Optimal power transformer sizing

Case study

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Contents

1. OBJECT DESCRIPTION

In this study, multiple scenarios are simulated to find the optimal size for a 110/6.3 kV power transformer. Four cases are analyzed:

- Case 1 (25MVA transformers)
- Case 2 (40MVA transformers)
- Case 3 (31.5MVA transformers)
- Case 4 (20MVA transformers, reserve not considered)

All simulation results are calculated according to the peak demand of each substation in the plant. The list of power demands is provided in

Table 1.

Table 1 Apparent power list of loads

Local substations	Apparent power, kVA
Bus 2	1010
Bus 3	1038
Bus 4	6309
Bus 5	3054
Bus 7	2361
Bus 9	3720
Bus 17	1444
Bus 18	8010
Bus 20	369
Bus 21	8182
Substation 1 (considering reserve)	9070
Substation 1 (not considering reserve)	7570

In carried out calculations, the voltage level in the infinete busbar is assumed to be 115kV. It is also assumed that the short circuit current in the infinite busbar is equal to 11.6 kA. The network single-line diagram can be found in Annex no. 1. Calculations are performed with a power system modeling software EA-PSM.

2. Case 1 – 25MVA power transformers

Case 1 represents the existing situation and is calculated for comparison purposes. Transformer characteristics used in calculations can be found in Table 2.

Table 2 25MVA transformer characteristics

Rated capacity	Rated Voltage		No-load loss	Load loss	Short circuit voltage
MVA	H.V. (kV)	L.V. (kV)	%	kW	%
25	115 +/- 11x1%	6.3	0.15	125	9.89

2.1.Maximum load operation mode (considering reserve power)

In maximum load operation mode (both transformers are operating) calculations showed that transformer TR1 loading reaches up to 26.7MVA (26.15MW and 5.56MVar), transformer TR2 loading reaches up to 18.4MVA (17.86MW and 4.30MVar). Based on the expected situation, transformer **TR1 is loaded at 106.94%** and transformer **TR2 is loaded at 73.49%**. The power reserve for transformer TR2 is 6.63 MVA and transformer TR1 is overloaded by 1.74 MVA. These results were reached by **considering 1.8 MW reserve power of substation 1**. Calculation results are depicted in Figure 1.

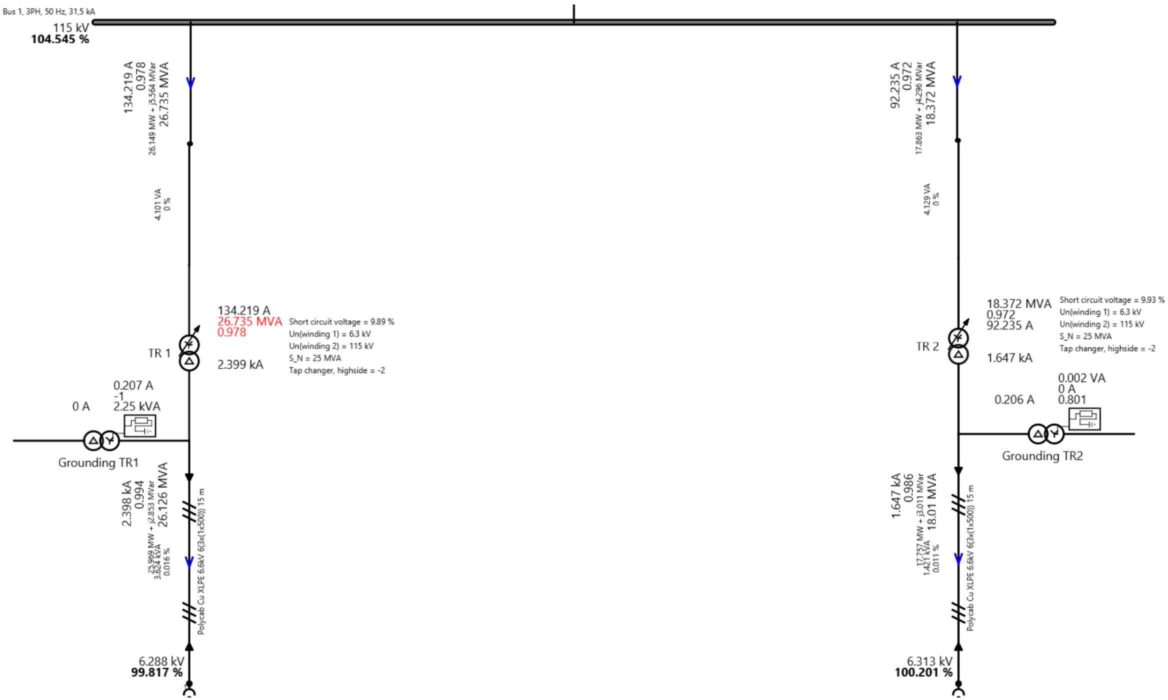


Figure 1 Calculation results for Case 1, when considering the reserve power

2.2. Maximum load operation mode (reserve power not considered)

If this reserve power mentioned above is not included in the calculations, transformer TR1 loading does not exceed 25 MVA and it is loaded at 99.8% while transformer TR2 loading does not change. The full result for the described situation can be seen in Figure 2.

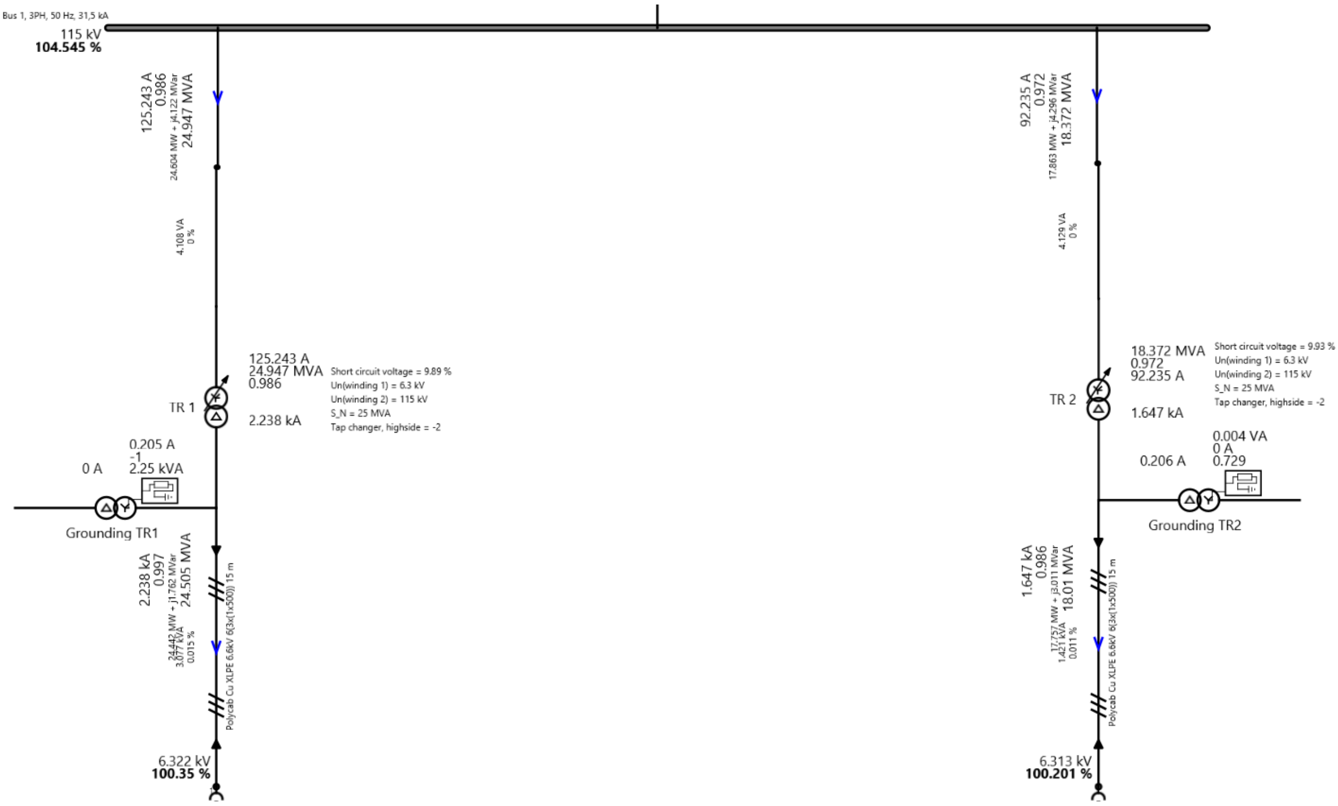


Figure 2 Calculation results for Case 1, when not considering the reserve power

When comparing results, the reserve power of CM8 and storage silo will not be included in Case 1 – 25MVA power transformers' calculation results.

2.3. Repair/Maintenance mode

In repair/maintenance mode only one of two transformers is working. After installing new loads, the total apparent power without considering the reserve or CM8 and storage silo would be 44.45MVA. The operating transformer could only handle up to 25MVA of power. Consequently, the transformer would be **177.8% loaded**. In this mode, the factory can only work at about half of its maximum power capacity.

3. CASE 2 – 40MVA POWER TRANSFORMERS

Case 2 is the situation that would occur after upgrading high to medium voltage transformers to 40MVA power. 40MVA transformer characteristics used in calculations can be found in Table 3.

Table 3 40MVA transformer characteristics

Rated capacity	Rated Voltage		No-load loss	Load loss	Short circuit voltage
MVA	H.V. (kV)	L.V. (kV)	%	kW	%
40	115 +/- 9x1.78%	6.3	0.055	170	10.5

3.1.Maximum load operation mode

In maximum load operation mode (both transformers are operating) calculations showed that transformer TR1 loading reaches up to 26.5MVA (26.07MW and 4.72MVar), transformer TR2 loading reaches up to 18.2MVA (17.82MW and 3.85MVar). Based on the expected situation, transformer **TR1 is loaded 66.23%** and transformer **TR2 is loaded 45.57%**. The power reserve for transformer TR1 is 13.51 MVA and for transformer, TR2 is 21.77 MVA. Calculation results are depicted in Figure 3.

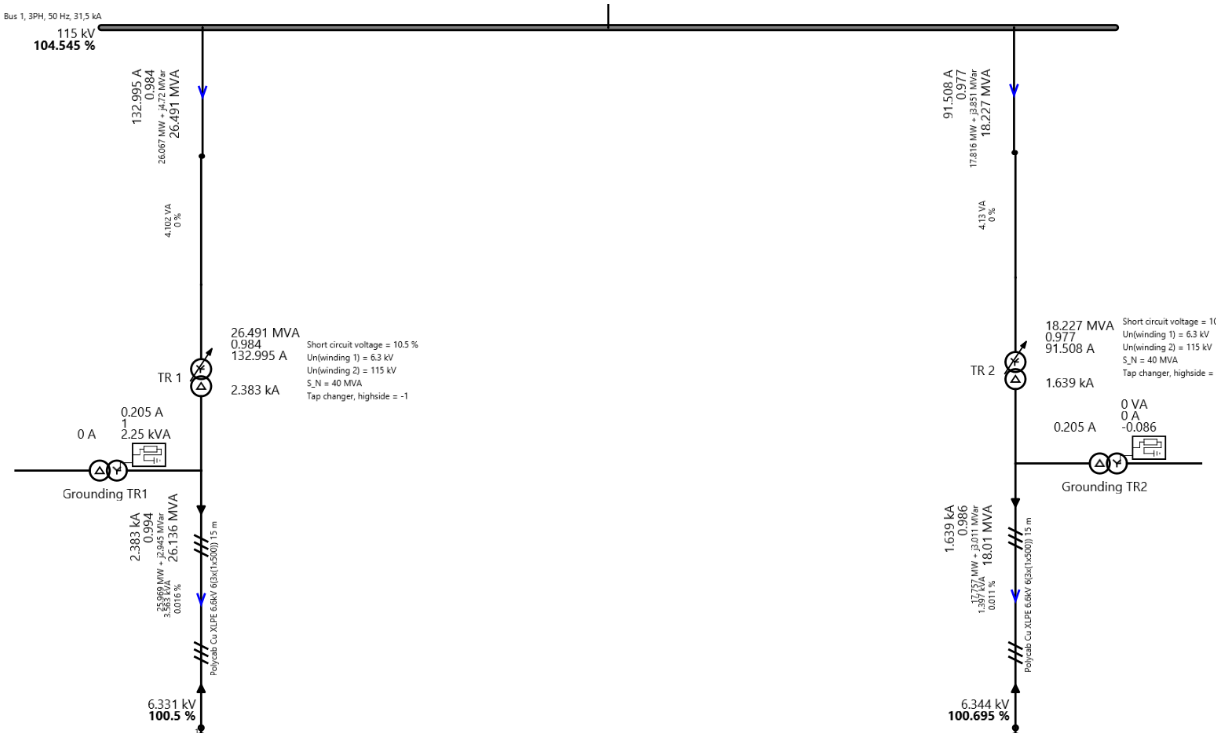


Figure 3 Calculation results for Case 2 maximum load operation mode

3.2. Repair/Maintenance mode

In repair/maintenance mode only one of two transformers is working. After installing new loads and not considering reserve power, the total apparent power would be 43.46MVA. The operating 40MVA transformer would be **loaded at 108.7%**. Simulated situation results are depicted in Figure 4.

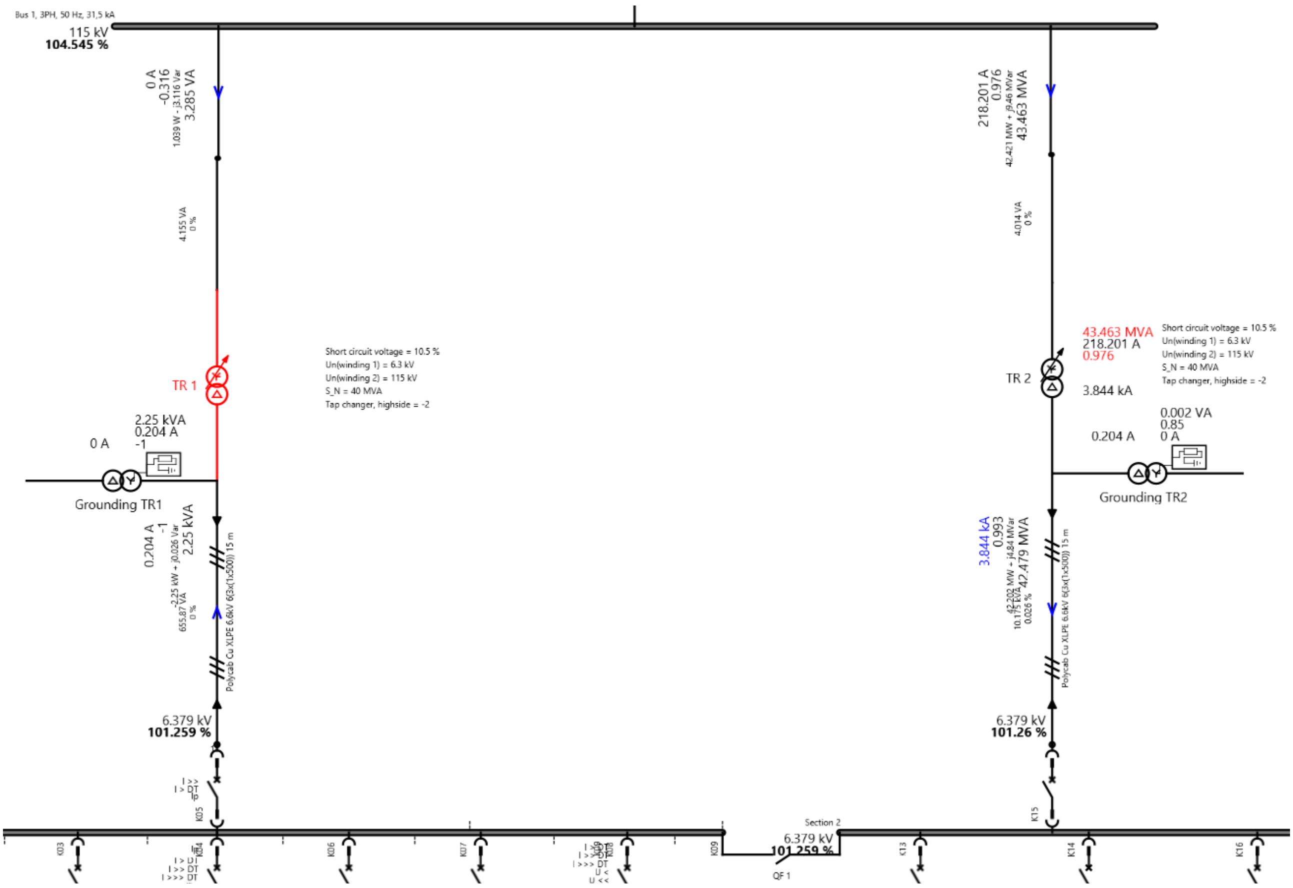


Figure 4 Calculation results for Case 2 repair/maintenance operation mode

4. CASE 3 – 31.5MVA TRANSFORMERS

Case 3 is the situation that would occur after upgrading high to medium voltage transformers to 31.5MVA power. 31.5MVA transformer characteristics used in calculations can be found in Table 4.

Table 4 31.5MVA transformer characteristics

Rated capacity	Rated Voltage		No-load loss	Load loss	Short circuit voltage
MVA	H.V. (kV)	L.V. (kV)	%	kW	%
31.5	110 +/- 8x1.25%	6.3	0.073	125	10.5

4.1.Maximum load operation mode

In maximum load operation mode (both transformers are operating) calculations showed that transformer TR1 loading reaches up to 26.6MVA (26.08MW and 5.24MVar), transformer TR2 loading reaches up to 18.2MVA (17.82MW and 4.08MVar). Based on the expected situation, transformer **TR1 is loaded 84.44%** and transformer **TR2 is loaded 58.04%**. The power reserve for transformer TR1 is 4.9 MVA and for transformer, TR2 is 13.3 MVA. Calculation results are depicted in Figure 5.

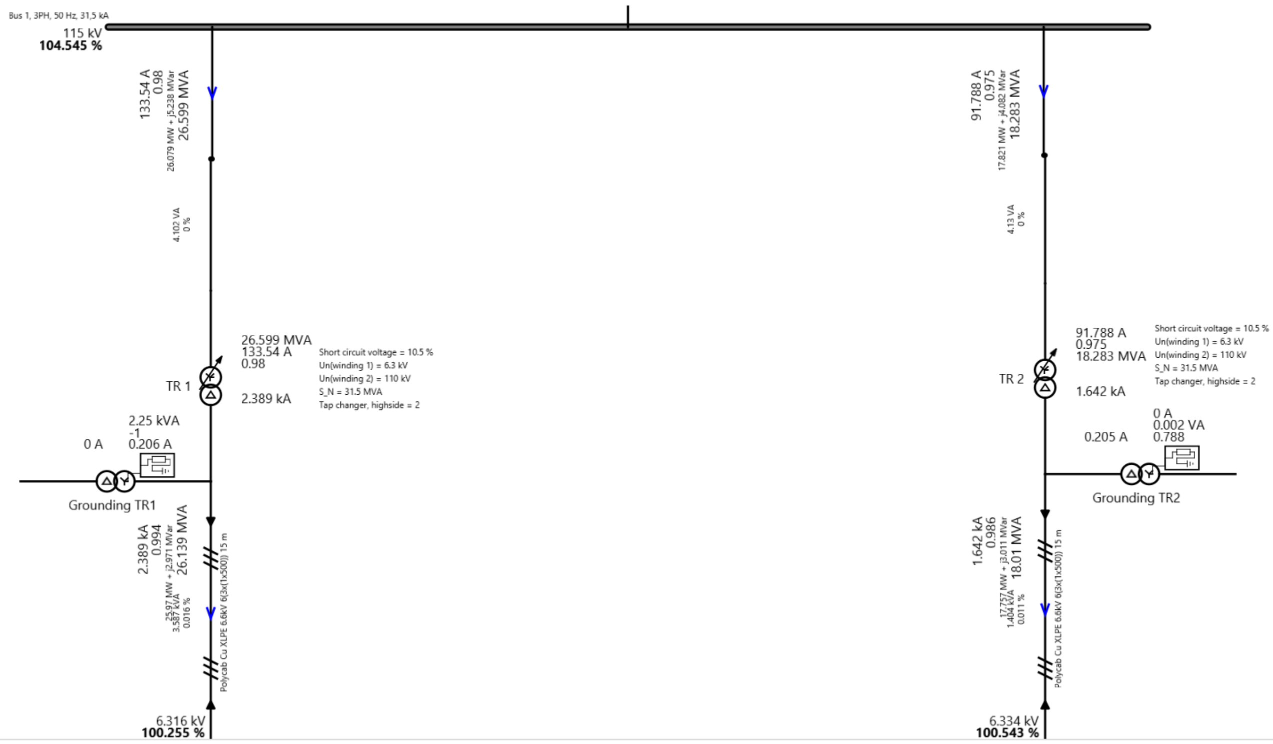


Figure 5 Calculation results for Case 3 maximum load operation mode

4.2.Repair/Maintenance mode

In repair/maintenance mode only one of two transformers is working. After installing new loads and not considering reserve power, the total apparent power would be 43.85MVA. The operating 31.5MVA transformer would be **loaded at 139.2%**. Case 3 emergency operation mode simulation results are shown in Figure 6.

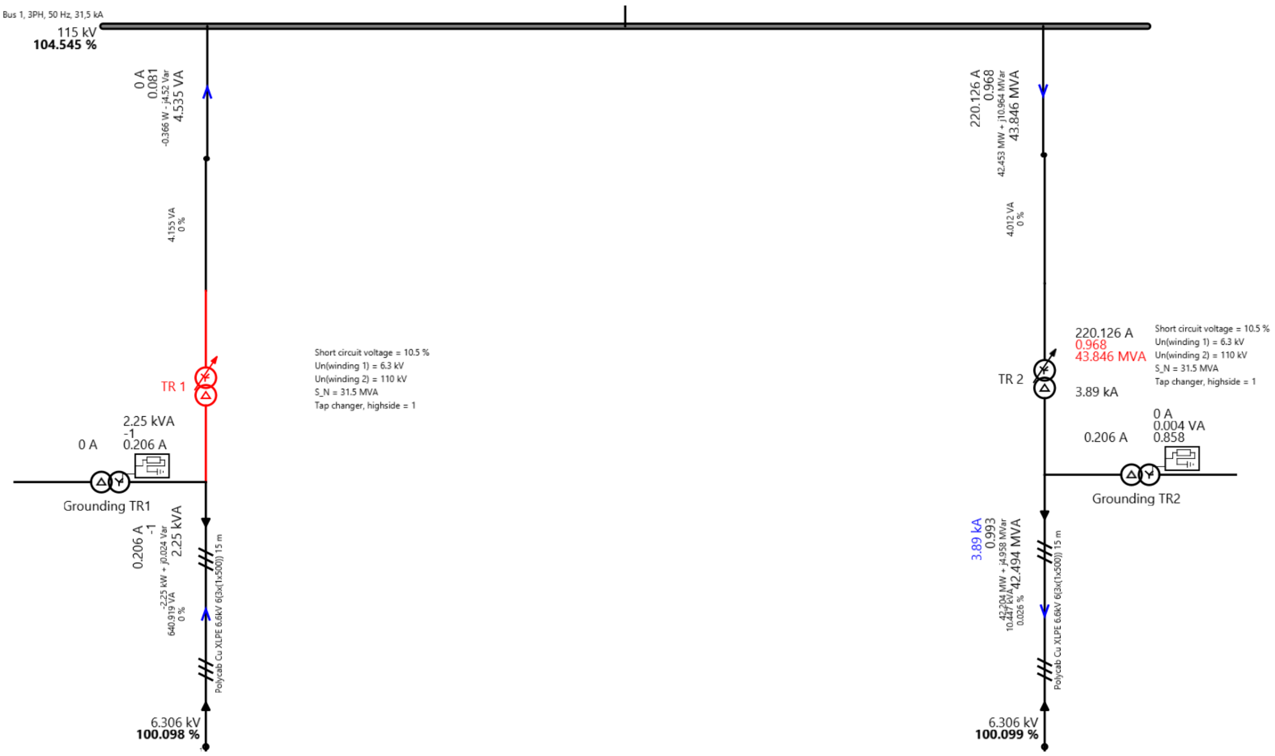


Figure 6 Calculation results for Case 3 repair/maintenance operation mode

5. CASE 4 – 20MVA TRANSFORMERS

Case 4 is the situation that would occur after downgrading high to medium voltage transformers to 20MVA power. Because the transformers, in this case, are downgraded, the reserve power of CM8 and the new storage silo are not considered when carrying out calculations. 20MVA transformer characteristics used in the analysis can be found in Table 5.

Table 5 20MVA transformer characteristics

Rated capacity	Rated Voltage		No-load loss	Load loss	Short circuit voltage
MVA	H.V. (kV)	L.V. (kV)	%	kW	%
20	110 +/- 8x1.25%	6.3	0.0825	88.5	10.5

5.1. Maximum load operation mode

In maximum load operation mode (both transformers are operating) calculations showed that transformer TR1 loading reaches up to 25.1MVA (24.59MW and 4.95MVar), transformer TR2 loading reaches up to 18.5MVA (17.85MW and 4.69MVar). Based on the expected situation, transformer **TR1 is loaded 125.41%** and transformer **TR2 is loaded 92.25%**. The power reserve for transformer TR2 is 1.55 MVA and transformer TR1 is overloaded by 5.08 MVA. Calculation results are depicted in Figure 7.

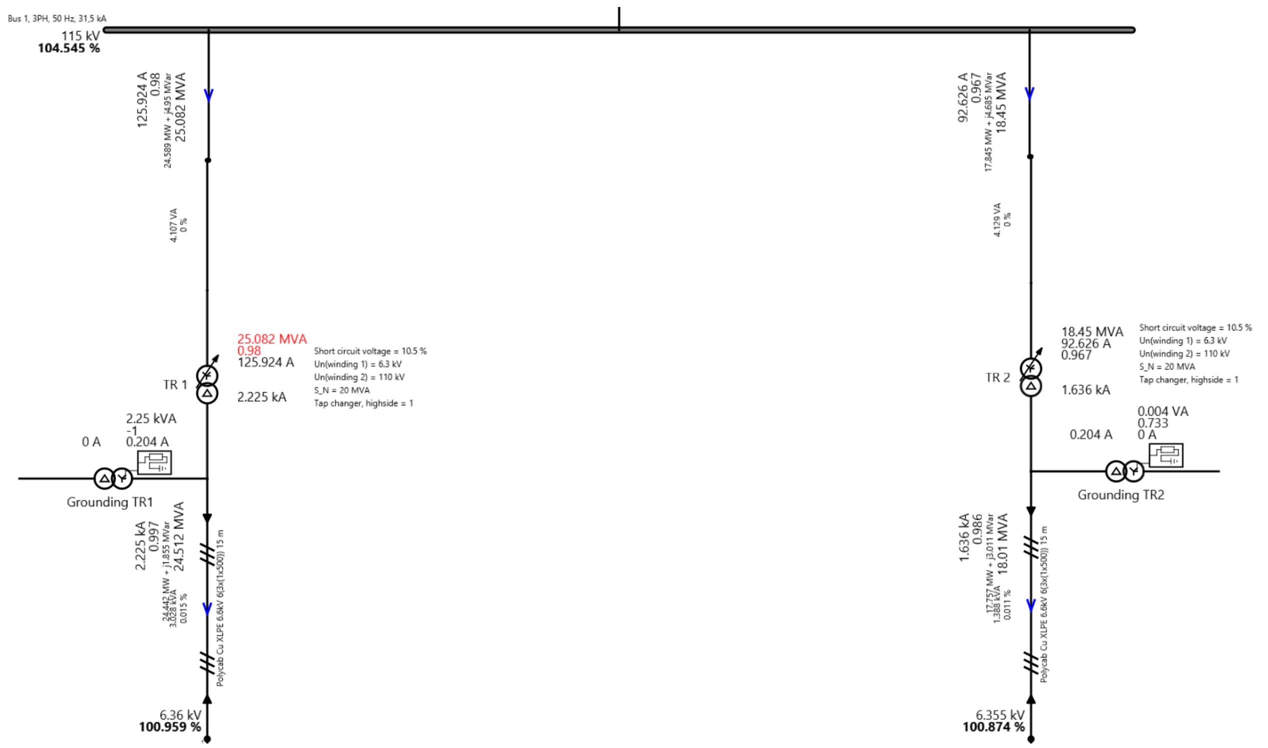


Figure 7 Calculation results for Case 4 maximum load operation mode

5.2.Repair/Maintenance mode

In repair/maintenance mode only one of two transformers is working. The operating transformer could only handle up to 20MVA of power, while the entire demanded apparent power would be equal to 44.86MVA. Therefore, the transformer would be **224.3% loaded**. In this mode, the factory can only work at about 45% of its maximum power capacity.

6. COMPARING VOLTAGE DROP CALCULATION RESULTS

Voltage drop in high to medium voltage transformers as well as voltage level at section 1 and section 2 are provided in Table 6. This analysis was carried out only for maximum load operation mode (both transformers are operating). Results for case 1 and case 4 were reached by not considering the reserve power. However, it was considered for case 2 and case 3 calculations. In Table 6 all calculations were done when the tap changer position was not adjusted.

Table 6 Voltage drop in transformers and voltage level in main sections comparison

	Transformer	Transformer's rated voltage	Transformer power, MVA	Tap changer position	Voltage drop in transformer's MV windings, V	Voltage drop in transformer's MV windings, %	Section	The voltage level in the main 6.3kV bus, kV
Case 1	TR-1	115/6.3	25	0	311.2	5.16	Section 1	6.18
	TR-2	115/6.3	25	0	229.6	3.81	Section 2	6.184
Case 2	TR-1	115/6.3	40	0	219.3	3.64	Section 1	6.21
	TR-2	115/6.3	40	0	150.6	2.50	Section 2	6.23
Case 3	TR-1	110/6.3	31.5	0	248.7	3.95	Section 1	6.52
	TR-2	110/6.3	31.5	0	183.3	2.91	Section 2	6.50
Case 4	TR-1	110/6.3	20	0	395.7	6.28	Section 1	6.45
	TR-2	110/6.3	20	0	291.4	4.63	Section 2	6.44

The transformers have automatic tap changers, that can automatically compensate for voltage drop by changing their positions. Consequently, during power flow calculations, the transformer tap changer's position is automatically selected according to voltage level in the medium voltage network (6.3 kV voltage is maintained). Calculation results for when the tap position is changed to maintain the nominal voltage level in the network are displayed in Table 7.

Table 7 Voltage drop and voltage level after tap charger position is adjusted

	Transformer	Transformer's rated voltage	Transformer power, MVA	Tap changer position	Tap changer step, %	Voltage drop in transformer's MV windings, V	Voltage drop in transformer's MV windings, %	Section	The voltage level in the main 6.3kV bus, kV
Case 1	TR-1	115/6.3	25	-2	1.00	298.69	4.86	Section 1	6.32
	TR-2	115/6.3	25	-2	1.00	220.49	3.59	Section 2	6.31
Case 2	TR-1	115/6.3	40	-1	1.78	211.3	3.45	Section 1	6.33
	TR-2	115/6.3	40	-1	1.78	145.32	2.37	Section 2	6.34
Case 3	TR-1	110/6.3	31.5	2	1.25	279.77	4.56	Section 1	6.32
	TR-2	110/6.3	31.5	2	1.25	192.92	3.14	Section 2	6.33
Case 4	TR-1	110/6.3	20	1	1.25	406.60	6.54	Section 1	6.36
	TR-2	110/6.3	20	1	1.25	299.02	4.81	Section 2	6.36

The results in the table above show that in all cases it is possible to compensate voltage drop in transformers with the help of a tap changer.

7. MOTOR STARTING CURRENTS

Motor data used in calculating motor starting currents and voltage levels in the network are provided in Table 8.

Table 8 Motor data

Motor name	Nominal power, kW	Nominal voltage, V	Nominal current, A	Starting current ratio
Motor 1	1255	6300	115	5
Motor 2	4300	6300	394	5.5
Motor 3	132	400	190	6.7
Motor 4	315	400	455	6.7
Motor 5	355	400	513	6.3
Motor 7	1200	6300	110	5
Motor 8	4256	6300	390	5
Motor 9	2237	6300	205	5
Motor 10	3710	6300	340	5

Motor starting current study was calculated only for maximum load operation mode (both transformers are operating). Results for case 1 and case 4 were reached by not considering the reserve power. However, it was considered for case 2 and case 3 calculations. Results can be seen in Table 9. As it can be seen in results, case 2 and case 3 show significantly lower voltage drops and smaller currents than in case 1. In case 4 many motors start dropped voltage levels lower than 10%. This could have some negative effects on motor starting and the entire network overall.

Table 9 Motor start current and voltage calculation results

<table>
<tr><th></th><th>Starting motors</th><th>The voltage level at connected busbar, kV</th><th>Voltage level at connected busbar, %</th><th>The voltage level at the main section, kV</th><th>The voltage level at section, %</th><th>Current at connecting line, kA</th><th>Current at the transformer, kA</th></tr>
<tr><td rowspan="6">Case 1</td><td>Motor 1</td><td>6.17</td><td>97.94</td><td>6.18</td><td>98.12</td><td>0.67</td><td>2.66</td></tr>
<tr><td>Motor 2</td><td>5.73</td><td>90.97</td><td>5.82</td><td>92.33</td><td>2.24</td><td>3.99</td></tr>
<tr><td>Motor 3
&
Motor 4</td><td>0.375</td><td>93.67</td><td>6.25</td><td>99.16</td><td>5.38</td><td>2.47</td></tr>
<tr><td>Motor 5</td><td>0.383</td><td>95.64</td><td>6.27</td><td>99.45</td><td>4.41</td><td>2.42</td></tr>
<tr><td>Motor 7
&
Motor 8</td><td>5.67</td><td>90.07</td><td>5.70</td><td>90.50</td><td>2.97</td><td>3.81</td></tr>
<tr><td>Motor 9
&
Motor 10</td><td>5.61</td><td>89.01</td><td>5.63</td><td>89.31</td><td>3.23</td><td>4.09</td></tr>
</table>

	Starting motors	The voltage level at connected busbar, kV	Voltage level at connected busbar, %	The voltage level at the main section, kV	The voltage level at section, %	Current at connecting line, kA	Current at the transformer, kA
Case 2	Motor 1	6.23	98.95	6.25	99.13	0.66	2.79
	Motor 2	5.93	94.19	6.02	95.59	2.16	4.03
	Motor 3 & Motor 4	0.371	92.79	6.29	99.77	6.60	2.62
	Motor 5	0.379	94.72	6.30	99.96	5.58	2.56
	Motor 7 & Motor 8	5.94	94.33	5.97	94.74	2.84	3.64
	Motor 9 & Motor 10	5.91	93.77	5.93	94.06	3.07	3.88
Case 3	Motor 1	6.19	98.31	6.21	98.49	0.66	2.81
	Motor 2	5.82	92.35	5.91	93.78	2.21	4.11
	Motor 3 & Motor 4	0.369	92.29	6.26	99.31	6.63	2.63
	Motor 5	0.377	94.30	6.27	99.57	5.60	2.57
	Motor 7 & Motor 8	5.82	92.31	5.84	92.72	2.90	3.72
	Motor 9 & Motor 10	5.77	91.50	5.78	91.79	3.14	3.97
Case 4	Motor 1	6.17	97.79	6.17	97.97	0.67	2.66
	Motor 2	5.56	88.24	5.65	89.65	2.31	4.11
	Motor 3 & Motor 4	0.376	93.93	6.26	99.40	5.36	2.47
	Motor 5	0.384	96.00	6.29	99.79	4.39	2.41
	Motor 7 & Motor 8	5.46	86.71	5.49	87.15	3.09	3.96
	Motor 9 & Motor 10	5.36	85.01	5.38	85.32	3.38	4.28

8. SHORT CIRCUIT CURRENTS CALCULATION

Three-phase (K3), phase-to-phase (K2), phase-to-earth (K1), and two-phase-to-earth (K11) short circuit calculation results are provided in Table 10.

Table 10 Short circuit calculation results

		Min				Max			
		K3	**K2**	**K1**	**K11**	**K3**	**K2**	**K1**	**K11**
Case 1	**Section 1**	21.2 kA	18.3 kA	397.4 A	21.2 kA	26.7 kA	23.1 kA	449.5 A	26.7 kA
	Section 2	21.1 kA	18.3 kA	397.4 A	21.1 kA	23.4 kA	20.2 kA	449.5 A	23.4 kA
Case 2	**Section 1**	30.4 kA	26.3 kA	397.2 A	30.4 kA	36.8 kA	31.9 kA	447.5 A	36.8 kA
	Section 2	30.4 kA	26.4 kA	397.2 A	30.4 kA	33.7 kA	29.2 kA	447.5 A	33.7 kA
Case 3	**Section 1**	24.9 kA	21.5 kA	396.7 A	24.9 kA	30.7 kA	26.6 kA	448.6 A	30.7 kA
	Section 2	24.9 kA	21.5 kA	396.7 A	24.9 kA	27.5 kA	23.8 kA	448.6 A	27.5 kA
Case 4	**Section 1**	16.4 kA	14.2 kA	396.4 A	16.4 kA	21.4 kA	18.5 kA	451.4 A	21.4 kA
	Section 2	16.4 kA	14.2 kA	1.4 A	16.4 kA	18.1 kA	15.7 kA	451.4 A	18.1 kA

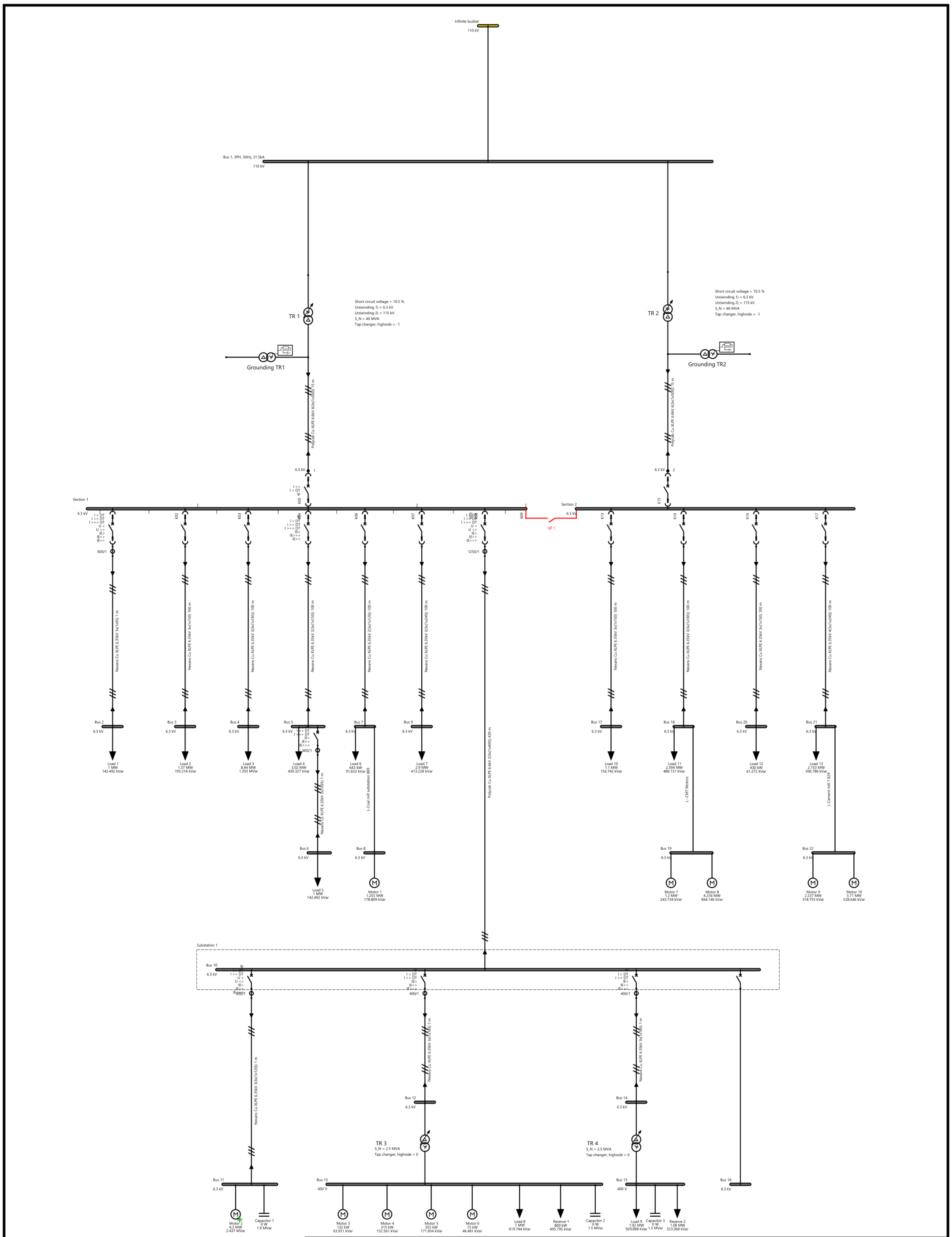
In the current situation, the K3 minimum short circuit current can reach up to 21.2 kA. With a 40 MVA transformer, the short circuit current would increase by 43% to 30.4 kA. In the case of 31 MVA transformers, the short circuit current would increase by 17%. In the case of 20 MVA transformers, the short circuit current would reduce by 23%. These are quite significant changes, therefore equipment and protection relay settings will have to be upgraded.

9. CONCLUSIONS

After performing calculations for different size transformers (case 2 – 40MVA, case 3 – 31.5MVA, case 4 – 20MVA), results show:

- that reducing the existing transformer size to 20MVA would cause problems for main motors starting and might limit plants operation,
- that increasing existing transformer size would result in smoother motor staring, factory's ability to work at higher capacity at emergency mode, potential to fully utilize reserve power or expand further.
    - However, upgrading transformers would cause short circuit currents to be larger. Short circuit current value increase for 40MVA transformers is significant and should be considered, while short circuit current size increase when installing 31.5MVA transformers is not as noteworthy. This value increase could require some equipment to be upgraded to withstand higher short circuit currents.
    - It should be noted, that a single 40MVA transformer could operate at maximum factory capacity in emergency mode.

10. ANNEX NO. 1



	2021-07-13				
Rev.	Date of issue	Reason of change			
Certificate No.	EA-PSM	UAB "Energy Advice" K. Baršausko g. 59, LT-51423 Kaunas LITHUANIA		Transformer sizing	
			2021-07-13	Electrical single line diagram	Rev.
			2021-07-13		
			2021-07-13		
Stage				Sheet	Pages
				1	1