Assignment 1: Power Flow

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In this assignment you will work in small groups to use the implemented Python code from Exercise 1 to conduct power flow simulations of a test system. The purpose of the assignment is to:

- Translate physical power system data into per-unit models by converting generator, transformer, transmission line, and load parameters onto a common system base and explaining the rationale behind base selection.
- Prepare structured and consistent input data for numerical power flow analysis, including correct identification and handling of slack, PV, and PQ buses.
- Apply numerical power flow algorithms to a small transmission system using a Python-based implementation and obtain steady-state operating points.
- Interpret power flow results with respect to operational constraints by analysing bus voltages, line and transformer loadings, and reactive power outputs.
- Explain voltage control principles in transmission networks by identifying and discussing multiple technical measures and reasoning about their expected impact on system operation.
- Evaluate and compare alternative grid operation and reinforcement strategies using power flow results, and justify the effectiveness of different solutions based on system performance.
- Assess reliability-driven design choices by investigating the impact of replacing overhead lines with underground cables and verifying compliance with operational constraints.
- Communicate technical results in a professional engineering report, clearly presenting methods, assumptions, results, and interpretations using appropriate figures, tables, and terminology.

Test System

In this case study you will analyse the transmission system described below.

Table 1: System parameters and limits.

Generator Ratings
G_1: $100\,\mathrm{MVA}$, $13.8\,\mathrm{kV}$, $x = 0.14\,\mathrm{p.u.}$, $-87\,\mathrm{MVAr} \leq Q_{G2} \leq 87\,\mathrm{MVAr}$
G_2: $200\,\mathrm{MVA}$, $15\,\mathrm{kV}$,$x = 0.14\,\mathrm{p.u.}$, $-43.5\,\mathrm{MVAr} \leq Q_{G1} \leq 43.5\,\mathrm{MVAr}$
Transformer Ratings
T_1: $100\,\mathrm{MVA}$, $13.8\,\mathrm{kV}\Delta/\ 230\,\mathrm{kVY}$, $x = 0.1\,\mathrm{p.u.}$
T_2: $200\,\mathrm{MVA}$, $15\,\mathrm{kV}\Delta/230\,\mathrm{kVY}$, $x = 0.1\,\mathrm{p.u.}$
Transformer neutrals are solidly grounded.
Transmission Line Ratings
All lines: $230\,\mathrm{kV}$, $z' = (0.08 + j0.5)\Omega\,\mathrm{km}^{-1}$, $y' = j3.3\mathrm{\mu S\,km}^{-1}$
Maximum Loading: $400\,\mathrm{MVA}$
Line lengths ℓ are provided in the single line diagram. x corresponds to the number of your group.
Power Flow Data
Bus 1: Swing bus $V_1 = 13.8\,\mathrm{kV}\angle 0°$
Bus 2,3,4,5,6: Load buses
Bus 7: Constant voltage magnitude bus
$V_7 = 15\,\mathrm{kV}$
Generators G_1 and G_2 share active power according to the ratio of their nominal capacities.
Voltage limits: ± 0.05 p.u.
System Base Quantities
$S_{base} = 100\,\mathrm{MVA}$ (Three-phase)
$V_{base} = 13.8\,\mathrm{kV}$ (line-to-line) in the zone of G1

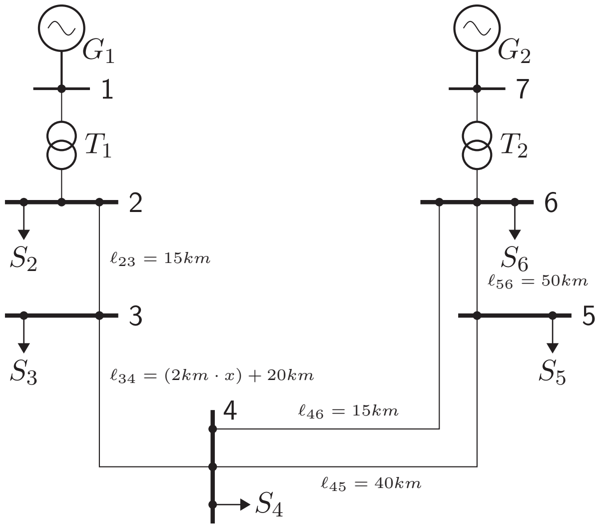

Figure 1: Single line diagramm of the three phase transmission system.

Table 2: Operating points.

High Loading Point (Operating Point A)
S^a=$S_2^a = S_3^a = S_4^a = S_5^a = S_6^a = 50\,\mathrm{MW}$+j $30\,\mathrm{MVAr}$
Low Loading Condition (Operating Point B)
At every node, the apparent power for condition B is calculated as $S^b = c \cdot S_a$ with : $c = [0.2 + (x-1) \cdot 0.01]$ and x is your group number.

Tasks

1. **Prepare Power Flow Data**

   Prepare the provided system data from Figure 1 and Table 1 to be used with the code developed in Exercise 1.

   (a) Compute the length the line connecting bus 3 and bus 4 according to the following equation:

   $$\ell_{34} = 2\,\mathrm{km} \cdot x + 20\,\mathrm{km}, \tag{1}$$

   where x is your group number.

   (b) Compute the apparent power for the low loading condition, labeled by the superscript b, at every bus. The high load condition is referenced by superscript a. At every bus holds:

   $$S^b = c \cdot S^a, \tag{2}$$
   $$c = 0.2 + (x-1) \cdot 0.01, \tag{3}$$

   where x is your group number.

   (c) Convert all impedance, load and voltage data for the entire system in Fig. 1 to the system per unit quantities. Report the conversion steps and the final results.

(d) Prepare the input data files to run a power flow with the developed python script from exercise 1. Note that bus 1 is the slack bus, and that generators share active power according to the nominal capacity ratio of both generators. Include the developed data files in the upload for this assignment and describe how you prepared the input data in your report.

2. **Conduct Power Flow**
Run the power flow program for both operating conditions and obtain the solutions. Report the bus voltage and magnitudes, the power flows across all lines and transformers, the apparent power generation of each transformer. Are these power flow solution within the standard operational limits provided in Table 1?

3. **Enhance the Voltage Profile**
As the grid operator, you wish to increase the voltage magnitude for the high loading condition (Operating Point A) at bus 4 by $5\,\%$ and make sure that all equipment is operating within its design limits. You have the following options available:

- Change the active power dispatch of the generators
- Adjust the voltage setpoint of the generators
- Add reactor banks at selected nodes
- Add capacitor banks at selected nodes

Complete the following tasks:

(a) For each of the available options, discuss how you expect the power flow results to change and why it could be successful. Furthermore, briefly discuss the pros and cons of the different options. No simulations are required for this step and a discussion of different options is expected in the report.

(b) Test the available options for the high loading conditions using the developed power flow algorithm. Compare the effectiveness of the methods using figures and tables.

(c) How do the selected methods impact the voltages during the low loading condition (Operating Point B)?

(d) Discuss which method has been most effective for the high loading point A and provide reasoning why it performs better than the other methods. Would you expect the same result for a different power system? And how should you operate during the low loading condition?

(e) Present your solution to the grid operator. The solution can be a combination of different measures. Justify why you proposed this solution.

4. **Replacing Overhead Transmission Lines with Cables**
The grid operator has adopted your suggestions and has been operating the system in such a state for several years. However, the existing overhead lines connecting bus 4 to busses 5 and 6 are soon reaching their end of life and are due to be replaced. The grid operator wants you to assess the option of exchanging the overhead lines with underground cables. The grid operator provides you a list of available cable options, which you will find attached. Current practice of the grid operator is to lay all cables in a flat formation with cross bonding. You should choose suitable cables with an equivalent nominal rating of the existing transmission lines, while keeping costs low. Assume that costs scale with conductor diameter, i.e. the larger the conductor diameter, the higher the cost.

(a) Choose appropriate cables from the provided cable data sheets and report suitable options.

(b) Compute and report the system per unit parameters of the suitable cable options. Comparing the parameters of the cable and the previously used overhead transmission line, what difference do you observe?

(c) How do the cables affect the voltage profiles in the system across the different loading conditions? Conduct power flow analysis and report your results.

(d) Reevaluate the voltage control strategy that you previously adopted. Is it still suitable considering the system topology change? Propose a suitable solution considering the new system topology to the operator. Provide power flow results to support your answers.

5. **Add Tap Changing Transformers**
So far you have only considered the system, which is under the responsibility of the transmission system operator, where all loads have been aggregated on the transmission system level. Now we will additionally consider the interface point between the transmission and distribution system level by including 75 MVA, 230/66 kV transformers, with a short-circuit reactance of $15\,\%$ at all substations interfacing with the loads S_2 - S_6 as indicated in Figure 2. To increase the flexibility of the voltage regulation in the distribution system, all transformers are equipped with tap changers. The tap changers are located on the high-voltage (HV) side of the transformer and allow to manipulate the transformer ratio such that under no-load conditions the voltage at the low voltage (LV) side can be adjusted in the range of $-5\,\%$ and $+15\,\%$ in 16 steps.

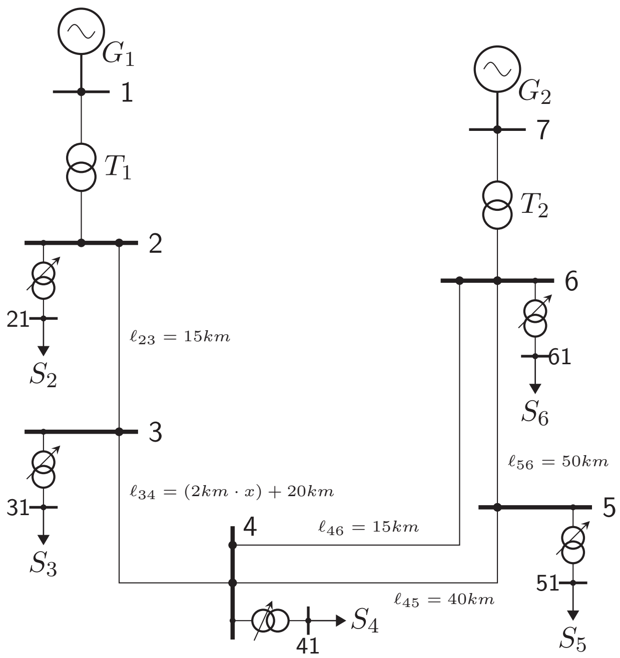

Figure 2: Single-line diagram of the adjusted three-phase transmission system including the tap changing transformers. While tap changers are located on the high voltage side of the transformers, they regulate the voltage on the low-voltage terminals.

(a) Determine the equivalent off-nominal turns ratio in per unit for each of the available tap positions considering that the HV side is the from- and the LV side is the to-bus.

(b) To optimize the voltage profile and minimize the losses in the distribution system, the distribution system operator is aiming to maintain a voltage between 1.00 p.u. and 1.01 p.u. on the LV side of each of its substations. By executing the power flow for each of the scenarios, that is your proposed solutions for questions 3 and 4 for both loading conditions, identify the suitable tap positions of the different transformers. If the desired voltage cannot be achieved explain suggest a potential solution to the distribution system operator.

6. **Reflections and Discussion**
   What have you learned in this assignment for the operation of real power systems where significant daily, weekly, and seasonal load variations occur? What are your recommendations regarding voltage regulation measures, installations of cables and operating of tap-changing transformers? Formulate guidelines for transmission system operators.

Guidelines for Report Writing

When writing the report for the assignment, the below listed points should be followed:

- The report must start with a self-evaluation section, where the authors state whether the report represents an even contribution from all group members or whether some participants were not effectively contributing to the report. All group members must sign the self-evaluation section.
- The report must contain a section informing about the AI policy of the group, and the usage of AI in completing the assignment and the report. All group members must sign the declaration of the usage of AI.
- The front page of the report should contain your names and student numbers.
- Your Python code used for the solution of this assignment has to be included in appendix.
- The report shall contain the answer to each of the questions. The answers shall be clearly separated from each other and come in the same order as the questions in the assignment. It is not necessary to repeat the text from the assignment in your report.
- When answering the questions, both the results as well as an explanation on how you came up with your results should be included in the answer.
- Always when asked to provide plots of something (time responses, curves etc.) you must provide your interpretation of the figure.
- Make sure that the assignment's learning objectives are reflected in your report.
- When your reports are evaluated, points are awarded for the general setup of the report. We are looking for a professional look of the report, where among others the following is considered:
  - Readability (appropriate font sizes, margins etc.) and consistence in styles applied (same look for body text, headings, captions etc. throughout the report).
  - Presentation of equations should be of an appropriate quality (do not copy/paste equations as screenshot pictures from the lecture handouts).
  - Plots and figures should be of good quality (no fuzzy looking screenshots in the report). You can always ask the teachers how you can export figures of good quality in Python/-Matlab.
  - Figures and tables must have a label and caption (e.g. Figure 1: plot of active power in respect to ....).
  - If you are citing external material, you need to include a properly set-up reference list (you can use any citation style you prefer).
  - Does the report contain a conclusion section?
- You will also be awarded points for the general formulation of the report where focus is on:
  - The flow in the text when explaining how you came up with your answers and correct use of relevant terminology.
  - Interpretation and reflection of results when appropriate.
  - Grammar and spelling.

Guidelines for the Upload of the Report and the Python Code

The report submission is carried out on DTU-LEARN where the following shall be uploaded:

- PDF versions of your report, with your Python code in appendix.
- Your Python code used for solving the assignment (the *.py). The code shall include your comments where you explain the meaning behind the code.