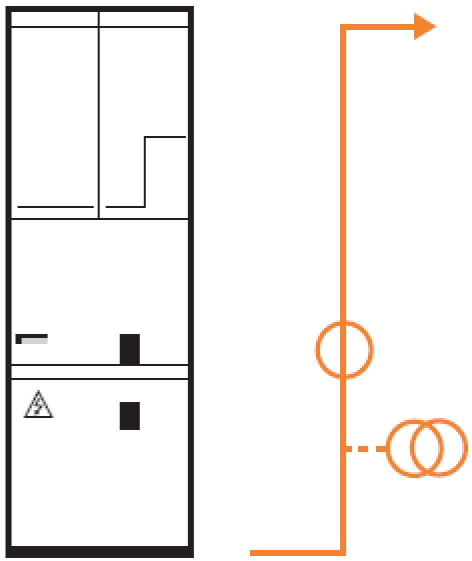
Voltage and current
measurement unit



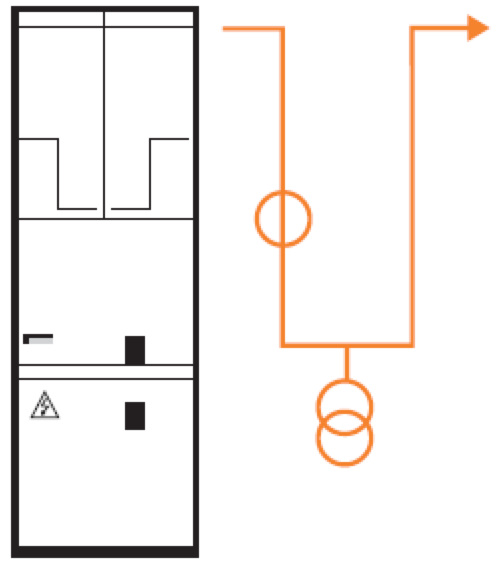
Input-output with
circuit breaker
(phase-ground VT)

Substation Design

Cubicals: Measurements



Voltage and/or current measurement unit plus busbar elevation



Voltage and/or current measurement unit

Substation Design

Example Design:

- A private company intend to build a new factory. Maxium required power for this factory is estimated as 1150 kVA.

Public Utility mentions the conditions as follows;
Your company will grid to a 36 kV cable network between Kartal and Pendik Distribution substations. Short circuit current of this network is 15,3 kA , Rated operational current is 525 A. Rated operational voltage is 31,5 kV.
A new indoor type transformer substation will be built by the Company, and including the following switchboard.

- *A load break switch feeder as incoming*
- *A circuit breaker feeder as outgoing*
- *A circuit breaker cubicle in order to isolate and protect of customer side*
- *A metering cubicle*
- *A transformer protection cubicle with CB*

a) Decide transformer power and ratings?
b) Draw single line diagramed including all necessary and related ratings of all devices

Example Design:

Standard ratings of Measurement current transformers
Powers: 10 VA, 15 VA, 20 VA, 30 VA
Currents (A/A) : 5/5,10/5,15/5,20/5,25/5,30/5,40/5,50/5
75/5,100/5,150/5,200/5,250/5,300/5,350/5,400/5,450/5,500/5,600/5,700/5,800/5,900/5,
1000/51250/5,1500/5
Types:
0,5 Fs 5 - 0,5 Fs 10 - 1 Fs 5 - 1Fs 10
5P10, 10p10, 5P20, 10P20
Thermal Withstand currents
100 In, 150 In, 200 In, 250 In, 300 In, 350 In, 400 In, 450 In, 500 In, 600 In, 700 In,
800 In, 900 In, 1000 In

Standart ratings of Measurement voltage transformes in Medium Voltage
Powers: 10 VA, 15 VA, 20 VA, 30 VA, 60 VA
Classes: 0,5, 1, 5
Primary voltages: (phase to phase) 6kV, 7,2 kV,10 kV,12 kV, 22 kV, 24 kV, 31,5 kV, 33 kV, 34,5 kV, 35 kV, 36 kV
Secondary voltages: (phase to phase): 100 V, 110 V, 220 V

Substation Design

Example Design:

Standart ratings of HRC fuses in Medium Voltage
Rated nominal currents:1 A, 5 A, 10 A, 15 A, 20 A, 25 A
Rated nominal voltages: 6 kV, 7,2 kV, 12 kV, 24 kV, 36 kV

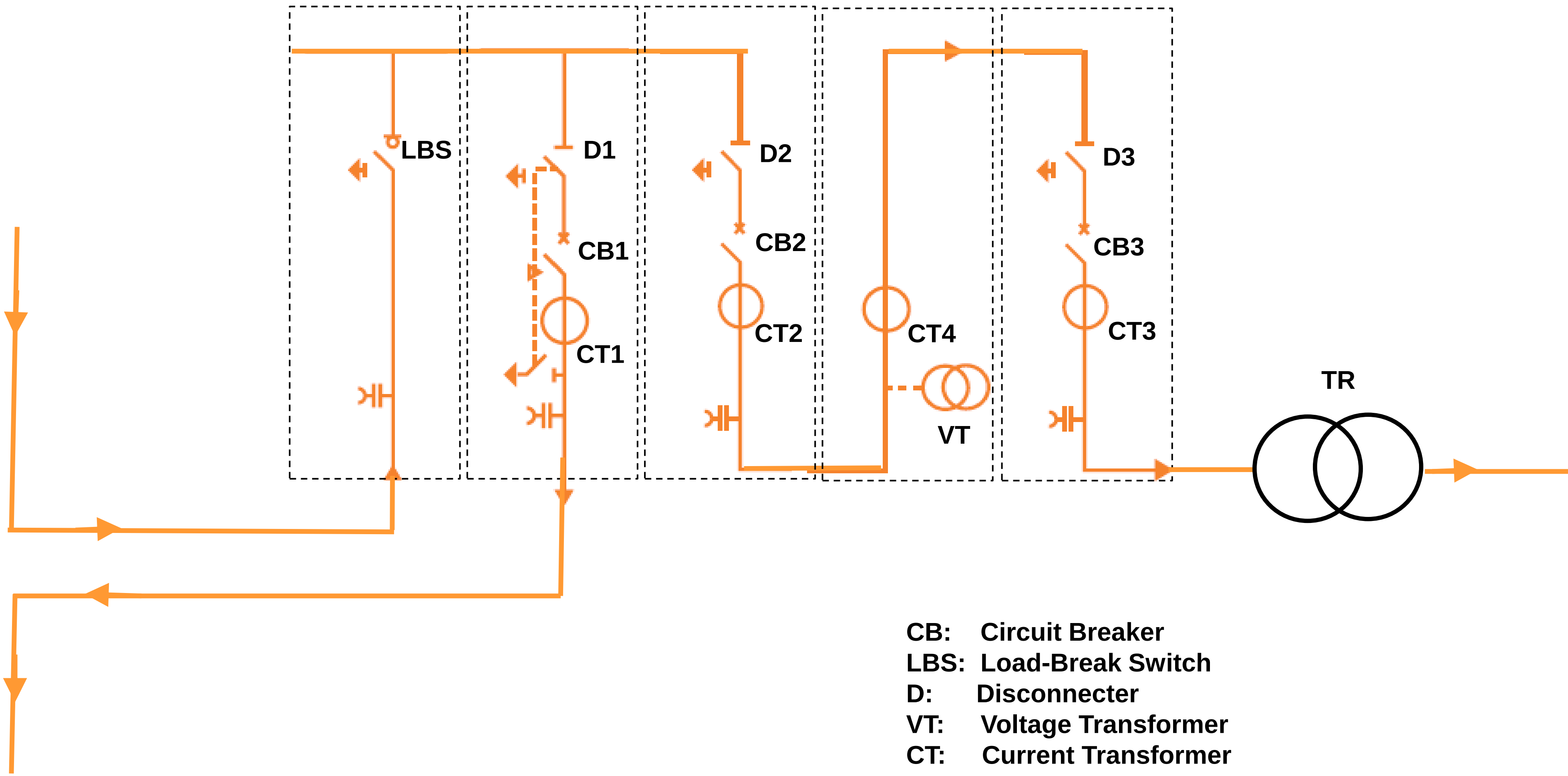
Standart ratings of Distrubiton Transformers in Medium Voltage
Powers: 25 kVA, 50kVA, 100kVA, 250 kVA,400 kVA, 630 kVA, 800 kVA, 1000 kVA, 1250 kVA, 1600 kVA, 2000 kVA, 2500 kVA
Primary voltages: (phase to phase): 6kV, 7,2 kV,10 kV,12 kV, 22 kV, 24 kV, 31,5 kV, 33 kV, 34,5 kV, 35 kV, 36 kV
Secondary voltages: (phase to phase): 380 V, 400 V

Standard ratings of Switchgears in Medium Voltage

Short circuit currents:	8 kA,12,5 kA, 16 kA, 20 kA, 25 kA
Rated nominal currents:	630 A, 800 A, 1250 A, 1600 A, 2000 A, 2500 A
Rated nominal voltages:	6 kV, 7,2 kV, 12 kV, 24 kV, 36 kV

Substation Design

Solution:



CB: Circuit Breaker
LBS: Load-Break Switch
D: Disconnecter
VT: Voltage Transformer
CT: Current Transformer

Substation Design

Solution: