TSE2220 Oblig: Power Factory

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Introduction

This work accounts for 10% of the total grade of the subject TSE2220. It uses Python to solve 3 tasks.

- **Task 1** (25%): Build a 11kV distribution network.
- **Task 2** (35%): Do Load flow analysis on the network.
- **Task 3** (40%): Do Short-circuit analysis on the network.

This work is hosted on Github as project there, where you can find the most up to date version @ https://github.com/Arxcis/TSE2220-elkraftsys/tree/main/oblig-power-factory. The project files are as follows:

- `README.pdf` – The text you are currently reading.
- `tasks.pdf` – The tasks as given by the lecturer.
- `task1_network_configuration.py` – Python script for the network configuration.
- `task2_load_analysis.py` – Load-analysis using Gauss-Seidel method.
- `task3_short_circuit.py` – Short-circuit analysis using the impedance method.

Task 1: Network Configuration

The given network contains 4 transformers, 3 cable stretches, an external grid, and 8 buses. 6 of the buses are of special interest: `Area1HV`, `Area1LV`, `Area2HV`, `Area2LV`, `Area3HV`, and `Area3LV`.

Listing 1: ASCII-sketch of the network

```
The default network:
                 ________
                 | Grid |   min/max: 60/100MVA
                 ‾‾‾‾‾‾‾‾
                     |
Bus 1    ____________________
    Trafo 1          | 132kV
                     O 40MVA
                     O j0.03
                     | 11kV
Bus 2    ____________________
                     |
    Cable 1          |    |----- - Cable 2 2km ------------|----- Cable 3 1km --------------|
       200m          |    |                                |                                |
Area 1 HV ______________________      Area 2 HV ____________________      Area 3 HV ____________________
      Trafo 2        | 11kV              Trafo 3           | 11kV           Trafo 4           | 11kV
                     O 400kVA                              O 700kVA                           O 2000kVA
                     O j0.06                               O j0.06                            O j0.06
                     | 230V                                | 230V                             | 230V
Area 1 LV ______________________      Area 2 LV ____________________      Area 3 LV ____________________
                     |                                     |                                  |
                     v                                     v                                  v
                  Load 1                                Load 2                             Load 3
```

Mathematically the static components of the network can be expressed as an Y-bus matrix. The matrix can be derived from Kirchoff's current law (KCL).

$$Y_{\text{bus}} = \begin{bmatrix} +Y_{11} & -Y_{12} & \cdots & -Y_{1n} \\ -Y_{21} & +Y_{22} & \cdots & -Y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -Y_{n1} & -Y_{n2} & \cdots & +Y_{nn} \end{bmatrix} \tag{1}$$

The Y-bus matrix for this specific network is set up as a Numpy 2D-array in Python. In itself, it gives a good overview of how the different busses of the network are connected together.

Listing 2: 2D-numpy array with Ybus matrix in task1_network_configuration.py

```
Ybus_pu = array([
    [+YT1,      -YT1,              0,    0,              0,    0,           0,    0],
    [-YT1, (YT1+YC1),           -YC1,    0,              0,    0,           0,    0],
    [   0,      -YC1, (YC1+YT2+YC2), -YT2,           -YC2,    0,           0,    0],
    [   0,         0,           -YT2, +YT2,              0,    0,           0,    0],
    [   0,         0,           -YC2,    0, (YC2+YT3+YC3), -YT3,        -YC3,    0],
    [   0,         0,              0,    0,           -YT3, +YT3,           0,    0],
    [   0,         0,              0,    0,           -YC3,    0, (YC3+YT4), -YT4],
    [   0,         0,              0,    0,              0,    0,        -YT4, +YT4],
])
```

The Ybus matrix can be multiplied by the voltages for each bus, to get the resulting current injected into (if positive sign) or leaving the bus (if negative sign).

$$\left[Y_{bus}\right] \cdot \begin{bmatrix} V_{11} \\ V_{22} \\ \vdots \\ V_{nn} \end{bmatrix} = \begin{bmatrix} I_{11} \\ I_{22} \\ \vdots \\ I_{nn} \end{bmatrix} \tag{2}$$

Task 2: Load-flow Analysis

2a) Load Flow Simulation

Gauss-Siedel method uses the KCL equations for each bus to iteratively approximate the voltages for each bus.

$$V_{ii,next} = \frac{1}{Y_{ii}}\left(\frac{S^*}{V^*_{ii,prev}} - \sum_{\substack{j=0\\j\neq i}}^{n} Y_{ij}V_{ij}\right) \tag{3}$$

The trick is to reset the voltage of bus1 (the slack-bus) to V=1pu after each iteration, to make sure it does not change. This forces all the other voltages to converge to a specific value.

Listing 3: Gauss-Siedel-method implementation found in task2_load_flow_analysis.py

```

N = 10_000
Vbus_pu = ones(8) # V = [1pu, 1pu, 1pu, 1pu, ...]
Yii_pu = array([net.Ybus_pu[i][i] for i in range(8)])

for _ in range(N):
    I_pu = conjugate(net.Sload_pu / Vbus_pu)

    YVij_pu = net.Ybus_pu.dot(Vbus_pu)
    YVii_pu = Yii_pu*Vbus_pu

    Vbus_pu = (1/Yii_pu) * (I_pu - YVij_pu + YVii_pu)

    # Always reset slack-bus to 1pu
    Vbus_pu[0] = 1
\\
```

The results from the initial network show that the biggest voltage drop can be found in Area 3 on the low-voltage side, where a -2.4% voltage drop is observed.

Listing 4: Results for task 2a) given by running task2-power-flow-analysis.py

```
$ python task2-power-flow-analysis.py

        Task 2a): Do a load flow simulation

    |----------------|---------|---------|---------|---------|---------|---------|
    |                | Area1HV | Area1LV | Area2HV | Area2LV | Area3HV | Area3LV |
    |----------------|---------|---------|---------|---------|---------|---------|
    | Vnominal  [V]  |  1.1e+04|      230|  1.1e+04|      230|  1.1e+04|      230|
    | Vactual   [V]  |  1.1e+04|      228| 1.09e+04|      226| 1.09e+04|      225|
    | Vactual  [pu]  |    0.999|    0.992|    0.993|    0.982|    0.991|    0.976|
    |----------------|---------|---------|---------|---------|---------|---------|

    |----------------------|---------|---------|---------|
    |                      | Area 1  | Area 2  | Area 3  |
    |----------------------|---------|---------|---------|
    | StrafoMax     [VA]   |    4e+05|    7e+05|    2e+06|
    | StrafoLoad    [VA]   | 1.56e+05| 4.17e+05| 1.56e+06|
    | StrafoLoad/Max [%]   |     39.1|     59.5|     78.1|
    |----------------------|---------|---------|---------|
```

2b) Add 200kW to the system

Å sette inn en ekstra 200kW last i Area 1, gir et totalt spenningsfall levert til forbruker på -4V eller -1.7%. Om lasten settes inn i enten område 2 eller 3 blir spenningsfallet levert til forbruker i begge disse områdene på -6V eller -2.6%. Dette er et akseptabelt fall for det meste av utstyr. NEK400 anbefaler maksimalt spenningsfall på 5% på generell basis og 2-3% spesifikt for motorer. Tallene taler til fordel for å legge til 200kW last til Area 1, fordi dette fører til minst spenningsfall levert til forbruker, bare 1.7%. Om lasten legges til område 2 eller 3 blir spenningsfallet levert i grenseland for det som er anbefalt for motorer. Konklusjonen blir derfor at det anbefales å sette inn den ekstra 200kW lasten i Area1.

Table 1: Sammenligning av hvordan spenningsfall blir om last settes inn på Area 1, 2 eller 3

Vactual [V]	Area1LV	Area2LV	Area3LV
Before +0kW	228	226	225
After +200kW	226	224	224
Voltage drop [V]	-4	-6	-6
Voltage drop [%]	-1.7%	-2.6%	-2.6%

Om vi ser på trafo sin utnyttelsesgrad, vil den bli påvirket veldig ulikt avhengig av hvor lasten plasseres. For Area1 øker utnyttelsesgrad til trafo fra 39.1% til 91.1% (+52%) økning. På en måte er dette positivt. Area 1 sin trafo var underutnyttet før lasten ble lagt til. Å legge til lasten til area 1 skaper en mer jevn fordeling av belastningen på tvers av alle 3 områdene, med 91%, 60% og 78% belastning på de respektive trafoene.

Table 2: Sammenligning av trafobruk om last settes inn på Area 1, 2 eller 3

StrafoLoad/Max [%]	Area1LV	Area2LV	Area3LV
Before +0kW	39.1	59.5	78.1
After +200kW	91.1	89.3	88.5
Delta [%]	+52.0	+29.8	+10.4

Konklusjonen blir, at det er anbefalt å plassere 200kW last i Area 1, da dette vil føre til lavest spenningsfall levert til forbruker på tvers av alle 3 områder og en jevnest mulig belastningsgrad av de 3 trafoene.

Listing 5: Raw results of load flow simulation adding 200kW to area 1

```
$ python task2_power_flow_analysis.py

        Task 2b-1): Add 200kW load to Area 1

    |---------------|---------|---------|---------|---------|---------|---------|
    |               | Area1HV | Area1LV | Area2HV | Area2LV | Area3HV | Area3LV |
    |---------------|---------|---------|---------|---------|---------|---------|
    | Vnominal [V]  | 1.1e+04 |     230 | 1.1e+04 |     230 | 1.1e+04 |     230 |
    | Vactual  [V]  | 1.1e+04 |     226 |1.09e+04 |     226 |1.09e+04 |     224 |
    | Vactual [pu]  |   0.998 |   0.981 |   0.991 |   0.981 |   0.989 |   0.974 |
    |---------------|---------|---------|---------|---------|---------|---------|


    |-------------------|---------|---------|---------|
    |                   | Area 1  | Area 2  | Area 3  |
    |-------------------|---------|---------|---------|
    | Strafo_max   [VA] |   4e+05 |   7e+05 |   2e+06 |
    | StrafoLoad  [VA]  |3.65e+05 |4.17e+05 |1.56e+06 |
    | StrafoLoad  [%]   |    91.1 |    59.5 |    78.1 |
    |-------------------|---------|---------|---------|
```

Listing 6: Raw results of load flow simulation adding 200kW to area 2

```
$ python task2_power_flow_analysis.py
        Task 2b-2): Add 200kW load to Area 2

    |---------------|---------|---------|---------|---------|---------|---------|
    |               | Area1HV | Area1LV | Area2HV | Area2LV | Area3HV | Area3LV |
    |---------------|---------|---------|---------|---------|---------|---------|
    | Vnominal [V]  | 1.1e+04 |     230 | 1.1e+04 |     230 | 1.1e+04 |     230 |
    | Vactual  [V]  | 1.1e+04 |     228 |1.09e+04 |     224 |1.09e+04 |     224 |
    | Vactual [pu]  |   0.998 |   0.991 |   0.991 |   0.974 |   0.988 |   0.974 |
    |---------------|---------|---------|---------|---------|---------|---------|


    |-------------------|---------|---------|---------|
    |                   | Area 1  | Area 2  | Area 3  |
    |-------------------|---------|---------|---------|
    | Strafo_max   [VA] |   4e+05 |   7e+05 |   2e+06 |
    | StrafoLoad  [VA]  |1.56e+05 |6.25e+05 |1.56e+06 |
    | StrafoLoad  [%]   |    39.1 |    89.3 |    78.1 |
    |-------------------|---------|---------|---------|
```

Listing 7: Raw results of load flow simulation adding 200kW to area 3

```
$ python task2_power_flow_analysis.py

        Task 2b-3): Add 200kW load to Area 3

    |---------------|---------|---------|---------|---------|---------|---------|
    |               | Area1HV | Area1LV | Area2HV | Area2LV | Area3HV | Area3LV |
    |---------------|---------|---------|---------|---------|---------|---------|
    | Vnominal [V]  | 1.1e+04 |     230 | 1.1e+04 |     230 | 1.1e+04 |     230 |
    | Vactual  [V]  | 1.1e+04 |     228 |1.09e+04 |     225 |1.09e+04 |     223 |
    | Vactual [pu]  |   0.998 |   0.991 |   0.991 |    0.98 |   0.988 |   0.971 |
    |---------------|---------|---------|---------|---------|---------|---------|


    |-------------------|---------|---------|---------|
    |                   | Area 1  | Area 2  | Area 3  |
    |-------------------|---------|---------|---------|
    | Strafo_max   [VA] |   4e+05 |   7e+05 |   2e+06 |
    | StrafoLoad  [VA]  |1.56e+05 |4.17e+05 |1.77e+06 |
    | StrafoLoad  [%]   |    39.1 |    59.5 |    88.5 |
    |-------------------|---------|---------|---------|
```

2c) Cable 1 extended to 16,000m

After changing the cable from 200m to 16km, we do not have a satisfactory network anymore. The voltage drop delivered to consumers now exceed 6% in Area1 and 7% in Area 2 and 3. This is way above the recommended NEK maximum of 5%. Consider upgrading the cross-sectional area of Cable1, or increase the voltage to 22kV to lower the voltage drop below 5% at least, and ideally below 3%.

Listing 8: Raw results of load flow simulation after extending cable 1 to 16km

```
$ python task2_power_flow_analysis.py

        Task 2c): Change length of the cable 1 from 200m to 16 000m

    |----------------|----------|----------|----------|----------|----------|----------|
    |                | Area1HV  | Area1LV  | Area2HV  | Area2LV  | Area3HV  | Area3LV  |
    |----------------|----------|----------|----------|----------|----------|----------|
    | Vnominal  [V]  |  1.1e+04 |      230 |  1.1e+04 |      230 |  1.1e+04 |      230 |
    | Vactual   [V]  | 1.04e+04 |      215 | 1.03e+04 |      212 | 1.03e+04 |      211 |
    | Vactual  [pu]  |    0.941 |    0.934 |    0.934 |    0.923 |    0.932 |    0.916 |
    |----------------|----------|----------|----------|----------|----------|----------|
```

2d) Active Power Losses

When the voltages for each busbar have been calculated the voltage difference can be found by checking the voltage drop from one busbar to another.

$$\Delta V_{busbar1-2} = V_{busbar2} - V_{busbar1} \tag{4}$$

Knowing the voltage drop across the cable and the admittance of the cable gives us the total power loss.

$$S_{cable} = VI^* = ((\Delta V_{busbar12})^2 \cdot Y_{cable})^* \tag{5}$$

The results show that the active power losses went from 2.96kW with 0.2km cable to 268kW with 16km cable. In other words the simulation show that when increasing the cable length 80x (16km/0.2km) the active power loss increase 90x (268kW/2.96kW).

Listing 9: Results of active power loss calculation

```
$ python task2_power_flow_analysis.py

        Task 2d): How much active power losses are there when running 2c)?
    0.2km:

    |---------------|----------|----------|----------|
    |               | Cable 1  | Cable 2  | Cable 3  |
    |---------------|----------|----------|----------|
    | Vcable  [V]   |     9.35 |     86.8 |     34.3 |
    | Icable  [A]   |      347 |      322 |      255 |
    | Pcable  [W]   | 2.96e+03 | 2.55e+04 | 7.97e+03 |
    |---------------|----------|----------|----------|

    16.0km:

    |---------------|----------|----------|----------|
    |               | Cable 1  | Cable 2  | Cable 3  |
    |---------------|----------|----------|----------|
    | Vcable  [V]   |      795 |     92.3 |     36.5 |
    | Icable  [A]   |      369 |      342 |      271 |
    | Pcable  [W]   | 2.68e+05 | 2.88e+04 | 9.02e+03 |
    |---------------|----------|----------|----------|
```

Task 3: Short-circuit Analysis

3abc) Max/Min Short-circuit currents

To compute the short-circuit current of the network at different bus-bars the impedance-method is used. Only the reactances (X) are considered since the impedance of the trafos in the network will dominate the total impedance of the network during a short-circuit, and the impedances of trafos are purely reactive. Including the resistances (R) as well would give more accurate results, but it would require knowing the cosfi of the external grid, which we assume not to know in this specific analysis. The reactances of each component are added to a vector where each element in the vector represents the total reactance of each respective busbar, if the short-circuit would happen at that very busbar.

Listing 10: The reactance-vector found in task3_short_circuit_analysis.py

```

# Kortslutningsreaktanser
Xkss = XT1 + XCable1 + array([
    0,              # Area 1 HV
    XT2,            # Area 1 LV
    XCable2,        # Area 2 HV
    XCable2 + XT3, # Area 2 LV
    XCable2 + XCable3,        # Area 3 HV
    XCable2 + XCable3 + XT4, # Area 3 LV
])

Xkss_min = Xgrid_min + Xkss
Xkss_max = Xgrid_max + Xkss
```

The results show that short-circuit values are much higher on the low-voltage side vs the high-voltage side in each area, but not as much as one would expect by a simple trafo-conversion factor. Going from 11kV -> 0.230V (a 47.8x decrease in voltage) one would expect a corresponding 47.8x increase in current from 2.95kA -> 141kA. The reasons why the actual increase in short-circuit is only from 2.95kA -> 15kA (a 5x increase) is due to the fact that the trafo itself introduces a significant impedance to the short-circuit flow on the LV side, which is not present on the HV side. This extra impedance dampens the short-circuit by almost 10x.

Listing 11: Results of short-circuit analysis on basic network

```
$ python task3_short_circuit_analysis.py

        Task 3a) Do short circuit on Basic network:
-------------------------------------------------
Grid min: 6e+07, Grid max: 1e+08
-------------------------------------------------
XTrafo1: 0.03 | XTrafo2: 6 | XTrafo3: 3.43 | XTrafo4: 1.2
XCable1: 0.0156 | XCable2: 0.156 | XCable3: 0.0778
```

	Area1 HV	Area1 LV	Area2 HV	Area2 LV	Area3 HV	Area3 LV
Xkss_min	0.712	6.71	0.868	4.3	0.946	2.15
Ikss_min	2.95e+03	1.5e+04	2.42e+03	2.34e+04	2.22e+03	4.68e+04
Xkss_max	0.446	6.45	0.601	4.03	0.679	1.88
Ikss_max	4.71e+03	1.56e+04	3.49e+03	2.49e+04	3.09e+03	5.34e+04

3de) Short-circuit current with 10x more external grid power

Results show that increasing the short-circuit power of the external grid 10x increases the short-circuit current on the Area1 HV side significantly from 2.95kA -> 18.7kA (more than 5x), but on the Area1 LV side there is little change from 15kA -> 16.4kA (only 10% increase). The reason why there is no big change on the Area1 LV side is that the short-circuit impedance is dominated by the very small trafo between Area1 HV and LV sides. Even if the external grid's impedance is lowered to 1/10th, this does not have a big impact on the total impedance on the LV, which is what counts. In Area 3 LV, the impact is more significant. Due to a much larger trafo (2000kVA in Area 3 vs 400kVA in Area1), the short-circuit impedance of the trafo is lower and thus lowering the external grid impedance has a bigger impact, resulting in the short-circuit current at Area3 LV increasing from 46.8kA to 65kA (a 39% increase).

Listing 12: Results of short-circuit analysis after increasing external grid power 10x

```
$ python task3_short_circuit_analysis.py

        Task 3d) Do short circuit when grid has 10x more short circuit power:
-------------------------------------------
Grid min: 6e+08, Grid max: 1e+09
-------------------------------------------
XTrafo1: 0.03 | XTrafo2: 6 | XTrafo3: 3.43 | XTrafo4: 1.2
XCable1: 0.0156 | XCable2: 0.156 | XCable3: 0.0778

    |-----------|----------|----------|----------|----------|----------|----------|
    |           | Area1 HV | Area1 LV | Area2 HV | Area2 LV | Area3 HV | Area3 LV |
    |-----------|----------|----------|----------|----------|----------|----------|
    | Xkss_min  |    0.112 |     6.11 |    0.268 |      3.7 |    0.346 |     1.55 |
    | Ikss_min  | 1.87e+04 | 1.64e+04 | 7.84e+03 | 2.72e+04 | 6.07e+03 |  6.5e+04 |
    |-----------|----------|----------|----------|----------|----------|----------|
    | Xkss_max  |   0.0856 |     6.09 |    0.241 |     3.67 |    0.319 |     1.52 |
    | Ikss_max  | 2.45e+04 | 1.65e+04 | 8.71e+03 | 2.74e+04 | 6.58e+03 | 6.61e+04 |
    |-----------|----------|----------|----------|----------|----------|----------|
```

3fg) Short-circuit current with 13% reactance in Trafo 1

Keeping the external grid's short-circuit power at 600/1000MVA and increasing the reactance of Trafo1 to 13%, results now show an expected decrease in short-circuit current across all areas. Again the most significant decrease compared to c) can be observed on the HV sides with drops in short-circuit current of with 89% on Area1 HV, down to an 29% on Area3 HV. In Area 3 LV there was a 7% drop in short-circuit current and Area1 LV had only 1% drop in short-circuit current, again pointing out how dominant the trafo impedance is compared to the total short-circuit impedance in low voltage areas.

Compared to a) short-circuit current is up across all areas, because the 10x reduction in external grid impedance far outstrips the 4.33x increase in Trafo 1 impedance.

Listing 13: Results from short-circuit analysis after increasing Trafo 1 reactance to 13%

```
        Task 3f) Short circuit after increaseing internal inductance of trafo1 from 3% -> 13%:
------------------------------------
Grid min: 6e+08, Grid max: 1e+09
------------------------------------
XTrafo1: 0.13 | XTrafo2: 6 | XTrafo3: 3.43 | XTrafo4: 1.2
XCable1: 0.0156 | XCable2: 0.156 | XCable3: 0.0778

    |-----------|-----------|-----------|-----------|-----------|-----------|-----------|
    |           | Area1 HV  | Area1 LV  | Area2 HV  | Area2 LV  | Area3 HV  | Area3 LV  |
    |-----------|-----------|-----------|-----------|-----------|-----------|-----------|
    | Xkss_min  |     0.212 |      6.21 |     0.368 |       3.8 |     0.446 |      1.65 |
    | Ikss_min  |  9.89e+03 |  1.62e+04 |  5.71e+03 |  2.64e+04 |  4.71e+03 |   6.1e+04 |
    |-----------|-----------|-----------|-----------|-----------|-----------|-----------|
    | Xkss_max  |     0.186 |      6.19 |     0.341 |      3.77 |     0.419 |      1.62 |
    | Ikss_max  |  1.13e+04 |  1.62e+04 |  6.15e+03 |  2.66e+04 |  5.01e+03 |   6.2e+04 |
    |-----------|-----------|-----------|-----------|-----------|-----------|-----------|
```