Exercise 6.4 – Short-Circuit Current and Dimensioning in Medium-Low-Voltage Networks

For the electrical network represented in Figure 1, you must:

1. Define and verify the characteristics of the medium-voltage (MV) line cable (EPR insulation), taking into account a maximum intervention time of 350 ms for circuit breaker I1 after a three-phase short circuit.
2. Determine the direct and inverse impedances of the medium-voltage network.
3. Define and verify the characteristics of the low-voltage (LV) line cable (EPR insulation), considering a maximum intervention time of 150 ms for circuit breaker I3 after a three-phase short circuit.
4. Calculate the three-phase short-circuit current for circuit breakers I5 and define its characteristics in terms of breaking and re-closing capacities.

Medium-Voltage Network Data (MV):

- Nominal voltage: 20 kV
- Neutral state of the network: isolated
- Short-circuit power: 350 MVA
- Ratio $R_{cc}^{MV}/X_{cc}^{MV} = 0$

Transformer MV/LV Data (attached data):

- Nominal power: 500 kVA
- Nominal transformation ratio: 20/0.4 kV
- Winding connection: Delta (20 kV winding) – Star grounded (0.4 kV winding)
- Oil-cooled.

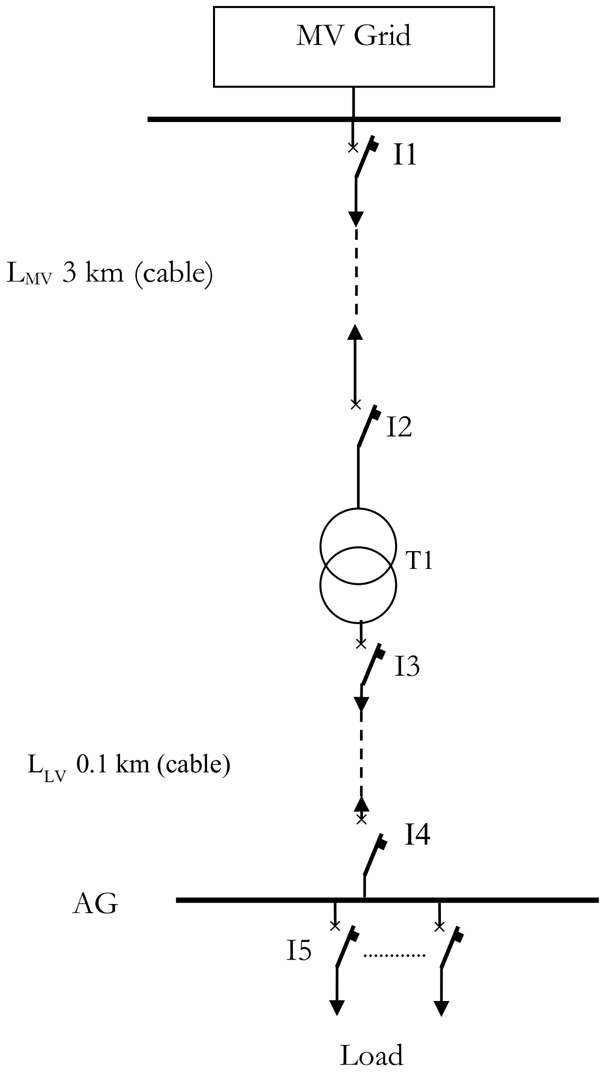

Figure 2 – Grid Schematics

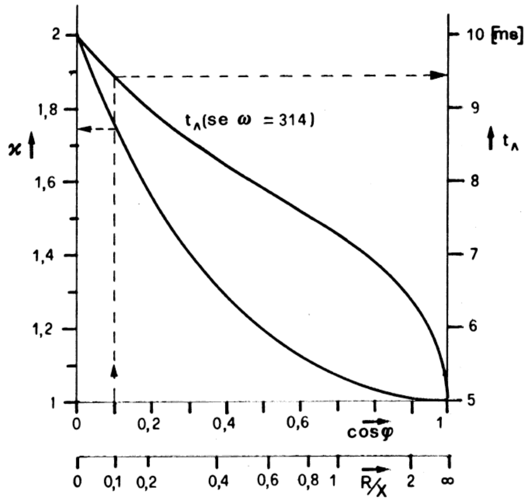

Figure 1 – χ Factor as a function of the ratio R_{CC}/X_{CC} of the short-circuit impedance $\bar{Z}_{CC}$.

Characteristics of low voltage cables (0.4kV) with EPR insulation ($K = 143$)

Conductor cross-section [mm2]	Maximum Amperage [A]					
	30 °C in air	at 30°C in air tube	at 20 °C buried tube		at 20°C buried	
			p=1	p=1.5	p=1	p=1.5
1.5	24	20	22	21	35	32
2.5	33	28	29	27	45	39
4	45	37	37	35	58	51
6	58	48	47	44	73	64
10	80	66	63	59	97	85
16	107	88	82	77	125	110
25	135	117	108	100	160	141
35	169	144	132	121	191	169
50	207	175	166	150	226	199
70	268	222	204	184	277	244
95	328	269	242	217	331	292
120	383	312	274	251	377	332
150	444	355	324	287	420	370
185	510	417	364	323	476	419
240	607	490	427	379	550	484
300	703	-	484	429	620	546
400	823	-	564	500	700	616

Conductor cross-section [mm2]	Resistance [ohm/km] at 70°C		Reactance [ohm/km] at 50°C	
	Dc	c.a	unipolar	multipolar
1.5	15.9	15.9	0.147	0.106
2.5	9.55	9.55	0.186	0.098
4	5.92	5.92	0.129	0.097
6	3.95	3.95	0.121	0.092
10	2.29	2.29	0.111	0.086
16	1.45	1.45	0.103	0.081
25	0.93	0.93	0.097	0.080
35	0.66	0.66	0.093	0.077
50	0.46	0.46	0.090	0.076
70	0.33	0.33	0.086	0.074
95	0.25	0.25	0.085	0.074
120	0.193	0.194	0.081	-
150	0.154	0.156	0.081	-
185	0.127	0.129	0.081	-
240	0.096	0.099	0.080	-
300	0.090	0.092	0.080	-
400	0.086	0.087	0.080	-

Characteristics of medium voltage cables (20kV) with EPR insulation ($K = 143$)

Section [mm2]	Specific Resistance [Ohm/km]	Reactance [Ohm/km]	Specific Capacity [$\mu F / km$]	Maximum Current Value [A]
25	0.929	0.15	0.18	157
35	0.670	0.14	0.17	190
50	0.495	0.13	0.19	228
70	0.344	0.13	0.21	284
95	0.248	0.12	0.23	346
120	0.198	0.12	0.25	399

MV/LV transformer data

TPRE - V SERIE **<= 24 KV**

Perdite ridotte Reduced losses SEA Pertes reduites SEA SEA abgesencte verluste — CEI-UNEL 21010	Tensione II° a vuoto Secondary voltage Tension secondaire Sekundär — 400 V.	Regolazione MT Tappings Regolation Klemmlasche — +/- 5%	Gruppo vettor. Vector group Gorupe vettoriel Schaltgruppe — Dyn11

DATI ELETTRICI — *ELECTRICAL DATA - DONNEES ELECTRIQUES - ELEKTRISCHE DATEN* — CEI 14-13 - DIN 42500 - CENELEC HD 428.1 S1 TAB."B"

Pot.	KVA	(50)	100	160	250	(315)	400	(500)	630	630	(800)	1000	1250	1600	2000	2500	3150
Wfe	Watt	150	250	360	520	510	740	740	1040	900	1090	1300	1600	2000	2400	3000	3600
Wcc (75 °C)	Watt	850	1400	1850	2600	3500	3650	4900	5200	5600	7000	9000	10600	13000	16000	21000	25500
Vcc (75 °C)	%	4	4	4	4	4	4	4	4	6	6	6	6	6	6	6	6
Ioo	%	1,9	1,5	1,3	1,1	1	0,9	0,9	0,8	0,8	0,8	0,7	0,6	0,5	0,5	0,5	0,5
Lwa	dB(A)	46	48	50	52	54	54	55	56	56	58	58	59	60	62	64	66
Lpa 1 mt.	dB(A)	41	42	44	46	48	48	49	49	49	50	50	51	51	52	54	55
μ cosfi 1 (75 °C)	4/4 %	98,04	98,38	98,64	98,77	98,74	98,91	98,88	99,02	98,98	99	98,98	99,03	99,07	99,09	99,05	99,08
	3/4 %	98,35	98,64	98,85	98,95	98,96	99,08	99,08	99,17	99,15	99,17	99,16	99,2	99,23	99,25	99,22	99,25
	2/4 %	98,57	98,81	98,98	99,07	99,13	99,18	99,22	99,26	99,28	99,3	99,3	99,32	99,35	99,36	99,34	99,37
μ cosfi 0,9 (75 °C)	4/4 %	97,83	98,2	98,49	98,63	98,61	98,8	98,76	98,91	98,87	98,89	98,87	98,93	98,97	98,99	98,94	98,98
	3/4 %	98,17	98,49	98,72	98,84	98,85	98,98	98,97	99,08	99,06	99,08	99,07	99,11	99,15	99,16	99,13	99,16
	2/4 %	98,41	98,68	98,87	98,97	99,03	99,09	99,13	99,18	99,2	99,22	99,22	99,25	99,28	99,29	99,27	99,3
μ cosfi 0,8 (75 °C)	4/4 %	97,56	97,98	98,3	98,46	98,43	98,65	98,61	98,78	98,73	98,75	98,73	98,79	98,84	98,86	98,81	98,86
	3/4 %	97,95	98,3	98,56	98,7	98,71	98,85	98,85	98,96	98,94	98,96	98,95	99	99,04	99,06	99,02	99,06
	2/4 %	98,22	98,52	98,73	98,84	98,91	98,98	99,03	99,08	99,1	99,12	99,12	99,16	99,19	99,21	99,18	99,21
Ie/In		12	11,5	11	10,5	10	9,5	9	8	8	8	7,5	7,5	7,4	7,2	7,2	7
T	sec.	0,06	0,07	0,08	0,08	0,1	0,12	0,14	0,15	0,16	0,18	0,2	0,22	0,25	0,27	0,3	0,35
In II°	A	72	144	231	361	455	577	722	909	909	1155	1443	1804	2309	2887	3608	4547
Icc	A	1800	3600	5775	9025	11375	14425	18050	22725	15150	19250	24050	30067	38483	48117	60133	75783
Rl (75 °C)	%	1,7	1,4	1,16	1,04	1,11	0,91	0,98	0,83	0,89	0,88	0,9	0,85	0,81	0,8	0,84	0,81
Xl	%	3,62	3,75	3,83	3,86	3,84	3,9	3,88	3,91	5,93	5,94	5,93	5,94	5,95	5,95	5,94	5,95
DV cosfi 1	4/4 %	1,77	1,47	1,23	1,11	1,18	0,99	1,06	0,91	1,07	1,06	1,08	1,03	0,99	0,98	1,02	0,99
cosfi 0,9	4/4 %	3,14	2,93	2,76	2,66	2,72	2,57	2,62	2,5	3,51	3,5	3,52	3,48	3,45	3,44	3,47	3,45
cosfi 0,8	4/4 %	3,55	3,39	3,25	3,18	3,22	3,1	3,14	3,04	4,36	4,36	4,37	4,33	4,31	4,3	4,33	4,31
Q o	KVAR	0,9	1,4	1,9	2,4	2,9	3,2	4,1	4,4	4,5	5,8	6,2	6,6	6,8	8,5	10,7	13,6
Q f l	KVAR	1,4	3,1	5,2	8,4	10,4	13,9	17	22	34,6	43,8	55	68,9	89,1	111,2	138,4	174,8

DATI TECNICI — *TECHNICAL DATA - DONNES TECHNIQUES - TECHNISCHE DATEN*

Pot.	KVA	(50)	100	160	250	(315)	400	(500)	630	630	(800)	1000	1250	1600	2000	2500	3150
DIMENSIONI	*OVERALL DIMENSIONS - DIMENSIONS - MABE*																
L	mm.	1200	1150	1270	1380	1400	1500	1550	1570	1650	1700	1730	1950	2020	2020	2400	2700
W	mm.	570	740	720	800	750	910	830	900	960	1020	1050	1150	1250	1260	1300	1500
H	mm.	1260	1300	1410	1400	1500	1560	1620	1680	1570	1720	1760	1850	2020	2170	2220	2420
L1	mm.	910	850	960	1200	1220	1450	1400	1450	1570	1620	1730	1850	1940	2000	2150	2420
H1	mm.	1210	1230	1290	1330	1450	1500	1520	1585	1480	1590	1640	1640	1800	1960	1980	2150
H2	mm.	810	830	890	930	1060	1100	1120	1200	1080	1190	1240	1240	1400	1560	1600	1750
I x I	mm.	420	520	520	520	670	670	670	670	670	670	620	820	820	1070	1070	1070
D	mm.	100	125	125	125	125	125	125	125	125	125	150	150	150	200	200	200
T	mm.	45	40	40	40	40	40	40	40	40	40	60	60	60	70	70	70
PESI	*WEIGHTS - MASSE - GEWICHT*																
Tot.	Kg	440	600	800	1050	1250	1420	1650	1970	1950	2250	2750	3200	3700	4300	5300	6400
Oil	Kg	80	85	130	160	190	220	240	280	290	400	480	600	650	800	950	1150
P.E.	Kg	250	400	520	700	830	1000	1100	1350	1300	1450	1700	1900	2270	2500	2950	3500

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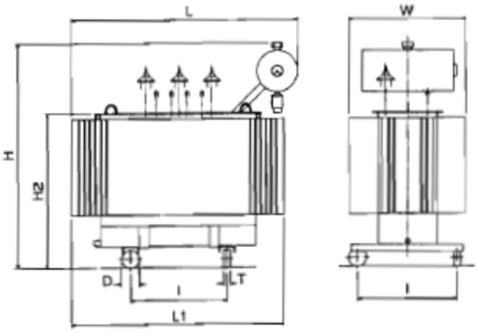

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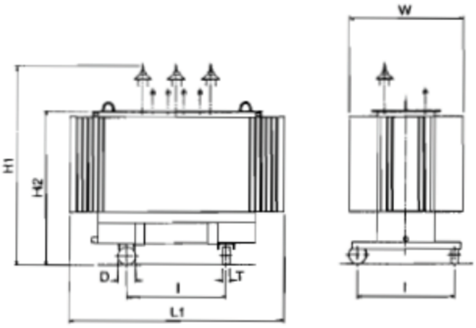
HERMETIQUE - HERMETISCHE AUSFÜHRUNG



Q1 – Define and verify the characteristics of the L_{MV} line in medium voltage cable (EPR insulation) taking into account a maximum intervention time of 350 ms of the I1 circuit breakers after a three-phase short circuit.

In order to define the characteristics of the line connecting the MV network and the T1 transformer, it must be taken into account that the line must guarantee the full power supply of the transformer. So, the maximum operating current of the line is simply:

$$I_{T_1} = \frac{S_{T_1}}{\sqrt{3}V_n^{MT}} = \frac{500 \cdot 10^3 VA}{\sqrt{3} \cdot 20 \cdot 10^3 V} = 14.4A$$

From the table of characteristics of medium-voltage cables, we will choose the cable $A^{L_{MV}} = 25mm^2$, whose maximum current value is $157\ A$. On the other hand, the minimum cross-section of the cable L= $25mm^2$ A_{MV} necessary to satisfy the Joule integral ($I_{cc}^2 \Delta t \leq K^2 A^2$) is:

$$A_{min}^{L_{MV}} = \sqrt{\frac{\left(I_{cc,3ph}^{MV}\right)^2 \Delta t}{K^2}}$$

To determine the minimum cable cross-section of the L_{MV} line, it is first necessary to determine the maximum short-circuit current for this cable which corresponds to the 3-ph short-circuit current of the MV network.

$$I_{cc,3ph}^{MT} = \frac{S_{cc}^{MT}}{\sqrt{3}V_n^{MT}} = \frac{350 \cdot 10^6 VA}{\sqrt{3} \cdot 20 \cdot 10^3 V} = 10.1kA$$

To determine the $A_{min}^{L_{MV}}$, the coefficient $K = 143$ (EPR insulation of the cable) must be taken into account:

$$A_{min}^{L_{MV}} = \sqrt{\frac{\left(I_{cc,3ph}^{MV}\right)^2 \Delta t}{K^2}} = \sqrt{\frac{(10.1 \cdot 10^3 A)^2 \cdot 0.35s}{143^2}} = 41.8mm^2$$

Therefore, the cross-section to choose for the $\mathbf{L_{MV}}$ cable is $A^{L_{MV}} = 50mm^2$.

For the chosen cable, here are the electrical parameters:

resistance per unit length: $r_{pul} = 0.495 \frac{\Omega}{km}$
reactance per unit length: $x_{pul} = 0.13 \frac{\Omega}{km}$
Capacity per unit length: $c_{pul} = 0.19 \frac{\mu F}{km}$

And the electrical parameters for $\mathbf{L_{MV}}$ cable:

Longitudinal resistance: $r^{L_{MV}} = 0.495 \frac{\Omega}{km} 3km = 1.485\Omega$
Longitudinal reactance: $x^{L_{MV}} = 0.13 \frac{\Omega}{km} 3km = 0.39\Omega$
Shunt Capacity: $c^{L_{MV}} = 0.19 \frac{\mu F}{km} 3km = 0.57\mu F$

Q2 – Determine the impedances at the direct sequence, inverse of the medium voltage network

With the knowledge of the short-circuit power of the MV network ($S_{cc}^{MT} = 350MVA$), and consequently of the 3-ph short-circuit current of the MV network ($I_{cc,3ph}^{MT} = 10.1kA$), we can calculate the absolute value of the short-circuit impedance of the MV network:

$$|\bar{Z}_{cc}^{MV}| = \frac{V_n^{MV}}{\sqrt{3}I_{cc,3ph}^{MT}} = \frac{20 \cdot 10^3 V}{\sqrt{3} \cdot 10.1 \cdot 10^3 A} = 1.14\Omega$$

The hypothesis $R_{cc}^{MV}/X_{cc}^{MV} = 0$ allows us to determine the complex value of the short-circuit impedance of the MV network:

$$\bar{Z}_{cc}^{MV} = 0 + j1.14\Omega$$

Therefore, we can determine the forward and inverse sequence impedances of the MV network:

$$\bar{Z}_d^{MV} = \bar{Z}_i^{MV} = \bar{Z}_{cc}^{MV} = 0 + j1.14\Omega$$

Q3 – Define and verify the characteristics of the L_{LV} low-voltage cable line (EPR insulation), taking into account a maximum intervention time of 150 ms of the I3 circuit breaker after a three-phase short circuit.

As with the L_{MV} line, in order to define the characteristics of the L_{LV} line connecting the T_1 transformer to the AG bus, it must be taken into account that the line must guarantee the full power supply of the AG bus. Therefore, the maximum operating current of this line is simply associated with the nominal power of the transformer T_1 and the nominal voltage at the secondary of this machine:

$$I_n^{T_1"} = \frac{S^{T_1}}{\sqrt{3}V_n^{LV}} = \frac{500 \cdot 10^3 VA}{\sqrt{3} \cdot 400V} = 721.7A$$

From the table of characteristics of low voltage cables, we will choose the cable $A^{L_{BT}} = 400mm^2$ with an installation at a maximum temperature of 30 °C in air (first column of the table of characteristics of low voltage cables, 0.4kV, with EPR insulation) because it has a maximum current intensity of $823\ A$.

On the other hand, the minimum cross-section of the cable L_{LV} necessary to satisfy the Joule integral (:$I_{cc}^2 \Delta t \leq K^2 A^2$) is

$$A_{min}^{L_{LV}} = \sqrt{\frac{\left(I_{cc,3ph}^{I_3}\right)^2 \Delta t}{K^2}}$$

To determine the minimum cross-section $A_{min}^{L_{LV}}$ of the cable of the L_{LV} line, it is first necessary to determine the maximum short-circuit current for this cable which corresponds to the short-circuit current 3-ph in correspondence of the circuit breaker I3 (i.e., just downstream of the transformer T_1) $I_{cc,3ph}^{I_3}$:

$$\bar{I}_{cc,3ph}^{I_3} = \frac{V_n^{bt}}{\sqrt{3}\bar{Z}_d^{I_3}}$$

It is therefore necessary to determine the impedance $\bar{Z}_d^{I_3}$ of the direct sequence upstream of the circuit breaker I_3.

Upstream of this circuit breaker, we have the T_1 transformer, the L_{MV} line and the MV network. Therefore, the $\bar{Z}_d^{I_3}$ is simply given by the sum of the direct sequence impedances of the transformer T_1, the L_{MV} line and the MV network.

$$\bar{Z}_d^{I_3} = \bar{Z}_d^{MV"} + \bar{Z}_d^{L_{MV}"} + \bar{Z}_d^{T_1"}$$

WARNING: the $\bar{I}_{cc,3ph}^{I_3}$ is calculated on the low voltage side of T_1, so the direct sequence impedances of the transformer T_1, the L_{MV} line and the MV network must be related to the secondary of the transformer T_1.

With knowledge of the transformation ratio of T_1 ($k = \frac{20kV}{0.4VkV} = 50$), we can calculate $\bar{Z}_d^{MT"}$ and $\bar{Z}_d^{LMT"}$:

$$\bar{Z}_d^{MV"} = \frac{\bar{Z}_d^{MV}}{k^2} = \frac{j1.14\Omega}{50^2} = j0.46 \cdot 10^{-3}\Omega$$

$$\bar{Z}_d^{L_{MV}"} = \frac{\bar{Z}_d^{L_{MV}}}{k^2} = \frac{r_{L_{MV}} + jx_{L_{MV}}}{k^2} = \frac{(1.485 + j0.39)\Omega}{50^2} = (0.59 + j0.16) \cdot 10^{-3}\Omega$$

To determine $\bar{Z}_d^{T_1"}$, we must use the characteristics of the transformers in the table "MV/LV transformer data" and recall that, for the T_1 transformer with the connections of the triangle winding (20kV winding) – earth-bound star (0.4 kV winding), we have that:

$$\bar{Z}_d^{T_1"} = \bar{Z}_i^{T_1"} = \bar{Z}_0^{T_1"} = \bar{Z}_{cc}^{T_1"}$$

For a machine of $500\ kVA$, we have:

$$V_{cc}^{T_1} = 4\%$$

$$P_{cc}^{T_1} = 4900\ W$$

Therefore, the short-circuit voltage (in V) at the secondary of the transformer $\left(V_{cc}^{T_1"}\right)$ is:

$$V_{cc}^{T_1"} = 0.04 \cdot 400V = 16V$$

Through the knowledge of the nominal current of the transformer at the secondary level $\left(I_n^{T_1"} = 721.7A\right)$ and the definition of the short-circuit voltage of a transformer $\left(V_{cc}^{T_1"} = \sqrt{3}\, Z_{cc}^{T_1"} I_n^{T_1"}\right)$, we can calculate the module of the short-circuit impedance:

$$Z_{cc}^{T_1"} = \frac{V_{cc}^{T_1"}}{\sqrt{3}\, I_n^{T_1"}} = \frac{16V}{\sqrt{3} \cdot 721.7A} = 12.8 \cdot 10^{-3}\Omega$$

The real part of the impedance $Z_{cc}^{T_1"}$ is associated with the losses $P_{cc}^{T_1}$ because $P_{cc}^{T_1} = 3R_{cc}^{T_1"}\left(I_n^{T_1"}\right)^2$, therefore:

$$R_{cc}^{T_1"} = \frac{P_{cc}^{T_1}}{3\left(I_n^{T_1"}\right)^2} = \frac{4900W}{3 \cdot (721.7A)^2} = 3.14 \cdot 10^{-3}\Omega$$

The imaginary part of the impedance $Z_{cc}^{T_1"}$ is:

$$X_{cc}^{T_1"} = \sqrt{\left(Z_{cc}^{T_1"}\right)^2 - \left(R_{cc}^{T_1"}\right)^2} = \sqrt{(12.8 \cdot 10^{-3}\Omega)^2 - (3.14 \cdot 10^{-3}\Omega)^2} = 12.41 \cdot 10^{-3}\Omega$$

And the complex impedance $\bar{Z}_{cc}^{T_1"}$

$$\bar{Z}_{cc}^{T_1"} = \bar{Z}_{d}^{T_1"} = (3.14 + j12.41) \cdot 10^{-3}\Omega$$

We can therefore calculate the complex impedance $\bar{Z}_d^{I_3}$ of the direct sequence upstream of the circuit breaker I_3

$$\begin{aligned}\bar{Z}_d^{I_3} = \bar{Z}_d^{MV"} + \bar{Z}_d^{L_{MV}"} + \bar{Z}_d^{T_1"} \\ &= j0.46 \cdot 10^{-3}\Omega + (0.59 + j0.16) \cdot 10^{-3}\Omega + (3.14 + j12.41) \cdot 10^{-3}\Omega \\ &= (3.73 + j13.03) \cdot 10^{-3}\Omega\end{aligned}$$

And also the module $\left|\bar{Z}_d^{I_3}\right| = \sqrt{(3.73 \cdot 10^{-3}\Omega)^2 + (13.03 \cdot 10^{-3}\Omega)^2} = 13.55 \cdot 10^{-3}\Omega$

The module of the 3-ph short-circuit current in correspondence with the I3 circuit breaker is:

$$I_{cc,3ph}^{I_3} = \frac{V_n^{bt}}{\sqrt{3}Z_d^{I_3}} = \frac{400V}{\sqrt{3} \cdot 13.55 \cdot 10^{-3}\Omega} = 17043A$$

Therefore, the minimum cross-section of the L_{LV} cable necessary to satisfy the Joule integral ($I_{cc}^2\Delta t \leq K^2A^2$) is (it should be remembered that in the data of the exercise we have a maximum intervention time of 150ms of the circuit breaker I_3 after a three-phase short circuit):

$$A_{min}^{L} = \sqrt{\frac{\left(I_{cc,3ph}^{I_3}\right)^2 \Delta t}{K^2}} = \sqrt{\frac{(17043A)^2 0.15s}{(143)^2}} = 46.1mm^2$$

Consequently, the cross-section $A^{L_{LV}} = 400mm^2$ is more than sufficient to satisfy the thermal verification of the Joule integral for a 3-ph short circuit in correspondence with the circuit breaker I_3.

For the chosen cable, here are the electrical parameters:

- resistance per unit length: $r_{pul} = 0.087\frac{\Omega}{km}$
- reactance per unit length: $x_{pul} = 0.080\frac{\Omega}{km}$

And the electrical parameters for L_{LV} cable:

- Longitudinal resistance: $r^{L_{LV}} = 0.087\frac{\Omega}{km}0.1km = 8.7\cdot 10^{-3}\Omega$
- Longitudinal reactance: $x^{L_{LV}} = 0.080\frac{\Omega}{km}0.1km = 8\cdot 10^{-3}\Omega$

Q4 – Calculate the three-phase short-circuit current for I_5 circuit breakers and define its characteristics in terms of breaking and restoring capacity. (0.75/4 pts).

For the breaking and restoring capacity of I_5, it is first necessary to determine the maximum short-circuit current corresponding to this circuit breaker, which corresponds to the short-circuit current 3-ph corresponding to the end of the L_{LV} cable:

$$\bar{I}_{cc,3ph}^{I_5} = \frac{V_n^{LV}}{\sqrt{3}\bar{Z}_d^{I_5}}$$

It is therefore necessary to determine the impedance $\bar{Z}_d^{I_5}$ of the direct sequence in correspondence to I_5. Upstream of this circuit breaker, we have:

- the line L_{LV},
- the T_1 transformer,
- the L_{MV} line and
- the MV network.

Therefore, the $\bar{Z}_d^{I_5}$ is simply given by the sum of the direct sequence impedances of the L_{LV} cable, the T1 transformer, the $\mathbf{L_{MV}}$ line and the MV network. It should be noted that the sum of the direct sequence impedances of the transformer T1, the $\mathbf{L_{MV}}$ line and the MV network has already been calculated when the short-circuit current for the circuit breaker I3 has been calculated $\left(\bar{Z}_d^{I_3}\right)$.

We can therefore calculate the complex impedance $\bar{Z}_d^{I_5}$ of direct sequence upstream of the circuit breaker I_5.

$$\bar{Z}_d^{I_5} = \left(\bar{Z}_d^{MV"} + \bar{Z}_d^{L_{MV}"} + \bar{Z}_d^{T_1"}\right) + \bar{Z}_d^{L_{LV}} = \bar{Z}_d^{I_3} + \bar{Z}_d^{L_{LV}} == \bar{Z}_d^{I_3} + (r^{L_{LV}} + jx^{L_{LV}})$$

$$= (3.73 + j13.03)\cdot 10^{-3}\Omega + (8.7 + j8)\cdot 10^{-3}\Omega = (12.43 + j21.03)\cdot 10^{-3}\Omega$$

And also, the module $\left|\bar{Z}_d^{I_5}\right| = \sqrt{(12.43\cdot 10^{-3}\Omega)^2 + (21.03\cdot 10^{-3}\Omega)^2} = 24.43\cdot 10^{-3}\Omega$

The module of the 3-ph short-circuit current in correspondence with the I5 circuit breaker is:

$$I_{cc,3ph}^{I_5} = \frac{V_n^{LV}}{\sqrt{3}Z_d^{I_5}} = \frac{400V}{\sqrt{3}\cdot 24.43\cdot 10^{-3}\Omega} = 9453A$$

Therefore, the breaking capacity of the I5 circuit breaker must be greater than $I_{cc,3ph}^{I_5}$

$PC_{I_5} > 9453A.$

For the restoring power, the factor χ for the impedance $\bar{Z}_d^{I_5}$ must be determined. First, we need to calculate the ratio between the real and imaginary part of $\bar{Z}_d^{I_5}$:

$$\frac{R_d^{I_5}}{X_d^{I_5}} = \frac{12.43 \cdot 10^{-3}\Omega}{21.03 \cdot 10^{-3}\Omega} = 0.59$$

Through Fig. 2, we have that $\chi^{I_5} \approx 1.2$. Therefore, the peak current for a 3-ph short circuit in correspondence to the I_5 circuit breaker is:

$$I_{peak,3ph}^{I_5} = \sqrt{2}\chi^{I_5} I_{cc,3ph}^{I_5} = \sqrt{2} \cdot 1.2 \cdot 9453A = 16042A$$

Therefore, the restoring power of the I5 circuit breaker must be greater than $I_{peak,3ph}^{I_5}$:

$PR_{I_5} > 16042A$.