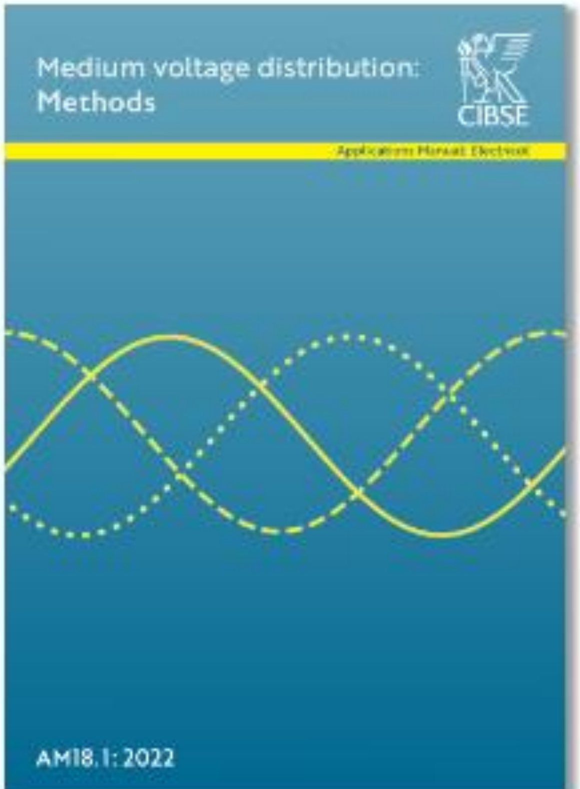
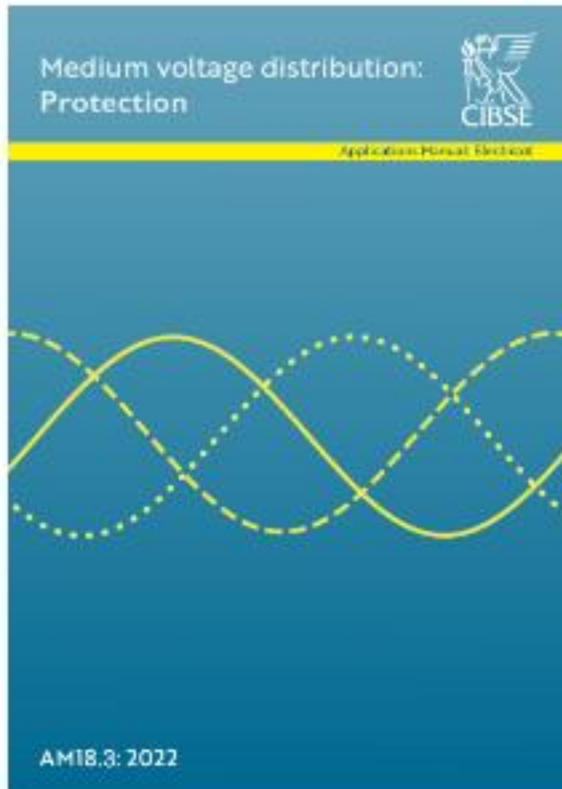
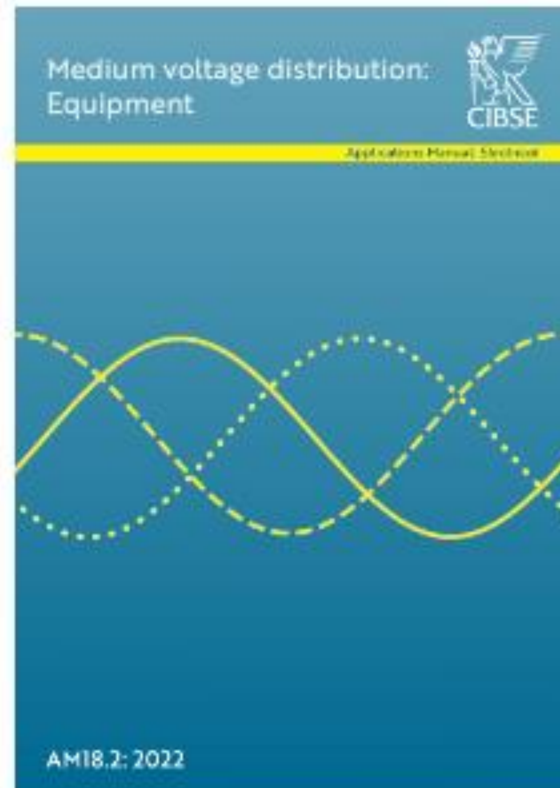
Les Norman
Adam Rawlinson
Phil Read

Applications Manual 18…
Medium Voltage Distribution







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AM18.1: Methods

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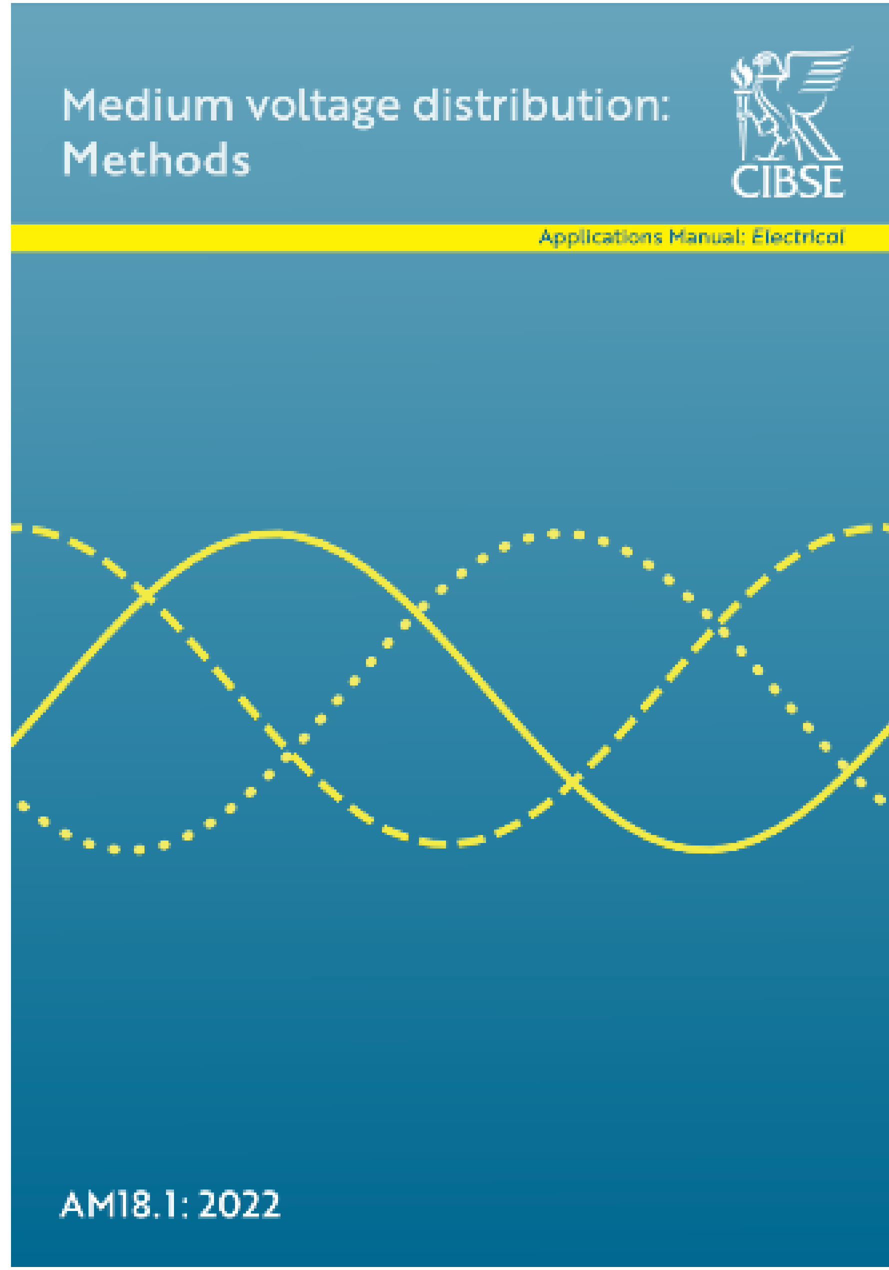


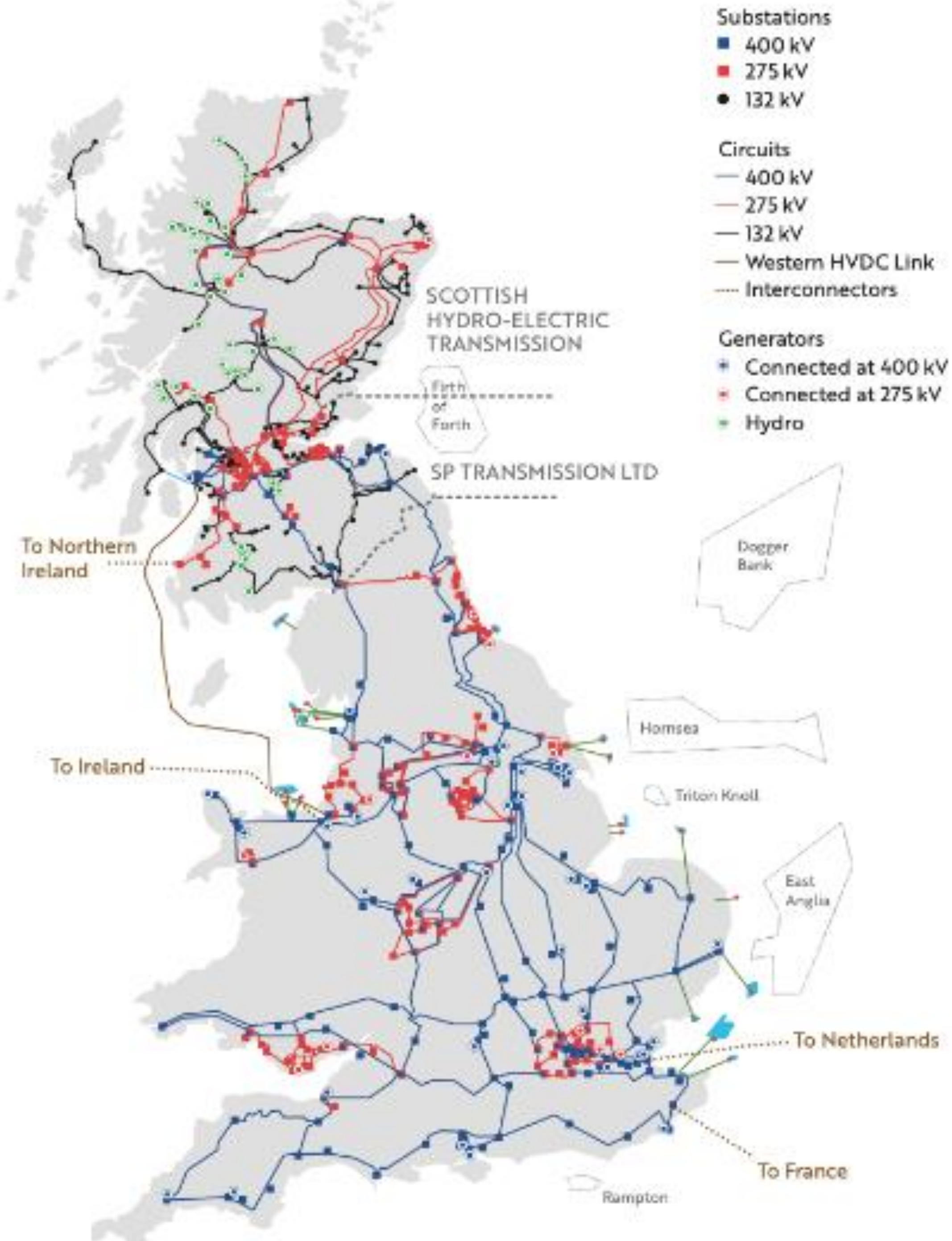
What is 'Medium' Voltage?

- BS 7671:2018, defines 'High Voltage' as anything exceeding 1,000 V AC
- But that is too broad a definition for the industries that deal with:
  Power Generation, Transmission, and Distribution

So, the following definitions are used for AM18….

- Low Voltage (LV): below 1 kV
- Medium Voltage (MV): 1 kV – 35 kV
- High Voltage (HV): 35 kV – 230 kV
- Extra High Voltage: (EHV) > 230 kV

Transmission System of Great Britain



Why MV?

- For any given load, the current requirement is lower
- Voltage losses are lower and a smaller fraction of the supply voltage

BUT

- Increased danger levels
- Higher cost of insulation
- Staff training mandatory for operation and maintenance

MV Protective Systems

Have three main functions:

- To safeguard the entire power system and maintain continuity of supply where it is safe to do so
- To minimise damage (and repair costs) if a fault occurs
- To ensure the safety of personnel

Protection Relays
(and the Circuit Breakers they control)

Main functions:

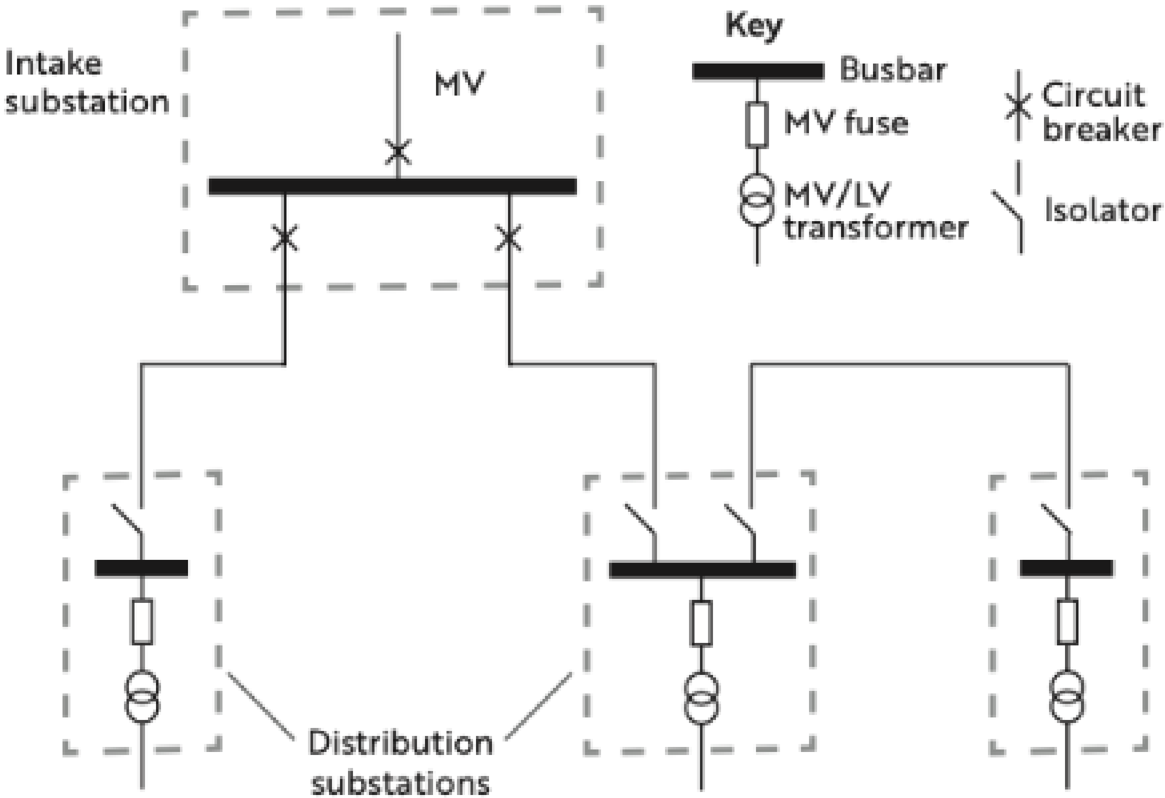
- Selectivity (Discrimination) – to detect and isolate the faulty equipment and leave all remaining heathy circuits intact; thereby ensuring continuity of supply
- Sensitivity – to detect a fault before it can cause excessive damage or danger to life
- Speed – to operate dependably and rapidly when necessary – again to minimise damage and ensure safety to personnel.

Methods of Distribution

In practical terms, these resolve themselves into Radial and Ring-circuit, for example:

- Radial Distribution:
  - Cheapest method
  - **ALL** complex systems are broken down into a series of radial circuit calculations
  - Not very secure since a fault at any point will disconnect the remainder of the site
  - But may be appropriate where single overhead line is the source of power.

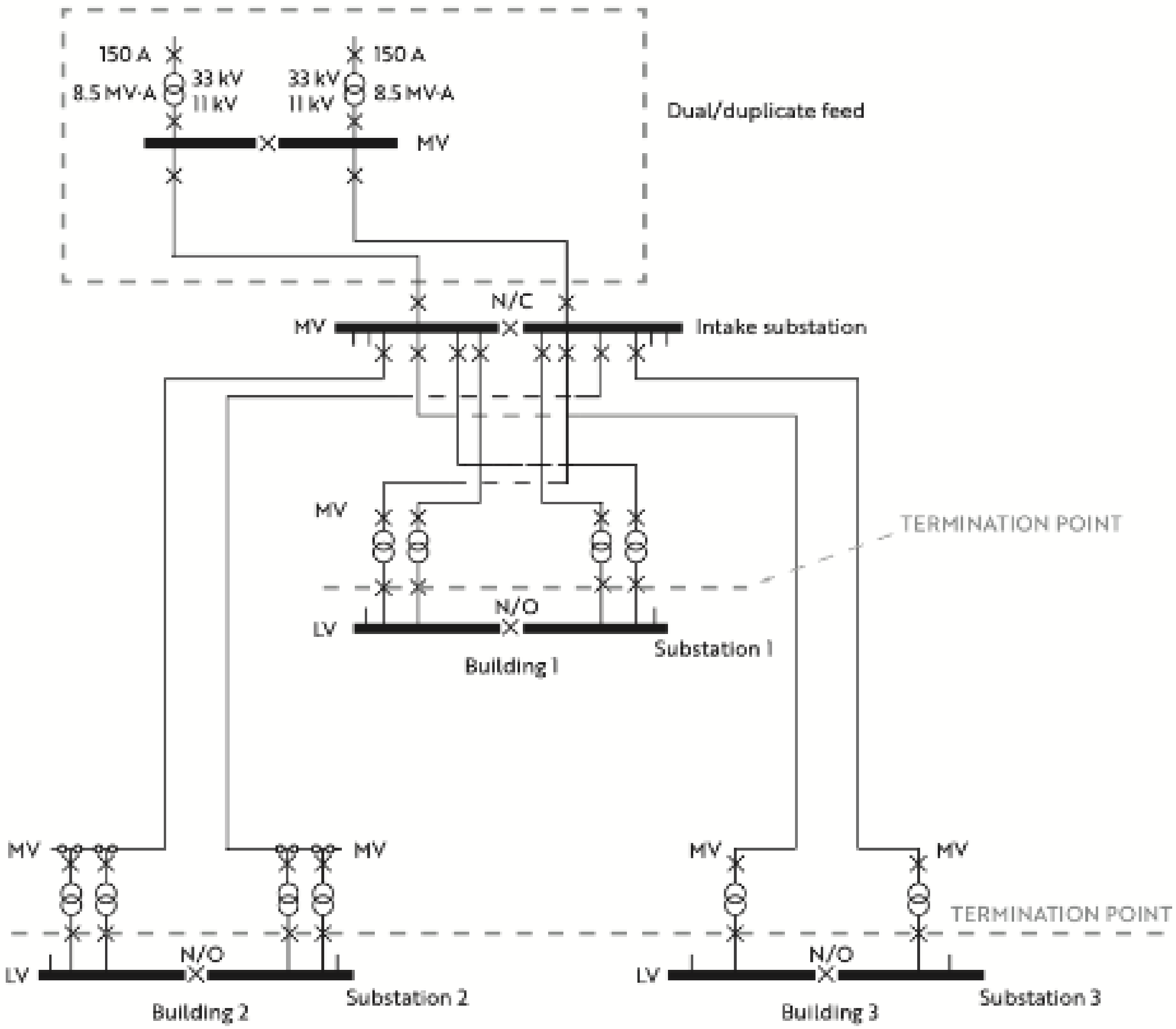
Radial Circuit Control



The type of switchgear often depends on the size of the load, e.g.

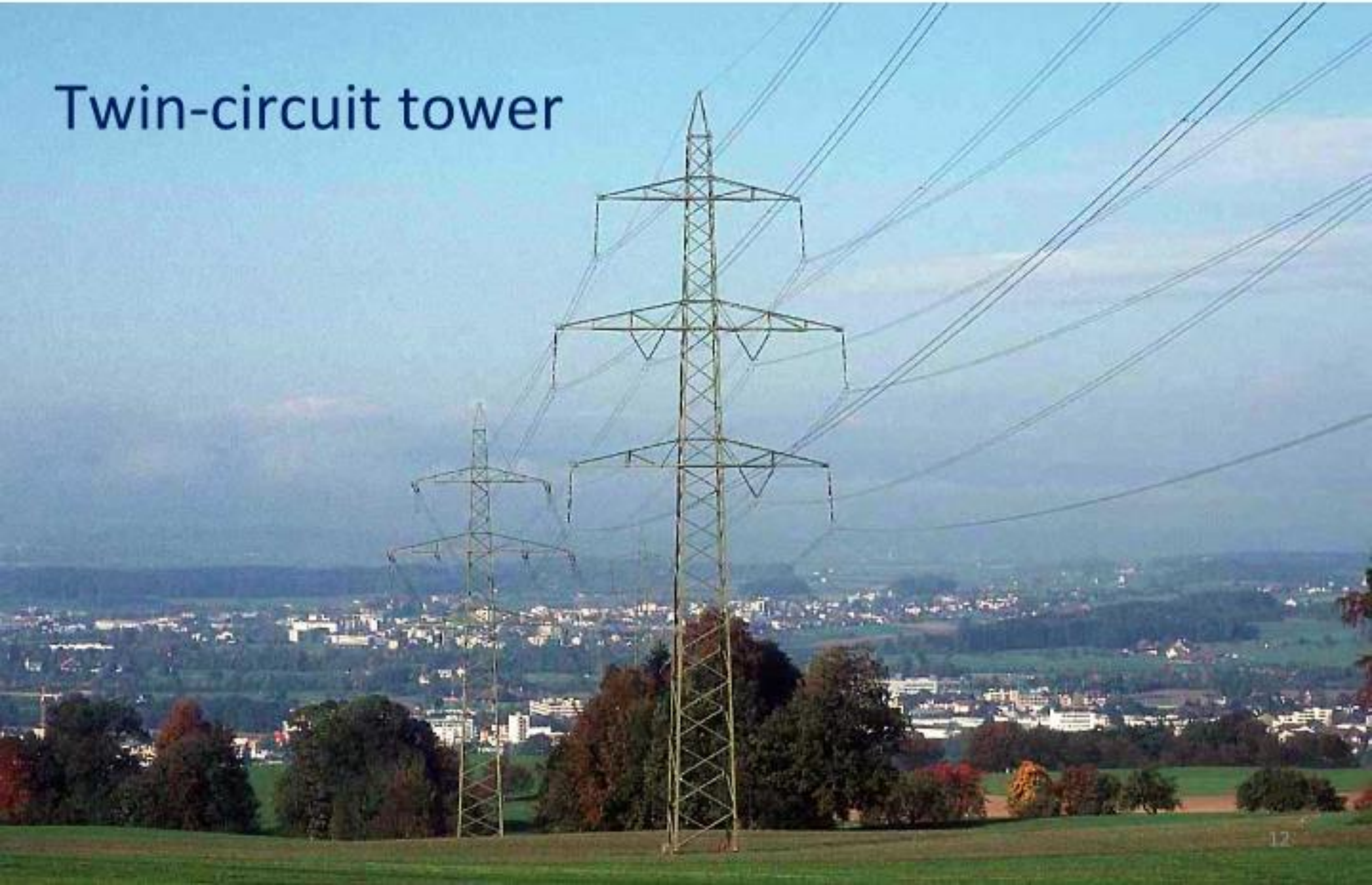
- load < 1000 kVA and **no** standby generation: still common to use MV fuse-switches or circuit-breakers controlled by time-limit fuses (TLFs).
- Otherwise, circuit-breakers controlled by overcurrent relays are usually required.

Dual/Duplicate Feed

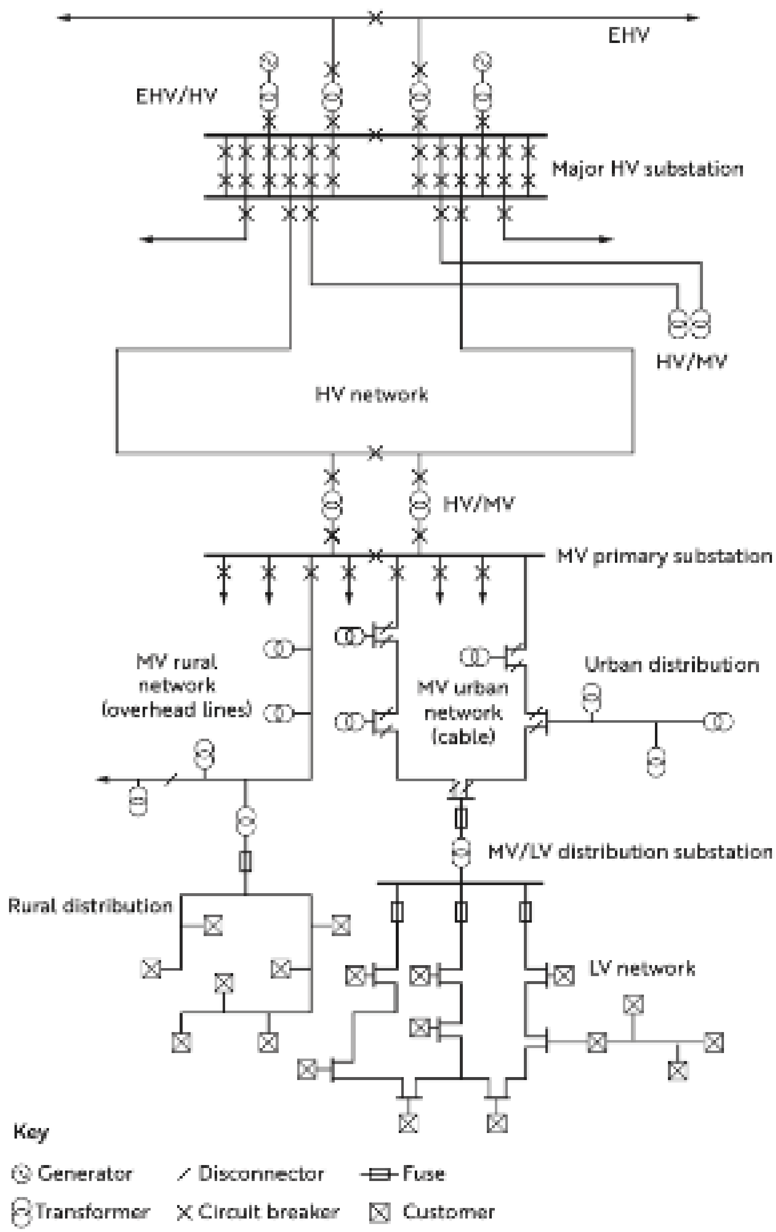


- More secure but expensive since it requires each feeder to be equipped with circuit breakers at each end and other controls for automatic changeover.
- The system is not common for building services.

• The method is more appropriate for transmission lines where the loss of service can disrupt major portions of the network.



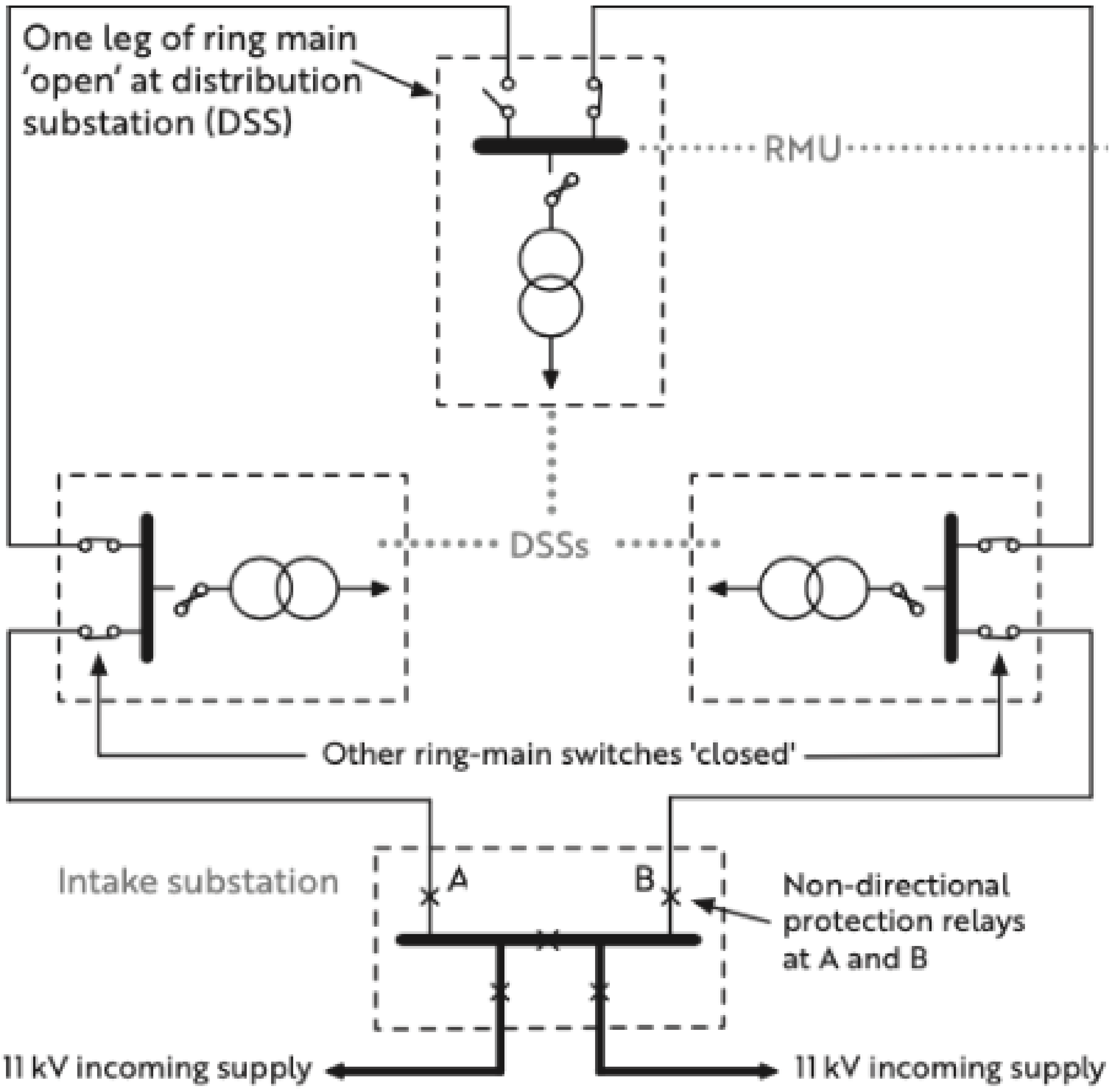
Security of Supply



- For many users, a single incoming MV supply is all that can be justified, and in remote areas (where the 11 kV supply may be derived from a single overhead line) there is little point in trying to make any local distribution more secure. Money is better spent in providing standby generation.

- Urban supplies offer ring-main possibilites; the most secure being where the normal and the alternative supply are drived from separate sections of the DNO (Distribution Network Operator) network with automatic changeover.

Open Ring-main



- The most cost-effective and common method of MV distribution – it effectively ensures supply from two alternative directions to each part of the installation.

The ring-main is operated with an open point; usually set to evenly apportion the normal load across each leg of the ring.

Ring Main Unit (RMU)

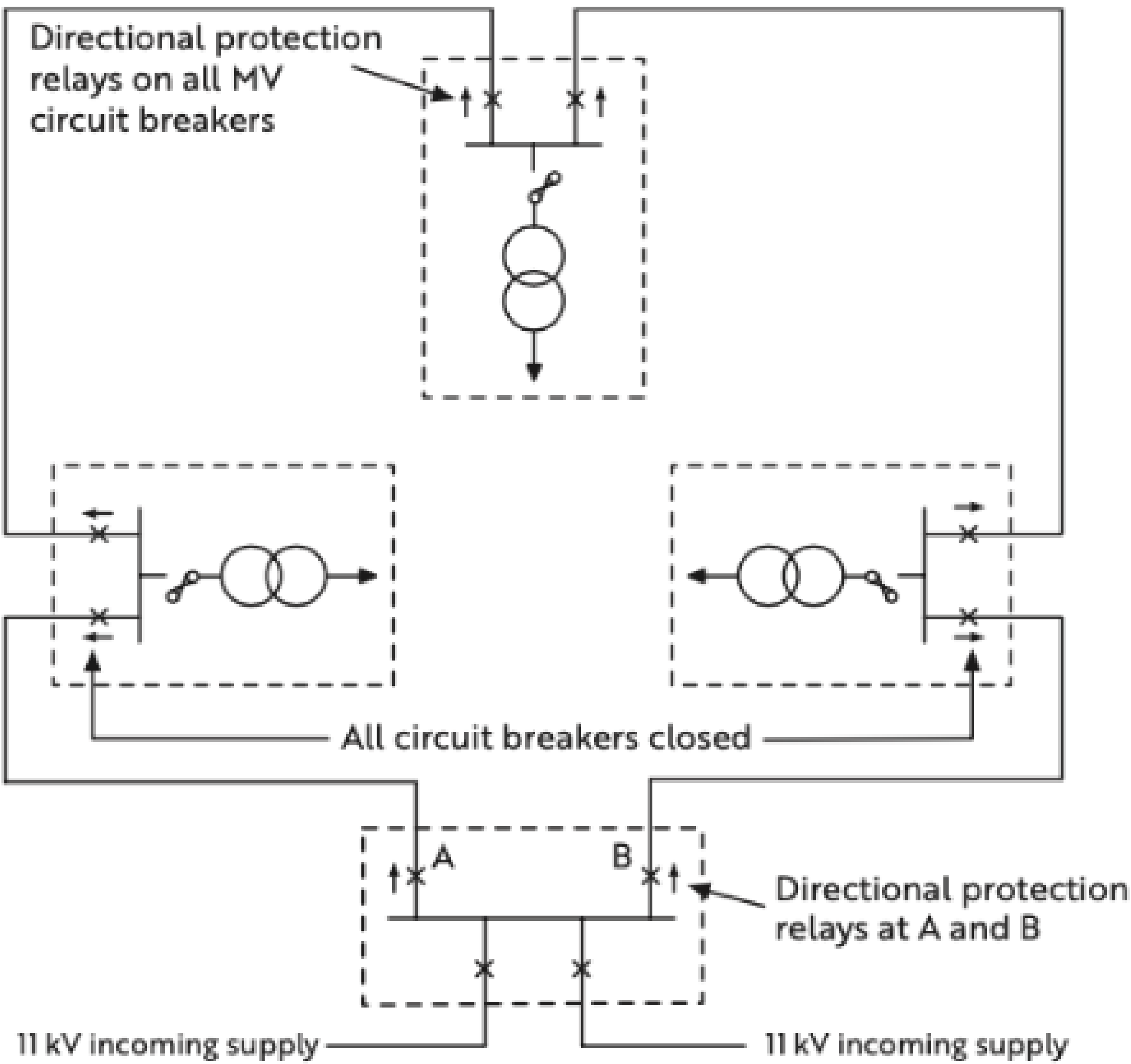
- Usual configuration is:
  – 2 ring switches and a
  – 'T-off' fuse-switch or circuit breaker.

- Each **ring switch** will have three positions of operation: **ON, OFF** and **EARTH** (applies earth to the ring-main cable)

- The '**T-off**' fuse switch will again have three operating positions: **ON, OFF** and **EARTH** (applies earth to the T-Section)

- Circuit-breakers can be Oil, Gas-insulated or Vacuum and can be operated by Time Limit Fuses or Protection Relays

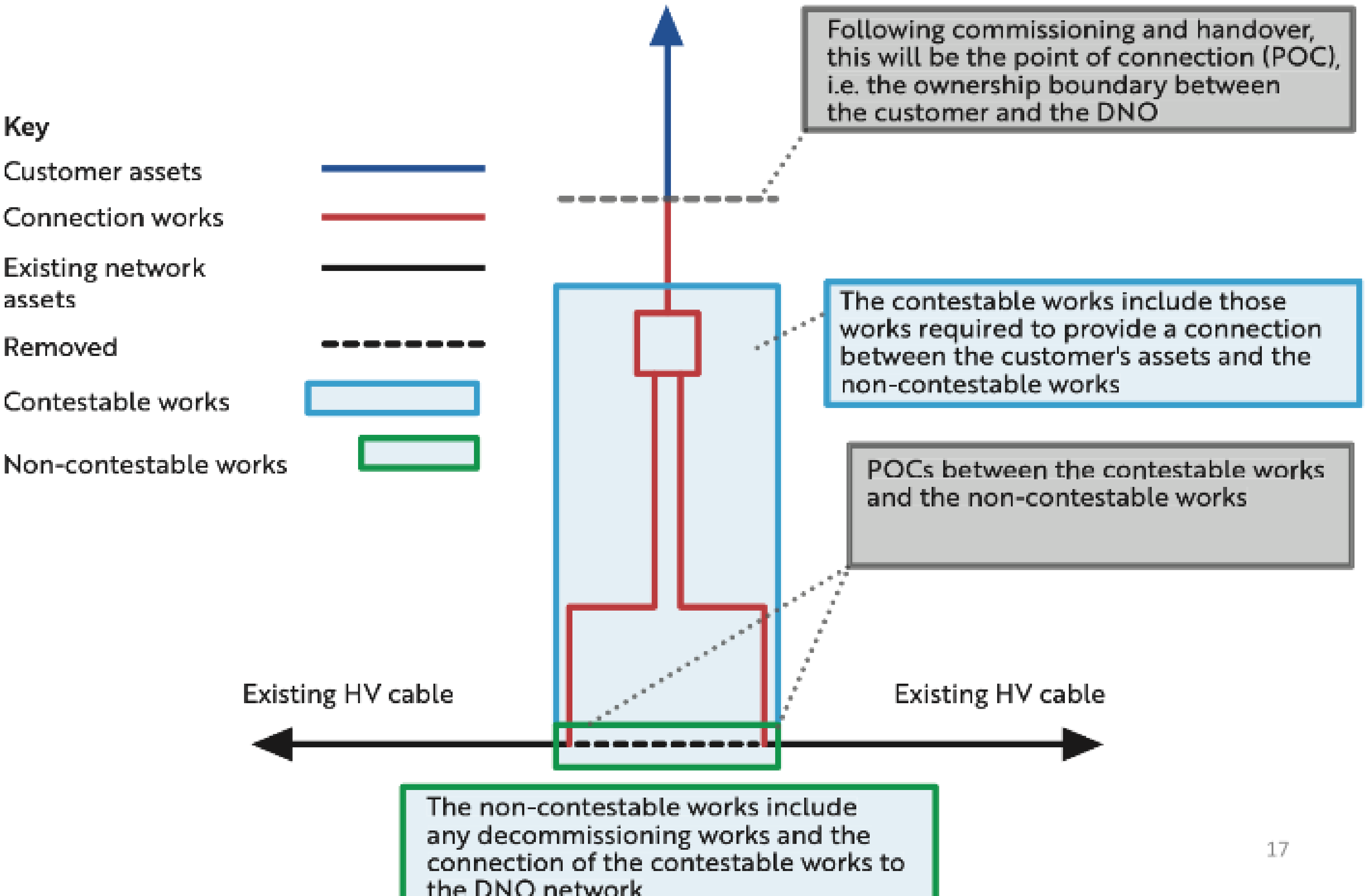
Closed Ring-main



- More secure but expensive option. However, in the event of a fault only the faulty section isolated

- Because each substation is permanently fed from two directions it is necessary to provide directional protection or unit protection relays.

New Connections



Electrical Safety

- The EAW Regulations – made under Section 15 of the Health and Safety at Work etc. Act 1974 – require precautions to be taken against the risk of death or personal injury from electricity in work and work-related activities.

- Injuries are those caused by electric shock, electric burns, electrical explosion or arcing, or from fire or explosion initiated by electrical energy.

- Their general effect is to require that all electrical systems, irrespective of operating voltage, are designed, installed, operated and maintained so as to prevent ‘danger’, which is defined as ‘risk of injury’.

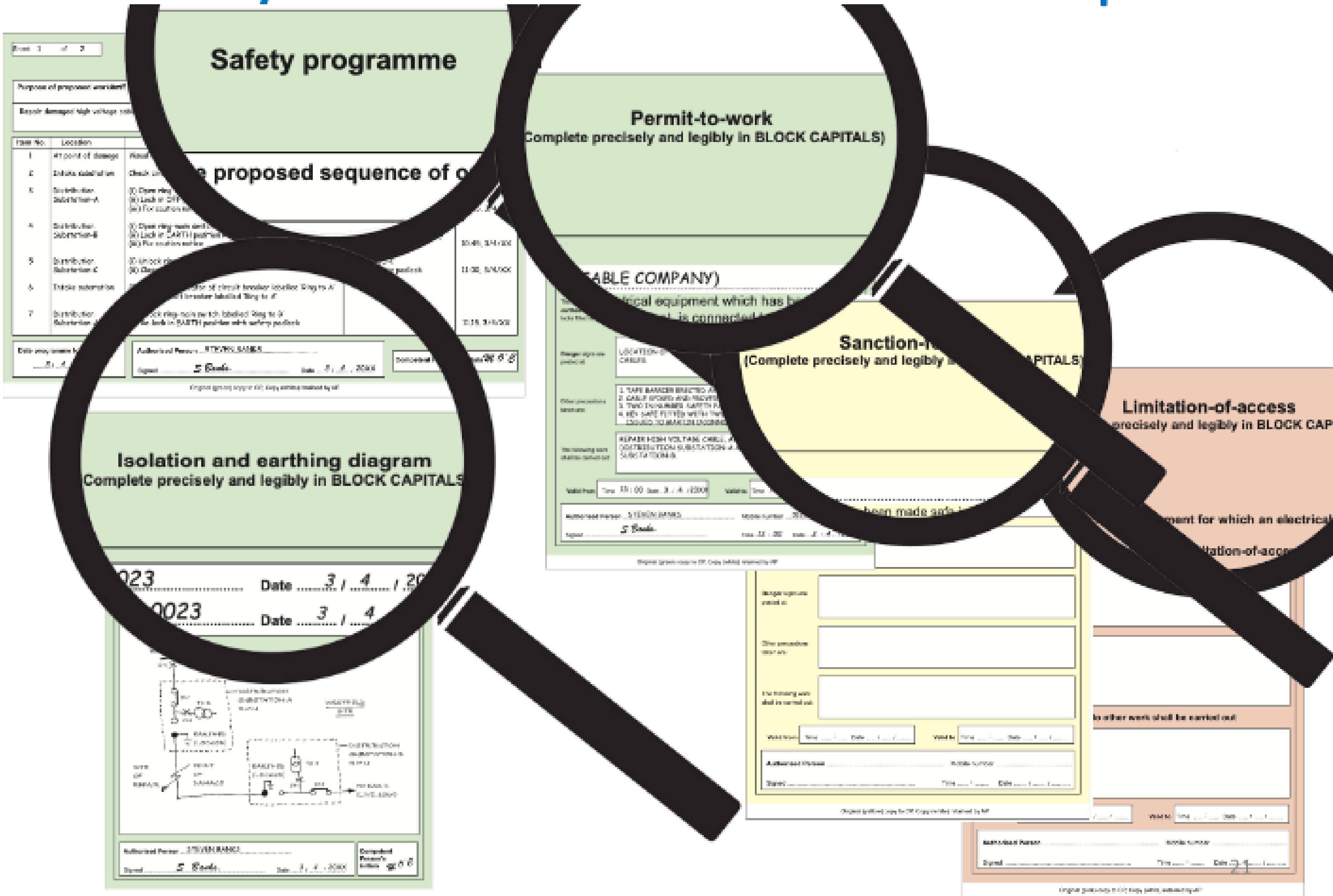
Designated Personnel

- Authorising Engineer
- Senior Authorised Person
- Authorised Person
- Competent Person
- Responsible Person

Safety Documentation

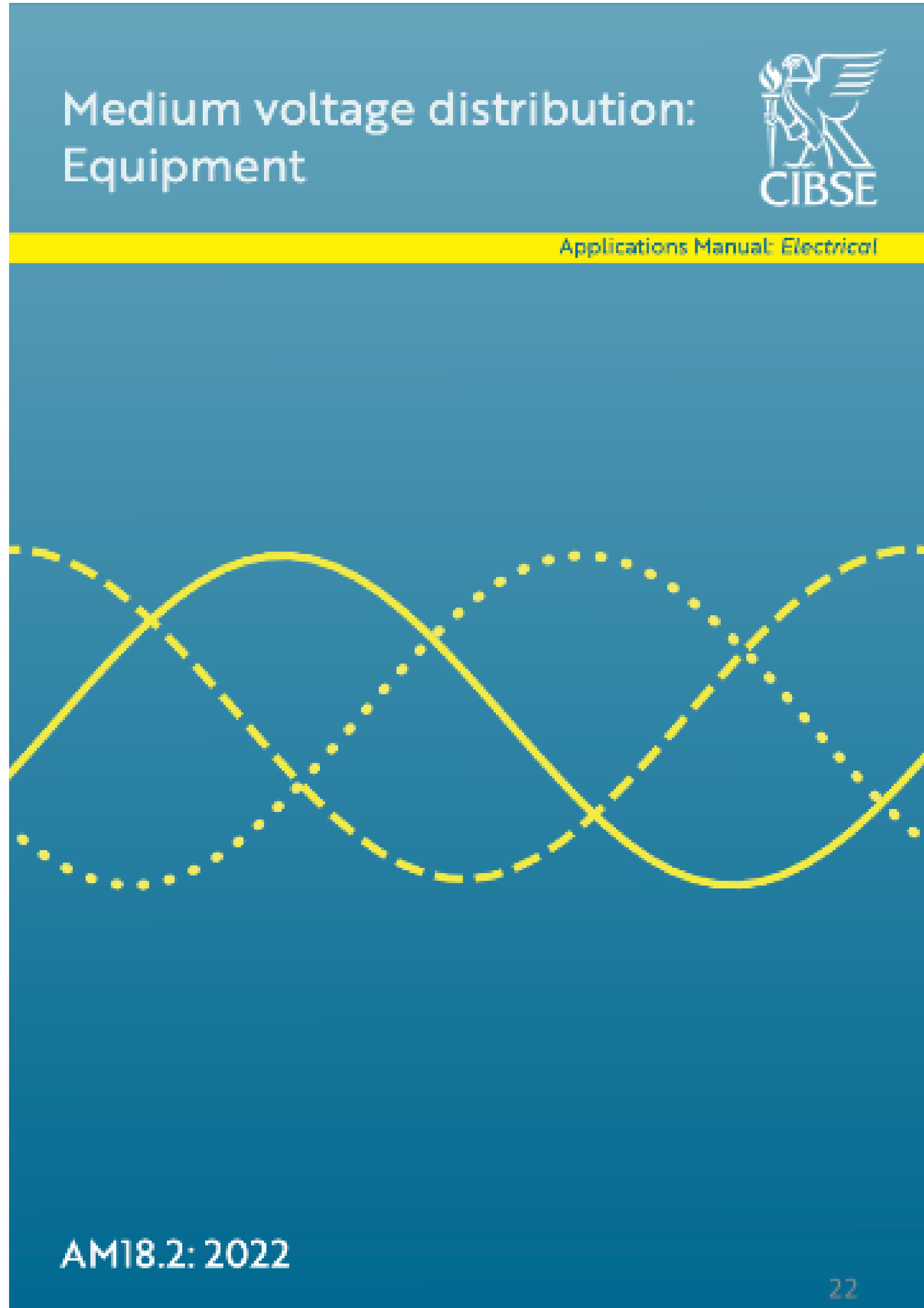
- Safety Programme (Switching Schedule)
- Isolation and Earthing Diagram
- Permit to Work
- Sanction for Test
- Limitation of Access

Safety Documentation – Examples

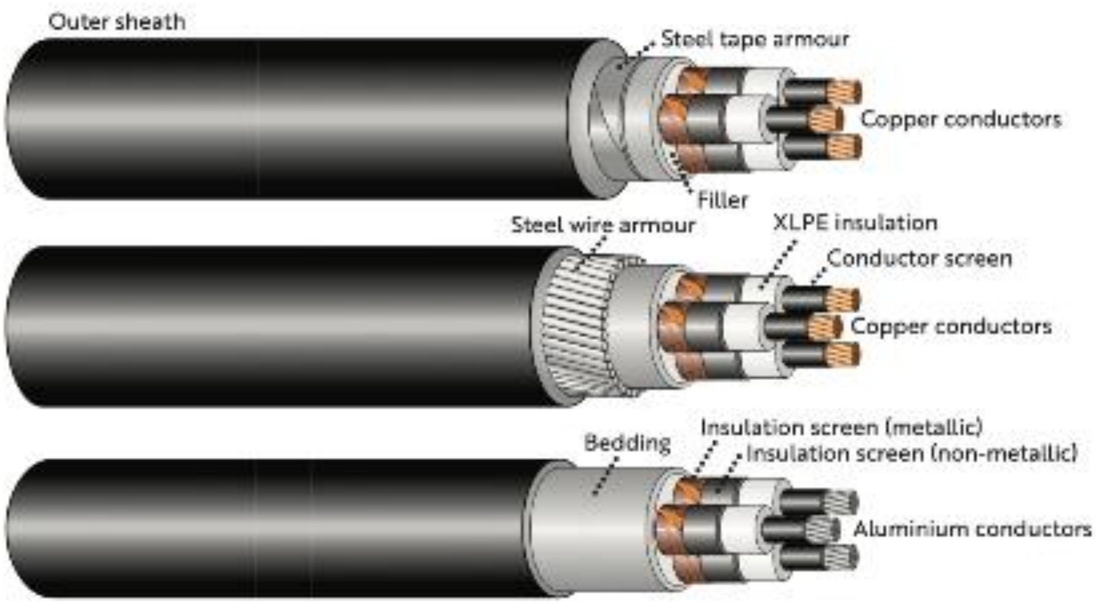


AM18.2: Equipment

- Cable Types
- MV Switchgear
  - Isolation Methods
- Circuit Breakers
  - Oil
  - Gas-Insulated
  - Alternatives to SF6
  - Vacuum
- Transformers
  - Types
  - Harmonics
  - Specification
- MV Maintenance



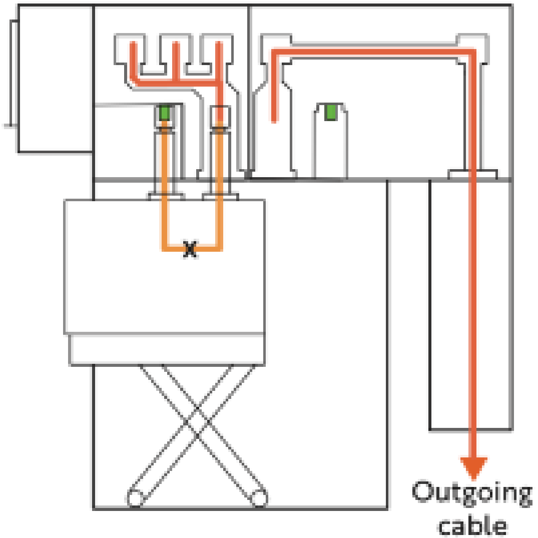
Cable Types



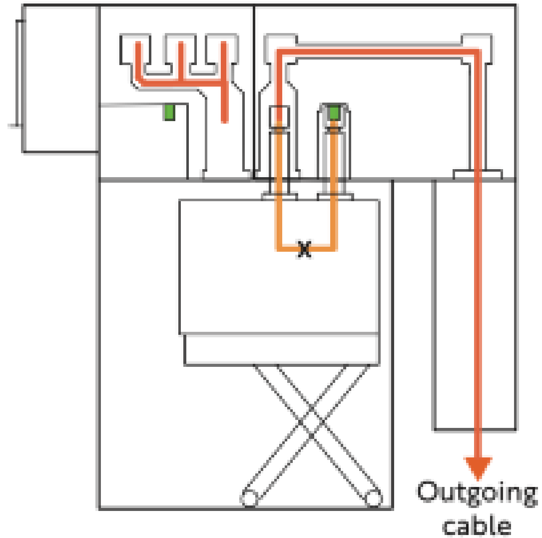
- Cable parameters
- Short-circuit ratings
- Selection Flowchart
- Cable Data for:
  - XLPE/SWA
  - XLPE/LSZH/SWA
  - XLPE/MDPE/SWA
  - XLPE/PVC

MV Switchgear

Isolation Methods



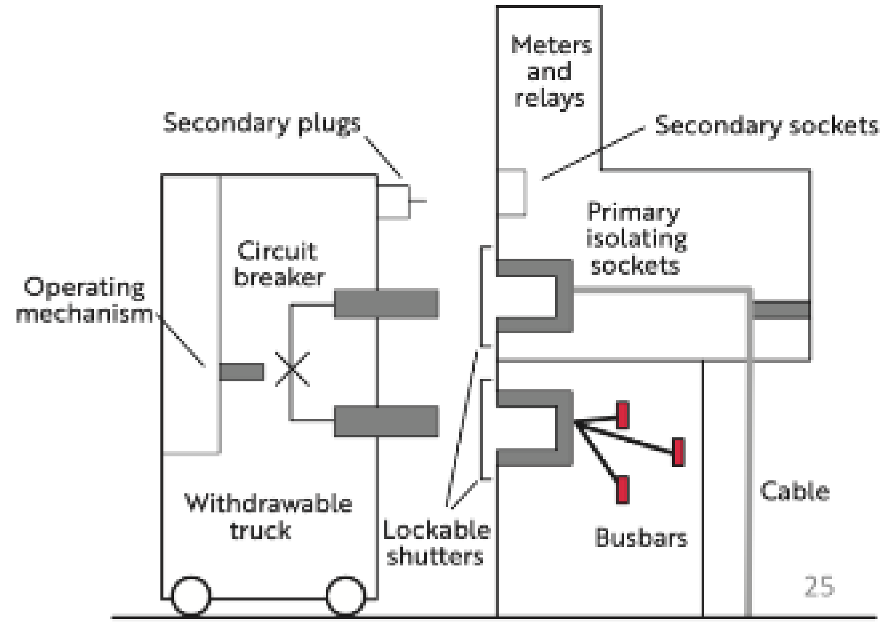
(a)



(b)

- Vertical Isolation

- Horizontal Isolation



Types of Circuit Breaker

- Circuit-breakers offer a very flexible form of protection and control for both the HV and the LV sides of the transformer. On the HV side common types include: ‘Oil’, ‘SF_6’ (Sulphur Hexafluoride) and ‘Vacuum’ circuit breakers.
- However, the need to install adequate fire precautions with oil-filled equipment meant that SF_6 or Vacuum circuit-breakers were usually the most suitable choice.

But … !!!

- SF_6 (Sulphur Hexafluoride) is an extremely potent greenhouse gas …
  - Global Warming Potential (GWP) = 23,900
  - CO_2 has a GWP = 1
- So although there are still a number of SF_6 breakers still in operation, the aim is to phase it out over time (Kyoto Protocol)

Gas-Insulated Switchgear

- Alternative to SF_6 include:

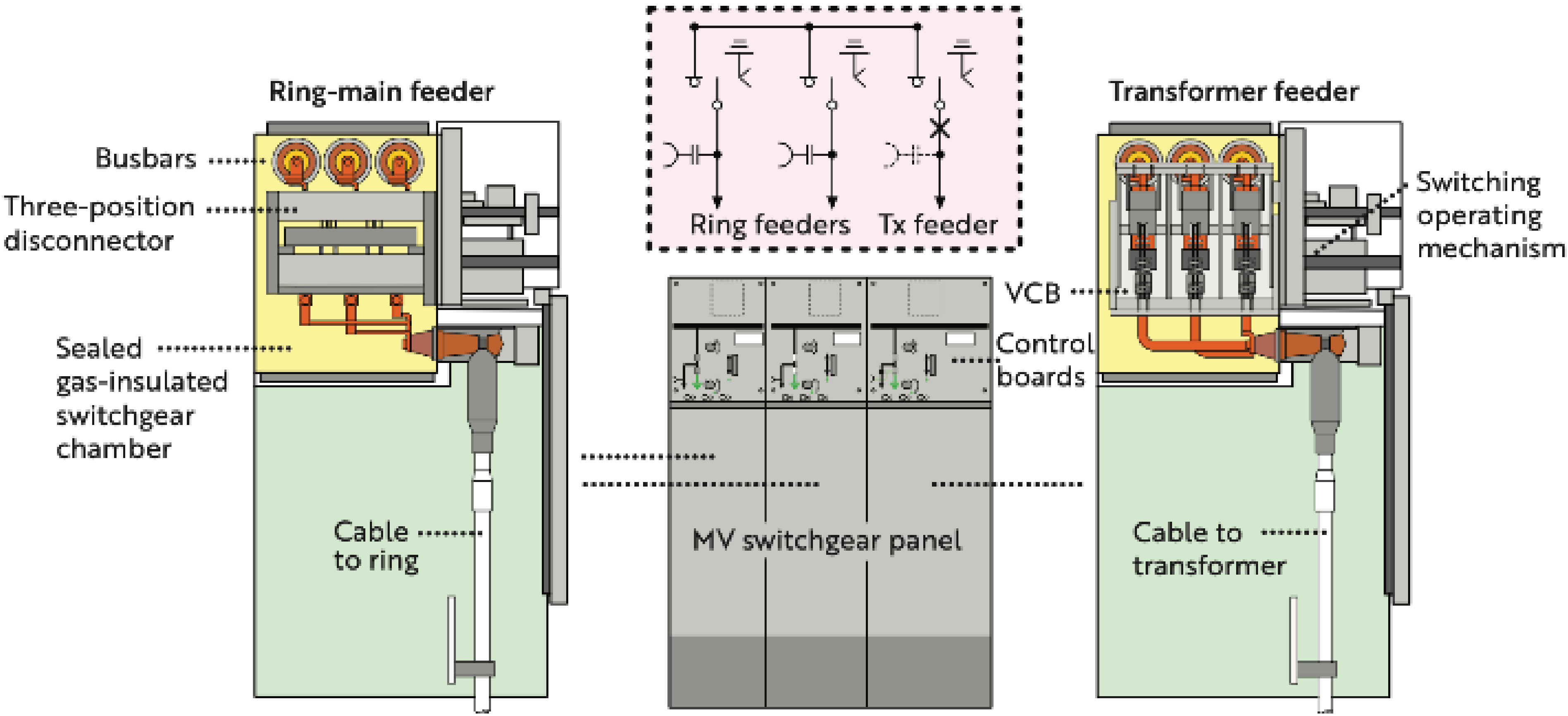
- '**AirPlus**' (3M in collaboration with ABB) – a mixture of NOVEC (a fluoroketone) and dry air

- **g^3** ('g-cubed' – 3M in collaboration with GE) – a fluoronitrile with nitrogen

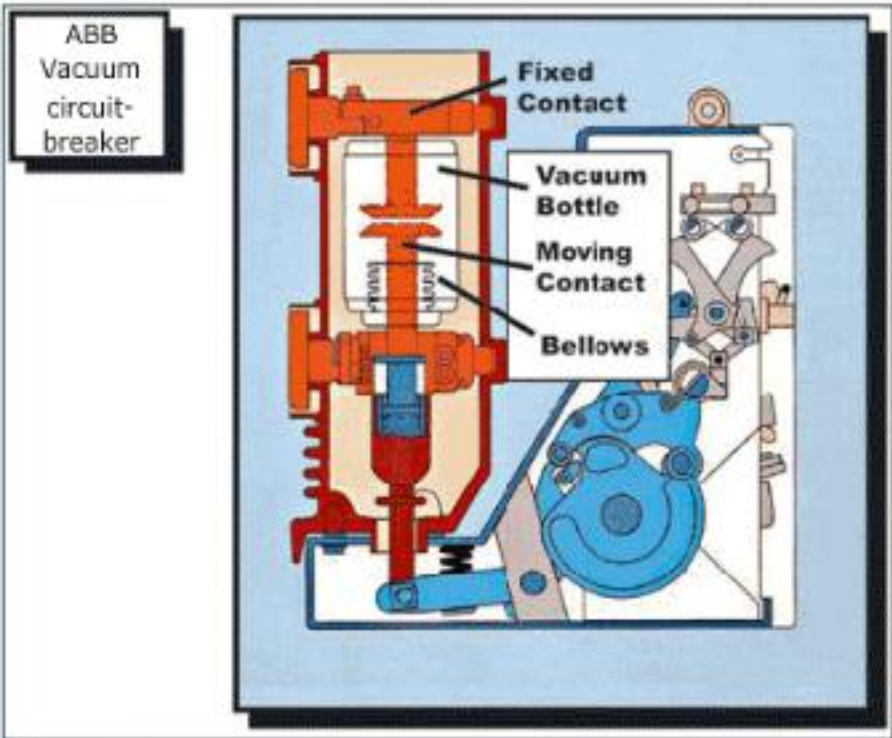
- **Synthetic air** (Nuventura) – 80% nitrogen + 20% oxygen

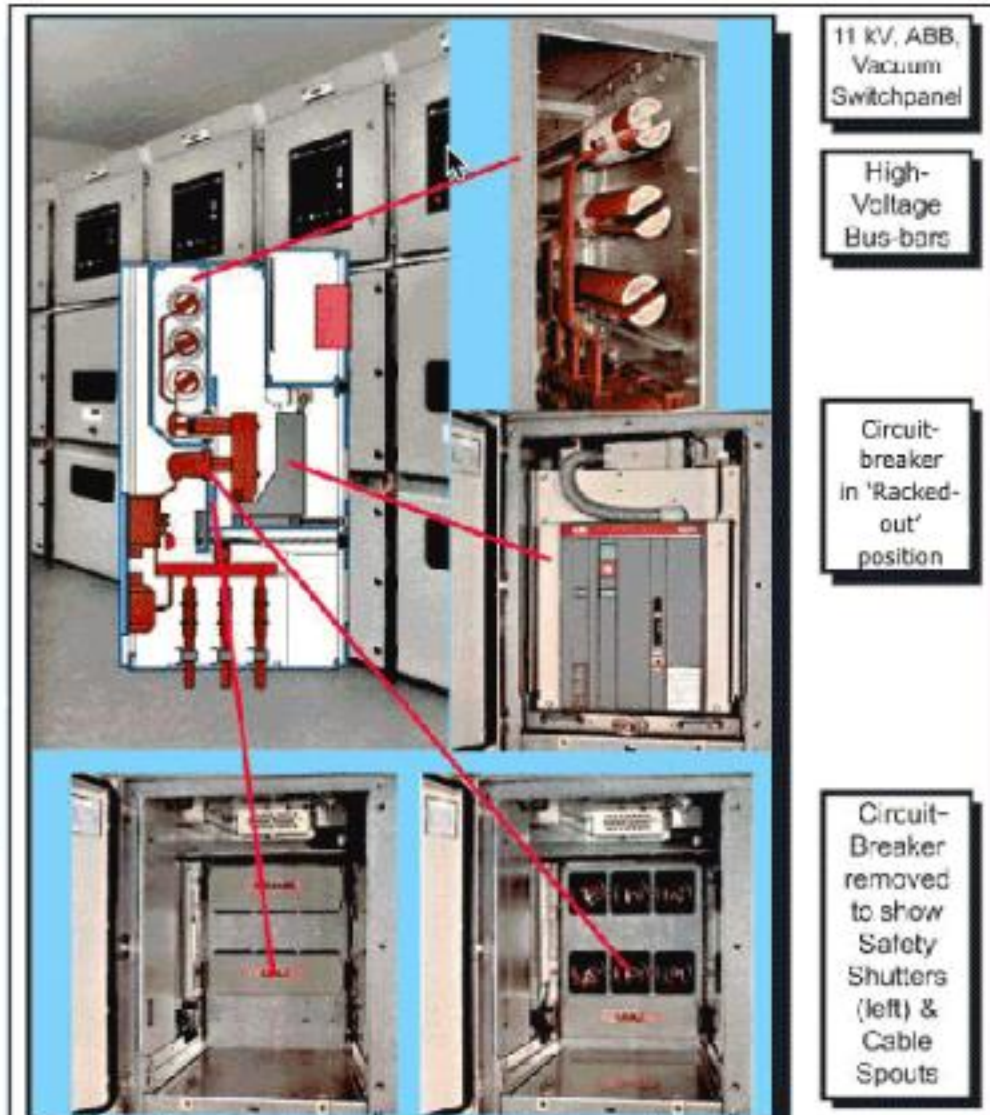
- And of course, **vacuum** circuit breakers

Gas-Filled, Ring-Main Unit (RMU)



Vacuum Circuit-breaker

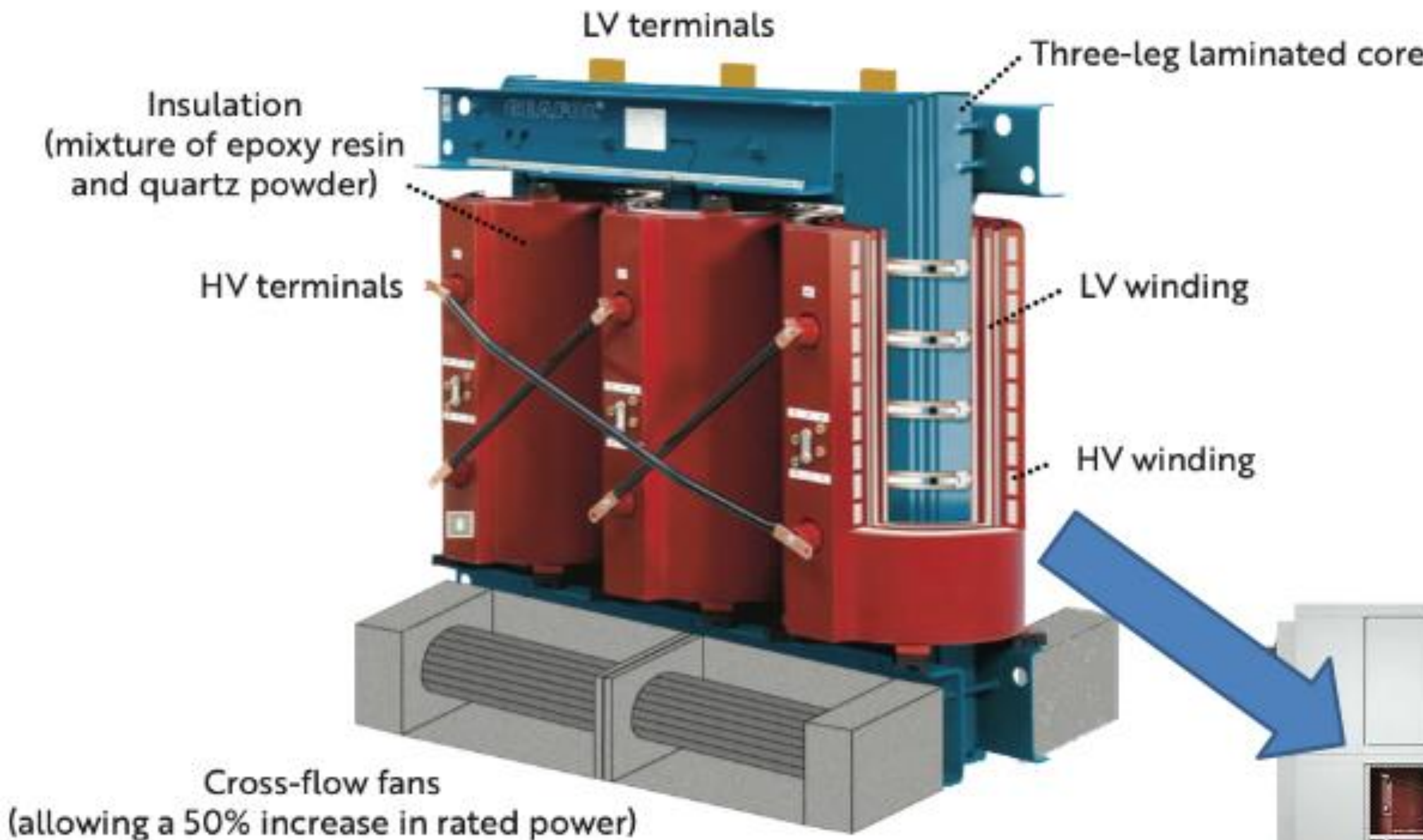




Current Chopping

- When CBs operate, the current does not always smoothly come to zero – whilst the current is still a few amperes, the arc becomes unstable and can be prematurely extinguished – current chopping.
- This can then produce large transient voltage peaks, but because of their mode of operation, with vacuum breakers this can occur at higher current levels – with the possibility of very high voltage peaks.
- Several mitigation methods are possible.

Transformers



Types

- Dry-type transformers
  - Air-cooled
  - Cast resin

- Liquid-filled transformers
  - Mineral oil
  - Midel or silicon fluid

A comparison: relevant to supplies to buildings

Transformer Specification

- Design/construction standards
- Type of transformer
- Insulation and cooling
- Transformer rating
- Vector group
- Primary/secondary supplies
- Transformer duty
- Location

- Location
- Impedance
- Neutral earthing
- Voltage tappings
- Cable boxes
- Tank fittings
- Enclosures
- Testing requirements

Harmonics

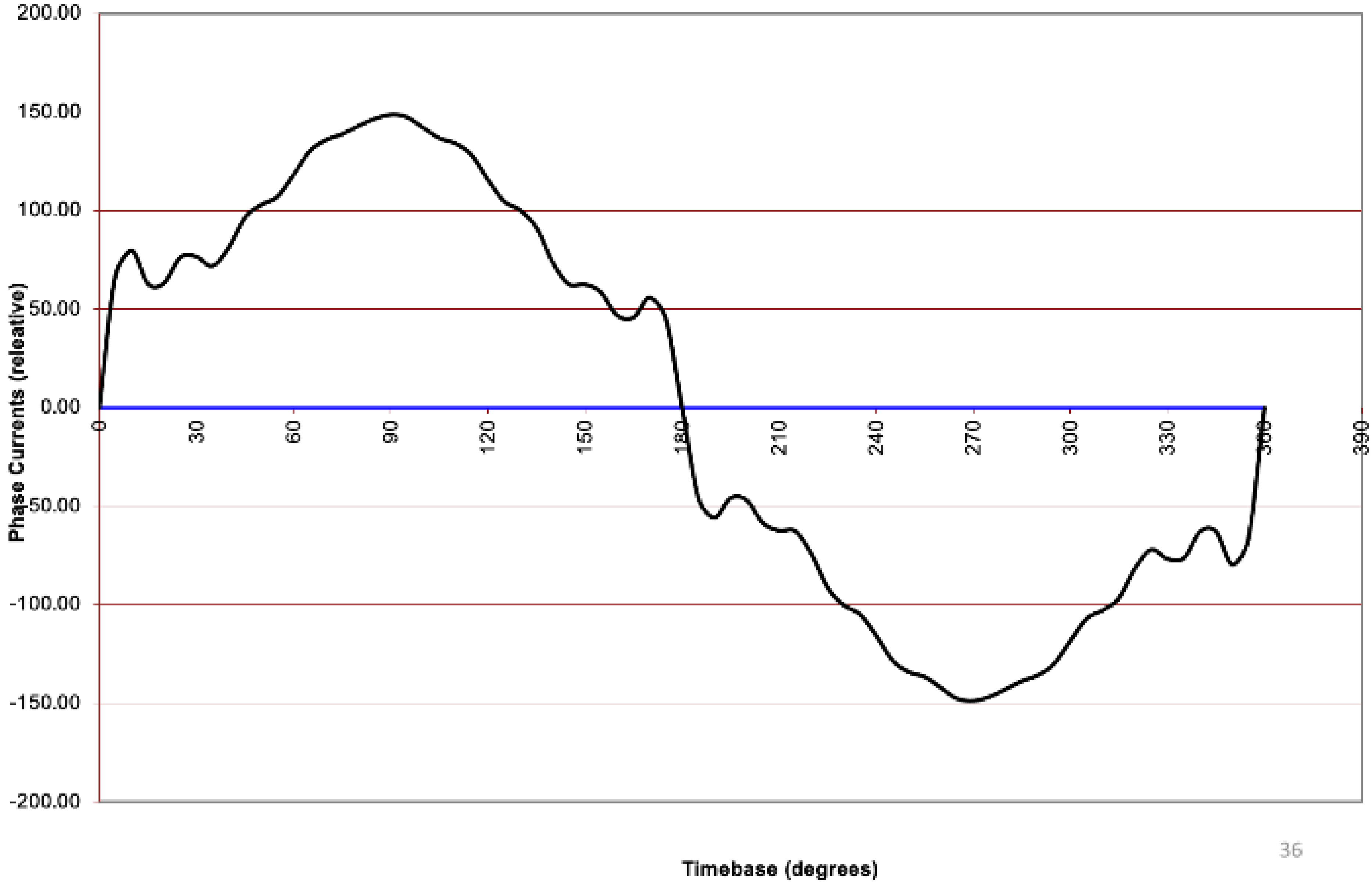
- Factor K (Europe) – De-rating factor

$$K = \left[1 + \frac{e}{1+e}\left(\frac{I_1}{I}\right)^2 \cdot \sum_{n=2}^{n=N}\left(n^q \cdot \left(\frac{I_n}{I_1}\right)^2\right)\right]^{0.5}$$

- K-factor (USA) – Multiplier

$$K = \sum_{n=1}^{n=N}\left(I_n^2 \cdot n^2\right)$$

Harmonics – Example



Harmonics – Example

Current @ 50 Hz = 100 A

Total RMS = 101.5A

Table F1 Harmonic number and current (%)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
100	3.47	20.32	3.22	9.45	2.21	8.12	1.15	6.19	0.77	4.55	0.90	3.84	0.75	3.30	0.83	4.86	0.56	2.47	0.49

Table F2 Factor K and K-factor calculations

n	RMS current, I_n	I_n/I_1	$(I_n/I_1)^2$	n^q	$n^q \times (I_n/I_1)^2$			I_n/I_{RMS}	$(I_n/I_{RMS})^2$	$(I_n/I_{RMS})^2 \times n^2$
1	100.00	1	1	–	–	q	1.7	0.9661	0.9333	0.9333
2	3.47	0.0347	0.0012	3.2490	0.0039	e	0.1	0.0335	0.0011	0.0045
3	20.32	0.2032	0.0413	6.4730	0.2673			0.1963	0.0385	0.3468
4	3.22	0.0322	0.0010	10.5561	0.0109			0.0311	0.0010	0.0155
5	9.45	0.0945	0.0089	15.4258	0.1378			0.0913	0.0083	0.2084
6	2.21	0.0221	0.0005	21.0309	0.0103			0.0214	0.0005	0.0164
7	8.12	0.0812	0.0066	27.3317	0.1802			0.0784	0.0062	0.3015
8	1.15	0.0115	0.0001	34.2968	0.0045			0.0111	0.0001	0.0079
9	6.19	0.0619	0.0038	41.8998	0.1605			0.0598	0.0036	0.2897
10	0.77	0.0077	0.0001	50.1187	0.0030			0.0074	0.0001	0.0055
11	4.55	0.0455	0.0021	58.9342	0.1220			0.0440	0.0019	0.2338
12	0.90	0.009	0.0001	68.3295	0.0055			0.0087	0.0001	0.0109
13	3.84	0.0384	0.0015	78.2895	0.1154			0.0371	0.0014	0.2326
14	0.75	0.0075	0.0001	88.8010	0.0050			0.0072	0.0001	0.0103
15	3.30	0.033	0.0011	99.8516	0.1087			0.0319	0.0010	0.2287
16	0.83	0.0083	0.0001	111.4305	0.0077			0.0080	0.0001	0.0165
17	4.86	0.0486	0.0024	123.5274	0.2918			0.0470	0.0022	0.6371
18	0.56	0.0056	0.0000	136.1330	0.0043			0.0054	0.0000	0.0095
19	2.47	0.0247	0.0006	149.2386	0.0910			0.0239	0.0006	0.2056
20	0.49	0.0049	0.0000	162.8362	0.0039			0.0047	0.0000	0.0090
		Σ_1	1.0714	Σ_2	1.5338				Sum	3.7234
								K-factor		**3.72**

Factor K = 1.06

i.e., derate to 94%

$\left({}^{1}/_{1.06}\right)$

K-factor = 3.72

Select TX with a K-factor of 4

Maintenance of MV Networks

Guidance on:

- Periodic inspections
- Planned intrusive maintenance
- 11kV, SF_6 and gas-filled CBs and RMUs
- 11kV transformer inspection and maintenance

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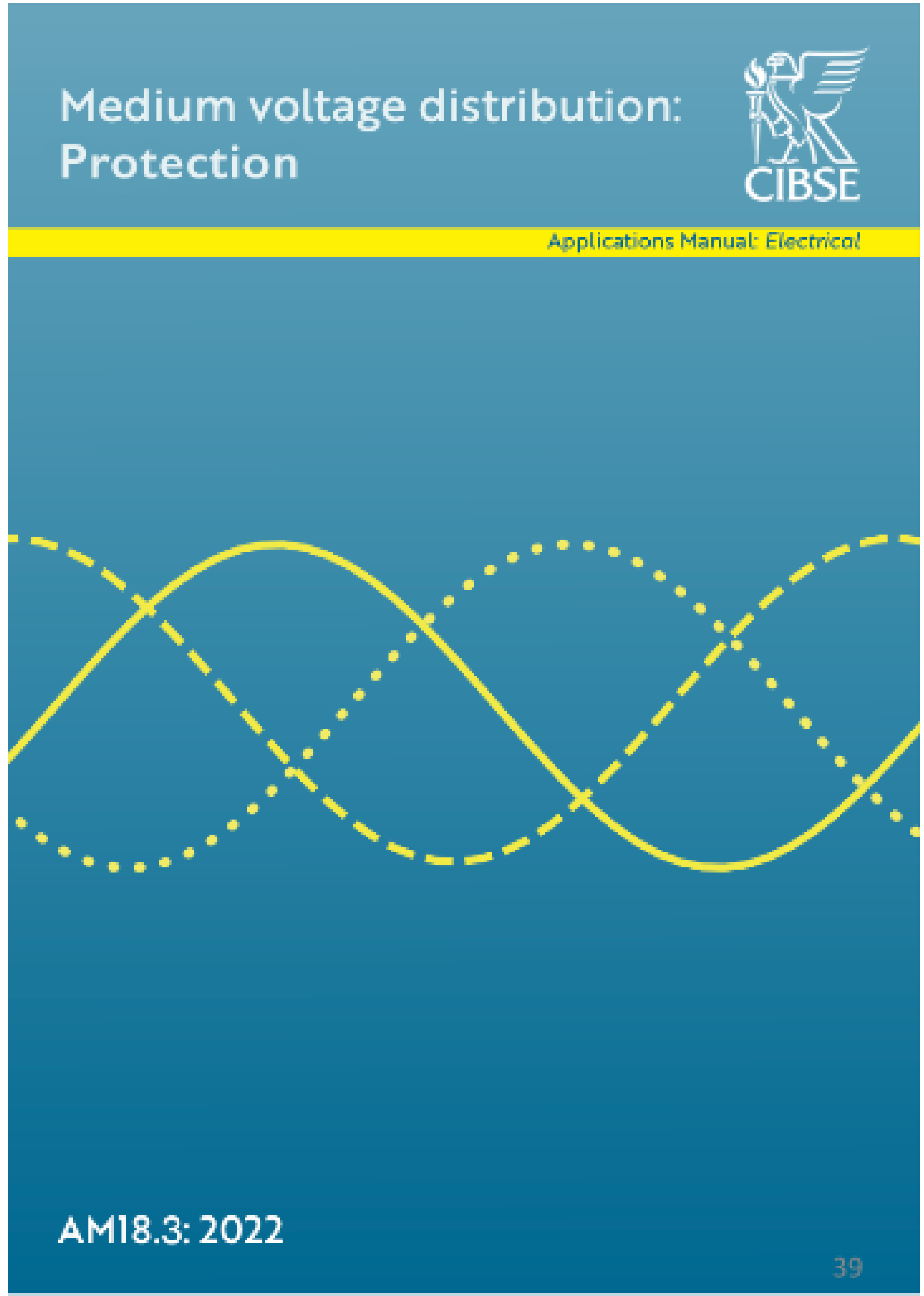
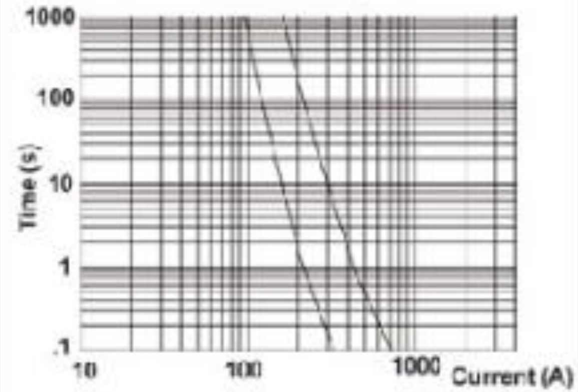


High Voltage Fuses (IEC 282-1)

HV fuses
GEC
Type 'K'

90 A & 50 A, BS 2692
HV Fuses



Typical High-Voltage Fuse Ratings for 11 kV Distribution Transformers

Transformer Rating (kVA)	Fuse Rating (A)	Transformer Rating (kVA)	Fuse Rating (A)
25	5	315	36
30	10	400	40
40	10	450	45
63	10	500	50
75	16	600	56
100	16	630	56
125	20	750	80
150	20	800	80
200	25	1000	90
225	25	1250	100
300	36	1500	125

Fuse vs. Circuit Breakers?

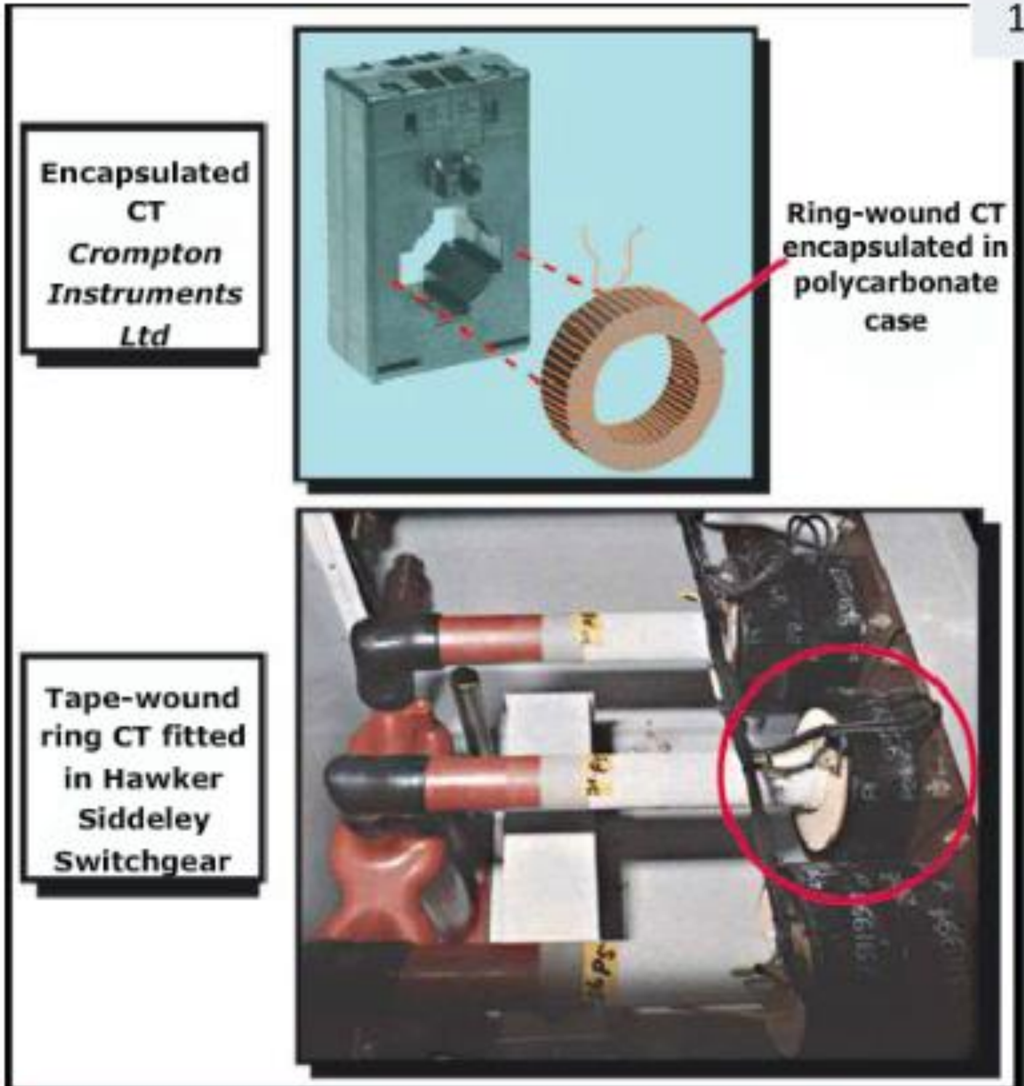
- Fast with large fault currents, but slow with currents less than 3 times their rated values.
- So do very little to protect against overloads.
- Often a practical choice for smaller installations or those in remote areas.

Current Transformers

- Current transformers are used to provide a barrier between MV equipment and the protection relay.
- **PROTECTION CLASS** CTs are designated by the letter ‘**P**’ e.g. 5**P**, 10**P** etc, where the 5 or 10 are the % ratio error, as measured by the ‘Accuracy Limit Factor’.

CT Construction

Class	Current Error (%) at Rated Primary Current	Error (%) at Rated Accuracy Limit
5P	± 1	5
10P	± 3	10



Standard **accuracy limit factors (ALFs)** are: 5, 10, 15, 20 and 30.

e.g., a 50:1 CT used where the fault current is 1,000 A, then an ALF of 1000/50 = 20 would be required.

Specifying CTs

- Burden: 2.5, 5, 7.5, 10, 15, 30 VA
- Accuracy Class: 5P (5%), 10P (10%)
- Accuracy Limit Factor: 5, 10, 15, 20, 30
- e.g 15 VA, class 10P20 ≡ AC = 10P, ALF = 20

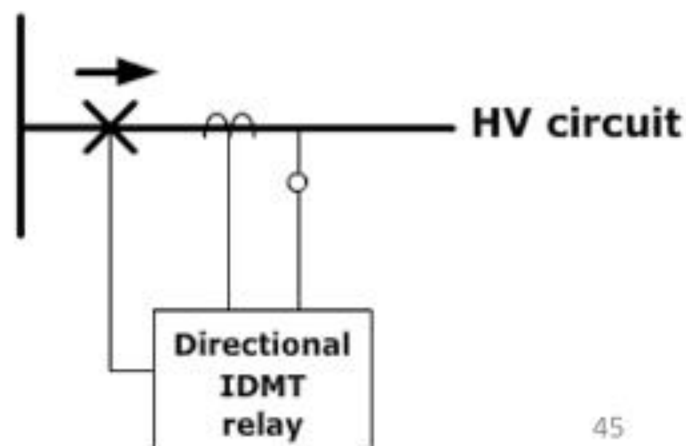
Relay Type	Typical CT Requirement		
	VA	Class	A.L.F.
IDMT	15	10P	10 - 15
Earth-fault	15	10P	10

Modern protection relays have very low burdens (~ 0.1 – 0.5 VA) and this does **NOT CHANGE** with current setting.

Protection Relays

- Typically mounted in a separate compartment and connected to the circuit being protected by CTs and VTs.

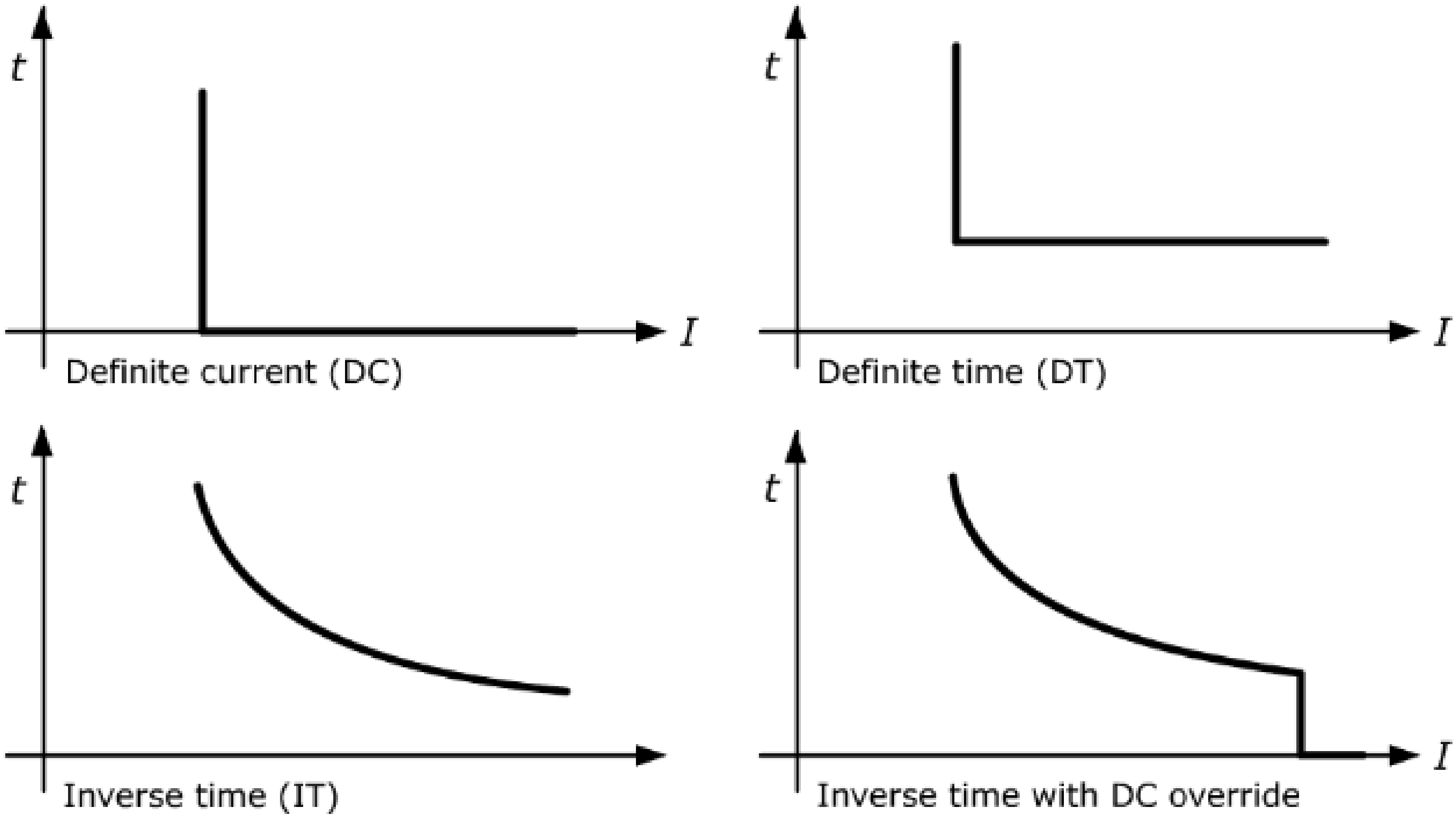
- With a ring-circuit, current can flow in either of two directions. Hence the need for a **directional relay** – ONLY responds when current is flowing in one direction.



ANSI Numbering

ANSI Code[18]	Name of function	Definition
49	Thermal overload	Protection against overloads
50	Instantaneous phase overcurrent	3-phase protection against short-circuits
50BF	Breaker failure	Checking and protection if the circuit breaker fails to trip
50N or 50G	Instantaneous earth fault	Protection against earth faults: 50N: residual current calculated or measured by 3 CTs 50G: residual current measured by single sensor CT or core balance CT
50V	Instantaneous voltage-restrained overcurrent	3-phase protection against short-circuits with voltage-dependent threshold
51	Delayed phase overcurrent	3-phase protection against overloads and short-circuits
51N or 51G	Delayed earth fault	Delayed protection against earth faults: 51N: residual current calculated or measured by 3 CTs 51G: residual current measured by single sensor CT or core balance CT
51V	Delayed voltage-restrained phase overcurrent	3-phase protection against short-circuits with voltage-dependent threshold
64REF	Restricted earth fault differential	Earth fault protection, star-connected 3-phase winding with earthed neutral
64G	100% generator stator earth fault	Detection of stator winding earth fault
67	Directional phase overcurrent	3-phase short-circuit protection dependent on direction of current flow
67N or 67NC	Directional earth fault	Earth fault protection dependent on direction of current flow (NC: neutral compensation)
87B	Busbar differential	3-phase protection against busbar internal faults
87G	Generator differential	3-phase protection against internal faults for AC generators
87L	Line differential	3-phase protection against line internal faults
87M	Motor differential	3-phase protection against internal faults for motors
87T	Transformer differential	3-ohase protection against internal faults for transformers

Overcurrent Characteristics

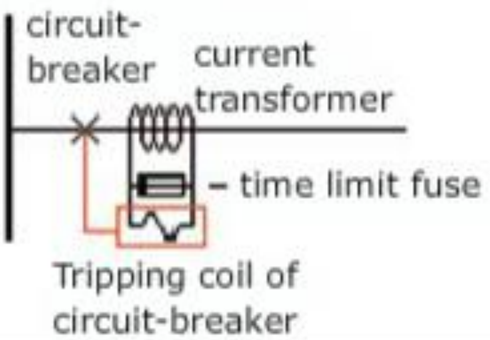


Applications limited for relays using:

- Definite current – variations network fault currents during operation
- Definite time – produce long fault clearance times

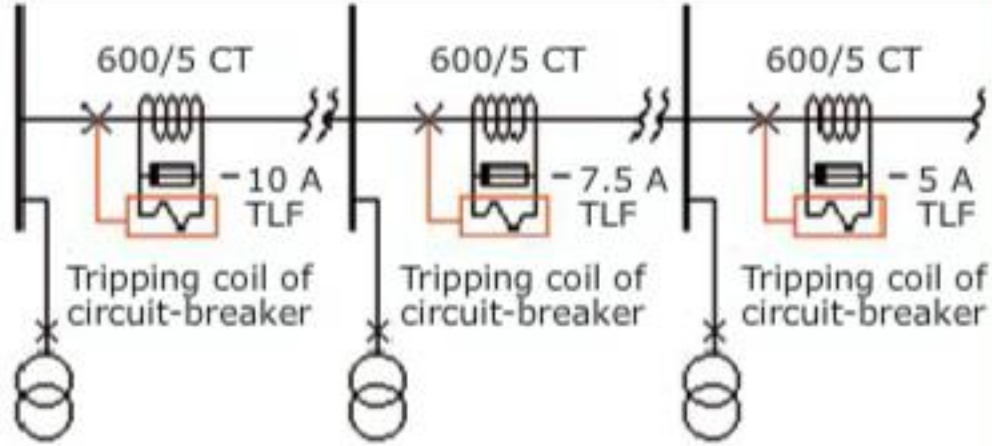
Time Limit Fuses (TLFs)

TLF - connection



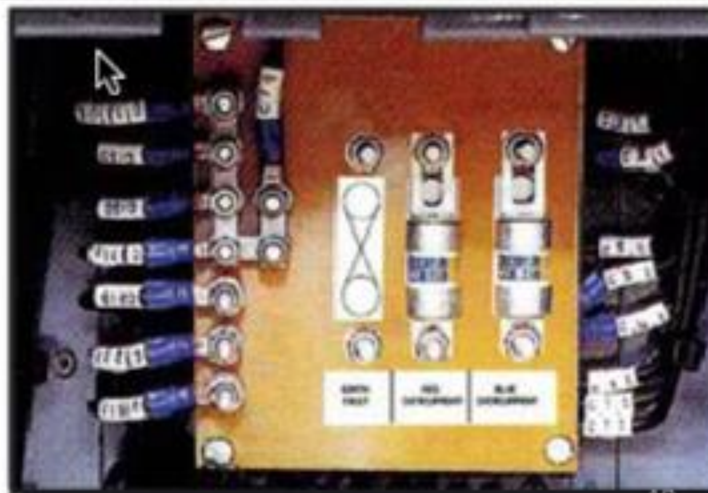
50/5 CT, 10-A TLF

Operating time(s)	Current (A)
0.1	400 - 480
0.5	200 - 240
1	166 - 198
2	150 - 176
3	145 - 170
10	136 - 162
20	135 - 160

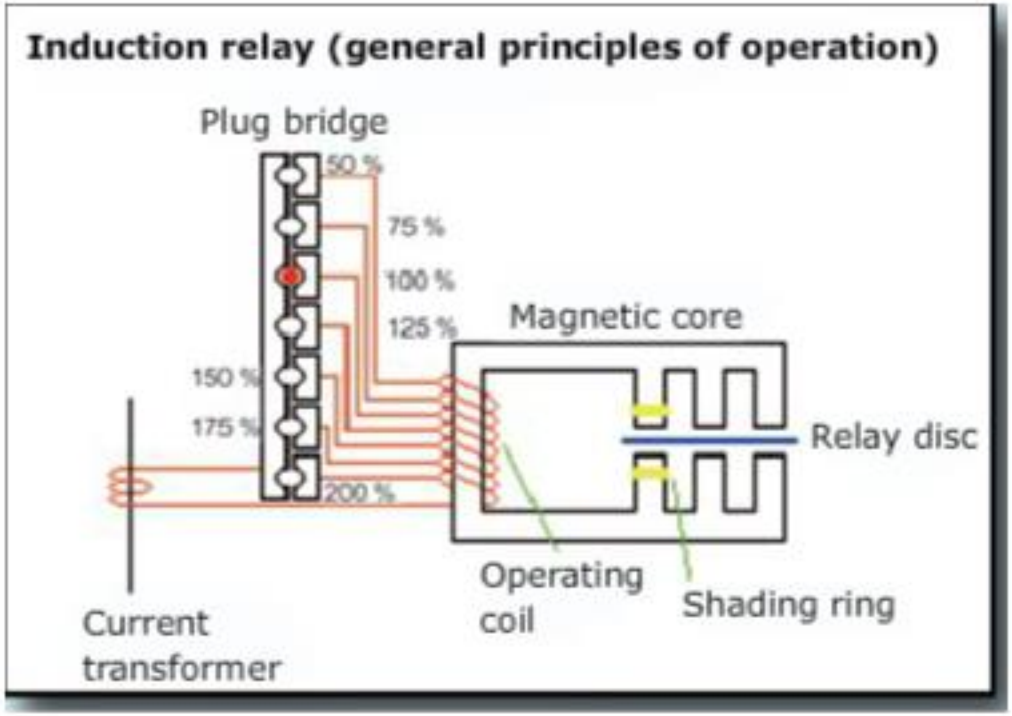


Discrimination is progressively achieved by increasing the rating of the Time Limit Fuse

TLFs
fitted to
Merlin Gerin RMU

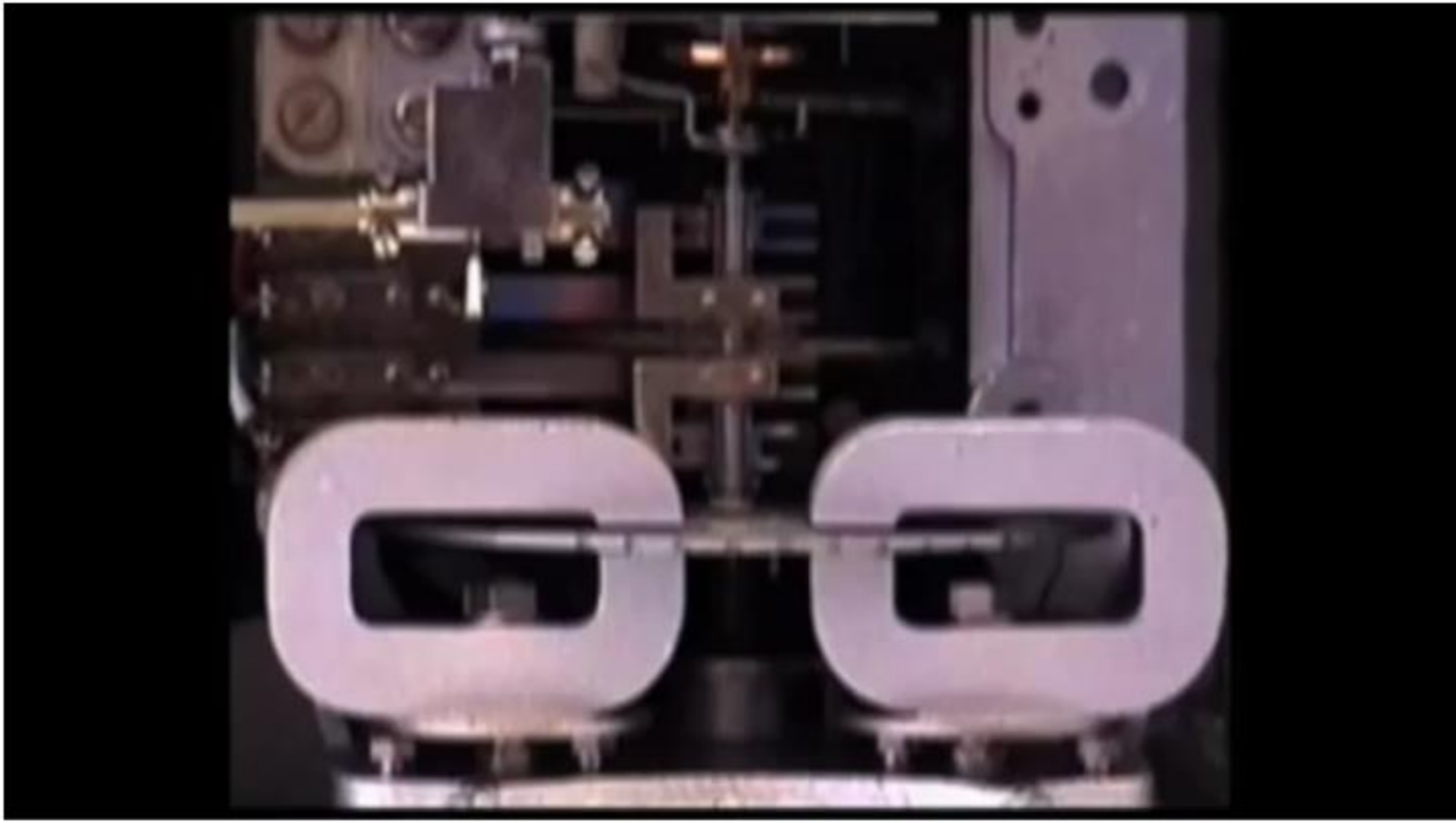


Induction Relays

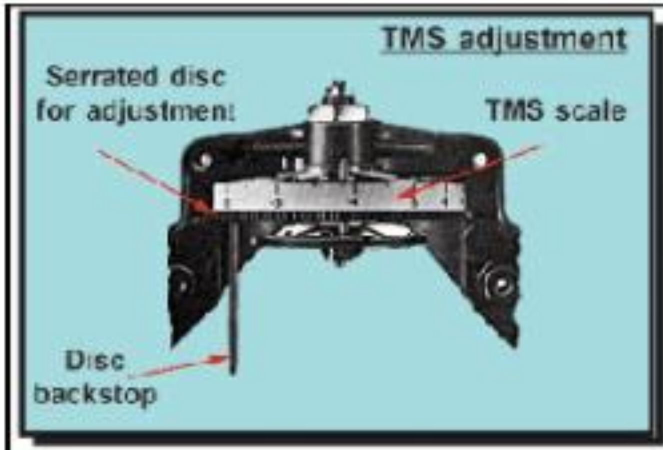


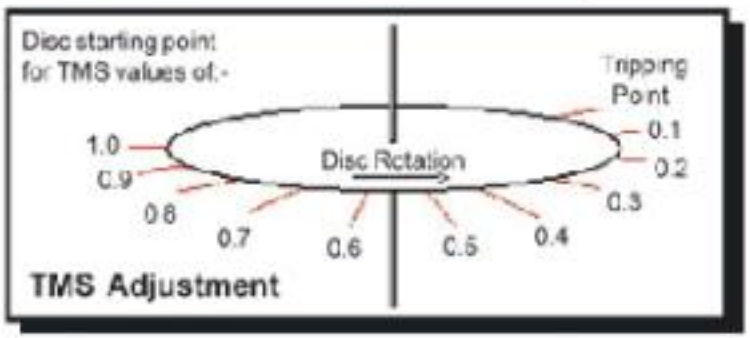
- Induction relays operate on the same basis as an induction motor – relay current causing the relay disc to rotate.
- The rotation is restrained by a simple spiral spring which must be overcome before disc rotation starts. – typically 110% of full-load current.

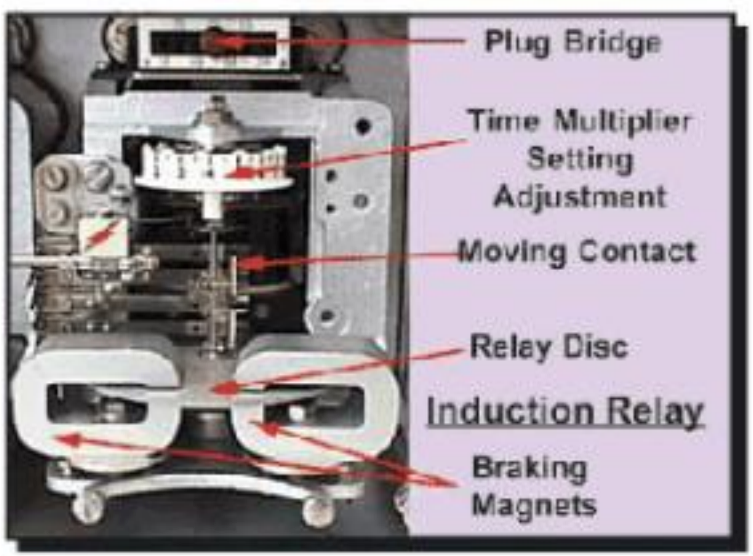
Relays Operation



Relay Adjustments







Electro-Mechanical Relays:

<u>Plus Settings</u> (**PS**) (%):

50, 75, 100, 125, 150, 175, 200

<u>Time Multiplier Settings</u> (TMS):

0.1 (10%) to 1 (100%)
in 0.05 (5%) steps

Digital/Numeric Relays:

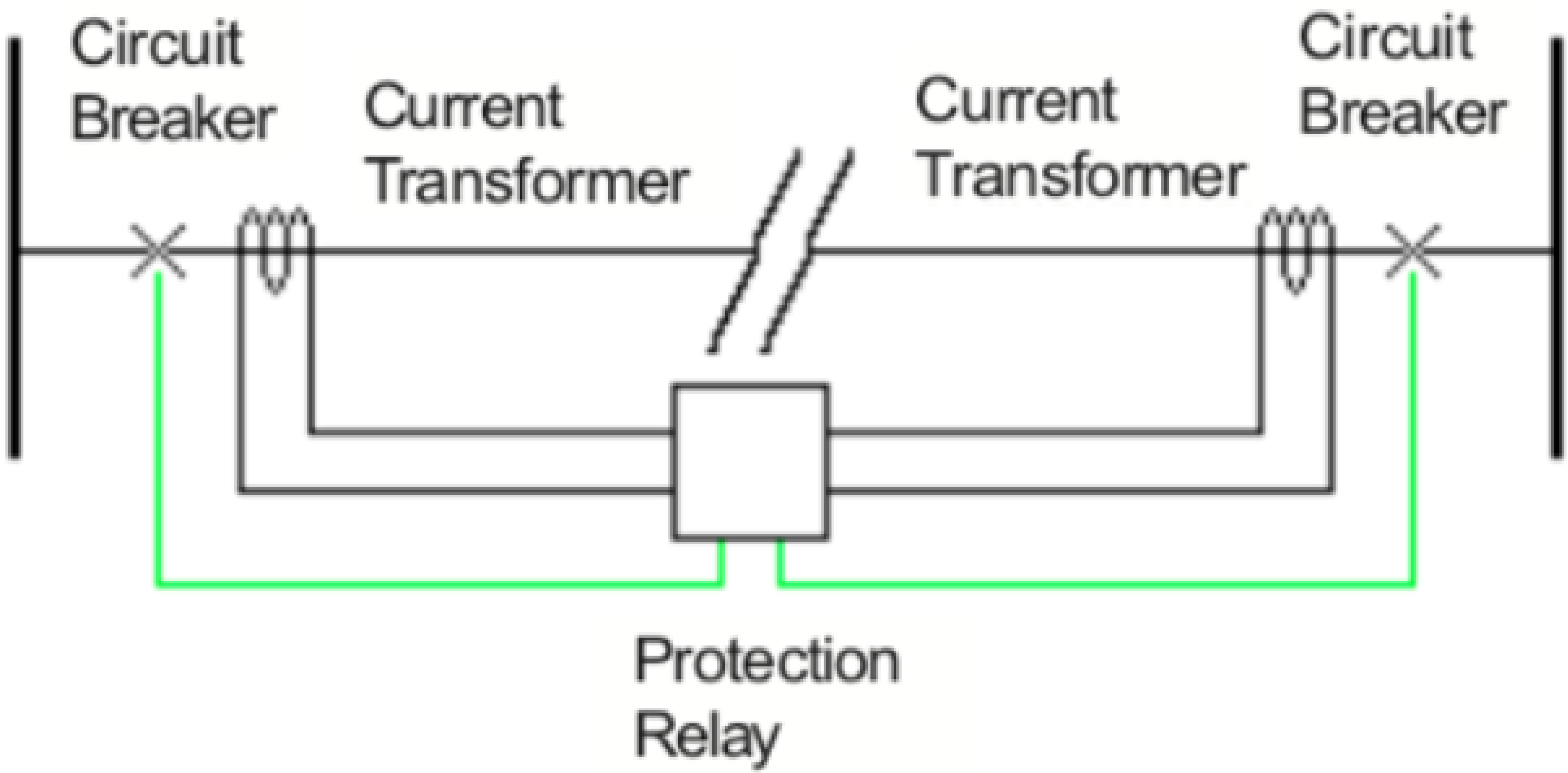
<u>Current Multiplier</u> (**CM**):

5% to 240% in 5% steps

<u>Time Multiplier Settings</u> (TMS):

0.1 (10%) to 1 (100%)
in 0.05 (5%) steps

Unit Protection



- High speed operation [typically operating within 10 - 50 milliseconds (½ to 2½ cycles)] coupled with high sensitivity.
- Do not provide backup for each other, requires additional, time graded overcurrent relays or other breaker failure protection.

Grading Margin between Relays

The **minimum time difference** between relays:

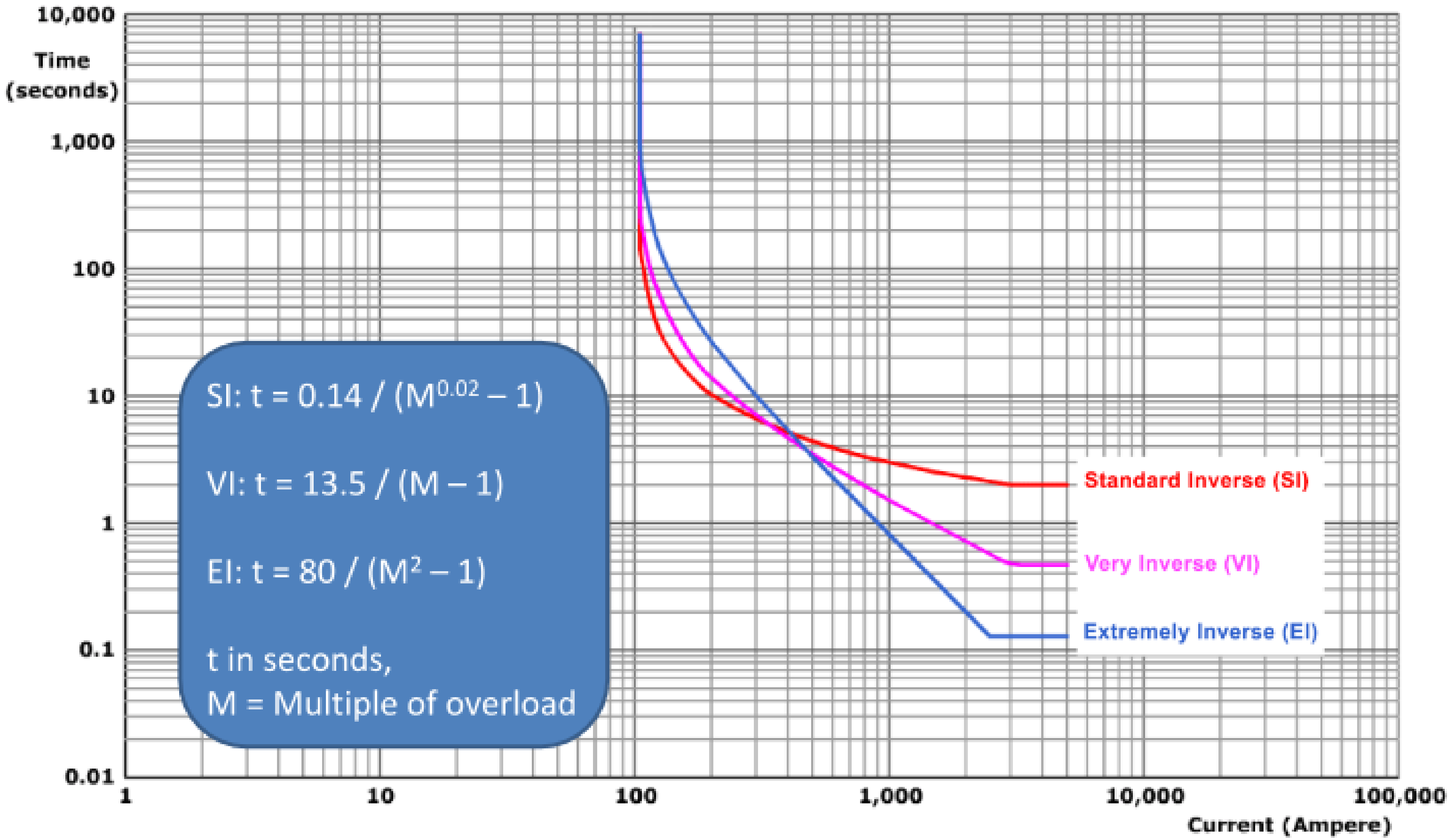
- The operating time of the circuit-breaker
- Timing errors and overshoot of the relay
- A final 'time-safety margin' between relays.

Nominal values are:

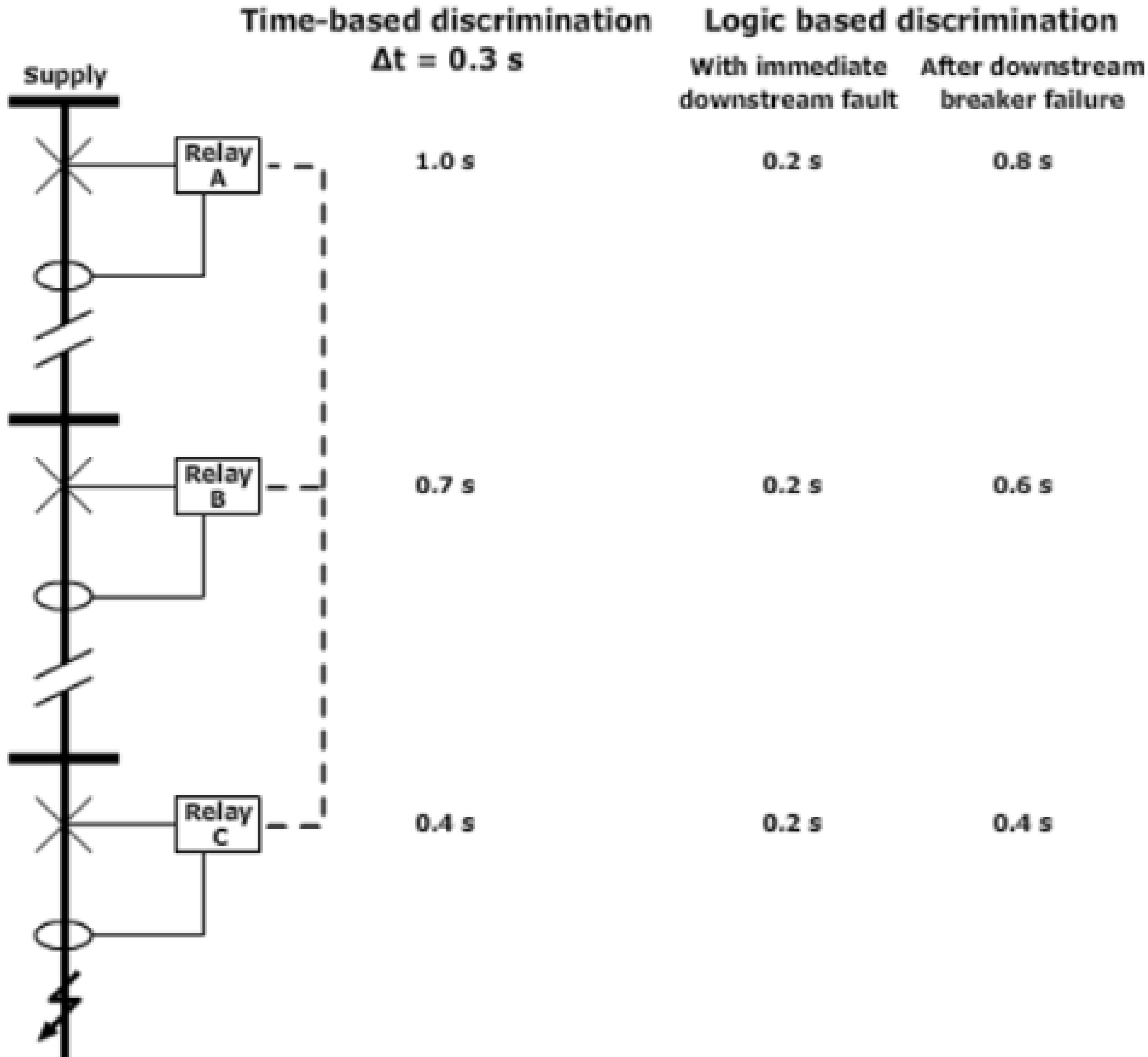
- 0.1 s (relay and CT error) [E_R, E_{CT}]
- 0.05 (overshoot) [t_o]
- 0.15 (breaker operating time) [t_{CB}]
- <u>0.1</u> (safety margin) [t_S]
- **Sum** **<u>0.4</u> seconds**

Or we could use the equation: $t' = \left[\frac{2E_R + E_{CT}}{100}\right] \times t + t_{CB} + t_O + t_S$

Relay Characteristics

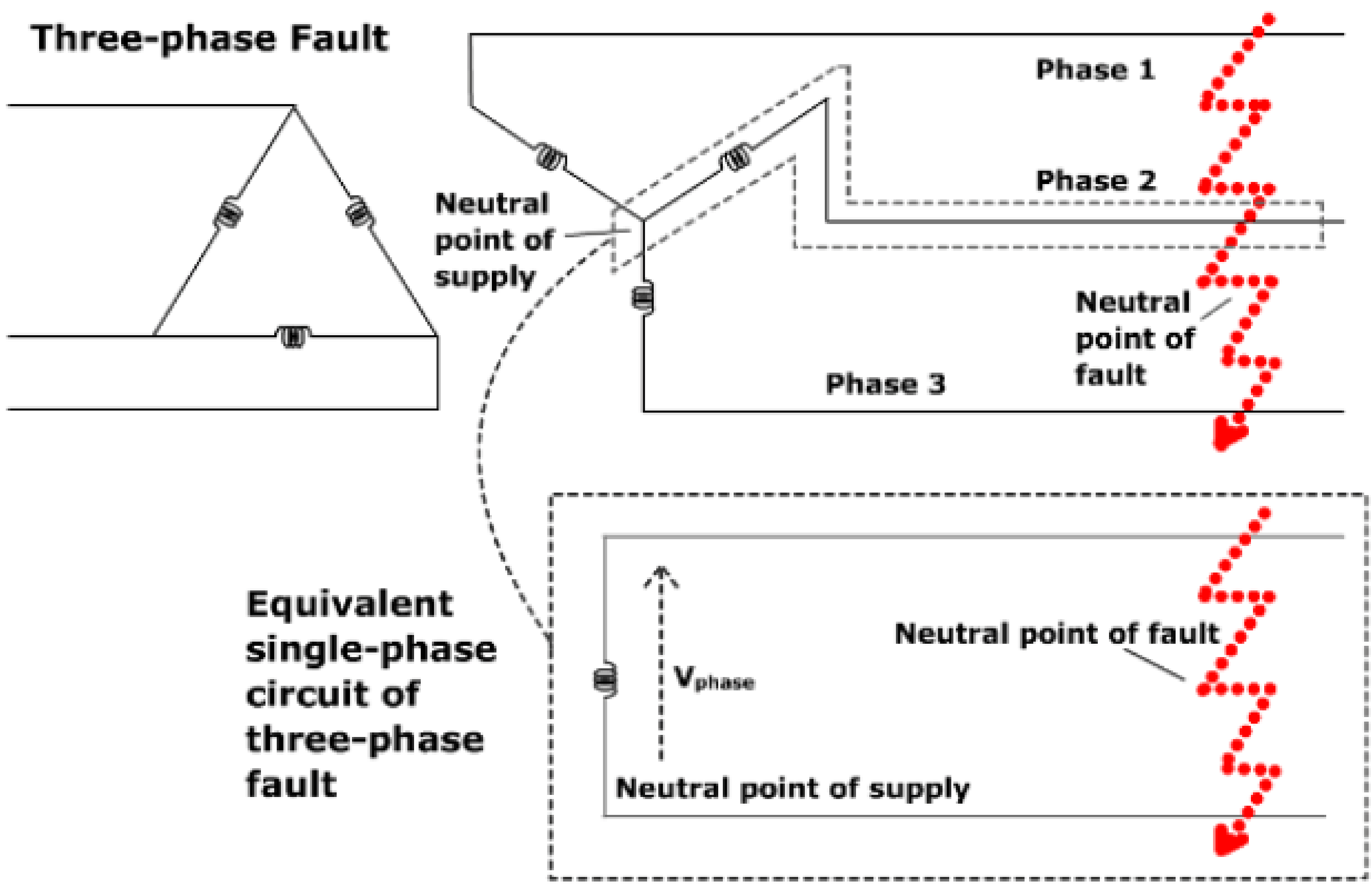


Logic Discrimination

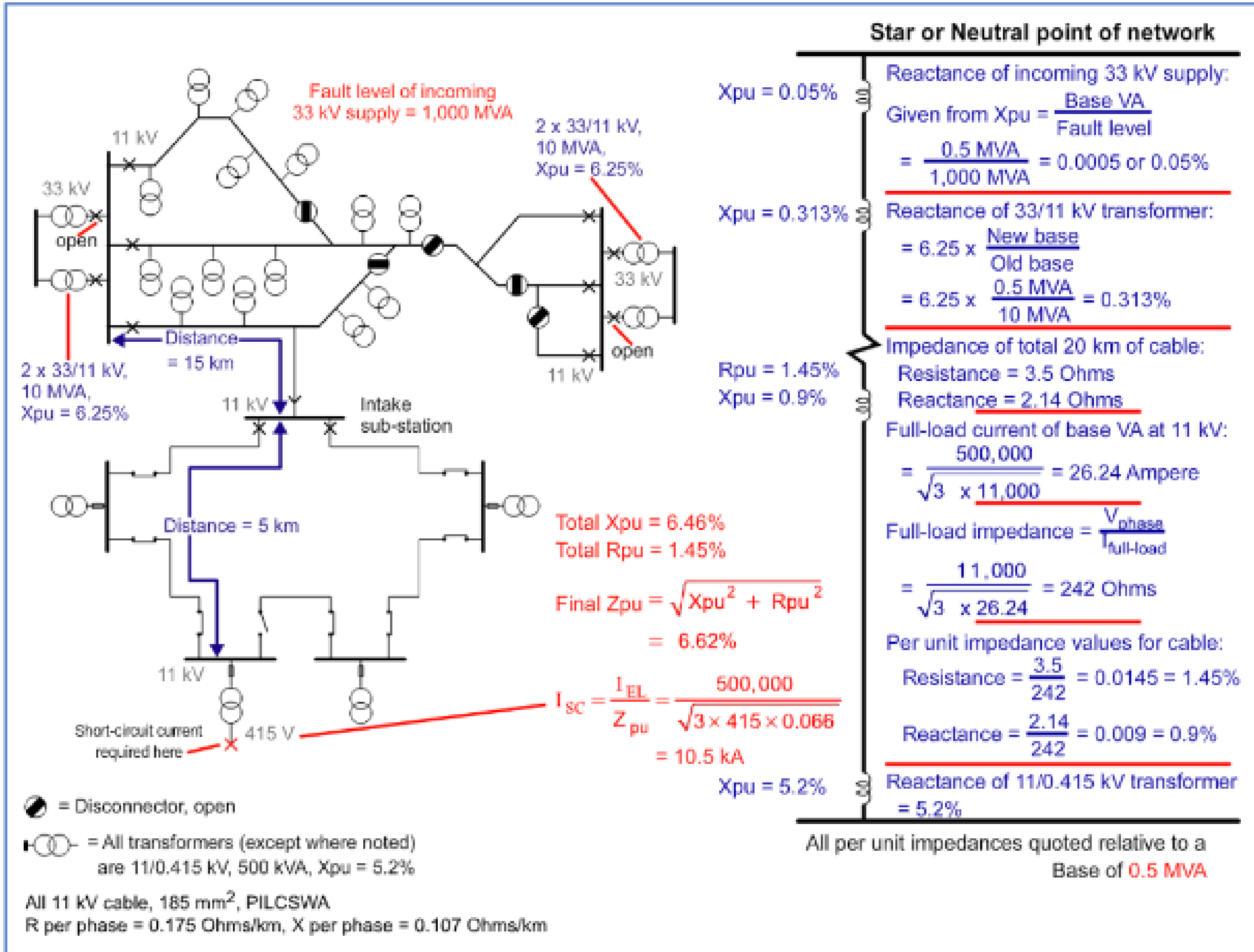


AM18.4 and AM18.5

AM 18.4: Fault Calculations

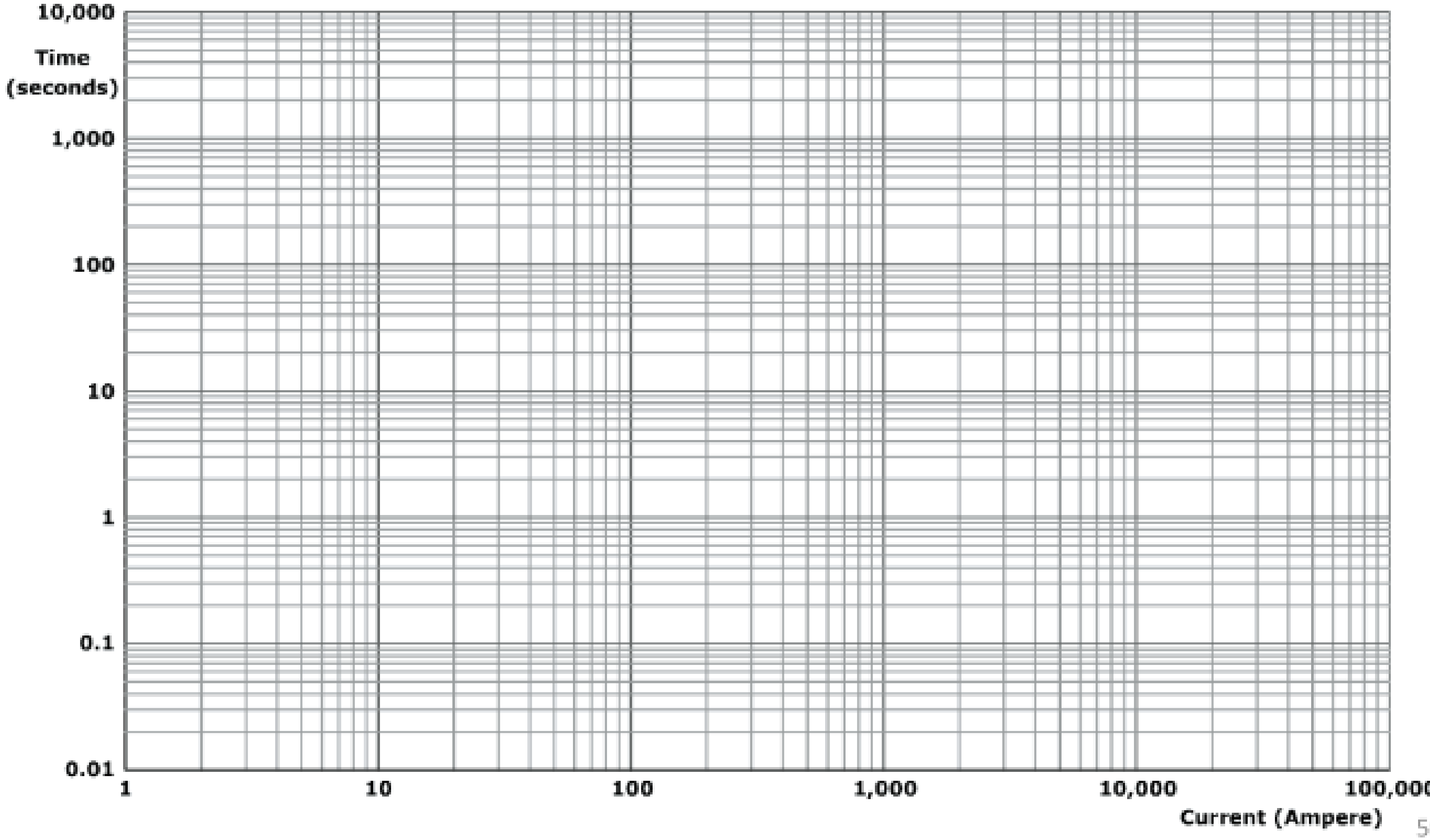


Example Calculations



AM 18.5: Grading

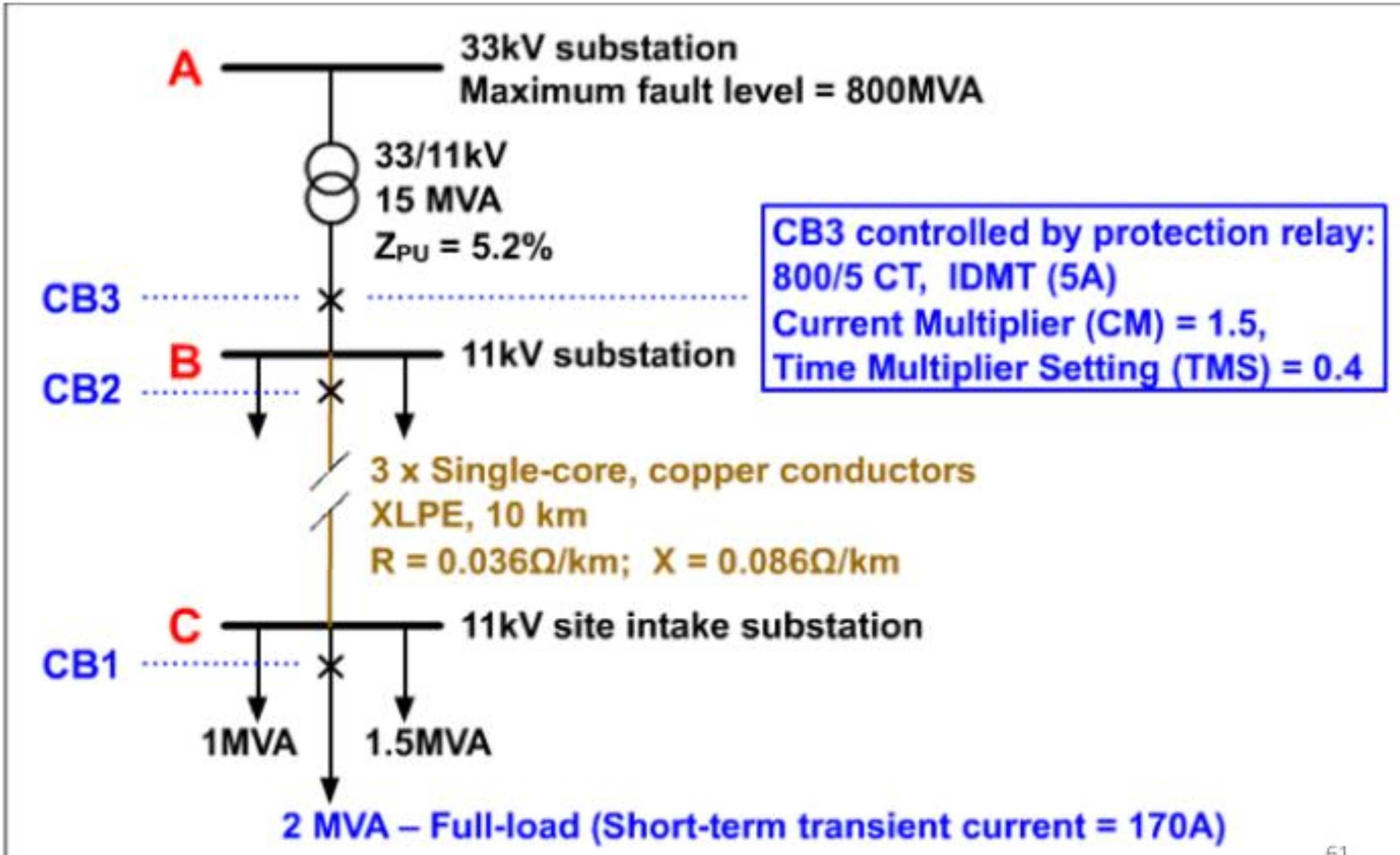
- A graphical approach to design



Setting the Protection ?

- Transformer magnetising current
- Co-ordination between MV breaker and largest Low Voltage fuse or circuit breaker
- Protection must allow '*permissible overload current*'
  - typically 1.5 x transformer rated load

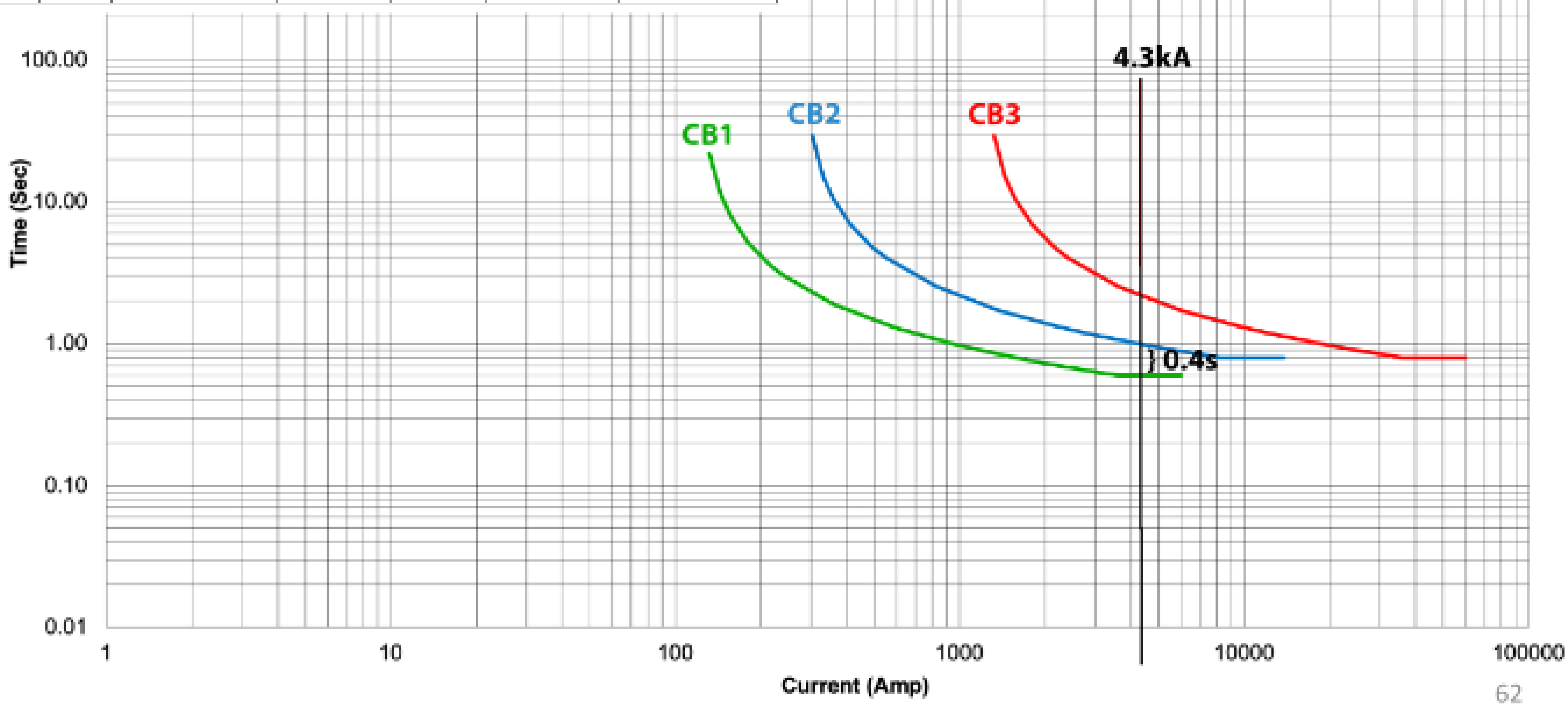
11kV Radial System



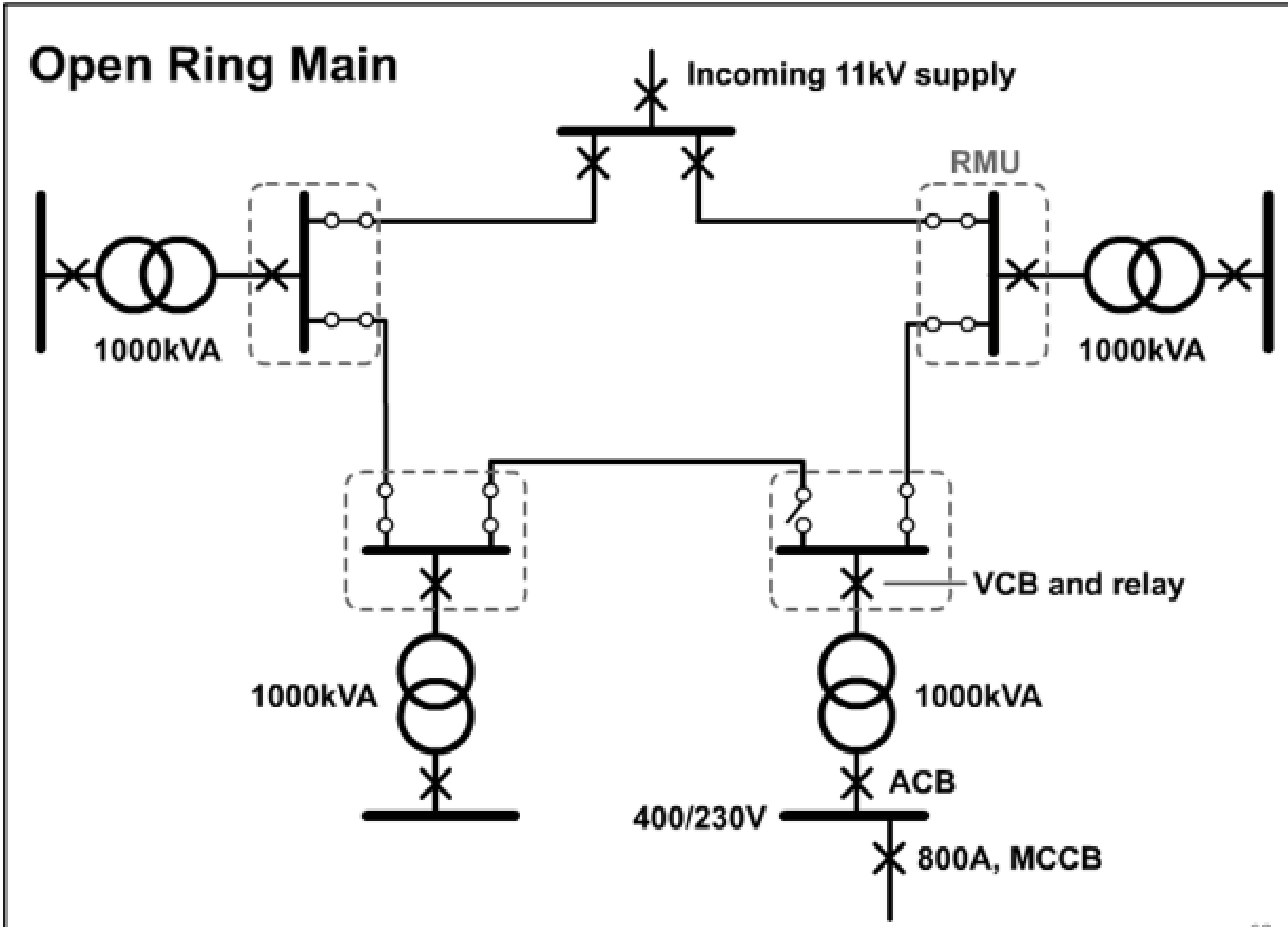
Fully Worked Solution

Current/Time Characteristic

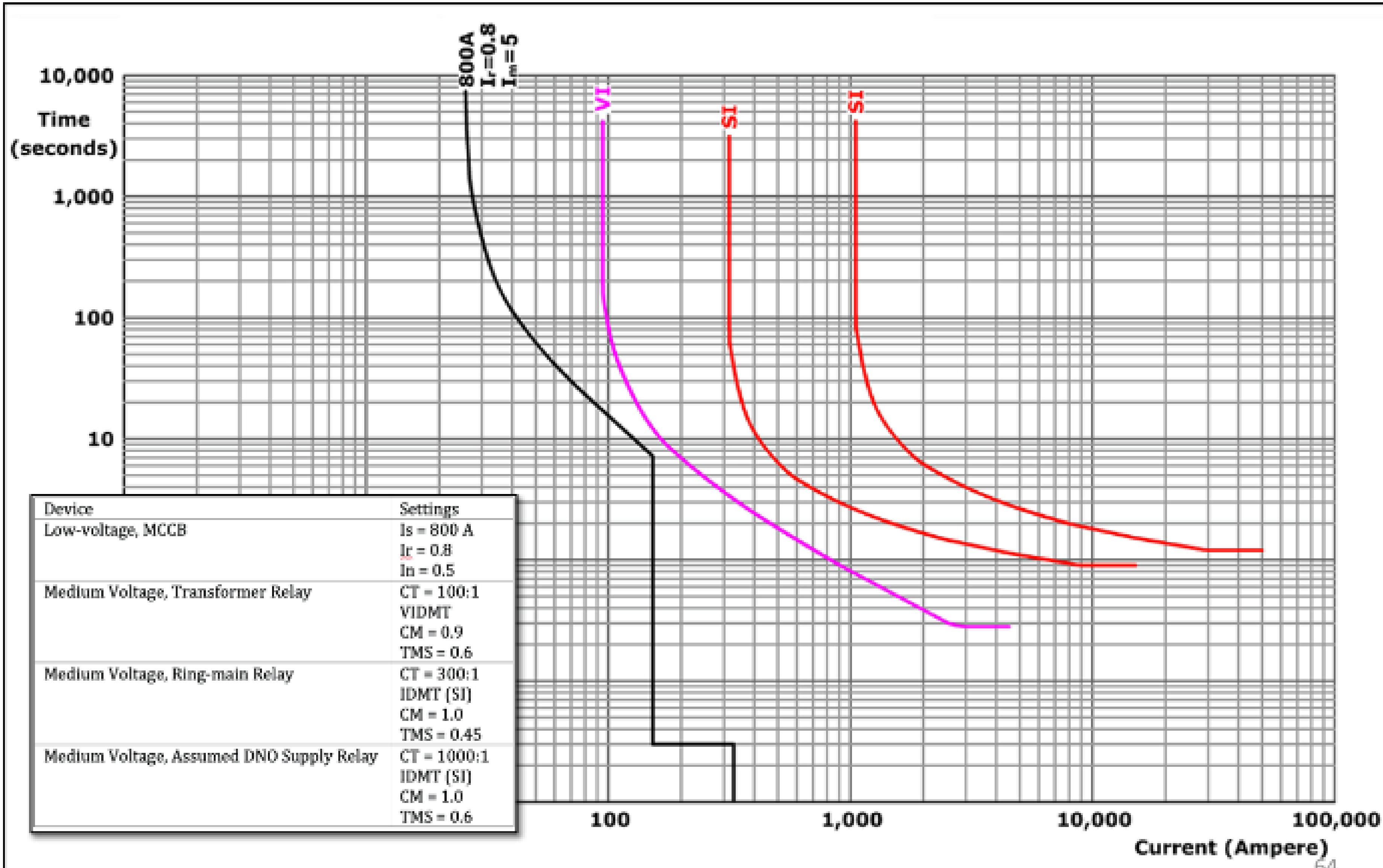
CB#	CT ratio	Relay Characteristic	Current Multiplier (CM)	Relay Setting Current (A)	Time Multiplier Setting (TMS)	Maximum Short-circuit Current (kA)
CB3	800:5	IDMT	1.5	1200	0.4	
CB2	250:1	IDMT	1.1	275	0.4	11.2
CB1	100:1	IDMT	1.2	120	0.3	4.3



Open Ring Main

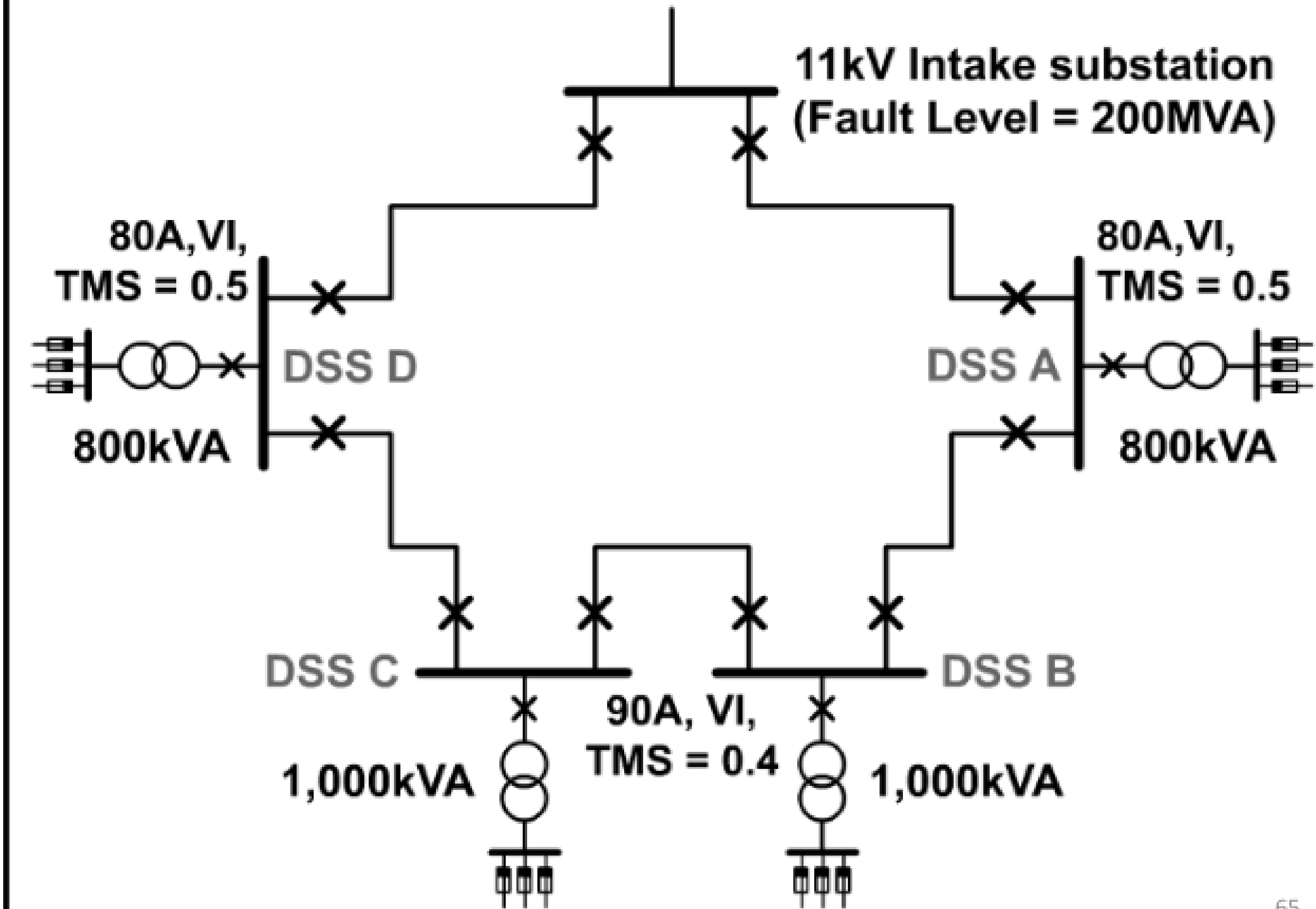


Fully Worked Solution

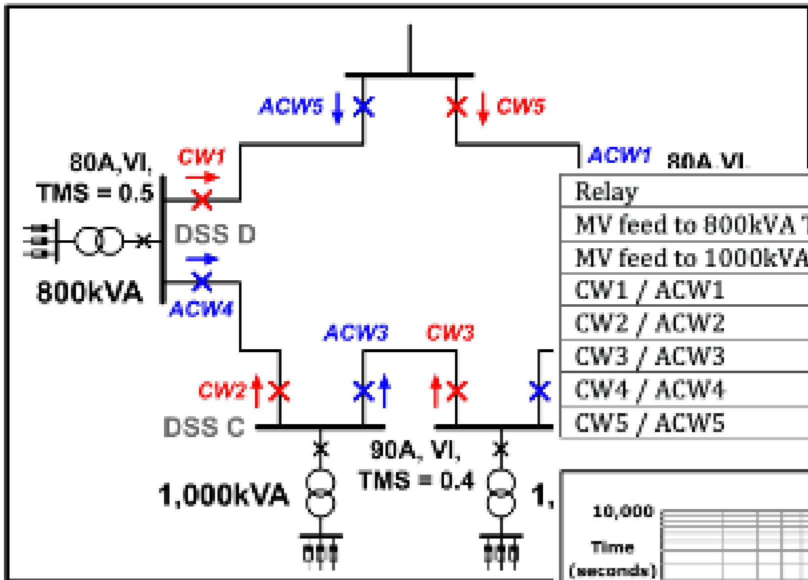


Device	Settings
Low-voltage, MCCB	Is = 800 A Ir = 0.8 In = 0.5
Medium Voltage, Transformer Relay	CT = 100:1 VIDMT CM = 0.9 TMS = 0.6
Medium Voltage, Ring-main Relay	CT = 300:1 IDMT (SI) CM = 1.0 TMS = 0.45
Medium Voltage, Assumed DNO Supply Relay	CT = 1000:1 IDMT (SI) CM = 1.0 TMS = 0.6

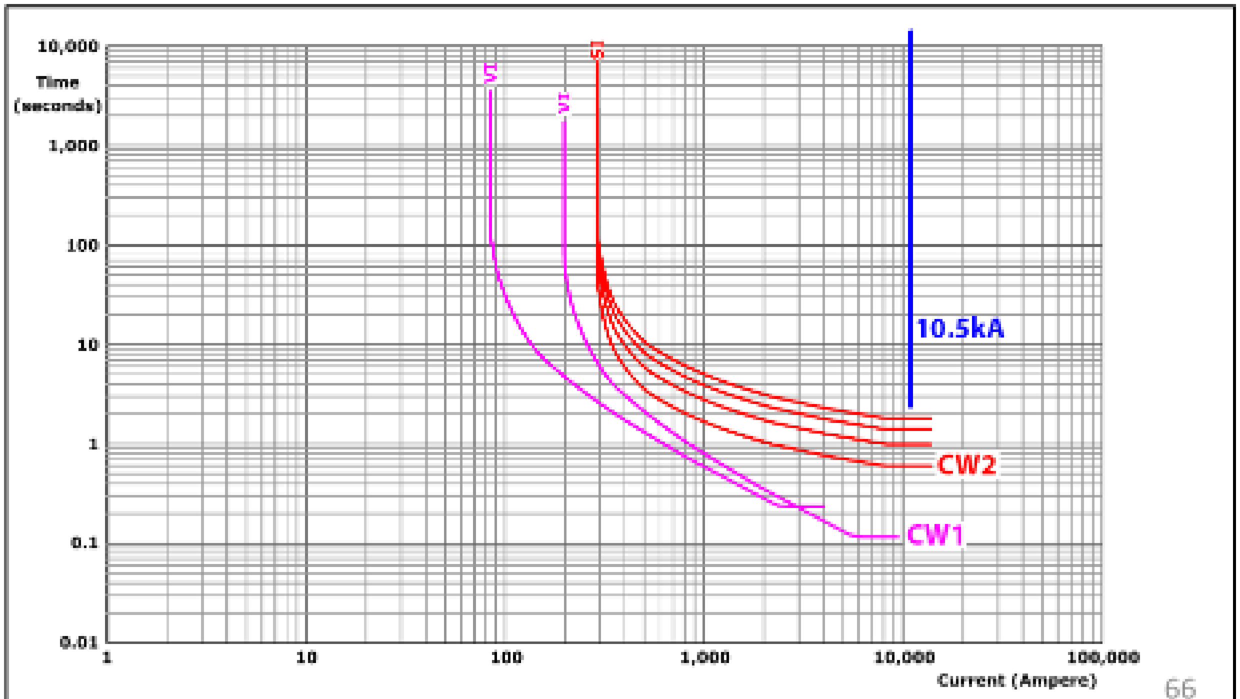
Closed Ring Main



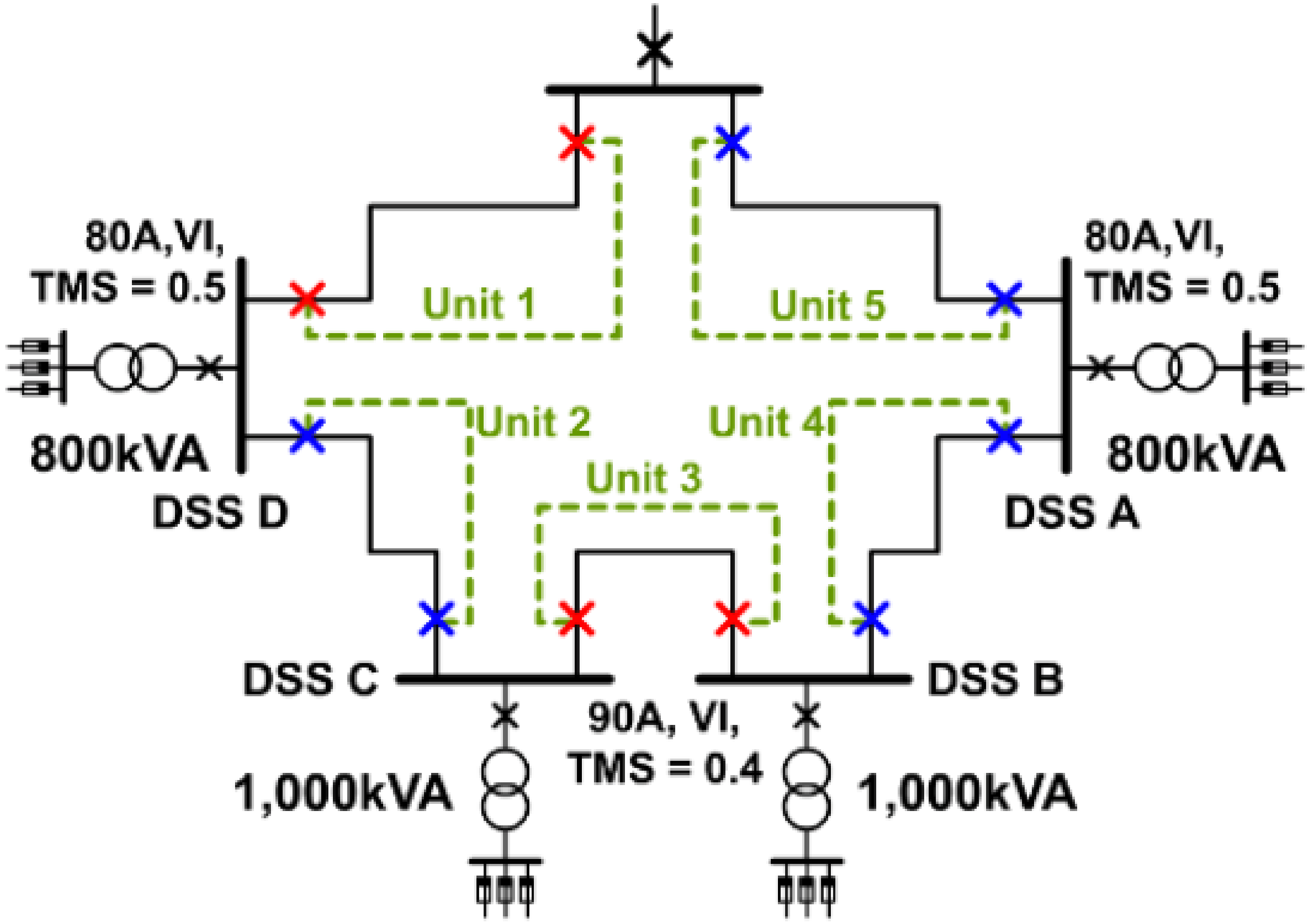
Fully Worked Solution – Time Graded



Relay	CT	CM	Type	TMS	Relay operating time at 10.5kA (seconds)
MV feed to 800kVA Tx	100:1	0.8	VIDMT	0.5	0.23
MV feed to 1000kVA Tx	100:1	0.9	EIDMT	0.4	0.05
CW1 / ACW1	250:1	0.75	VIDMT	0.25	0.12
CW2 / ACW2	250:1	1.1	IDMT (SI)	0.3	0.6
CW3 / ACW3	250:1	1.1	IDMT (SI)	0.5	1.0
CW4 / ACW4	250:1	1.1	IDMT (SI)	0.7	1.4
CW5 / ACW5	250:1	1.1	IDMT (SI)	0.9	1.8



Fully Worked Solution – Unit Protection



And More …

- Transformer Balanced and Restricted Earth-Fault Protection (BEF and REF)
- Buchholz Relay
- Generator Protection
- Engineering Recommendation G99 (2019) (Generator connection in parallel with the grid)
- Typical Relay Configurations for Transformers and Generators.
- IEC Loading Guide for Transformers

Thank you

- Questions?