S-18.3154 Electricity distribution and markets Exam 8.4.2015

R.J. Millar

Q1. General

a) What are 3 main considerations regarding protection when planning an MV network?
b) Mention one of the savings that a new primary substation brings with it.
c) Mention one of the advantages for distribution networks that come with distributed generation.
d) Mention one of the disadvantages for distribution networks that come with distributed generation.

Answer briefly!

Q2. Markets

a) Why do the system and area prices sometimes differ in the ESLPOT market (Nordic electricity spot market)? (3p)
b) What is one thing the regulation of distribution networks try to keep up, and one thing it tries to keep down? (2p)
c) What is one method for regulation of the distribution network business? (1p)

Q3. Power quality

List 4 kinds of power quality problems that one can observe in the voltage of a distribution network?

What might you do if one substation is experiencing voltage disturbance from an industrial customer connected to the same point (i.e. the same PCC or point of common coupling)?

Distribution Network Analysis

Q4. Technical constraints

The figure below shows two feeders that feed large industrial loads (lumped to nodes 2-5)
The load growth is 0.12 % / year, the interest rate is 6 % and the network life is 40 years.
Are the feeders in Fig. 1 technically feasible? Justify your answer.

All cables (new and existing):

r (Ω/m)	x (Ω/m)	I_{max} (A)	$I_{sc,1s}$ (kA)
1.50E-04	1.10E-04	385	22.6

Substation circuit breakers operate within 400 ms

- Nodes 0 and 1 are primary substations
- Nodes 2 to 5 are lumped loads of 2350 kW each, $\cos\varphi = 1$

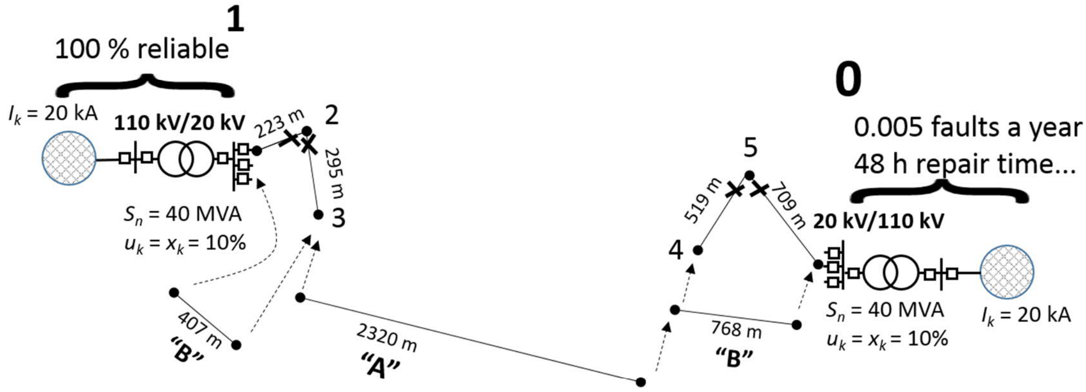
Q5. Reliability

All cables (new and existing):

r (Ω/m)	x (Ω/m)	I_{max} (A)	$I_{sc,1s}$ (kA)
1.50E-04	1.10E-04	385	22.6

Fault rate for both new and old lines is 2.0 faults / 100 km / year

Repair time is 10 h



- The primary substation at node 0 has, on average, 0.005 faults a year with an average repair time of 48h
- Node 1 is a fully reliable primary substation
- Nodes 2 to 5 are lumped loads of 2350 kW each, cosφ = 1
- Interruption costs (CIC) are 1.1 €/kW/fault and 11 €/kWh for each load node
- All line sections have switches at both ends that are remote operated and operate in 5 minutes
- New line costs are 90 €/m
- New remote switches cost 3000€/switch station + 3500 €/switch

Backup connection(s) are needed! Which is the best alternative to provide backup, "A" (a new line from node 3 to node 4) or "B" (two shorter lines: from node 2 to node 3 and from node 4 to node 5)?

$$\kappa = \gamma \frac{\gamma^t - 1}{\gamma - 1} \qquad \gamma = \frac{(1+r)}{(1+p)}$$

ELEC-E8406 Electricity distribution and markets Exam 6.4.2016

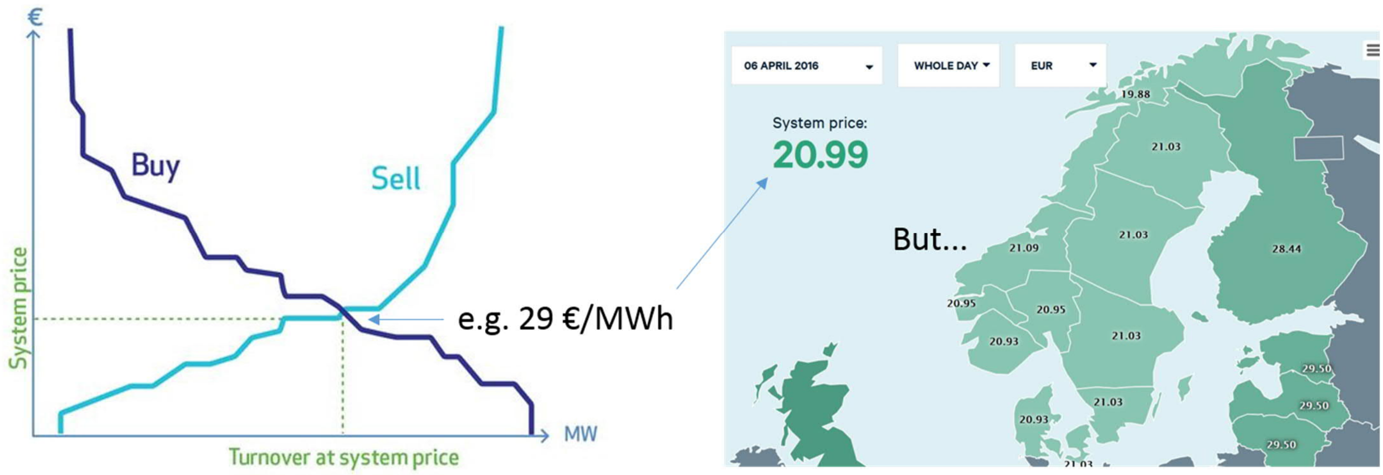
You may answer in English, Finnish or Swedish – this is not a language test! R.J. Millar

Q1. General

a) How might a strong grid (distribution and transmission) aid the integration of renewable generation? (2p)
b) What are two potential benefits of local (decentralised or embedded) generation (DG)? (2p)
c) What are two challenges involved with integrating renewable energy sources in the power system? (2p)

Answer briefly!

Q2. Electricity Markets and Regulation



a) What happens when the system price, computed by aggregating all the bids and all the offers in the Nordic region, is technically unsustainable? (3p)

b) Regulation of the electricity market tries to do two things: Keep prices reasonable (down) and keep performance high! Mention, and briefly explain, **three methods** for doing either of these two things. (3p)

Distribution Network Analysis

Table 1 Line data for Q3 and Q4

	Resistance (Ω/km)	**Reactance** (Ω/km)	I_{max} (A)	$I_{k,1s}$ (kA)
Al/Fe 85/14 (Pigeon)	0.337	0.354	360	8.4
AHXAMK-W3x120	0.3	0.123	265	11.4

Q3. Technical constraints (6p)

The figure below shows a single feeder that feeds a large industrial load.
The load growth is 0.12 % / year, the interest rate is 4 % and the network life is 40 years. The main circuit breaker operates within 0.4s.
Is the feeder in Fig. 1 technically feasible? Justify your answer.

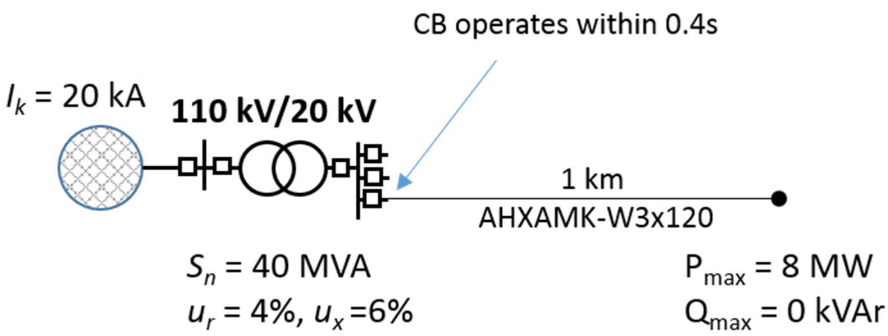


Figure 1

Q4. A sag sensitive customer and economic optimisation (6p)

The industrial customer in Fig. 1 is sensitive to voltage sags where the remaining voltage is <80%

The situation is shown in Fig. 2. There are two options. Option a) is to connect a fault prone overhead line (Pigeon) to the same transformer, a 40 MVA transformer costing 600 000 €. Option b) is to invest in two transformers (2 x 20 MVA, 400 000 €/transformer). **Is this worthwhile?** Both investments would be made in the present, i.e. their present value is 600 000 or 800 000€.

- The utilisation time for the industrial load losses based on maximum active power demand, T_{losses} = 4000 h/year
- The cost of losses is 5 euro cents / kWh (i.e. 0.00005 €/Wh)
- The time horizon for this exercise is 40 years, load growth is 0.12% / year, and the interest rate is 4% / year
- You can assume that each reclosing causes a short duration 3ph short-circuit on the Pigeon feeder with fault impedance = 0
- You can assume that the faults causing these reclosings are equally distributed along the Pigeon feeder.
- You can ignore the cost of no-load losses on the transformers, i.e., the transformers are modelled simply as series resistance and reactance
- You **should** consider the cost of load (I^2R) losses
- You can ignore the effect of the load flow in the Pigeon cable on the transformer(s) – it is insignificant compared to the industrial feeder

Q4 cont.

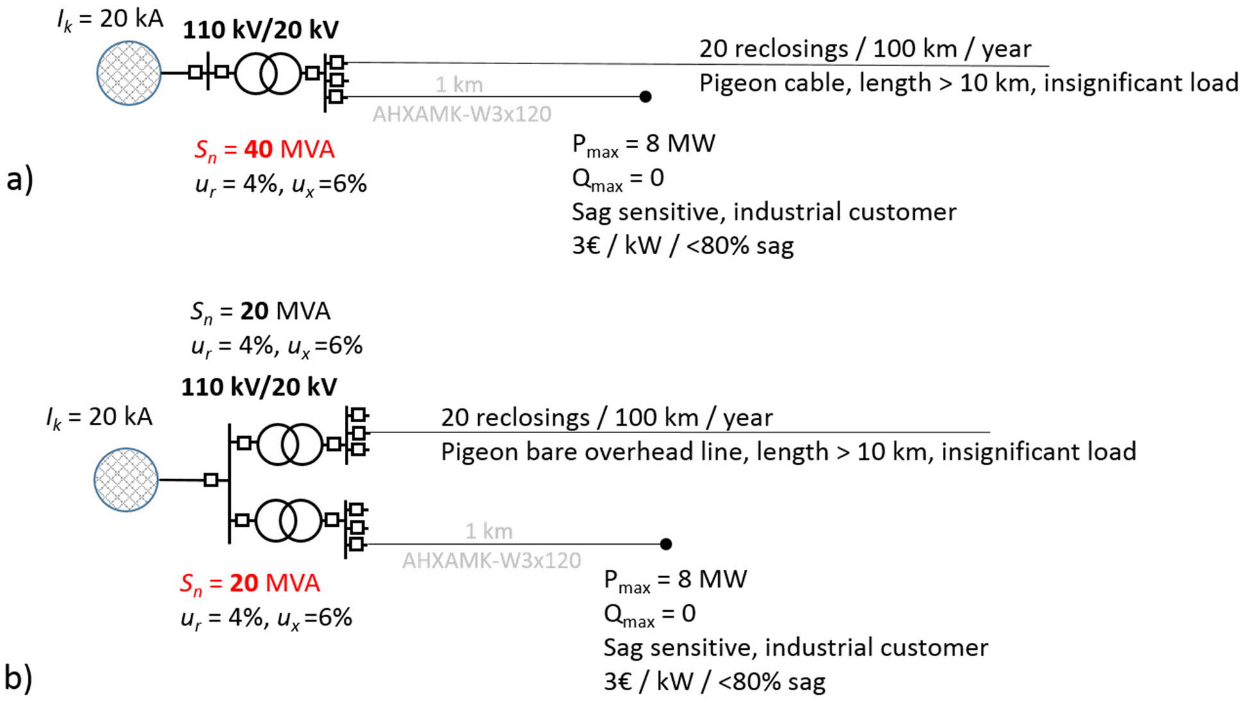


Figure 2 Option a) or b)?

These formulae may help you...

$$\kappa = \gamma \frac{\gamma^t - 1}{\gamma - 1} \quad \text{where} \quad \gamma = \frac{(1+r)}{(1+p)} \quad \text{or} \quad \gamma = \frac{(1+r)^2}{(1+p)}, \text{ depending on what your using these equations for...}$$

Q5. Your turn. What are 6 points you have learned, or issues related to electricity distribution?

Mention and briefly explain 6 clear points from the course that are not covered in the questions above, or, more generally, about the challenges in electricity distribution and markets. (6p)

(*Hint: Imagine you are a planner, or a policy maker, or a Green activist, or a member of the Tea Party, or a major customer – what points come to mind with respect to the subject areas that this course has covered?)*

ELEC-E8406 Electricity distribution and markets Exam 5.4.2017

*You may answer in English (preferred), Finnish or Swedish – this is not a language test! **Please keep your answers brief**! If John has left any parameters out, make your best guess, and indicate the assumptions you make when answering! There will be no discussion during this exam!*

R.J. Millar

Q1. General

a) What is the difference between **voltage sag** (dip) and **voltage drop**? Please give a formula and brief explanation for each. (4p)

b) What are two types of **electricity market?** (very brief explanation of the two out of many you choose) (2p)

Q2. General

a) What are 3 challenges associated with integrating renewable generation in the power system? (3p)

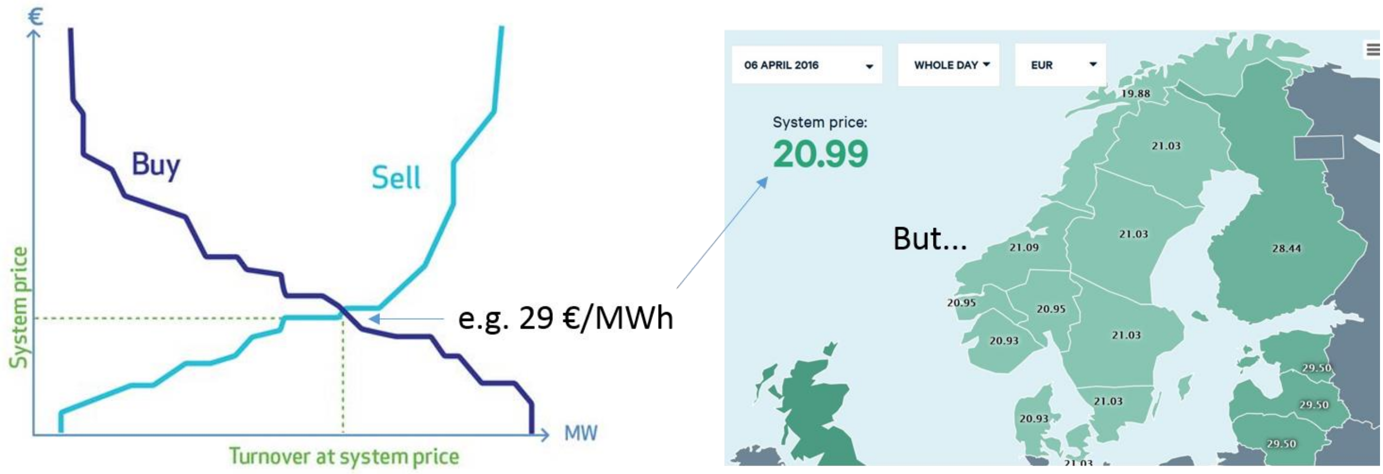


Figure 1

b) What happens when the **system price**, computed by aggregating all the bids and all the offers in the Nordic region, is **technically unsustainable**? Figure 1 may inspire you... (3p)

Q3. 3-phase short circuit limits and time-delayed autoreclosing (td) (6p)

Figure 2 below shows an underground cable connection that feeds a large industrial load, in turn connected to a fault-prone overhead line connected to a small load.

- The main primary substation circuit breaker operates within 600ms.
- The Pigeon cable has a (field) circuit breaker, which operates within 400ms.

The distribution network operator is debating whether or not to introduce time-delayed autoreclosing for the field circuit breaker.

a) First: Are the 3-phase short circuit ratings of the feeder in Fig. 2 OK (without autoreclosing)? Justify your answer.

Table 1 Line data for Q3

	Resistance (Ω/km)	**Reactance** (Ω/km)	$\mathbf{I_{max}}$ (A)	$\mathbf{I_{k,1s}}$ (kA)	**Cooling time constant, τ (s)**
Al/Fe 85/14 (Pigeon)	0.337	0.354	360	8.4	360
AHXAMK-W3x120	0.3	0.123	265	11.4	3600

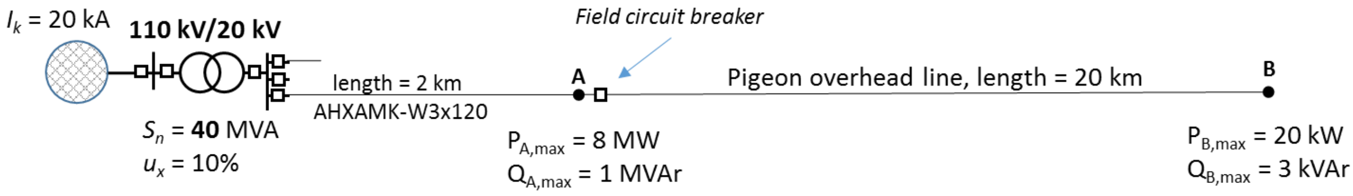


Figure 2

b) Second: Will the field circuit breaker reclosing scheme work (refer to Table 1, the text below and Fig. 3, where t_1 = 0.8s, t_2 = 0.4s and t_0 = 180s**):**

a. for the bare overhead conductor (Pigeon)?

b. for the underground cable (AHXAMK-W3x120)?

According to Fig. 3 below (taken from the lecture material, to aid your overworked memories!), for the field circuit breaker, t_1 = 0.8s, t_2 = 0.4s and t_0 = 180s. t_{ekv} is the equivalent time it takes for the circuit breaker to open if there is no reclosing.

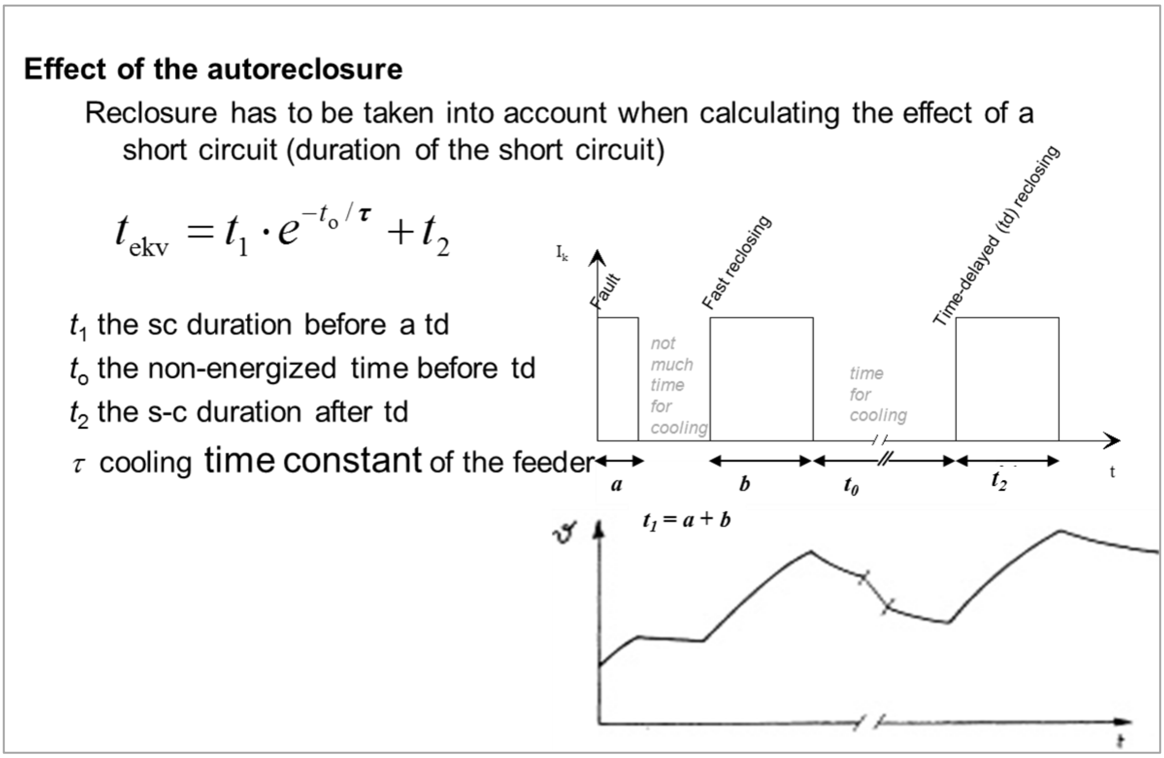


Figure 3

Q4. A single primary substation transformer feeds 100 x 1MW secondary substations (i.e. a total load of 100MW). Each secondary substation has CIC (KAH) costs of a = 1€ / kW / fault and b = 10 € / kWh. The discount factor load (which turns annual costs into the present value of the lifetime costs), κ_{losses} = 20 (years). The primary substation has an average fault frequency of 1 fault / 100 years. It takes 24 hours to replace/repair the single transformer primary substation including switching.

It will cost 110 000 € to provide backup to the 100 secondary substations from another (nearby) primary substation that has enough surplus capacity. The switching would take 30 minutes to make the backup. You can assume that the backup will not significantly affect interruption costs that are caused by line faults.

Is the investment worthwhile? (6pt)

Q5.

a) Explain, generally, what is going on in Fig. 4 (2pt)

b) Briefly explain 4 terms in this figure (4pt)

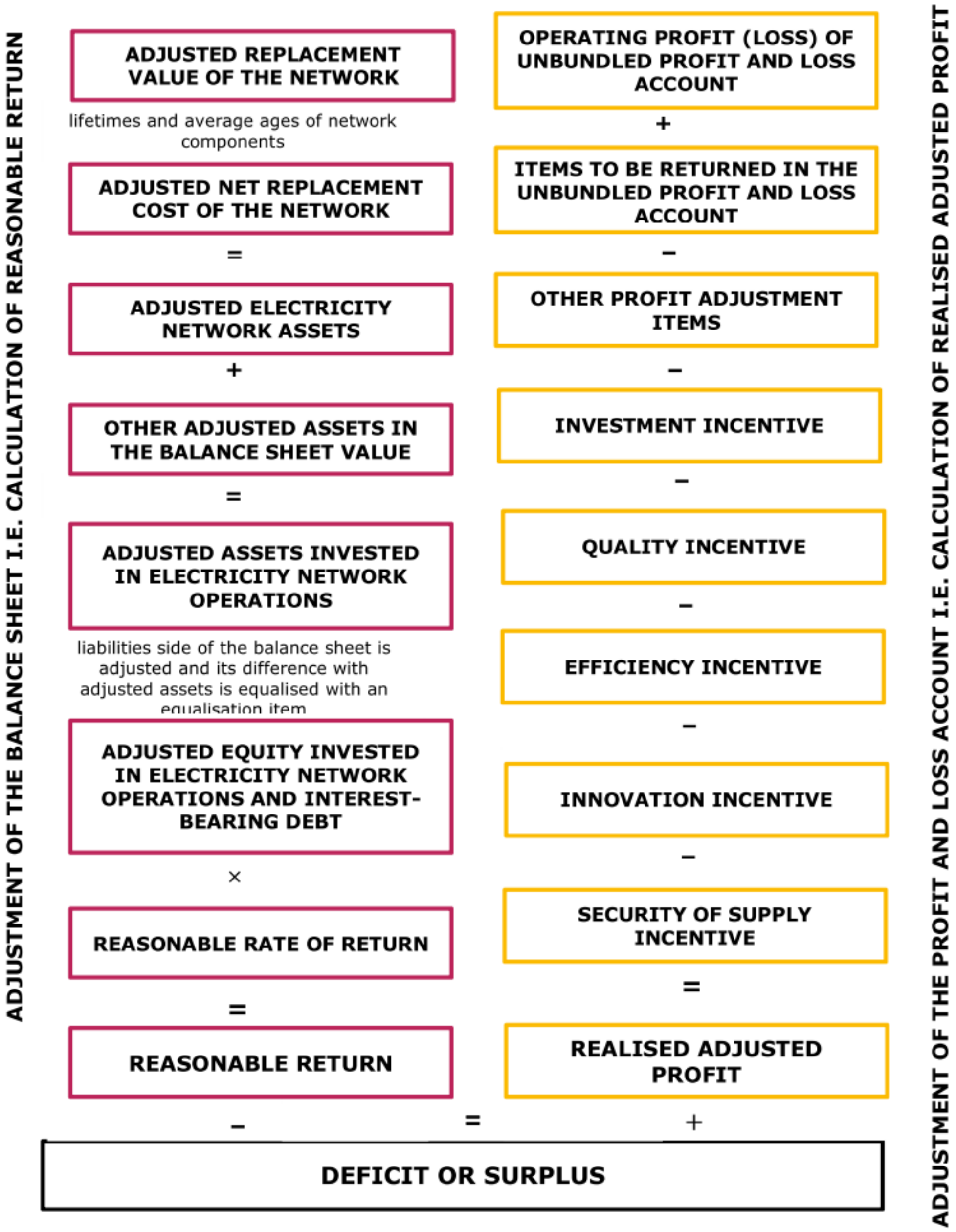


Figure 4 *Regulation methods during regulatory periods 2016-2019 and 2020-2023*

ELEC-E8406 Electricity distribution and markets Exam 4.4.2018

(Robert) John Millar

*You may answer in English (preferred), Finnish or Swedish – this is not a language test! **Please keep your answers brief**! If John has left any parameters out, make your best guess, and indicate the assumptions you make when answering! There will be **no discussion** during this exam! John will trash all papers involved in copying of any sort!*

Q1. General technical

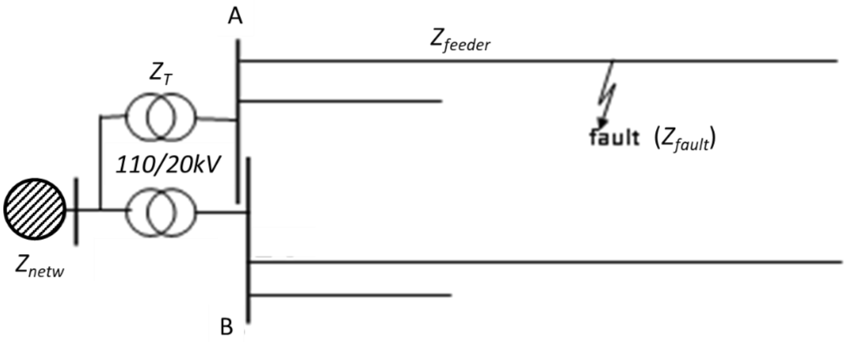


Figure 1

a) What is **voltage sag** (dip) (in words)? (1p)

b) What is the equation for the remaining voltage at busbar A if a 3-phase short circuit occurs at the indicated point in the top feeder and the impedance from busbar A to the fault is Z_{feeder}? (See Figure 1.) (1p)

c) What is the equation for the remaining voltage at busbar B? (2p)

d) What is the equation for **voltage drop** in terms of I, R, X and φ? (1p)

e) What is the equation for voltage drop in terms of P, Q, R, X, and U? (1p)

Q2. General

a) Name and briefly describe three types of **electricity market.** In approximately what time frame does each market operate relative to the time of delivery? (3p)

b) What is demand response and what is it good for? (2p)

c) What is one challenge associated with integrating renewable generation in the power system? (1p)

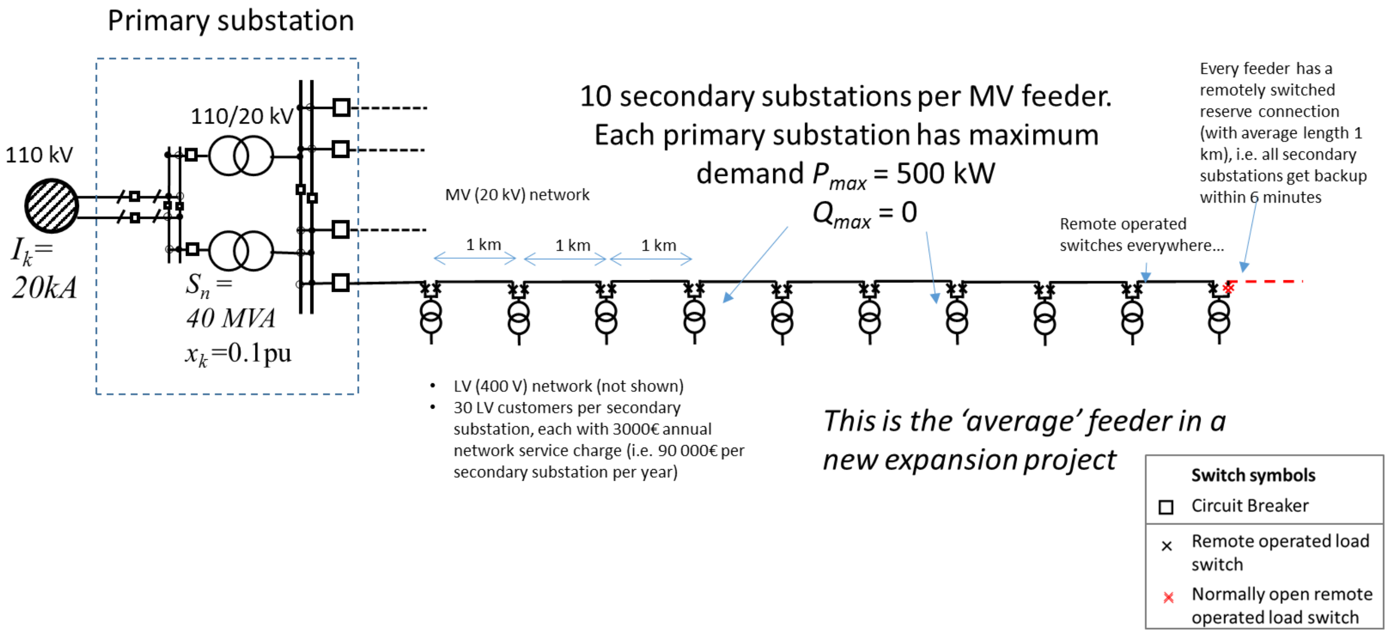


Figure 2 Average feeder dimensions and specifications for Questions 3 and 4

These equations may help you: $\kappa = \gamma \dfrac{\gamma^t - 1}{\gamma - 1}$ where $\gamma = \dfrac{(1+r)}{(1+p)}$

Table 1. Underground Cable costs and parameters

	Fixed cost (€/m)	**Resistance** (Ω/km)	**Reactance** (Ω/km)	I_{max} (A)	$I_{k,1s}$ (kA)
AHXAMK 240 mm^2	100	0.150	0.110	385	22.6

Table 2. Overhead line (covered conductors) costs and parameters (for Questions 3 and 4)

	Fixed cost (€/m)	**Resistance** (Ω/km)	**Reactance** (Ω/km)	I_{max} (A)	$I_{k,1s}$ (kA)
SAX-W 120 AlMgSi	35	0.45	0.128	360	8.6

12–24 hours: 10% of the annual network service fee
24–72 hours: 25 % of the annual network service fee
72–120 hours: 50% of the annual network service fee
120–192 hours: 100 %
192–288 hours: 150 %
More than 288 (12 days) hours: 200 % of the annual network service fee
Maximum compensation is EUR 2000.
If there is several interruptions to the supply of electricity during one calendar year, the amount of compensation shall not exceed 200 percent of the annual network service fee or EUR 2000.

Figure 3 Standard compensations for long interruptions (for Question 3)

Q3. Technical – Reliability and Investment – 'Going Underground' or not?

You must advise the authorities about a large new section of MV network. Two extreme solutions are being considered. The network will be entirely **underground** (Table 1) and not vulnerable to storms**,** or entirely **overhead,** with covered conductors on the downwind side of roads (Table 2), and vulnerable to some storms**.**

There will be several hundred secondary substations, but for quick calculation purposes, on average there will be:

- 10 secondary substations per MV feeder with full backup provided by an adjacent feeder of similar specifications (see Fig. 2).
- Each secondary (MV/LV) substation has a maximum demand of **500 kW**.
- The distance between secondary substations is **1 km**
- The length of the reserve connections is also **1 km**. It is open at one end.
- CIC (KAH) values are universally 1 €/kW/fault, and 10 €/kWh.
- Remote switches at both ends of all line sections enable restoration of power to all substations affected by a single fault anywhere in the network in 6 minutes (**0.1 h**).
- The fault rate for underground cable is **1 fault per 100 km** on average.
- The fault rate for covered conductors is **3 faults per 100 km** on average.
- There are 30 low voltage customers connected to each secondary substation (low voltage network and customers are not shown in Fig. 2, but there are 30 of them for each substation).
- The average **annual network service fee** for each of these LV customers is **3000 €/year** (see Fig. 3 for the standard compensations for long interruptions).

Further, it is assumed that:

- major storm events will **not** affect the underground network option
- major storm events will strike the network area once every 20 years and cause an outage lasting **36** hours for **100**% of the customers if the overhead (covered conductor) option is chosen for the network.
- You can assume then, that for the overhead (covered conductor) network, **all customers** will lose supply at year **10** and year **30** of the (**40** year) review period (*this is the best guess by a wild curly-haired Kiwi mistakenly let into Finland*).
- For each major storm event, there will be an additional cost of **20% the replacement value of the (covered conductor) network** to cover replacement components and repair work.
- The review period is **40 years**, over which the interest rate will average **3%/year** and load growth will be negligible (**0%/year**). (*The interest rate over the next 40 years has been reliably estimated by 5 chimpanzees*.)

TASK: Which is best option considering the present value of <u>investment</u> costs, <u>single fault-based interruption costs</u> (like we normally calculate) **and <u>large storm damage</u> costs?** (You do **not** have to calculate the economic cost of losses**.)** (6p)

Q4. Technical Constraints (quick and dirty**)**

Are both line options (overhead covered conductor and underground cable) technically acceptable for the network shown in Fig. 2? Think about what is necessary to calculate! (6p)

You can assume that the power factor is 1, i.e., $Q_{max} = 0$, and the voltage at all secondary substations in this rough calculation is close to 20 kV.

Q5.

Statement: “The transmission and distribution grids are enablers for getting carbon out of the power system”

Question: Give six opinions, with short explanations, supporting and/or refuting this statement.

(*The opinions can be, for example, reasons in support of the statement, reasons for opposing the statement, challenges involved with the statement...)* (6p)

ELEC-E8406 Electricity distribution and markets Exam 10.4.2019, 14-17, AS1

Examiner: John Millar

Student Name: **Student Number:**

Signature:

1. General

a. Explain 3 main functions or technical characteristics of an electricity distribution network **(3p)**

i.

ii.

iii.

b. What are 3 contemporary (modern) challenges in electricity distribution? **(3p)**

i.

ii.

iii.

Student Name:

2. Given question: Explain shortly, the Elbas, Elspot and Balance markets **(6p)**

a. Elbas:

b. Elspot:

c. Balance:

Student Name: **Student Number:**

Signature:

3. Markets (note, part C of the question is on the following page)

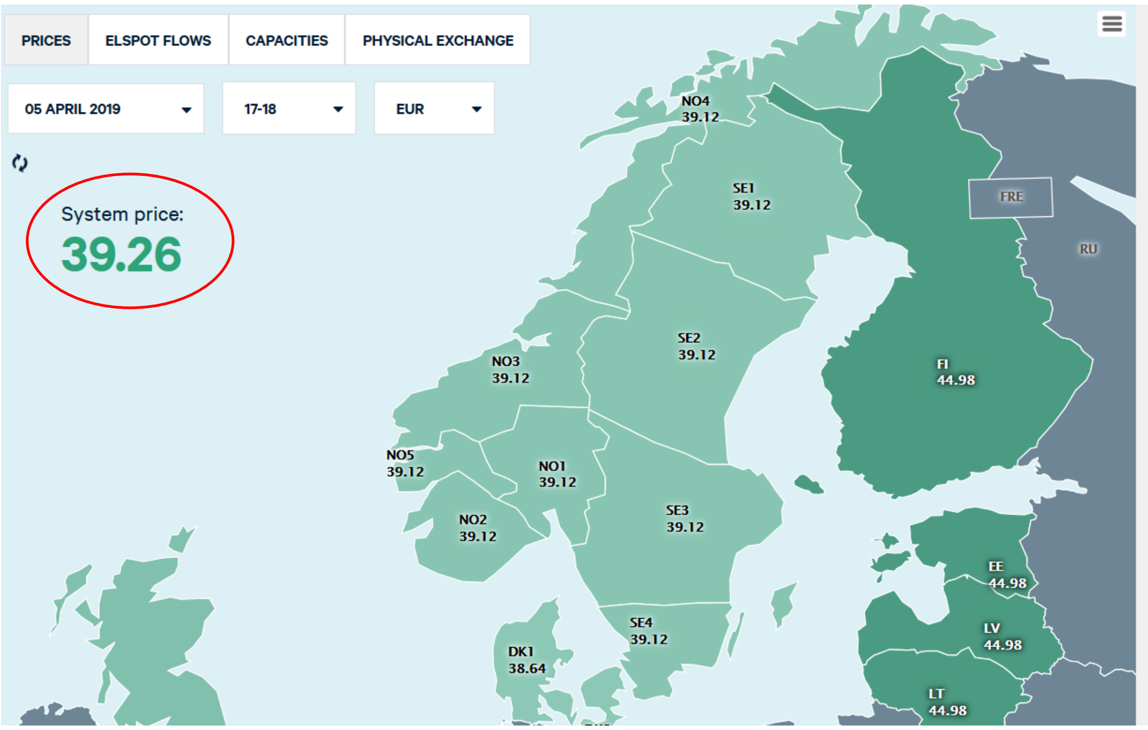


Figure 1 The system price breaks up... *Source: https://www.nordpoolgroup.com/maps/#/nordic*

a. Briefly explain how the system price is formed in the Nordic electricity market (relates to previous question) **(1p)**

b. Explain what happens when the system price cannot be sustained by the power system, as in Fig. 1. How is this dealt with, i.e., how and why are the area prices formed? **(3p)**

c. What do you think would be the impact of 3 x 1.4 GW HVDC (high voltage direct current) cables (i.e. a lot of transmission capacity!) connecting Norway with Germany on electricity prices in Finland?

(2p)

(Your response might start, “It depends on...”), in other words, there is no exact answer to this question!

Student Name:

4. Voltage sag (dip)

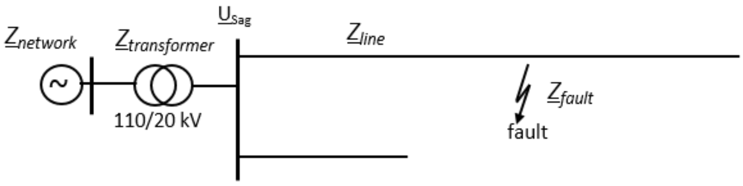


Figure 2 A single-transformer, single busbar arrangement

a. What is the formula for $\underline{U}_{sag}$ for the transformer connection shown in Fig. 2? **(2p)**

b. How might you change the connection arrangement to help voltage sag (e.g. to lessen the impact of voltage sag in the lower feeder due to faults in the upper feeder) if money is no object? E.g., you have permission to purchase another transformer, busbars and protection equipment? **Draw a new single-line diagram showing your solution** in the space provided below**.** **(2p)**

c. What is the formula for voltage sag now? **(1p)**

d. List 2 other power quality issues. **(1p)**

Student Name:

5. **Cost optimum solution subject to technical constraints:** A distribution company has old stock of Pigeon overhead line which they are considering in the 20 kV planning scenario shown in Fig. 3. Since the company is trying to get rid of old stock, it values the Pigeon line at 21€/m. The other option is to install the larger cross-section Suur-Savo overhead line, which costs 27.66 €/m to install, Table 1. The review period is 20 years, but the load growth is non-linear, Table 2, so you are given κ_{losses} and κ_{load} in Table 3

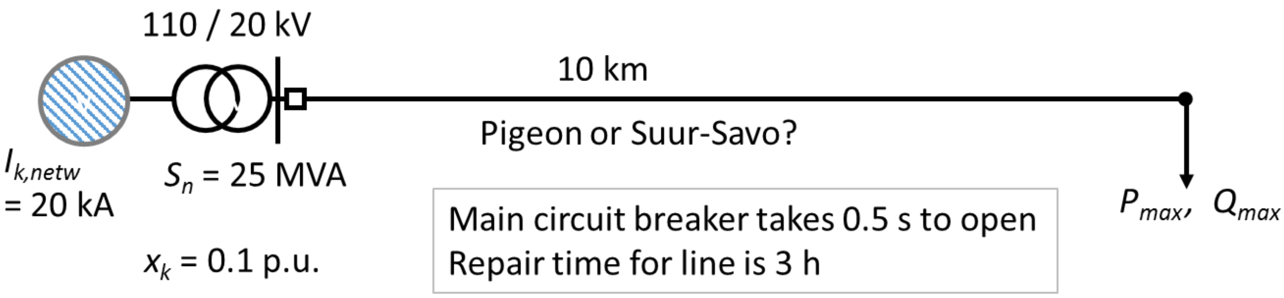


Figure 3 Single line diagram of planned 20 kV feeder

Table 1 Cost and electro-technical parameters for overhead lines

	Fixed cost (€/m)	**Resistance** (Ω/km)	**Reactance** (Ω/km)	**I_{max}** (A)	**$I_{k,1s}$** (kA)
Al/Fe 85/14 (Pigeon)	21.00	0.337	0.354	360	8.4
Al/Fe 106/25 (Suur-Savo)	27.66	0.279	0.344	430	10.5

Table 2

Year	**P_{max}** (kW)	**Q_{max}** (kvar)		
1	3000	986		
2	3090	1016		
3	3183	1046		
4	3278	1077		
5	3377	1110		
6	3478	1143		
7	3582	1177		
8	3690	1213		
9	3800	1249		
10	3914	1287		
11	4149	1364		
12	4398	1446		
13	4662	1532		
14	4942	1624		
15	5238	1722		
16	5553	1825		
17	5886	1935		
18	6239	2051		
19	6613	2174		
20	7010	2304		

Table 3 gives some useful economic parameters...

Table 3 Economic parameters

κ_{losses}	31.38 (years)
κ_{load}	20.73 (years)
T_{losses}	3000 hours (per year)
c_{losses}	0.05 €/kWh

Student Name:

Questions:

a) Which cable has the cheapest present day value of investment and loss costs **(2p)**

b) Is it technically OK? **(2p)**

c) What is the cost of interruption (present value) if the line has a failure rate of 4 faults/100km/year and the CIC (KAH) values for the customer are a=1.1 €/kW/fault and b = 11 €/kWh? **(2p)**

You may answer in English (preferred), Finnish or Swedish – this is not a language test! ***Please keep your answers brief****! If John has left any parameters out, make your best guess, and indicate the assumptions you make when answering! Please, no discussion or communication during this exam, online or offline, but you can refer to course material.*

Please type your workings and answers in this document, saved with the name:

ELEC-E8406AprilExam_*YourName_YourStudentNumber*

Remember to keep saving the document as you work, then upload it to MyCourses with any attachments, and if that fails, email the document to john.millar@aalto.fi, with ELEC-E8406AprilExam_YourNameYourStudentNumber in the subject.

Q1. General

- List 3 general differences between **rural** and **urban** electricity distribution systems. (3p)

  Answers:
  i.
  ii.
  iii.

- *In this course we have learnt how to calculate customer interruption costs in terms of* CIC *costs* (€/kW/fault *and* €/kWh). *We also mention in the course about* "Standard Compensations for Long Interruptions" *which are being tightened. For urban customers, distribution companies will have to start compensating customers (up to 2000 €/year) directly for interruptions to supply that last longer than* 6h.

  What does this mean for urban distribution network planning? What kind of topological and technological changes and considerations would you expect are needed in an urban network that still has some overhead network? (3p)

  Answers:
  i.
  ii.
  iii.

Q2. Electricity Markets and Regulation

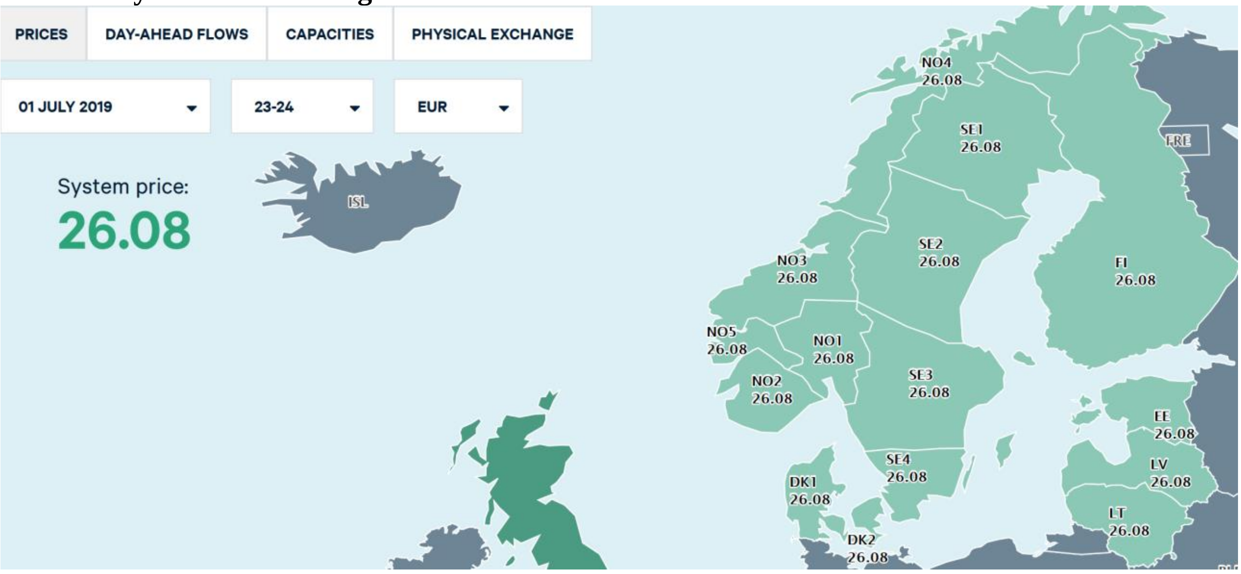


Figure 1 System vs Bidding area prices (when system and bidding area prices are the same)

Source: https://www.nordpoolgroup.com/maps/#/nordic

a) What happens when the system price **cannot** be supported by the transmission system (i) and why does this happen (ii)? (2p)

Answers:

i.

ii.

b) What happens to the price in an area with generation surplus when supply and demand are calculated in each area (e.g. Norway) rather than the entire system (e.g. all the Nordic countries covered by Nordpool) (1p)

Answer:

iii.

c) What happens to the price in an area with generation deficit (consumption surplus) when supply and demand are calculated in each area (e.g. Finland) rather than the entire system (1p)

Answer:

iv.

d) What happens to the price (in the surplus area) when some transmission capacity is allowed for? (1p)

Answer:

v.

e) What happens to the price in the deficit area when some transmission capacity is allowed for? (1p)

Answer:

vi.

Q3.

Figure 2 UN Sustainable Development Goals

Write **6 clear statements** about Sustainable Development Goals (SDG) relevant to this course, Electricity Distribution and Markets, e.g., "Which of the SDGs does this course touch on (and how)?", "Where could we do better?" (6p)

Answers:

i.
ii.
iii.
iv.
v.
vi.

Distribution Network Analysis (Data on this page are for **Q4** and **Q5)**

Table 1 20 kV Line data for Q4 and Q5

	Fault rate (faults/100km/year)	**Resistance** (Ω/km)	**Reactance** (Ω/km)	$\mathbf{I_{max}}$ (A)	$\mathbf{I_{sc,1s}}$ (kA)
AHXAMK-W3x150 underground cable	2	0.25	0.123	240	14.1

Table 2 Nodal (substation) data for Q4 and Q5

Node No	$\boldsymbol{P_{max}}$ (kW)	$\boldsymbol{Q_{max}}$ (kVAr)	CIC (***a***: €/kW/fault)	CIC (***b***: €/kWh)
0 (Primary substation)	0	0	0	0
1 (Primary substation)	0	0	0	0
2 (secondary substation)	1000	0	1.1	11
3 (secondary substation)	800	0	1.1	11
4 (secondary substation)	1800	0	1.1	11

Table 3. Switching times

Remote switch	0.1667 h
Circuit breaker	0.4 sec

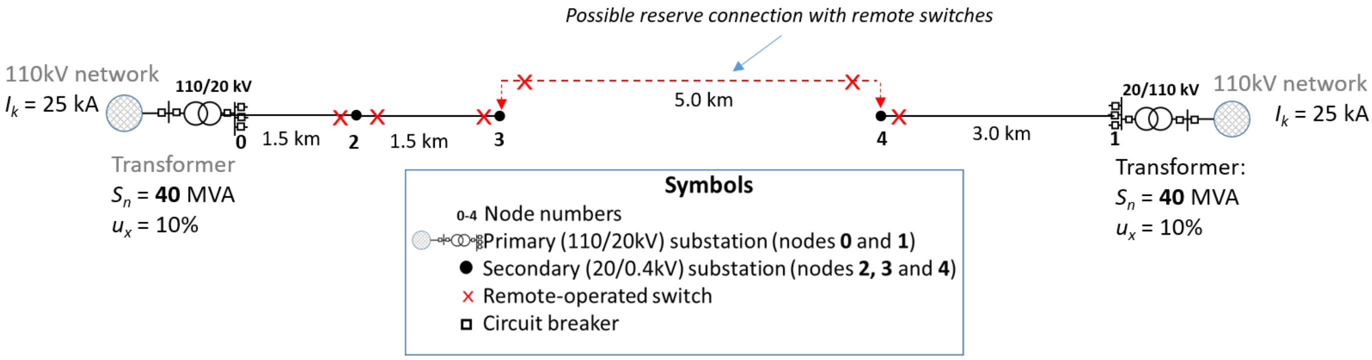


Figure 3 Network diagram for Q4 and Q5

You may need some of the following formulae:

$$\gamma = \frac{(1+r)}{(1+p)}, \quad \gamma_1 = \frac{(1+r)^2}{(1+p)} \quad \text{and} \quad \gamma_2 = \frac{1}{1+p}$$

$$\kappa_{losses} = \gamma_1 \frac{\gamma_1^{t'} - 1}{\gamma_1 - 1} + \frac{(1+r)^{2t'}}{(1+p)^{t'}} \gamma_2 \frac{\gamma_2^{T-t'} - 1}{\gamma_2 - 1}$$

$$\kappa_{load} = \gamma \frac{\gamma^{t'} - 1}{\gamma - 1} + \frac{(1+r)^{t'}}{(1+p)^{t'}} \gamma_2 \frac{\gamma_2^{T-t'} - 1}{\gamma_2 - 1}$$

Fig. 1 shows an underground cable connection that is planned to be built between two primary substations feeding 3 important secondary substations. Apart from the primary substation circuit breakers, all switches are remote operated, and can isolate faulted sections and restore supply to the affected customers in 0.1667 h.

The load growth is 3 % / year for **20 years**, then remains constant for the remainder of the **40 year review period**. The interest rate is 4 % / year (for the entire network life of 40 years). The main circuit breakers operate within 0.4 seconds.

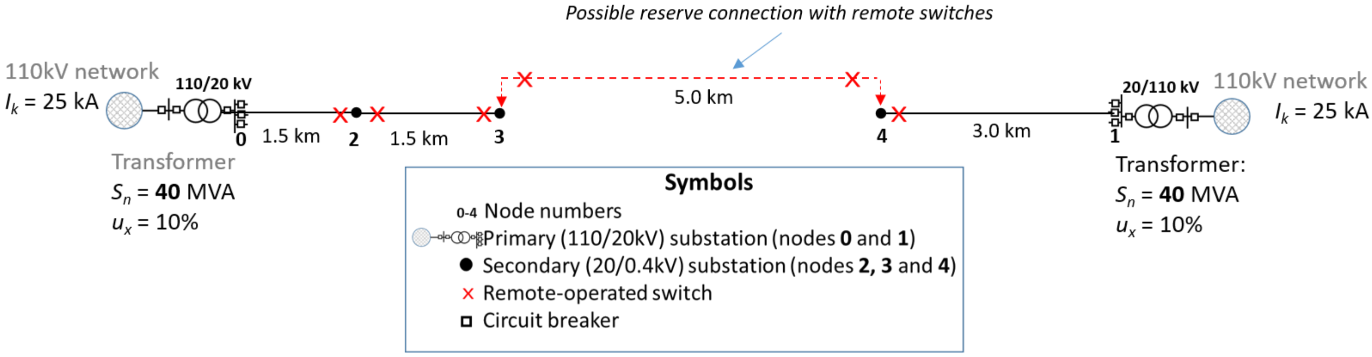


Figure 3 is repeated here for your convenience

Q4. Reliability and Optimal Open Point (6p)

How cheap would the *possible reserve connection with remote switches* (-x------------x-) in Fig. 3 have to be to be economically beneficial in terms of reliability? How reasonable would this investment cost be in your opinion? Is there any other consideration that may favour the investment?

Customer interruption costs are given in Table 2 *along with maximum demand for each secondary substation.*

Answers and calculations (if you prefer to make hand calculations, photograph and paste them here, but preferably type directly into this document!:

Q5. Technical Constraints (6p)

If the reserve connection in Fig. 3 is installed, is the network technically feasible? Justify your answer.

Answers and calculations (if you prefer to make hand calculations, photograph and paste them here, but preferably type directly into this document!):

ELEC-E8406 Electricity distribution and markets Online Exam 8.4.2020

R.J. Millar

You may answer in English (preferred), Finnish or Swedish – this is not a language test! ***Please keep your answers brief****! If John has left any parameters out, make your best guess, and indicate the assumptions you make when answering! Please, no discussion or communication during this exam, online or offline, but you can refer to course material.*

***Please type your workings and answers in this document, saved with the name*:**

ELEC-E8406AprilExam_*YourName_YourStudentNumber*

Remember to keep saving the document as you work, then upload it to MyCourses (as the assignment submission), and if that fails, email the document to john.millar@aalto.fi, with ELEC-E8406AprilExam_YourNameYourStudentNumber in the subject.

Student Name: **Student Number:**

Q1. General

a) Explain 3 technical characteristics of an electricity distribution network. **(3p)**

i.

ii.

iii.

b) What are 3 contemporary (modern) challenges in electricity distribution? **(3p)**

i.

ii.

iii.

Q2. Markets and Regulation **(6p)**

a) Explain shortly, the Elbas and Elspot markets

i. Elbas:

ii. Elspot:

b) What are 3 other markets (their names and brief descriptions) in the Nordic power system?

i.

ii.

iii.

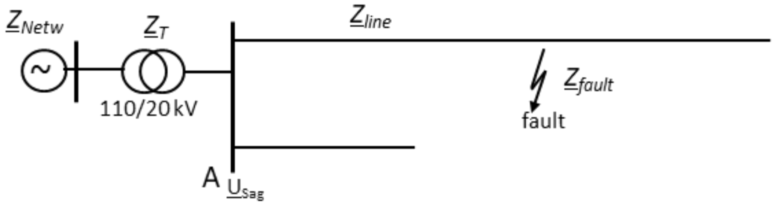
c) What parts of the electricity business require regulation and why?

Q3. **(6p)**

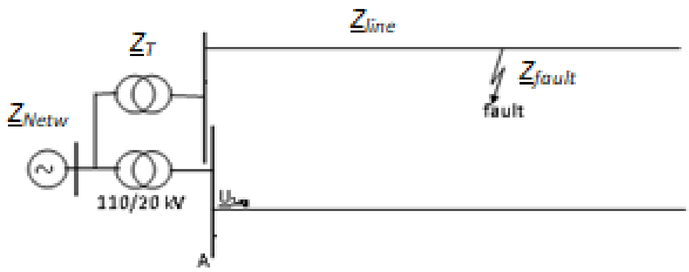
Figure 1 UN Sustainable Development Goals

Write **6 clear statements** about Sustainable Development Goals (SDG) relevant to this course, Electricity Distribution and Markets, e.g., “Which of the SDGs does this course touch on (and how)?”, “Where could we do better?”

Q4. Power Quality



a



b

Figure 2 Transformer and busbar arrangements for ***Q4***

i. Which arrangement, ***a*** or ***b***, best protects customers from voltage sags on the lower feeder from faults on the upper feeder **(1p)**

ii. What are the formulas for voltage sags (at point A) for arrangements ***a*** and ***b***? **(2p)**

iii. What other advantages would arrangement ***b*** offer (apart from its positive or negative effect on voltage sag)? **(1p)**

iv. List 2 other power quality issues. **(2p)**

Q5. Cost optimum solution subject to technical constraints

A distribution company is considering whether to use a Pigeon or Suur-Savo overhead line in the 20 kV planning scenario shown in Fig. 3. The installation cost for the Pigeon line is 21€/m, and the larger cross-section Suur-Savo overhead line costs 27.66 €/m, Table 1. The review period is 20 years, but the load growth is non-linear, see Table 2, so you are given κ_{losses} and κ_{load} in Table 3

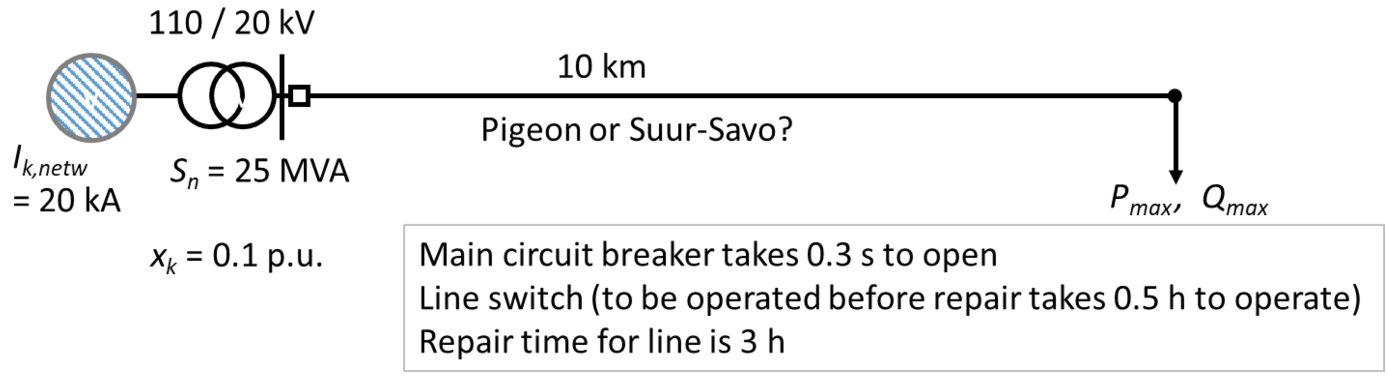


Figure 3 Single line diagram of planned 20 kV feeder

Table 1 Cost and electro-technical parameters for overhead lines

	Fixed cost (€/m)	**Resistance** (Ω/km)	**Reactance** (Ω/km)	I_{max} (A)	$I_{k,1s}$ (kA)
Al/Fe 85/14 (Pigeon)	21.00	0.337	0.354	360	8.4
Al/Fe 106/25 (Suur-Savo)	27.66	0.279	0.344	430	10.5

Table 2

Year	P_{max} (kW)	Q_{max} (kvar)
1	3000	986
2	3090	1016
3	3183	1046
4	3278	1077
5	3377	1110
6	3478	1143
7	3582	1177
8	3690	1213
9	3800	1249
10	3914	1287
11	4149	1364
12	4398	1446
13	4662	1532
14	4942	1624
15	5238	1722
16	5553	1825
17	5886	1935
18	6239	2051
19	6613	2174
20	7010	2304

Table 3 gives some useful economic parameters...

Table 3 Economic parameters

κ_{losses}	31.38 (years)
κ_{load}	20.73 (years)
T_{losses}	3000 hours (per year)
c_{losses}	0.05 €/kWh

Questions:

a) Which cable has the cheapest present day value of investment and loss costs (calculate these for at least one of them!) **(2p)**

b) What is the cost of interruption (present value) if the line has a failure rate of 4 faults/100km/year and the CIC (KAH) values for the customer are a=1.1 €/kW/fault and b = 11 €/kWh? **(1p)**

c) Is at least one of these lines capable of satisfying the relevant technical constraints? **(2p)**

d) Without calculation anything, give your opinion (briefly) about the merits of a choice between a bare overhead conductor through the forest, a cable through the forest, or a covered conductor along the road for rural distribution network planning (medium voltage). (**1p)**

*You may answer in English (preferred), Finnish or Swedish – this is not a language test! **Please keep your answers brief**! Please, no discussion or online communication during this exam. This is to assess you as individuals.*

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1) "Conservation of energy implies that supply must match demand in the power system, and market theory sets the price where supply matches demand, so what's the problem?"

   a) What are two challenges in the electrical power system?

   b) What are the main market solutions (2 points for 4 markets and their description)?

   c) What happens if the markets can't cope (2 available mechanisms for 2 points)?

2)

   a) How can a reliable power system enhance human wellbeing? (2p)

   b) Write about the (environmental) downsides of the power system (2p)

   c) What role will the distribution and transmission systems play in the energy transition? (2p)

3) You have a large investment decision to make to reduce customer interruption costs in an aging underground cable network where joints and some thermally stressed cable sections are starting to fail. You assess that the network has about 20 years life left and the time horizon for the cost analysis is **20 years**. The MV (20 kV) network has an overall length of **136 km** and has, on average, **2.5 faults per 100 km**. The network has full backup, but only has manual load breaking switches, which take, on average, 1 hour to isolate a line fault. The average CIC (customer interruption cost) values are 1.30 €/kW/fault and 13 €/kWh. On average, a fault affects 5 MW of load, but load is expected to grow at 3%/year for the next 20 years. The interest rate is projected to be 4%/year for the next 20 years. The company has been offered a good deal on remote switches, which will cost **1 250 k€** for a full upgrade from manual to remote. You estimate that you should be able to earn 40 k€ for the scrap metal from the old manual switchgear.

   a) Is it worth upgrading the entire network to remote switches? (4p)

   b) What about a full upgrade to network circuit breakers (CBs) and smart sensing and relay control of the CBs (like in a transmission grid) **if the full cost of the upgrade to CBs is 3 750 k€?** (1p)

   c) What does this analysis miss in terms of power quality (something to do with voltage!)? (1p)

Table 1 Fixed parameters for Q3

p	interest rate	4.0 %/year for 20 years
r	load growth (zero)	3.0 %/year for 20 years
a & b	CIC values	1.3 €/kW/fault & 13 €/kWh
$T_{sw,man}$	Manual switch time	1 h
$T_{sw,rem}$	Remote switch time	5 minutes

4) A new 20kV line is being planned to feed 2 wind turbines and a small amount of infrequent demand. The choice has to be made between an overhead line and an underground cable. You should realise, in part c), that the loss times (**T_{loss} = 3000 h**) are based on the distributed **generation** (wind turbines), i.e., the **P_{min} and Q_{min}** values (representing maximum generation, minimum demand), as the distributed generation is so dominant.

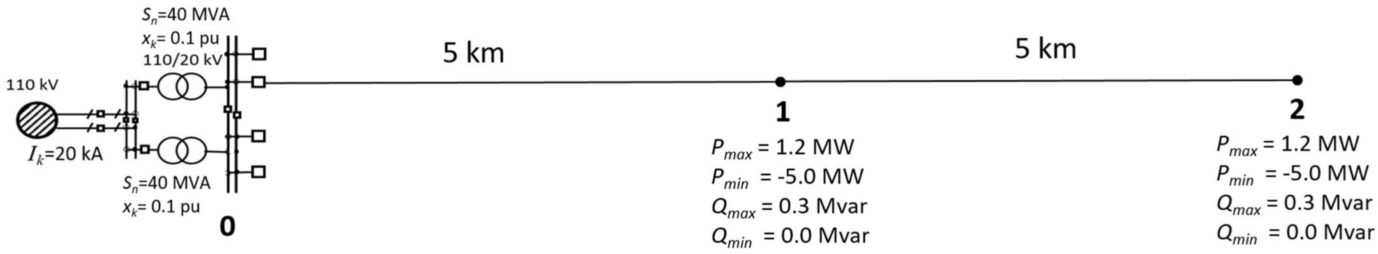

Figure 1 Substation and feeder arrangement for Q4

Table 2 Cost and technical parameters of an overhead line (Suur-Savo) and an underground cable

	Fixed cost (€/m)	**Resistance** (Ω/km)	**Reactance** (Ω/km)	**I_{max}** (A)	**$I_{k,1s}$** (kA)
Al/Fe 106/25 (Suur-Savo)	27.66	0.279	0.344	430	10.5
AHXAMK 240 mm^2	90.24	0.150	0.110	385	22.6

p	interest rate	4 %/year for 40 years
r	load growth (zero)	0.0 %/year for 40 years
c_l	Cost of energy losses	0.06 €/kWh

Voltage drop and rise should remain below 6%.

a) **How fast must the circuit breaker operate to keep within its thermo-mechanical limits for a maximum 3-phase short-circuit fault while the primary substation transformers are being run in parallel if the Suur-Savo overhead line is used?** You are given the 1 second short-circuit limit, **$I_{k,1s}$**, in Table 2. There is no reclosing planned for this line. **(2p)**

b) **Check that both line types are OK for voltage** (think about what you need to calculate!) **(2p)**

c) **Is it worth, economically, spending so much more on the underground cable option, when the lifetime cost of losses is taken into account?** (Remember, T_{loss} = 3000 h, and is related to P_{min} and Q_{min}) **(2p)**

5) Please make 6 clear points about the course content and style. The following items may be of help:
a) **What have you learnt in this course (Electricity Distribution and Markets)?**
b) **What would you have wanted to learn that you felt was missing?**
c) **What is your feeling about the unusual aspects of John's teaching (or facilitation)?**
i) The assignment essay topic on existential threats
ii) John not knowing everything, and learning from the students, and that not worrying him!
iii) The experiential forays into the 'deep questions' of life
Etc…! **(6p)**

You may need the following formulae, or parts from some of them:

$$\gamma = \frac{(1+r)}{(1+p)}, \quad \gamma_1 = \frac{(1+r)^2}{(1+p)} \text{ and } \gamma_2 = \frac{1}{1+p}$$

$$\kappa_{losses} = \gamma_1 \frac{\gamma_1^{t'} - 1}{\gamma_1 - 1} + \frac{(1+r)^{2t'}}{(1+p)^{t'}} \gamma_2 \frac{\gamma_2^{T-t'} - 1}{\gamma_2 - 1} \qquad \kappa_{load} = \gamma \frac{\gamma^{t'} - 1}{\gamma - 1} + \frac{(1+r)^{t'}}{(1+p)^{t'}} \gamma_2 \frac{\gamma_2^{T-t'} - 1}{\gamma_2 - 1}$$

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There are 5 questions, each worth 6 points

1) "Conservation of energy implies that supply must match demand in the power system, and market theory sets the price where supply matches demand, so what's the problem?"

a) What are two reasons for why it is becoming more difficult to balance supply with demand in real time in the electrical power system? (2p)

b) How do the electricity markets, e.g., Nordpool, attempt to achieve the balance between supply and demand at a good price? (2p)

c) What happens if the system price (which doesn't consider transmission constraints) implies power flows that exceed the transmission constraints between bidding areas? (2p)

2)

a) Hopefully, you recall the following:

$$Min \sum C_{investments} + C_{losses} + C_{interruption}$$

What are 3 ways these costs affect each other? (3p)

b) What are 4 of the most important technical constraints that the cost minimization is subject to? (2p)

c) Why are TSOs (transmission system operators) increasingly interested in what happens at the distribution level? (1p)

3) You must make a large investment decision to reduce customer interruption costs in an aging demand-only underground cable network where joints and some thermally stressed cable sections are starting to fail. You assess that the network has about **20 years** life left and the time horizon for the cost analysis is **20 years**. The MV (20 kV) network has an overall length of **136 km** and has, on average, **2.5 faults per 100 km**. The network has full backup, but only has manual load breaking switches, which take, on average, **1 hour** to isolate a line fault. The average CIC (customer interruption cost) values are **1.30 €/kW/fault** and **13 €/kWh**. On average, a fault affects **5 MW** of load, but **load** is expected to grow at **3%/year** for the next **20 years**. The **interest rate** is projected to be **4%/year** for the next **20 years**.

a) **Is a full upgrade to network circuit breakers (CBs) and smart sensing and relay control of the CBs** (like in a transmission grid) **worthwhile if the full cost of the upgrade to CBs is 3 750 k€?** **(2p)**

b) **Or, is it (more) worthwhile upgrading the entire network to remote switches** if it will cost **1 250 k€** for a full upgrade from manual to remote**?** **(3p)**

c) **What voltage related issue does this reliability analysis miss?** **(1p)**

Table 1 Fixed parameters for Q3

p	interest rate	4.0 %/year for 20 years
r	load growth (zero)	3.0 %/year for 20 years
a & b	CIC values	1.3 €/kW/fault & 13 €/kWh
$T_{sw,man}$	Manual switch time	1 h
$T_{sw,rem}$	Remote switch time	5 minutes
T_{CB}	Main circuit breaker opening time	200 ms

4) A new 20kV line is being planned to feed 2 wind turbines and a small amount of infrequent demand. The choice has to be made between an overhead line and an underground cable. You should realise, in part c), that the loss times (**T_{loss} = 3000 h**) are based on the distributed **generation** (wind turbines), i.e., the **P_{min} and Q_{min}** values (representing maximum generation, minimum demand), as the distributed generation is so dominant.

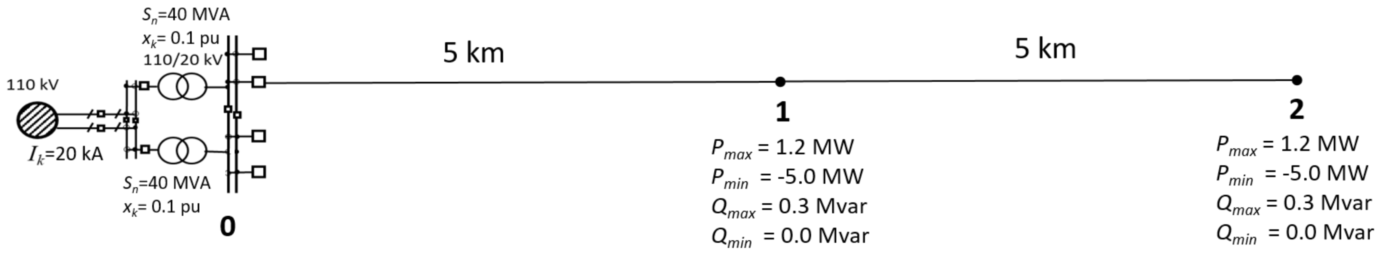

Figure 1 Substation and feeder arrangement for Q4

Table 2 Cost and technical parameters of an overhead line (Suur-Savo) and an underground cable

	Fixed cost (€/m)	**Resistance** (Ω/km)	**Reactance** (Ω/km)	**I_{max}** (A)	**$I_{k,1s}$** (kA)
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p	interest rate	4 %/year for 40 years
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c_l	Cost of energy losses	0.06 €/kWh

Voltage drop and rise should remain below 6%.

a) **How fast must the circuit breaker operate to keep within its thermo-mechanical limits for a maximum 3-phase short-circuit fault while the primary substation transformers are being run in parallel if the Suur-Savo overhead line is used?** You are given the 1 second short-circuit limit, **$I_{k,1s}$**, in Table 2. There is no reclosing planned for this line. **(2p)**

b) **Check that both line types are OK for <u>voltage</u>** (think about what you need to calculate!) **(2p)**

c) **Is it worth, economically, spending so much more on the underground cable option, when the lifetime cost of losses is taken into account?** (Remember, T_{loss} = 3000 h, and is related to P_{min} and Q_{min}) **(2p)**

5) Please make 6 clear points about the course content and style. The following items may be of help:

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   i) The assignment essay topic on existential threats
   ii) John not knowing everything, and learning from the students, and that not worrying him!
   iii) The experiential forays into the 'deep questions' of life
   Etc…! **(6p)**

You may need the following formulae, or parts from some of them:

$$\gamma = \frac{(1+r)}{(1+p)}, \quad \gamma_1 = \frac{(1+r)^2}{(1+p)} \quad \text{and} \quad \gamma_2 = \frac{1}{1+p}$$

$$\kappa_{losses} = \gamma_1 \frac{\gamma_1^{t'} - 1}{\gamma_1 - 1} + \frac{(1+r)^{2t'}}{(1+p)^{t'}} \gamma_2 \frac{\gamma_2^{T-t'} - 1}{\gamma_2 - 1} \qquad \kappa_{load} = \gamma \frac{\gamma^{t'} - 1}{\gamma - 1} + \frac{(1+r)^{t'}}{(1+p)^{t'}} \gamma_2 \frac{\gamma_2^{T-t'} - 1}{\gamma_2 - 1}$$

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The following figure and tables are for Q1 and Q2.

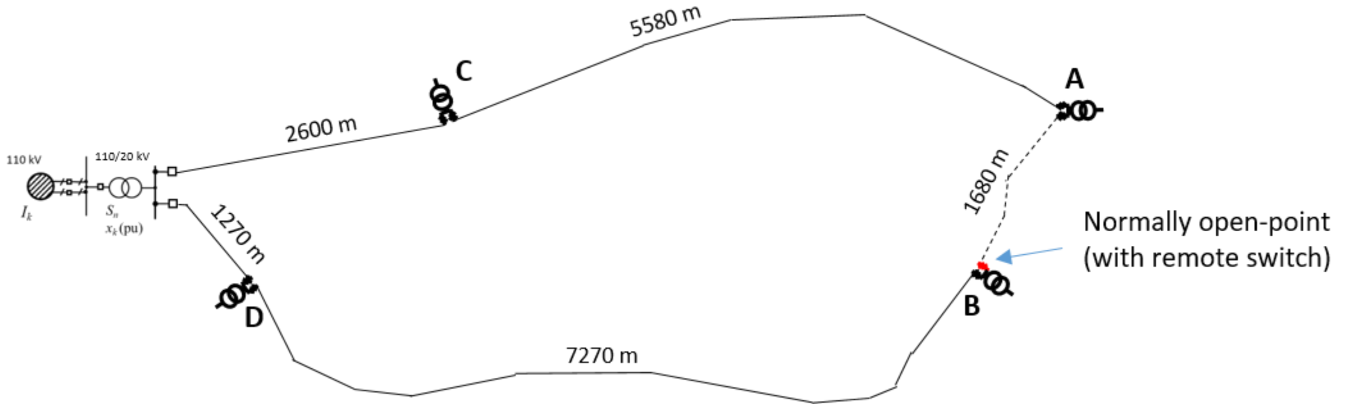


Figure 1 20 kV Network topology for Q1 and Q2. All switches are remote-operated

Table 1 Parameters (P_{max} and Q_{max} relate to maximum load/minimum generation and P_{min} and Q_{min} relate to minimum load/maximum generation)

Node ID	Load						CIC-parameters	
	P_{max} (kW)	P_{min} (kW)	Q_{max} (kvar)	Q_{min} (kvar)	T_{losses}[1] (h/a)	$f_{coincidence}$	*a* (€/kW)	*b* (€/kWh)
0	0	0	0	0	0	0	0	0
1	700	-2000	100	80	2000	1	1.23	12.3
2	700	-2000	100	80	2000	1	1.23	12.3
3	700	-2000	100	80	2000	1	1.23	12.3
4	700	-2000	100	80	2000	1	1.23	12.3

Table 2 HV grid and primary substation parameters

Node IDs	110 kV grid	Main transformer	
	I_k (MVA)	u_k (p.u.)	S_N (MVA)
0	24 kA	0.12	60

Table 3 Switching times

Remote switch	0.08 h
Circuit breaker (substation and field)	0.4 sec

Table 4 Line fault rates and voltage drop/rise constraints

	UGC
fault rate (1/100km/a)	2
Allowable max. normal/contingency Voltage Drop	3.5% / 7%
Allowable max. normal/contingency Voltage Rise	3.0% / 6.0%

Table 5. Underground cable parameters

	Fixed cost (€/m)	**Resistance** (Ω/km)	**Reactance** (Ω/km)	I_{max} (A)	$I_{k,1s}$ (kA)
AHXAMK 50 mm^2	70	0.641	0.145	155	4.7
AHXAMK 150 mm^2	90	0.250	0.123	300	13.5

Table 6 Fixed parameters for Task A

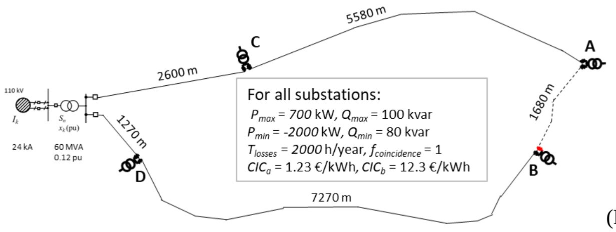
p	interest rate	3 %
r	load growth (zero)	0.0 % for 40 years
a & b	CIC values	1.23 €/kW & 12.3 €/kWh
c_l	Cost of energy losses	0.05 €/kWh

You may need the following formulae, or parts from them:

$$\gamma = \frac{(1+r)}{(1+p)}, \quad \gamma_1 = \frac{(1+r)^2}{(1+p)} \quad \text{and} \quad \gamma_2 = \frac{1}{1+p} \qquad \text{(1), (2) and (3)}$$

$$\kappa_{losses} = \gamma_1 \frac{\gamma_1^{t'} - 1}{\gamma_1 - 1} + \frac{(1+r)^{2t'}}{(1+p)^{t'}} \gamma_2 \frac{\gamma_2^{T-t'} - 1}{\gamma_2 - 1} \qquad (4)$$

$$\kappa_{load} = \gamma \frac{\gamma^{t'} - 1}{\gamma - 1} + \frac{(1+r)^{t'}}{(1+p)^{t'}} \gamma_2 \frac{\gamma_2^{T-t'} - 1}{\gamma_2 - 1} \qquad (5)$$



(Reduced picture for you to cut-and-paste to where it is of most use)

Q1. Fig. 1 shows a network topology. Tables 1 to 6 list various parameters that may be of use.

Check that the network is technically compliant. If the larger size (150 mm^2) is needed somewhere, use it everywhere. Think about what you need to calculate! You can use 19.5 kV when calculating the line currents and voltage drops to simplify things… **(6p)**

Q2. **What are the approximate net present values of the lifetime (40 year) losses ($3I^2R$) and interruption costs for the network in Fig. 1** with the conductor size you have chosen? Note, T_{losses} and the CIC values are related to maximum load / minimum generation parameters. Once again, you can use 19.5 kV when calculating the losses. **(5p)**

What would be the break-even cost for a protection upgrade so that the network could be operated with the normally open point closed (like a transmission network), with circuit breakers, sensors, relays, etc., on each side of every substation? **(1p)**

Q3. Figs. 2a to 2c show three network plans with insets summarizing the costs, etc. The network plans are upgrade target underground cable networks, capable of coping with a large amount of renewable energy and electric vehicle charging.

Make 4 observations about the plans – regarding the pros and cons of each plan. **(4p)**

Which one would you build and why? **(1p)**

This network (replacing old overhead lines) could be built in two years, but has a life expectancy of 50 years. Often we hear that the return on investment should occur in 3 years. **What is your opinion about that** (i.e., a 3-year return on investment)? **(1p)**

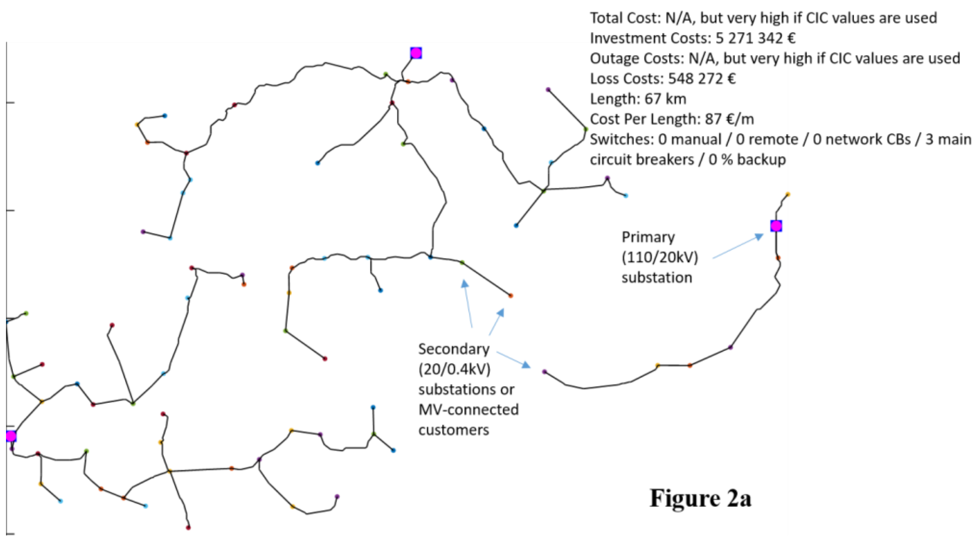


Figure 2a

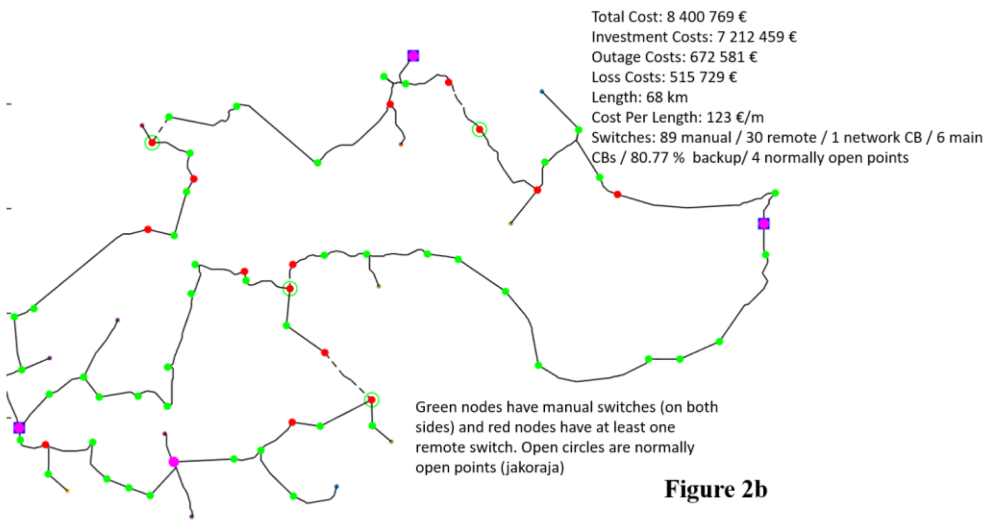


Figure 2b

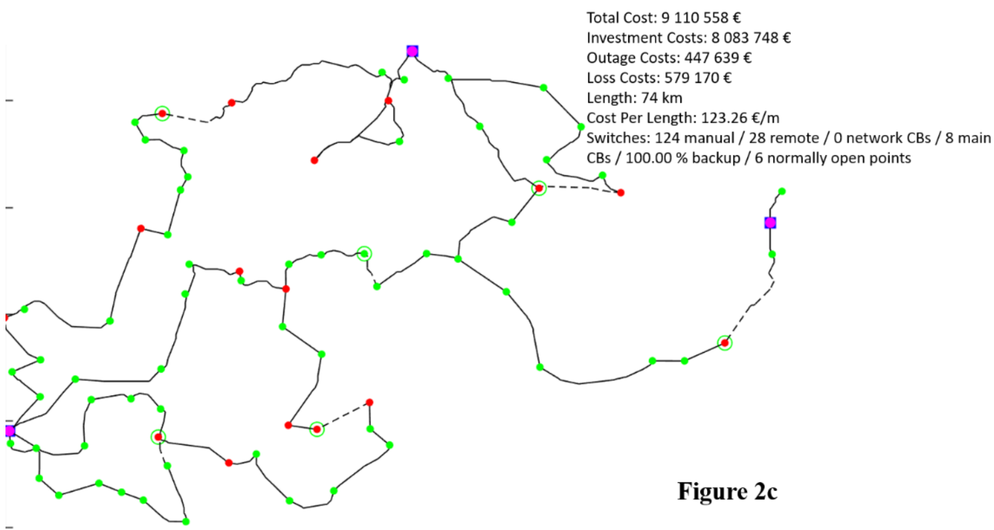


Figure 2c

Q4. What are the main differences between Options and Forwards? **(2p)**

Why do we need balance markets and out of market products? Name two such market or ancillary products. **(2p)**

Describe two challenges that exist when trying to regulate natural monopolies such as electricity distribution in order to keep prices reasonable and performance reasonable. **(2p)**

Q5.

Figure 2 UN Sustainable Development Goals

Which of these does this course touch on? How?

Where could we do better? How? Where did we do well? Why?

Form a short essay (<half a page) with (at least) 6 clear points. **(6p)**