Workshop 1: Training and workshop focusing on theory and practical calculation of technical losses in power networks with very high levels of RE generation.

07.09.2020 - 21.09.2020

Mikael Andersson, Anna-Maria Roslund

Power System Engineers at Sweco

Energy Partnership Programme between South Africa and Denmark

About the Programme

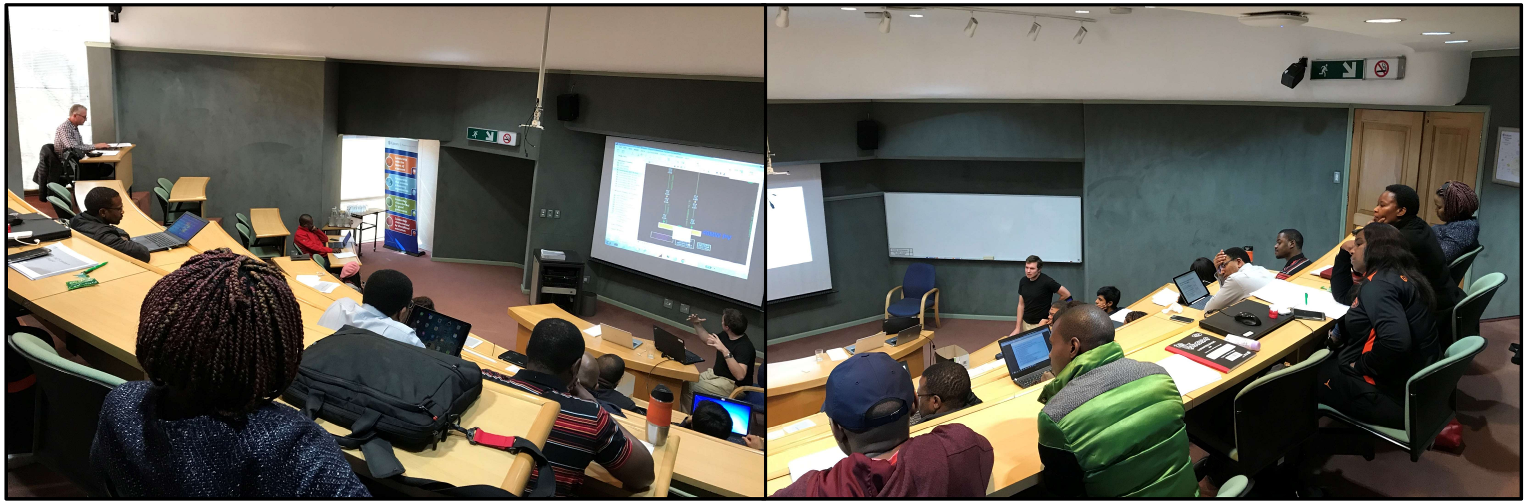
About the Programme

- 3. Technical assistance to ESKOM for renewable energy integration in electricity supply.

- Technical advisor on Renewables and Network Operations
  - Birk Sylvest Andersen 2015-2016
  - Mikael Andersson 2016-2017
    - Eskom Program
    - Municipality Program

About the Programme

- DE2 OUTPUT 3 - CONSULTANT SUPPORT FOR IMPLEMENTING WORKING ACTIVITIES ON RE INTEGRATION AT DISTRIBUTION LEVEL
  - Training of distribution network planners – Year 1 (2019)
  - Training of distribution network operators – Year 2 (2020)



About the Programme

- DE2 OUTPUT 3 - CONSULTANT SUPPORT FOR IMPLEMENTING WORKING ACTIVITIES ON RE INTEGRATION AT DISTRIBUTION LEVEL
- Training of distribution network operators – Year 2 (2020)
  - Activity 1: Calculating losses in networks with very high levels of RE generation embedded into the grid
    - Workshop 1 - Training and workshop with Eskom staff focusing on theory and practical calculation of technical losses in power networks with very high levels of RE generation
  - Activity 2: Mitigating solutions for distribution network power quality issues in relation to RE generation and penetration to the distribution network
  - Activity 3: Inputs to system operating guidelines
    - Workshop 2 - Theoretical and practical training activities as specified for Activity 2 & 3.

Workshop 1 – Part 1
Monday 07.09.2020 – Friday 11.09.2020

- Session 1
  - Generally about power system losses
  - Generally about loss calculation methodology
  - Basic theory behind power system losses
    - Simple exercise in Power Factory
- Session 2
  - Background – networks with high level of renewables – benchmarking
  - Distributed generation and its impact on power system losses
    - Exercise/discussion on challenges and solutions
- Session 3
  - 11 kV Power Factory study case – how the loss pattern changes with increased SSEG

Pre-recorded sessions released on Monday 07.09.2020

QA session: Monday 14.09.2020

Workshop 1 – Part 2
Monday 14.09.2020 – Friday 18.09.2020

- Session 4
  - 11 kV Power Factory study case – dynamic iterative loss calculation method
- Session 5
  - 132 kV Power Factory study case – how the loss pattern is affected by changes in power flow direction as the traditional top-down system is challenged
- Session 6
  - Review on loss calculation procedures and tools
    - Review note D1.1 with gap analysis

Pre-recorded sessions released on Monday 14.09.2020

QA session: Monday 21.09.2020

Mikael Andersson

- M.Sc. Energy Engineering direction Power Engineering, Lund University of Technology, Sweden, 2005.
- Employment record:
  - Controller, Control room operator, at E.ON, DSO in southern Sweden.
  - Strategic network planner, at DONG Energy, DSO in Denmark.
  - Consultant at Sweco, Sweden.
    - TANESCO, Tanzania, various missions
    - REA, Kenya, 2012-2014
    - TSO, Latvia, 2012
    - ECG, Ghana, 2015
    - ESKOM, South Africa, 2016-2017

Acronyms

- DG – Distributed Generation
- DVG – Distributed Variable Generation
- RE – Renewable Energy
- EG – Embedded Generation
- SSEG – Small Scale Embedded Generation
- RPP – Renewable Power Producer
- IPP – Independent Power Producer

Generally about power system losses

Generally about power system losses

- Generally about Distribution System Losses
  - ATC&C losses
  - Commercial Losses
  - Technical Losses
  - Collection Losses
- Technical Losses – Included components

Generally about power system losses

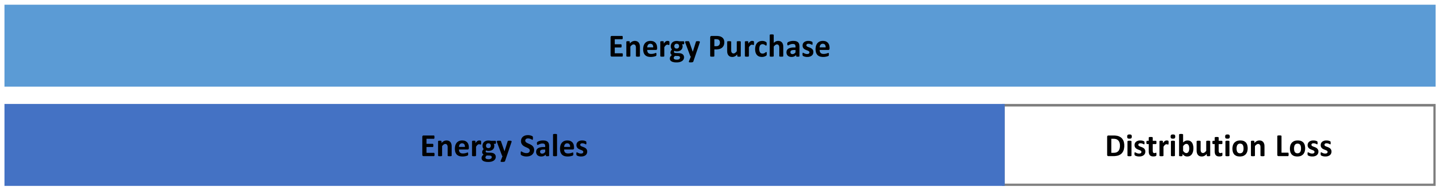
- Generally about Distribution System Losses
  - ATC&C losses
  - Commercial Losses
  - Technical Losses
  - Collection Losses
- Technical Losses – Included components

Generally about Distribution System Losses

- Power system losses consist of three components: Technical Losses, Commercial Losses and Collection Losses.
- The aggregate sum of these three components is often referred to as ATC&C losses or Aggregate Technical, Commercial and Collection Losses. ATC&C can also be referred to as the Total Losses.
- The factors responsible for losses and the measures used for loss reduction are totally different between the different types and they must be analysed separately.
- Deciding the sizes of the individual losses is a complex exercise and it is important to understand the relation between the losses before such an exercise is taken on.

Generally about Distribution System Losses

- The difference between the Energy Purchase and the Energy Sales is referred to as the Distribution Losses.



Generally about Distribution System Losses

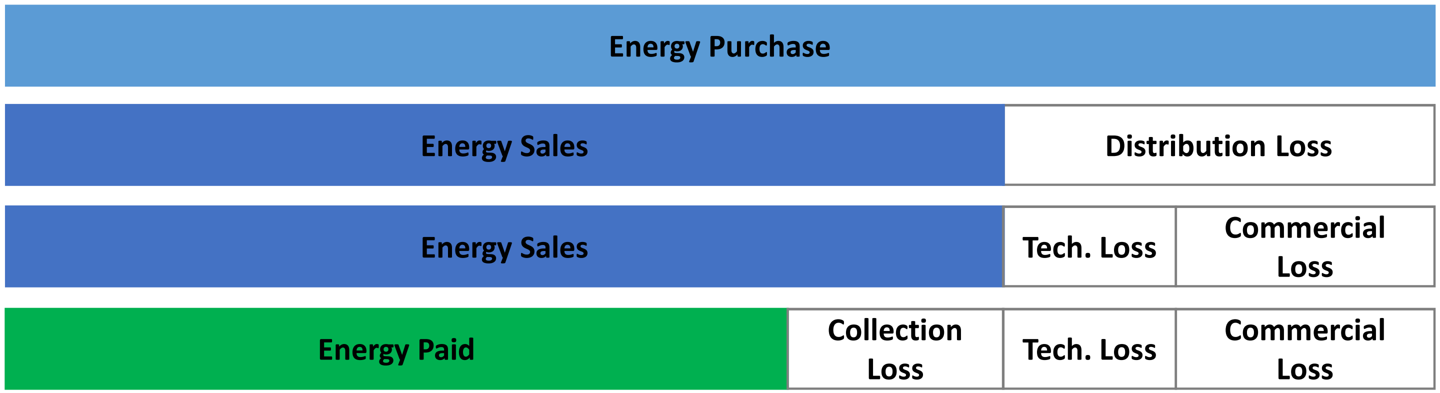
- The Distribution Losses consist both of the Technical Losses and the Commercial Losses. However none of them can be further measured to determine the share of each.

Generally about Distribution System Losses

- The Technical Losses can be estimated by load flow simulations in a network calculation tool. By determining the Technical Losses also the Commercial Losses can be quantified.

Generally about Distribution System Losses

- The difference between the Energy Sales and the Energy Paid is referred to as the Collection Losses.



Generally about Distribution System Losses

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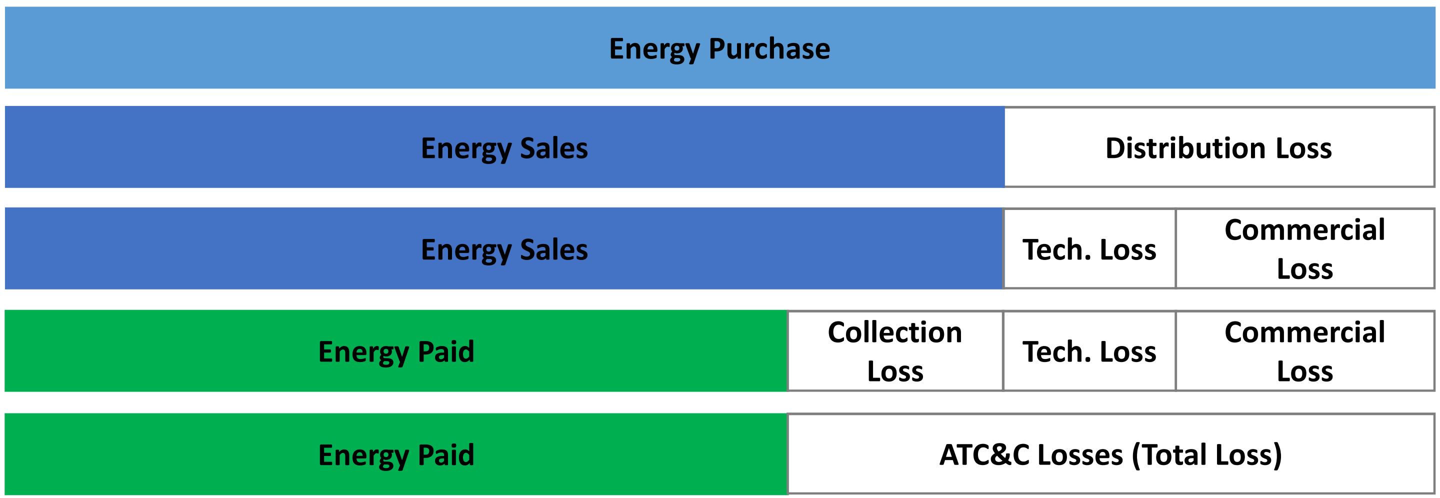
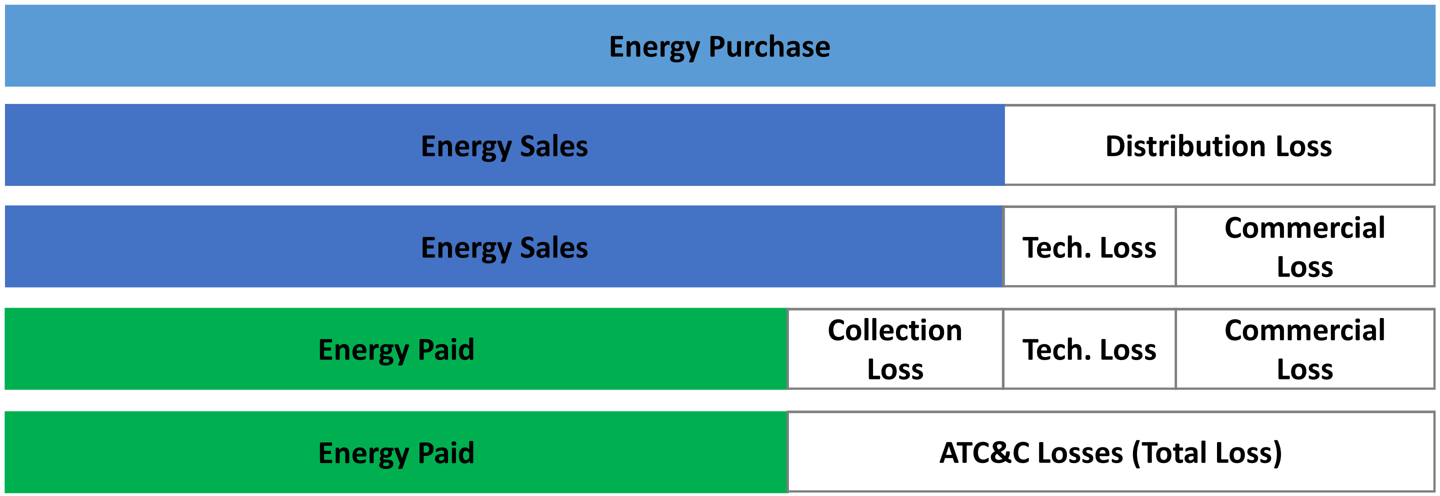


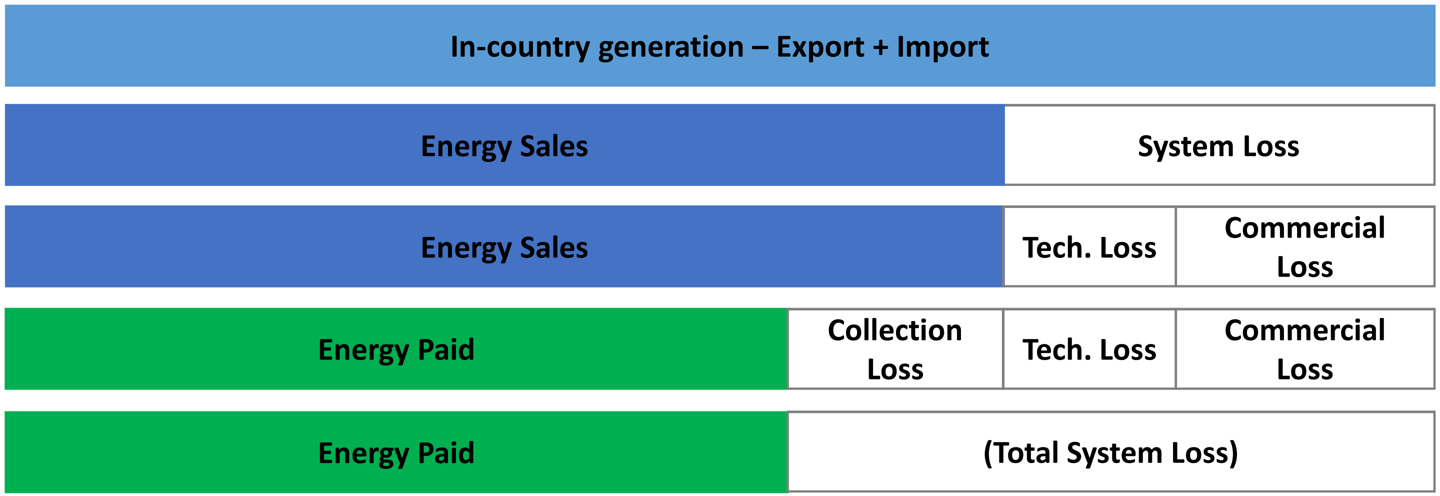
Generally about Distribution System Losses

- This perspective of presenting losses is adapted to distribution companies or regional branches buying electricity from a transmission company.



Generally about Distribution System Losses

- For the total system or for a country as a whole:
- System Losses = ((in-country generation – export + import) – electricity billed to customers) / (in-country generation – export + import).



ATC&C losses

- *Energy that is delivered to Customers but not paid for*
- ATC&C losses are considered as a key KPI to assess the energy efficiency, financial health and operational performance of a distribution utility.
- The as ATC&C losses can be expressed in both absolute numbers and in percent. It is defined as the difference between Energy Purchased and Energy Paid.

Commercial Losses

- *Energy that is delivered to Customers but not billed*
- Commercial losses come from electricity theft, defective energy meters, errors in meter reading and billing processes.
- The Commercial Losses are often also referred to as Non-Technical Losses (also heard of “dark or black losses”).

Commercial Losses

- A section from South African NRS 080:2004 specifies the problem (from the time the NRS was written):
- *To ensure that the energy balancing process is accurate and meaningful, all sales should be associated with the correct network. Therefore, meter reading schedules should ideally be planned in such a way that meters in a specific network are read on the same day. However, this is invariably not possible. Also, where customers have been provided with prepayment meters, energy sales will be in advance of energy delivered. To ensure the time and energy mismatches, and for comparison of results, a three-month moving average shall be used for all energy loss reports.*

Commercial Losses

- A section from South … the problem (from the time the NRS…
- *To ensure that the e… meaningful, all sal… work. Therefore, meter … such a way that meter… y. However, this is in… have been provided wit… advance of energy … mismatches, and for c… moving average shall be used for …*

We will mostly look into the technical losses when it comes to RPP impact. But how do you think the commercial losses are affected by the IPP/RPP/SSEG?

Ideas for discussion:
-The SSEG is not measured
-RPP introduce new players and more production data processing
-Currently RPP energy sales billed to Operator
-Energy seen by Operator is less due to RPP supply

Technical Losses

- *Energy that is produced but not delivered to Customers*
- The technical losses are the losses that are caused by the physical properties of the components of the system. It occurs in the conductors, transformers and the equipment used for transporting the power. The losses disappear as heat.
- The technical losses have to be minimized but cannot be avoided or reduced to zero since they depend on the always present impedance.
- Technical losses can only be estimated by load flow simulations in a network calculation tool. However the accuracy of the estimation depends on the model created in the tool and its resemblance to the reality.

Collection Losses

- *Energy that is billed but not paid for*
- Collection losses are the energy billed by the utility but where payment is not received from customers.
- The Collection Losses are result from customers that intentionally or unintentionally don't pay for the electricity they consume.
- Apart from deliberate action the source of the problem can also be unclear invoices or complex payment procedures.
- Collection Losses are estimated or determined as the difference between Energy Sales and Energy Paid.

“Maintenance losses”

- *Energy that cannot be delivered due to planned outages*
- *Energy that cannot be delivered due to outages*
- *“ENS – Energy Not Supplied”*

Technical Losses

- Technical Losses are the focus of this training.
- Technical losses occur in all levels of the system and in all components that carry a current. Also in segments that are idle (powered with voltage but without load).
- Technical losses depend on the impedance and the current. They are directly proportional to the impedance and to the square of the current.

$$Losses = I^2 \cdot R$$

Generally about power system losses

- Generally about Distribution System Losses
  - ATC&C losses
  - Commercial Losses
  - Technical Losses
  - Collection Losses
- Technical Losses – Included components

Technical Losses - Included components

- Losses that occur in the conductors (over head lines or underground cables) are called line losses.
- Losses that occur in transformers are either iron or copper losses (also called no load or load losses). The no load losses are constant and independent of if the transformer is idle (powered but with no load) or fully loaded. The no load losses depend on the iron core of the transformer. The load losses vary with the load and depend on the current through the copper windings of the transformer.
- Losses that occur in other components such as voltage and current transformers, terminations, breakers etc. are usually negligible if the components are in good shape.
- If components are failing, if they are old or corroded, or if any work or maintenance is not done properly, then any component can cause significant losses.

Technical Losses

- Split of technical losses components
- The voltage levels in the figure depend on the utility

Voltage Level	Network Component	Network Level	Loss Type
33 kV	Line	33 kV Sub-transmission	Line losses
	Line	33 kV Distribution	Line losses
	Transformer	33/11 kV Transformer	Iron / no load losses
			Copper / load losses
	Distribution Transformer	33/0,4 Distribution Transformer	Iron / no load losses
			Copper / load losses
11 kV	Line	11 kV Distribution	Line losses
	Distribution Transformer	11/0,4 Distribution Transformer	Iron / no load losses
			Copper / load losses
0,4 kV	Line	0,4 kV Distribution	Line losses

Technical Losses - Benchmark

Table 18 Benchmark for Ashanti – Yearly Losses

	Ashanti total 2014	Sub-Sahara Africa, Sweco rule of thumb	Scandinavia typical [2]	Latvia [2]	Case study, single feeder Tanzania [3]	WB - Target Levels [1]	ECG 2011 [1]
	%	%	%	%	%	%	%
Distribution losses	29,6		4,0	5,9	45		29,52
ATC&C losses	41,1						43,48
Collection losses	11,4						13,96
Technical losses	13,9	5 - 8	3,0			6,29	10,97
Commercial losses	15,7		1,0				18,55

Table 19 World Bank International Benchmark on System Losses

	Angola	Côte d' Ivoire	Benin	Nigeria	Ghana	Senegal	Cameroon	Togo	Swaziland
	%	%	%	%	%	%	%	%	%
System Losses	15	18	18	24	26	30	31	46	68

Table 17 Benchmark for Ashanti - Yearly Technical Energy Losses

Voltage level	Loss Type	Network Level	Ashanti Total 2014 %	WB - Target Levels [1] %	WB - Maximum to be tolerated [1] %
33 kV	Line	33 kV Sub-transmission	2,5	1,36	2,72
	Line	33 kV Distribution			
	Transformer	33/11 kV Transformer	0,6	0,17	0,34
	Distribution Transformer	33/0,4 Distribution Transformer	0,2		
11 kV	Line	11 kV Distribution	5,1	2,04	3,40
	Distribution Transformer	11/0,4 Distribution Transformer	1,6	0,68	1,36
0,4 kV	Line	0,4 kV Distribution	4,0	2,04	3,40
	Grand Total		**13,9**	**6,29**	**11,22**

References

[1] National Technical and Commercial Loss Study ECG, Ghana, Global Energy Consulting Engineers India (GECE), 2012
[2] Planning Target Report, Sweco International, 2013
[3] Rural Electrification in Urambo and Serengeti, Training Report Loss Reduction Basic Electric Safety And Distribution Standards, Sweco International, 2003
[4]https://www.researchgate.net/publication/304623559_A_STATISTICAL_ANALYSIS_OF_LOSS_FACTOR_A_CASE_STUDY_IN_APEPDCL-KAKINADA
[5]https://www.researchgate.net/publication/3792738_New_method_to_calculate_power_distribution_losses_in_an_environment_of_high_unregistered_loads
[6]https://www.researchgate.net/publication/224601813_Energy_loss_estimation_in_distribution_networks_for_planning_purposes

Generally about loss calculation methodology

Eskom Danish Energy Agency COWI

Generally about loss calculation methodology

- Generally about Loss Calculation Methods – “backbones”
- Different kinds of Methods
  - Absolute methods
  - Empirical methods
  - Intuitive or hypothesis based methods
- Determining Technical Losses – Discussion

Generally about loss calculation methodology

- Generally about Loss Calculation Methods – “backbones”
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Generally about Loss Calculation Methods "backbones"

- There are a number of different methods to determine technical losses.
- Even with the most advanced tools and procedures the exact technical losses are hard to capture. Assumptions and simplifications are part of any method.
- Three main backbones in every technical loss determination:
  - **Network model** (topology, line and transformer parameters)
    – things that don't change
  - **State/estimates/scenarios** (switching status, tap changer position, FACTS-status, load and production situation)
    – a single moment of things that change
  - **Load and production profiles over time** (daily, weekly, yearly profiles)

Generally about Loss Calculation Methods – "backbones"

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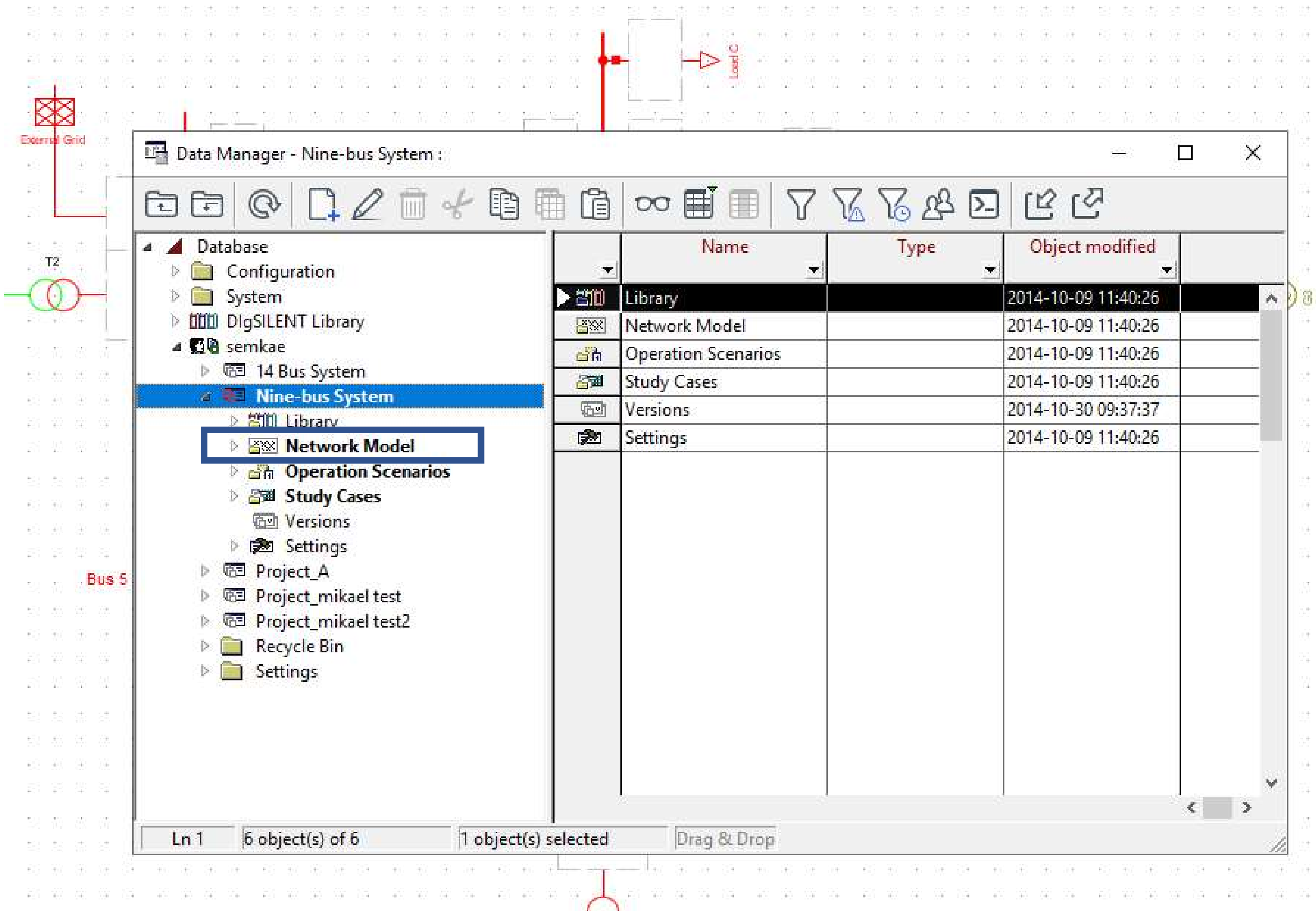
- **Load and production profiles over time** (daily, weekly, yearly profiles)

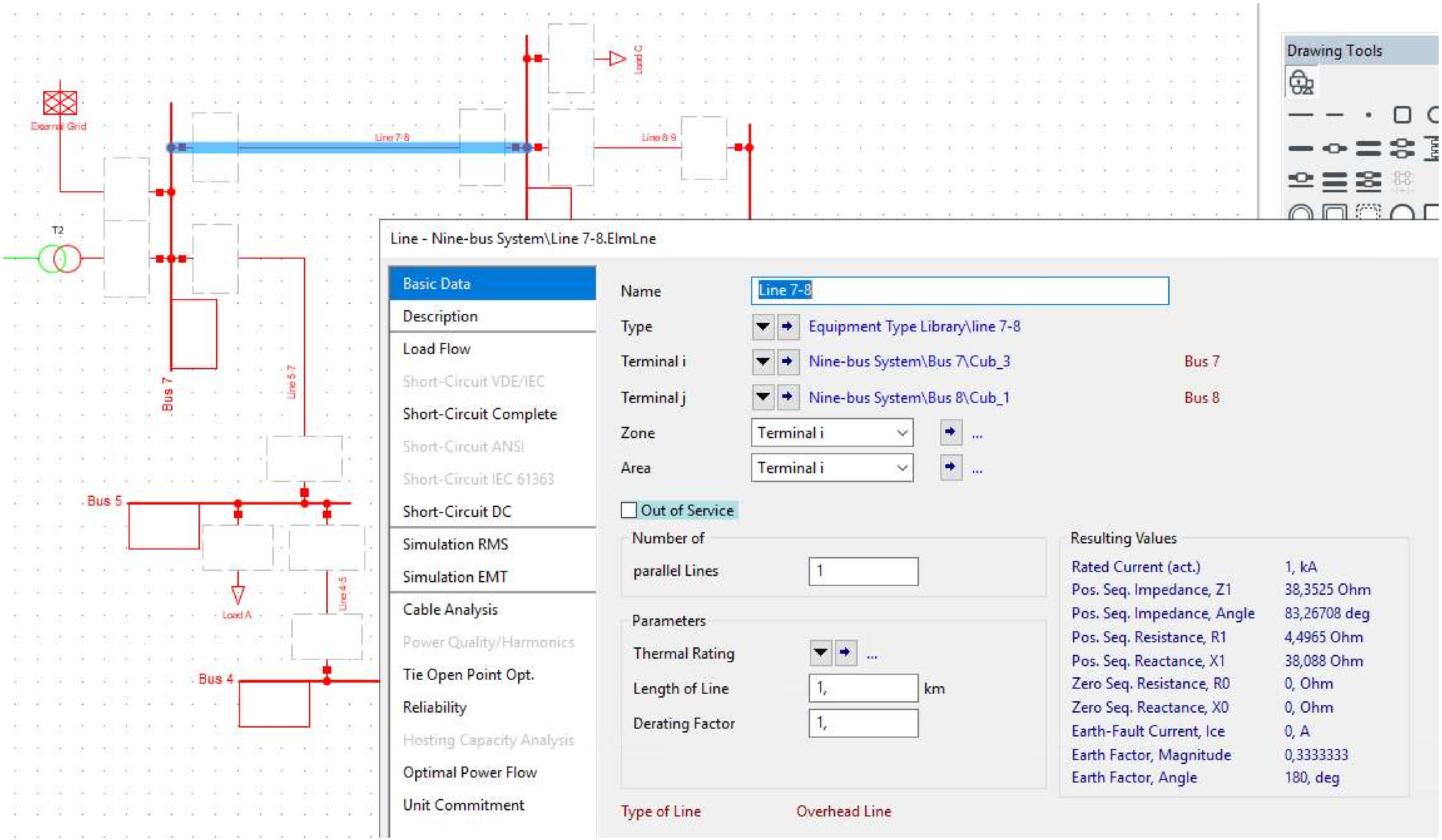
- A technical loss estimation method includes having an "approach" for each of these backbones.

Generally about Loss Calculation Methods – “backbones”

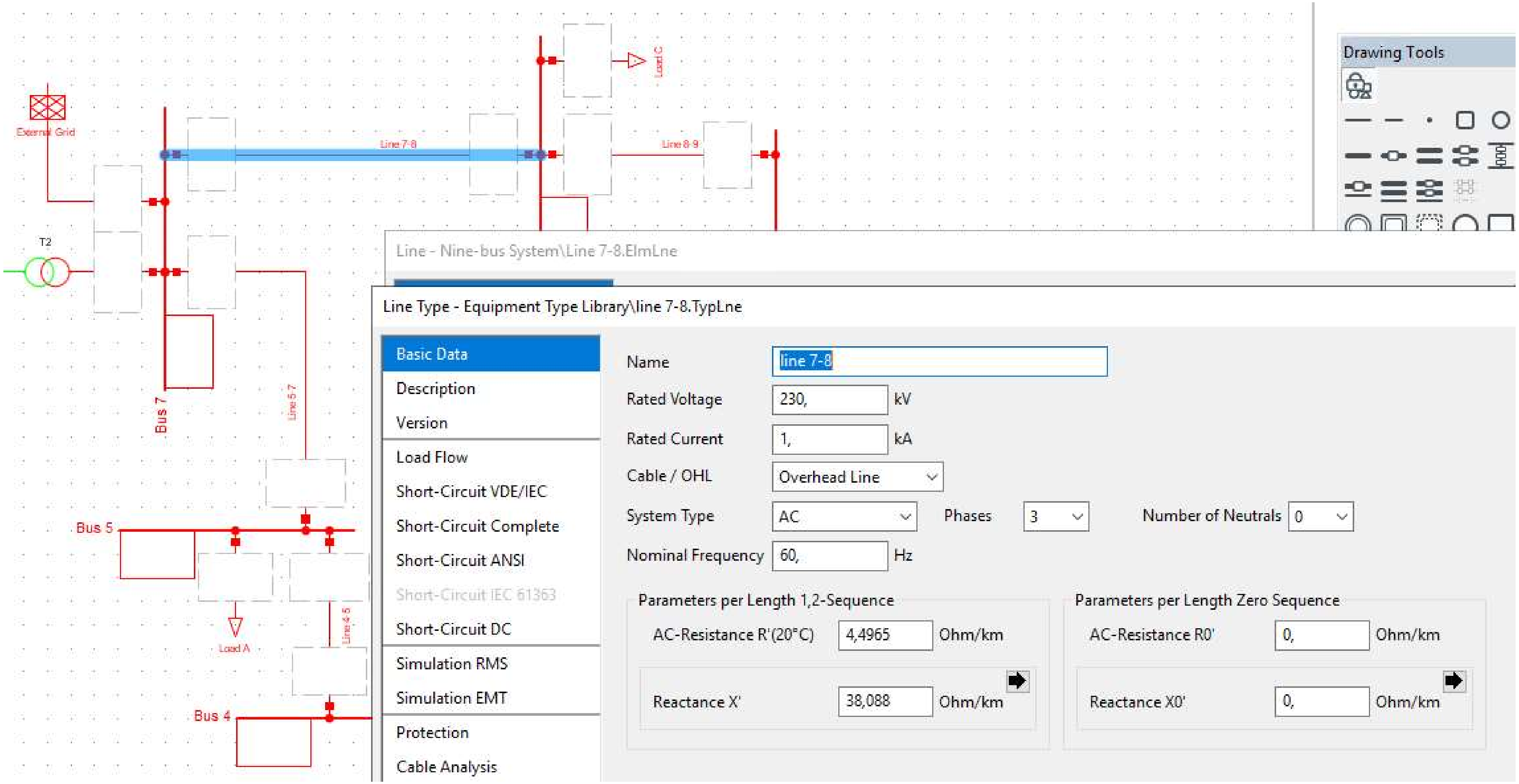
In Power Factory

- Network Model
    - Type (rated power, impedance per length etc.)
    - Element (length, status, connection topology of a Type)





External Grid
Line 7-8
Line 8-9
Load C
T2
Bus 7
Line 5-7
Bus 5
Load A
Line 4-5
Bus 4
Drawing Tools
Line - Nine-bus System\Line 7-8.ElmLne
Basic Data
Description
Load Flow
Short-Circuit VDE/IEC
Short-Circuit Complete
Short-Circuit ANSI
Short-Circuit IEC 61363
Short-Circuit DC
Simulation RMS
Simulation EMT
Cable Analysis
Power Quality/Harmonics
Tie Open Point Opt.
Reliability
Hosting Capacity Analysis
Optimal Power Flow
Unit Commitment
Name Line 7-8
Type Equipment Type Library\line 7-8
Terminal i Nine-bus System\Bus 7\Cub_3 Bus 7
Terminal j Nine-bus System\Bus 8\Cub_1 Bus 8
Zone Terminal i
Area Terminal i
Out of Service
Number of
parallel Lines 1
Parameters
Thermal Rating
Length of Line 1, km
Derating Factor 1,
Resulting Values
Rated Current (act.) 1, kA
Pos. Seq. Impedance, Z1 38,3525 Ohm
Pos. Seq. Impedance, Angle 83,26708 deg
Pos. Seq. Resistance, R1 4,4965 Ohm
Pos. Seq. Reactance, X1 38,088 Ohm
Zero Seq. Resistance, R0 0, Ohm
Zero Seq. Reactance, X0 0, Ohm
Earth-Fault Current, Ice 0, A
Earth Factor, Magnitude 0,3333333
Earth Factor, Angle 180, deg
Type of Line Overhead Line



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Basic Data
Description
Version
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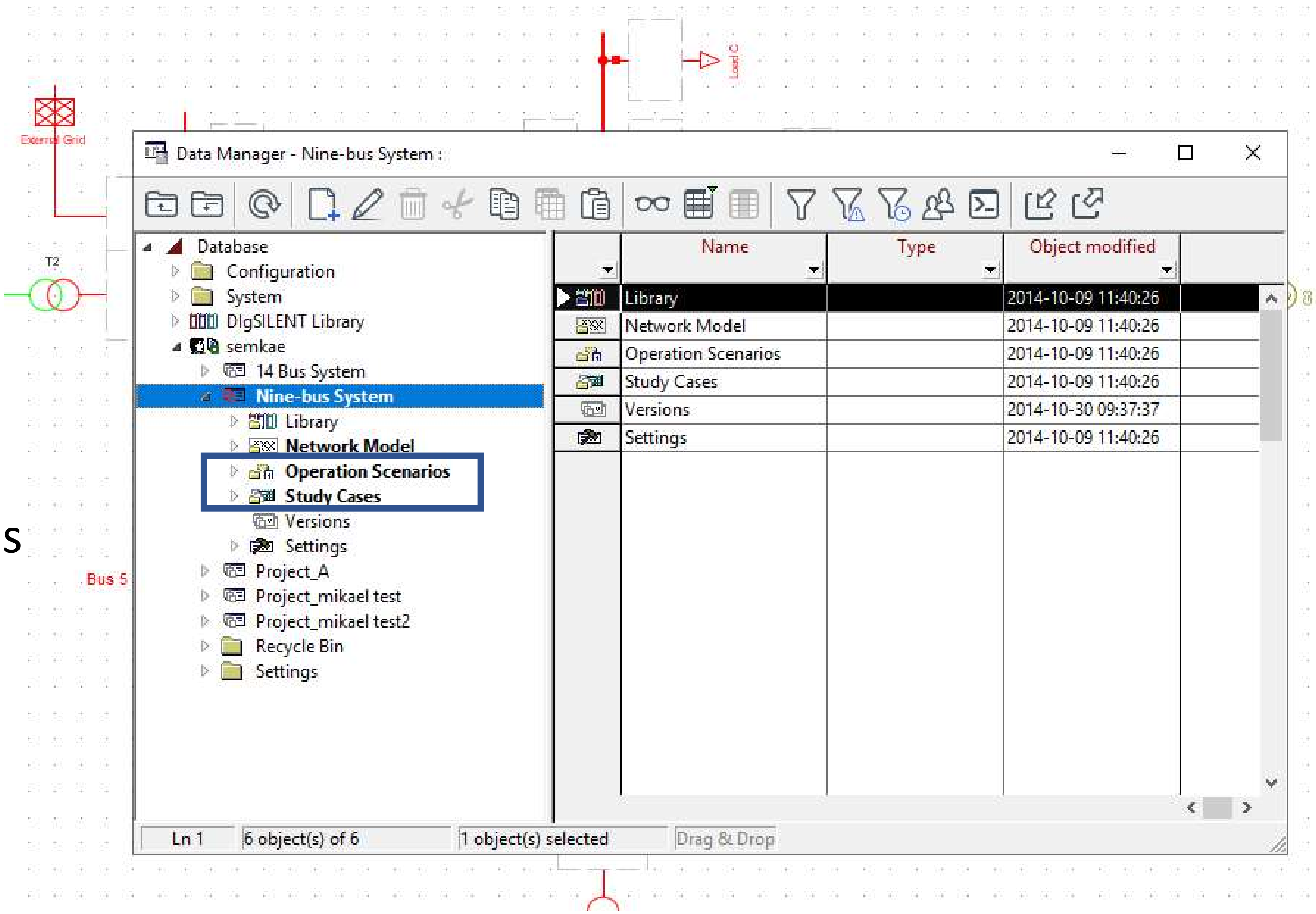
Short-Circuit VDE/IEC
Short-Circuit Complete
Short-Circuit ANSI
Short-Circuit IEC 61363
Short-Circuit DC
Simulation RMS
Simulation EMT
Protection
Cable Analysis
Name
line 7-8
Rated Voltage
230,
kV
Rated Current
1,
kA
Cable / OHL
Overhead Line
System Type
AC
Phases
3
Number of Neutrals
0
Nominal Frequency
60,
Hz
Parameters per Length 1,2-Sequence
AC-Resistance R'(20°C)
4,4965
Ohm/km
Reactance X'
38,088
Ohm/km
Parameters per Length Zero Sequence
AC-Resistance R0'
0,
Ohm/km
Reactance X0'
0,
Ohm/km

Generally about Loss Calculation Methods – "backbones"

In Power Factory

- State/scenarios
- Load and production profiles
  - Scripting and reading load/production tables



Generally about Loss Calculation Methods “backbones”

- **Network model** (topology, line and transformer parameters)
  – things that don’t change
- **State/estimates/scenarios** (switching status, tap changer position, FACTS-status, load and production situation)
  – a single moment of things that change
- **Load and production profiles over time** (daily, weekly, yearly profiles)

- Which one do you think impact the result the most?
- Which one is the hardest to get right?
- Which one has the highest “success factor” – meaning which one should we work with to get the highest benefit compared to time spent?

Generally about Loss Calculation Methods "backbones"

- **Network model** (topology, line and transformer parameters) – things that don't change

- To have a correct model of the network might sound easy but it is not – it's a challenge to any utility.
  - Some part of the network is old and its documentation might be lacking
  - Merger of different utilities with different documentation of its network assets
  - Voltage level dependent. The amount of network increases, and the quality of documentation decreases, as you move downwards to LV. The complete LV networks are often not documented in any network calculation tool like PF.
  - Some parameters are easier to get hold of than others (topology, line lengths compared to impedances, distribution transformer loss parameters) – is this also your experience?
- However – the **network model** is the base for technical loss calculation (and for much more). It's a quick win to focus on getting the model right for at least HV and MV networks.

Generally about Loss Calculation Methods "backbones"

- **State/estimates/scenarios** (switching status, tap changer position, FACTS-status, load and production situation)
- **Load and production profiles over time** (daily, weekly, yearly profiles)

- The states change all the time. The combinations are almost infinite. You hardly never get back to the exact same state.
  - The trick is to find the characteristic ones. Those that are typical for each network and can represent recurrent situations as base for simple loss calculations.
- Measurement, analogues dependent. Do you have the complete picture to create accurate states – usually not?
- Do you have historical databases where the measurements and analogues are saved with a reasonable frequency? Also saving the switching statuses?
- Again it is voltage level dependent. As you move from HV downwards into MV feeders this data get more scarce.
- You are put to the choice weather to use continuous measurement (some iterative loss calculation method) or satisfy with a few typical states that will give you an adequate average.

Generally about loss calculation methodology

- Generally about Loss Calculation Methods – “backbones”
- Different kinds of Methods
  - Absolute methods
  - Empirical methods
  - Intuitive or hypothesis based methods
- Determining Technical Losses – Discussion

Different kinds of Methods

- A technical loss estimation method includes having an “approach” for each of the backbones.
- Technical loss estimation methods can also be categorized after their “methodical type”

- **Empirical** (based on formulas derived from earlier studies)
- **Intuitive or hypothesis based** (using your engineering thinking and assumptions)
- **Absolute** (exact calculations from theory ($I^2 * R$) as an integral over time – if possible…)

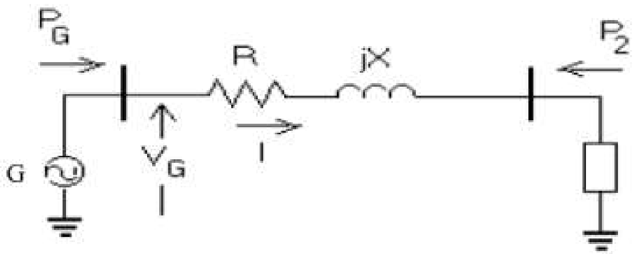
Different kinds of Methods

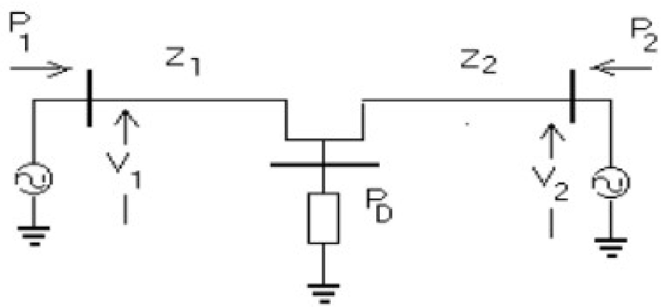
- An Absolute method is of course preferable, but there are many facts that make it hard to use
  - Data quality in network models, Data acquisition of measurements and analogues, State estimations, DVG, SSEG etc.
- For a single completely captured state where you have access to a network model with high data quality an absolute calculations is meaningful to do, but as an approach for the second and third backbone you often have to look into empirical or assumption based methods.
- Different levels of the network might require different methods.
  - For **HV** level you usually have the correct network model and hourly switching states and measurements – almost absolute method with hourly calculations?
  - For **MV** you might have a reasonable network model and measurements per feeder in the substation – empirical formula (load factor – loss factor) or intuitive method with typical states scaled to an average?
  - For **LV** – use your best estimation…

Absolute method

- Go to chapter “Basic theory behind power system losses”
- Integral over time with real energy schedules (continuous load and production data available throughout the system)

$$P_{Loss} = \frac{3 \cdot P^2 \cdot R}{U_{l-l}^{\;2} \cdot \sqrt{3}^2 \cdot \cos^2\varphi} = \boxed{\frac{R}{U_{l-l}^{\;2} \cdot \cos^2\varphi}}\, P^2 = \boxed{B} \cdot P^2 \qquad P_{Loss} = 3 \cdot I^2 \cdot R$$





$$P_L = P_1^2 B_{11} + 2P_1 P_2 B_{12} + P_2^2 B_{22}$$

Empirical method

- The current in the feeder is at the maximum value only at certain times. At all other times the current is less than the maximum current and it is necessary to use a factor to account for this fact.
- Loss factor is defined as,

$$Loss\ factor\ = \frac{Average\ power\ loss}{Power\ loss\ at\ peak\ load}$$

- If the load is constant throughout, the loss factor is one. In actual practice the load varies with time. If the actual load curve is known, the loss factor can be calculated. An approximate value of loss factor can be found from empirical studies.

Empirical method
Load Factor / Loss Factor Relation

- The most popular and widely used method for estimation of energy losses is by the use of an internationally accepted empirical loss formula. The empirical loss formula gives the Equivalent Hours Loss Factor, ELF [1].

The formula is:

- $ELF = (LDF)^2 (1-A) + (LDF)A$

Where,

- ELF = Equivalent hours loss factor
- LDF = Load factor
- A = Constant coefficient,
  - whose value varies between 0.3 to 0.04 for most of the utilities [4]
  - A adopts values between 0.3 and 0.2 for some load cycles [5]

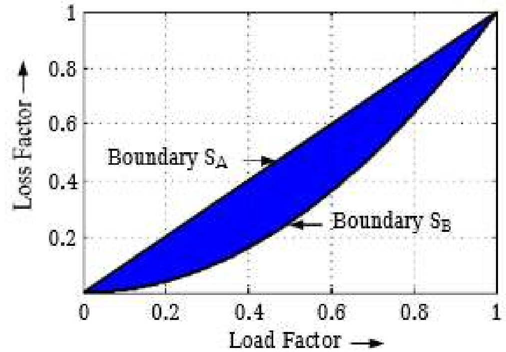
The ELF is multiplied with the peak power losses together with the number of hours per year (8760) and the yearly energy losses are received.

Empirical method
Load Factor / Loss Factor Relation

- A = Constant coefficient, whose value varies between 0.3 to 0.04 for most of the utilities
- A depends on the variety of load curves
- The load factor is usually obtained with energy and demand measurements, whereas to compute the loss factor it is necessary to understand the relation between demand and energy loss, which are not, in general, prone of direct measurements. Therefore, it is needed to determine the relationship between these factors.
- A=0 mean ELF = $(LDF)^2$ gives the lowest losses

Empirical method
Load Factor / Loss Factor Relation

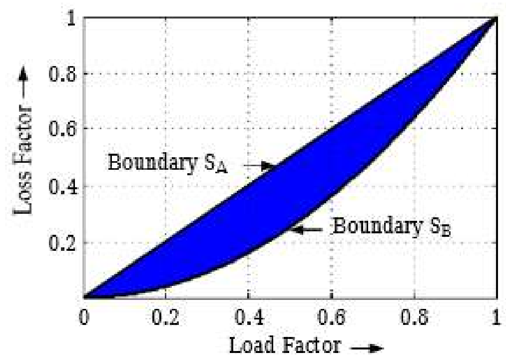
- It can be seen that the loss factor has to lie in the shaded area between the limiting boundaries. Boundary S_A indicates the loss factor when directly proportional to the load factor and boundary S_B the loss factor when proportional to the square of the load factor [6]
  - S_B means A=0
  - S_A means A=1
- As explained later, the loss factor is closer to boundary S_B than to boundary S_A. This is due to the fact that for load curves with distinct base loads the peak loads have relatively low impacts on the losses.
- When Eskom use A=0 (in Excel "Interim Technical Loss calculation method") you assume distinct base load curves. Is this a reasonable assumption?



Empirical method
Load Factor / Loss Factor Relation

How would the DVG impact?

- It can be seen that the loss factor has to lie in the shaded area between the limiting boundaries. Boundary S_A indicates the loss factor when directly proportional to the load factor and boundary S_B the loss factor when proportional to the square of the load factor [6]
  - S_B means A=0
  - S_A means A=1
- As explained later, the loss factor is closer to boundary S_B than to boundary S_A. This is due to the fact that for load curves with distinct base loads the peak loads have relatively low impacts on the losses.
- When Eskom use A=0 (in Excel "Interim Technical Loss calculation method") you assume distinct base load curves. Is this a reasonable assumption?



Intuitive or hypothesis based method
Average Load Profiles

- The empirical formula gives only an approximation. A more correct way is to use load profiles that gives the variation of the load over the day, week and year for different customer types.
- Collect typical load profiles for the studied region. For example hourly reading for a full year from a bulk supply point (transmission/distribution transformer).
- Capture weekly and yearly variations and develop into approximate levelled profiles.
- "The estimate that is usually made by adopting a value for the A constant produces erratic results confirmed in [5], and should be replaced by the estimate of energy of losses based on demand profiles registered for the electric power system".

Average Load Profiles

- Capture weekly and yearly variations and develop into approximate levelled profiles.
- Calculate the technical losses in a load flow tool for the steady state representing each level.

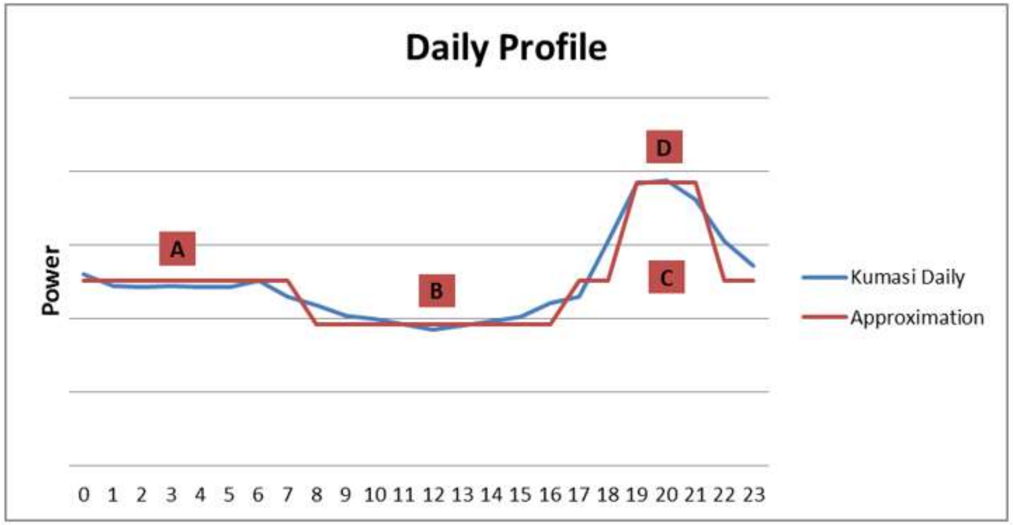


Figure 4 Daily load profile of the Kumasi BSP approximated to four levels

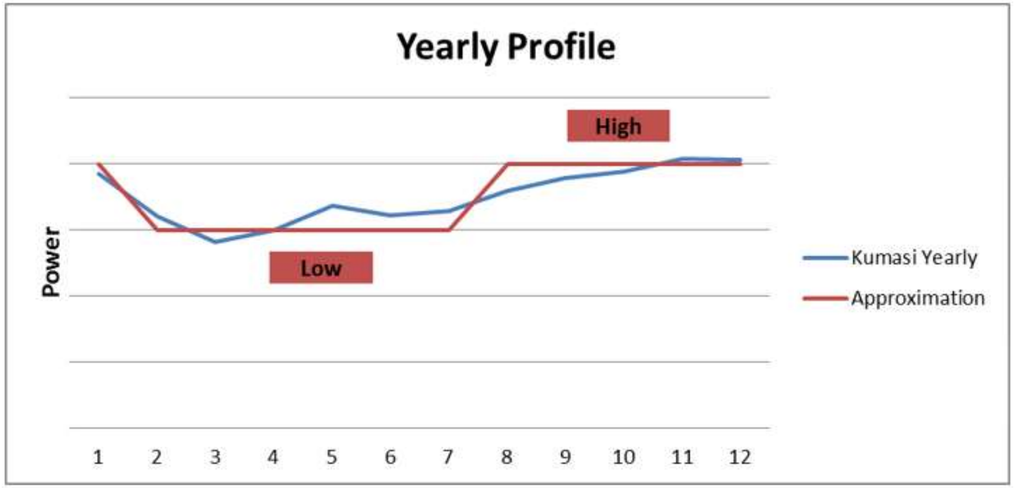


Figure 3 Yearly load profile of the Kumasi BSP approximated to two levels

Average Load Profiles

- Capture weekly and yearly variations and develop into approximate levelled profiles.
- By multiplying the power losses from each load level with the number of hours they last the energy losses over a year are calculated.

Table 5 Approximated load profile levels in relation to peak load

	Daily	A	B	C	D
Yearly	*factor*	0,83	0,75	0,83	1
High	1	0,83	0,75	0,83	1
Low	0,75	0,62	0,56	0,62	0,75

Table 6 Hours per year for each load profile level

	Daily	A	B	C	D
Yearly	*hours*	8	9	2+2	3
High	4380	1460	1642,5	730	547,5
Low	4380	1460	1642,5	730	547,5

Average Load Profiles
Dynamic or Iterative method

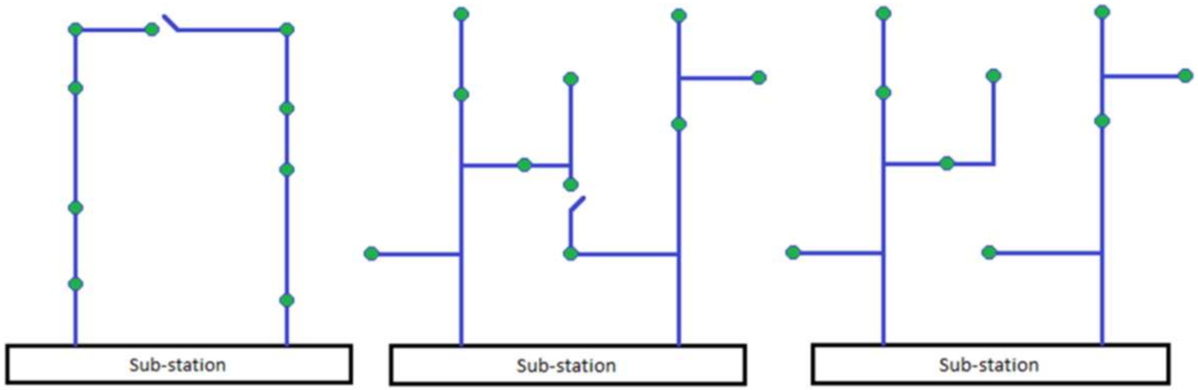
- The described method is a simple way if you want to limit the number of load flow calculations and the dependency on actual load profiles.
- In the furthest extension the number of calculations can represent every hour, half hour or 15 minutes of the studied period. This is usually called “Dynamic” or “Iterative” method. However the calculation might be time and computing capacity consuming.
- This would become close to an Absolute method if real energy schedules (continuous load and production data) are available and usable at enough strategic points in the system.

Average Load Profiles and Scaling

- Another simplification is to model only typical parts of the network and scale this to the whole network you want to study.
- Especially useful for distribution or reticulation feeders.
- While most utilities have their Transmission and Sub-transmission networks modeled in some network calculation tool, not all utilities have their complete distribution/reticulation feeders modeled, and especially not all LV-network modelled to be able to do loss calculations in LV.

Average Load Profiles and Scaling

- Assign each feeder with a network type of urban, peri-urban or rural. Also the topology for each feeder can be used for categorization to e.g. either *looped, meshed tree structure* or *radial tree structure*.
- Model and calculate losses only for selected feeders in each network type.



Average Load Profiles and Scaling

- Technical losses are directly proportional to the impedance and to the square of the power.
- The impedance depends on the conductor type and cross-section as well as the length. The conductor type and cross-section can be assumed the same between the feeders of the same type (urban, peri-urban and rural).
- To allow different feeders, with different lengths, within the same type to be scaled to each other the length of the feeders is used as one scaling parameter.

Average Load Profiles and Scaling

- Technical losses are proportional to the square of the power. The power (same as the load) is used as a second scaling parameter but with the difference that the **square** of the power difference to the typical feeder is used.
- If the length of a feeder is 1,2 times (20 %) longer and the load is 1,2 times higher than the calculated typical feeder of the same type the resulting technical power losses will be $1{,}2 \times 1{,}2^2 = 1{,}2 \times 1{,}44 = 1{,}73$ times higher.
- The summarized total length of a feeder is not always fair to use for scaling as the length of the backbone is more important than branches. In other words, where the main part of the load passes through, that’s also where you have the greatest losses. An *effective length* has been calculated for each feeder. The effective length is calculated from a formula where the share of the total load in a specific segment is used. The effective length is always shorter than the real length since the lengths of segments far out on the feeder give a considerably smaller impact.

Average Load Profiles and Scaling

- The described method of sampling and scaling of losses is usually a reasonable and straight forward method for MV-feeders in relation to the data available for most utilities.
- For LV-feeders it might be more troublesome since modeled network and measurements are more scarce. However the same approach can be applied but the sampling and scaling simplified.
    - Scaling only from the installed DT (Distribution Transformers) sizes?
    - Manuel collection of representable peak readings from selected distribution transformers?

Average Load Profiles and Scaling

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  - Scaling only from the installed DT (Distribution Transformers) sizes?
  - Manuel collection of representable peak readings from selected distribution transformers?

How would the SSEG impact?

Generally about loss calculation methodology

- Generally about Loss Calculation Methods – “backbones”
- Different kinds of Methods
  - Absolute methods
  - Empirical methods
  - Intuitive or hypothesis based methods
- Determining Technical Losses – Discussion

Determining Technical Losses - Discussion

- How does the intermittent RE (DVG and SSEG) impact this described methodology for technical loss calculation?
- As we said before, network calculation tools calculate the technical losses at a certain load. Usually the peak load. However the peak load only lasts for short moments. The rest of the day and year the load is much lower.
- The RE makes the approach with load profiles much more complex as the RE appears intermittently.

References

[1] National Technical and Commercial Loss Study ECG, Ghana, Global Energy Consulting Engineers India (GECE), 2012

[2] Planning Target Report, Sweco International, 2013

[3] Rural Electrification in Urambo and Serengeti, Training Report Loss Reduction Basic Electric Safety And Distribution Standards, Sweco International, 2003

[4]https://www.researchgate.net/publication/304623559_A_STATISTICAL_ANALYSIS_OF_LOSS_FACTOR_A_CASE_STUDY_IN_APEPDCL-KAKINADA

[5]https://www.researchgate.net/publication/3792738_New_method_to_calculate_power_distribution_losses_in_an_environment_of_high_unregistered_loads

[6]https://www.researchgate.net/publication/224601813_Energy_loss_estimation_in_distribution_networks_for_planning_purposes

Basic theory behind power system losses

Eskom Danish Energy Agency COWI

Basic theory behind power system losses

- Basic theory behind power system losses
  - Equations – simple single line DC case
  - Equations – simple single line AC case
  - Equations – 3 phase AC systems
- Power losses and voltage drop
- Exercise – simple case for hand calculation
- Exercise – simple case using Power Factory

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Basic theory behind power losses

- Ohm's law (direct current, DC) $U = R \cdot I$
- Power law $P = U \cdot I, \quad P = R \cdot I^2$

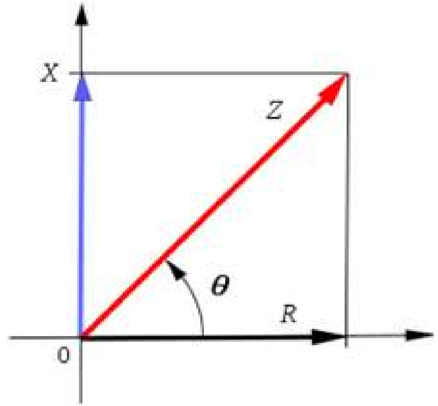
Basic theory behind power losses

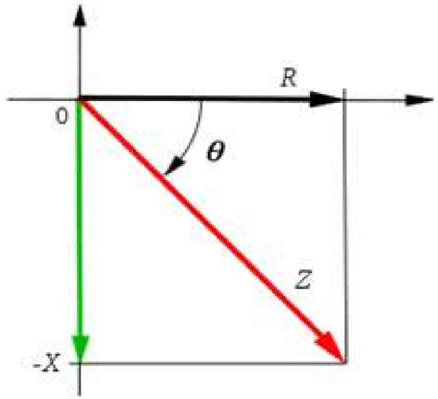
- Ohm's law (direct current, DC) $U = R \cdot I$
- Power law $P = U \cdot I, \quad P = R \cdot I^2$

- For alternating current (AC) the resistance part (R) will have to be modified due to the alternating magnetic field

Basic theory behind power losses

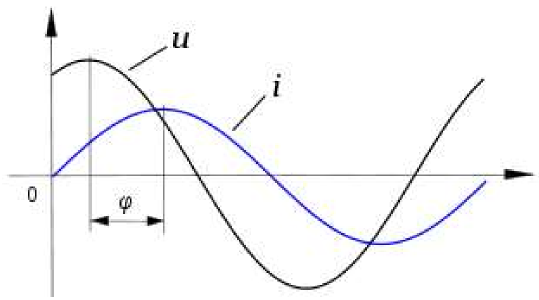
- Impedance (Z) is the electrical opposition for alternating current.
- Impedance consists of resistance (R) and reactance (X).
- Ohm's law (alternating current, AC)
- U = Z * I
- where Z = R + jX (complex)
- The Reactance is either of inductive or capacitive nature.
- The Reactance creates a phase shift between voltage and current.





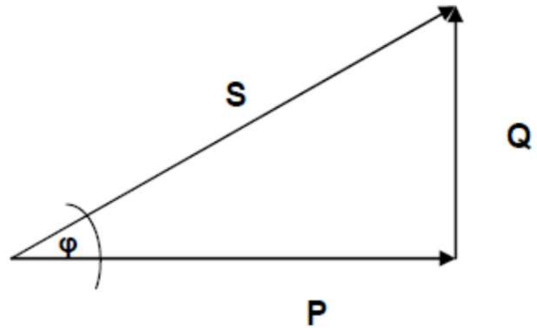
Basic theory behind power losses

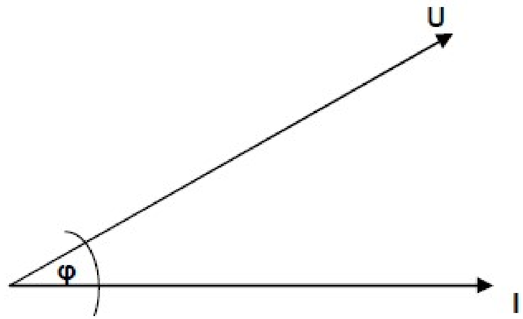
- Current and voltage gives a transfer of Power
- For DC it is very simple:
- P = U · I
- For AC the total power can be divided into two parts, active power (P) and reactive power (Q).
- P = U · I · cos ϕ
- Q = U · I · sin ϕ
- If voltage and current are in-phase (no phase difference) there will only be active power.
- If voltage and current are out-of-phase there will also be reactive power



Basic theory behind power losses

- P = active power [W]
- Q = reactive power [Var]
- S = apparent power [VA]
- U = voltage
- I = current
- ϕ = phase difference between voltage and current

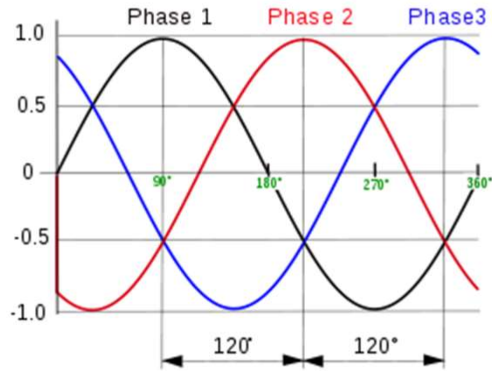


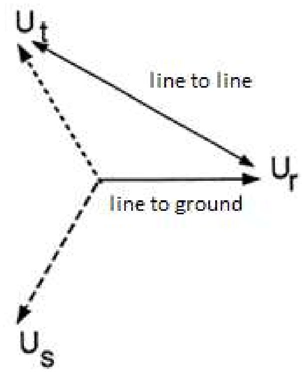


$$P = U \cdot I \cdot \cos(\varphi) \qquad [W]$$
$$Q = U \cdot I \cdot \sin(\varphi) \qquad [VAr]$$
$$S = U \cdot I = \sqrt{Q^2 + P^2} \qquad [VA]$$

Basic theory behind power losses

- Three symmetrical phases with a phase difference of 120º. The sum of the phases is zero in any point of time
- The voltage between two phases is called line-to-line voltage, U_{l-l}
- The voltage between a phase and neutral is called line-to-ground voltage, U_{l-g}





$$U_{l-g} \cdot \sqrt{3} = U_{l-l}$$

Basic theory behind power losses

- Ohm's law as it looks for standard AC circuits

$$U = Z \cdot I$$

- It is the line to ground voltage that is aimed

$$U_{l-g} = Z \cdot I$$

- For 3 phase systems often the line to line voltage is used. This was the relation between the two

$$U_{l-g} \cdot \sqrt{3} = U_{l-l}$$

- Ohm's law for 3 phase system

$$U_{l-l} = Z \cdot I \cdot \sqrt{3}$$

Basic theory behind power losses

- Power equation as it looks for standard AC circuits

$$P = U \cdot I \cdot \cos\varphi$$

- It is the line to ground voltage that is aimed

$$P = U_{l-g} \cdot I \cdot \cos\varphi$$

- For 3 phase systems often the line to line voltage is used. This was the relation between the two

$$U_{l-g} \cdot \sqrt{3} = U_{l-l}$$

- Power equation with line to line voltage

$$P = \frac{U_{l-l} \cdot I \cdot \cos\varphi}{\sqrt{3}}$$

Basic theory behind power losses

- Power equations for 3 phase system – multiply by 3

$$P_{3\,phase} = 3 \cdot \frac{U_{l-l} \cdot I \cdot \cos\varphi}{\sqrt{3}} = U_{l-l} \cdot I \cdot \sqrt{3} \cdot \cos\varphi$$

- For Q and S the same relations can be drawn

$$P_{3\,phase} = U_{l-l} \cdot I \cdot \sqrt{3} \cdot \cos\varphi$$

$$Q_{3\,phase} = U_{l-l} \cdot I \cdot \sqrt{3} \cdot \sin\varphi$$

$$S_{3\,phase} = U_{l-l} \cdot I \cdot \sqrt{3} \qquad S_{3\,phase} = \sqrt{P^2 + Q^2}$$

Basic theory behind power losses

- Power loss equation

$$P_{Loss} = I^2 \cdot R$$

- Power loss equation for 3 phase systems

$$P_{Loss} = 3 \cdot \; I^2 \cdot R$$

- Power equations for 3 phase system

$$P_{3\,phase} = 3 \cdot \frac{U_{l-l} \cdot I \cdot \cos\varphi}{\sqrt{3}} = U_{l-l} \cdot I \cdot \sqrt{3} \cdot \cos\varphi$$

$$I = \frac{P}{U_{l-l} \cdot \sqrt{3} \cdot \cos\varphi}$$

Basic theory behind power losses

$$P_{Loss} = 3 \cdot I^2 \cdot R$$

$$I = \frac{P}{U_{l-l} \cdot \sqrt{3} \cdot \cos\varphi}$$

- Combining power loss equation and power equation gives

$$P_{Loss} = \frac{3 \cdot P^2 \cdot R}{U_{l-l}{}^2 \cdot \sqrt{3}^2 \cdot \cos^2\varphi} = \frac{R}{U_{l-l}{}^2 \cdot \cos^2\varphi} P^2 = B \cdot P^2$$

- Using B, loss coefficient

Basic theory behind power losses

$$P_{Loss} = 3 \cdot I^2 \cdot R$$

$$I = \frac{P}{U_{l-l} \cdot \sqrt{3} \cdot \cos\varphi}$$

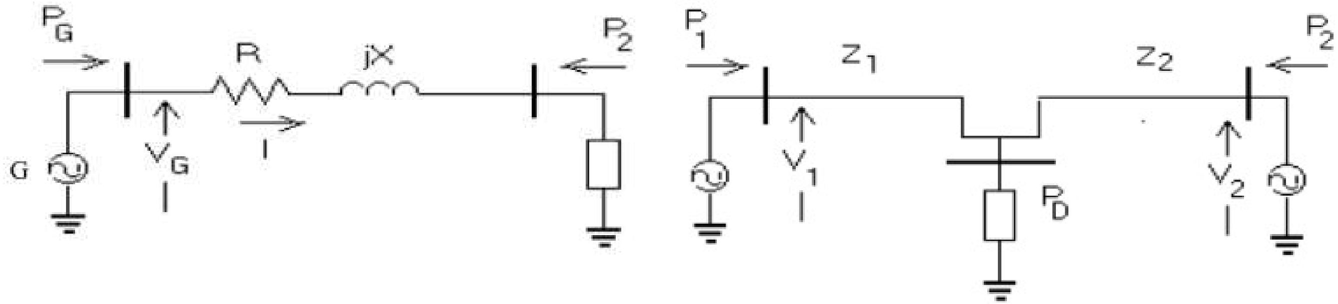
- Combining power loss equation and power equation gives

$$P_{Loss} = \frac{3 \cdot P^2 \cdot R}{U_{l-l}{}^2 \cdot \sqrt{3}^2 \cdot \cos^2\varphi} = \boxed{\frac{R}{U_{l-l}{}^2 \cdot \cos^2\varphi}}\, P^2 = \boxed{B} \cdot P^2$$

- Using B, loss coefficient

Basic theory behind power losses

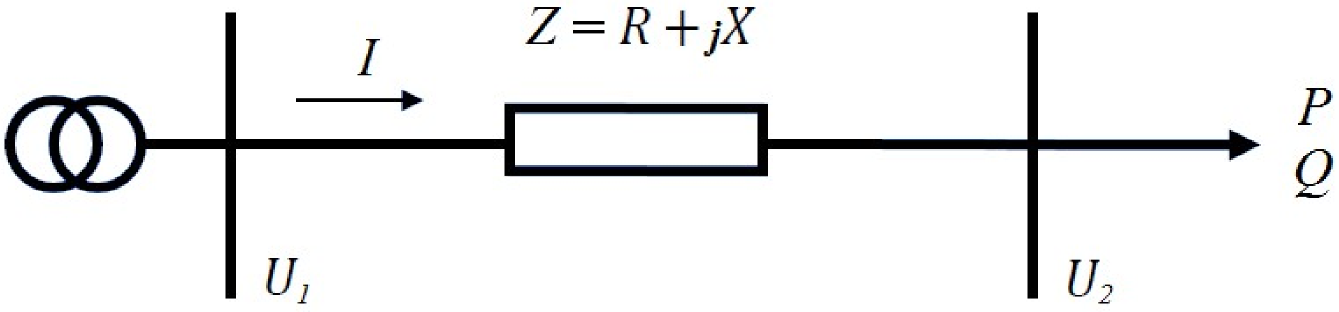
- Using B, loss coefficient simplifies equations. Especially when studying theoretical single line diagrams
- It simplifies when adding generators into the study



$$P_L = P_1^2 B_{11} + 2P_1 P_2 B_{12} + P_2^2 B_{22}$$

Basic theory behind power losses

- Expressing the power formula as $P = I^2 \cdot R$ indicates that the power is highly dependent on the current value.
- Given a power line, i.e. a fixed R value, it is possible to reduce the power loss in the line by reducing the current flow.



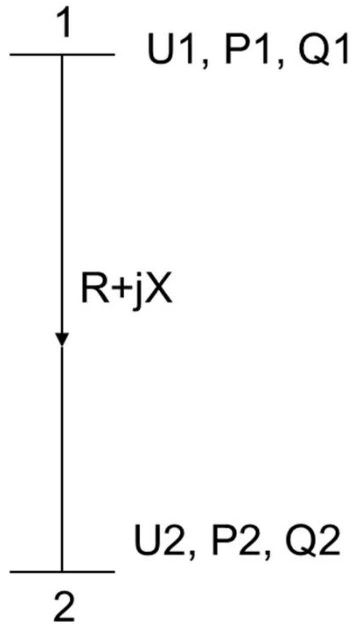
$$\Delta U = I \cdot (R + jX)$$

$$Losses = I^2 \cdot R$$

Basic theory behind power losses

- Voltage Drop, dU
- dU = U1-U2
- dU = R * P2/U2 + jX * Q2/U2

- Active Power losses, P_{Loss}
- P_{Loss} = P1-P2
- $P_{Loss} = R*(P2/U2)^2 + R*(Q2/U2)^2$



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Exercise

- Example: 10 MW is to be transmitted over a 200 km, 100 mm^2 line. The resistance for a 1 mm^2 aluminum conductor is 28 Ω/km, i.e. in this example $28 \cdot 200/100 = 56\ \Omega$.
- Calculate the losses with two different line voltages, 380 kV and 70 kV.
  - Start by doing the calculation “by hand” based on the equations presented for a theoretic single line.
  - Then model this simple network as common three phase system in PF and calculate the losses.
- As an option you can use the Eskom voltage levels of 275kV and 132kV (or 132kV and 88kV).

Workshop 1 – Part 1
Monday 07.09.2020 – Friday 11.09.2020

- Session 1
  - Generally about power system losses
  - Generally about loss calculation methodology
  - Basic theory behind power system losses
    - Simple exercise in Power Factory
- Session 2
  - Background – networks with high level of renewables – benchmarking
  - Distributed generation and its impact on power system losses
    - Exercise/discussion on challenges and solutions
- Session 3
  - 11 kV Power Factory study case – how the loss pattern changes with increased SSEG

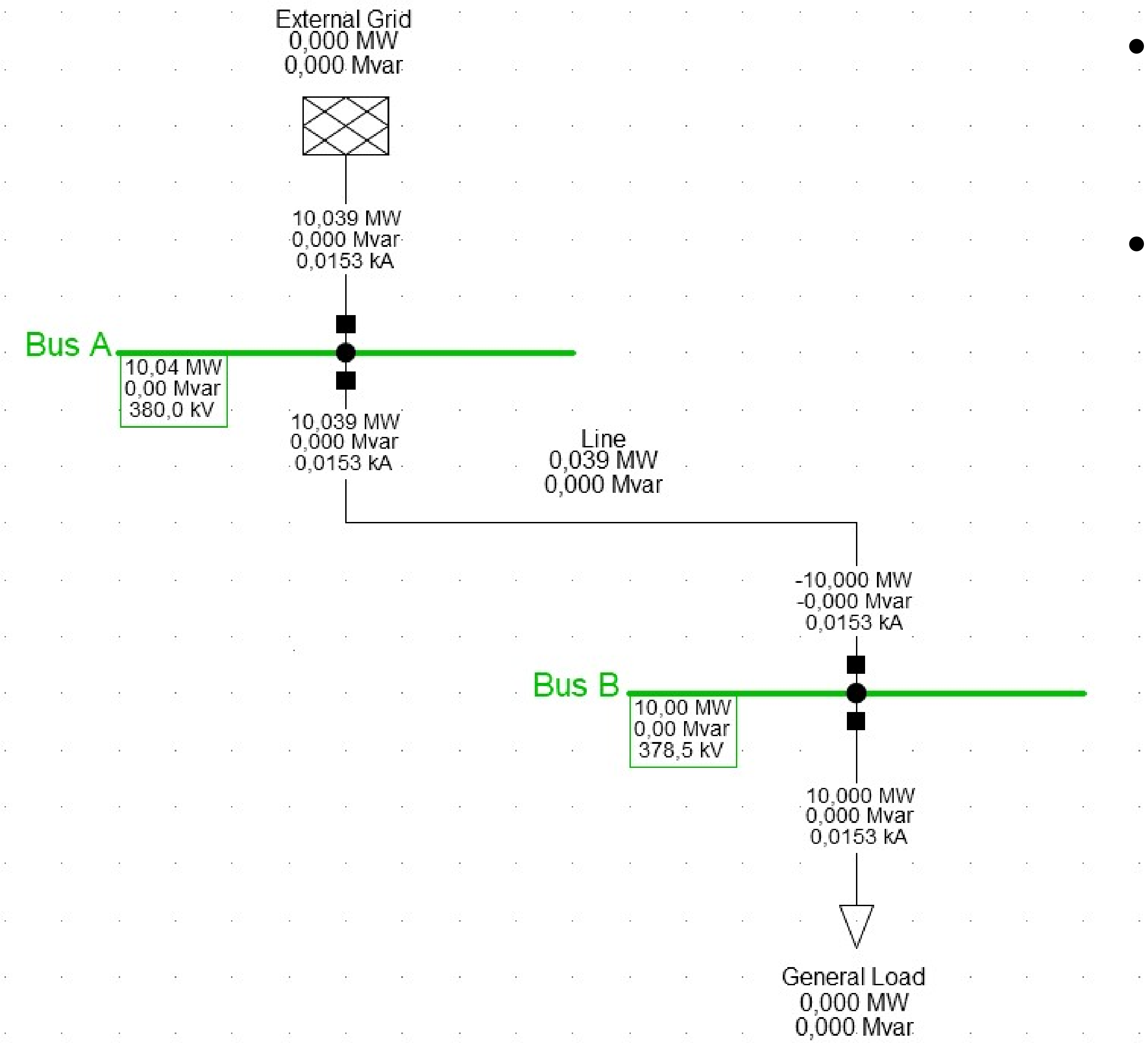
Pre-recorded sessions released on Monday 07.09.2020

QA session: Monday 14.09.2020

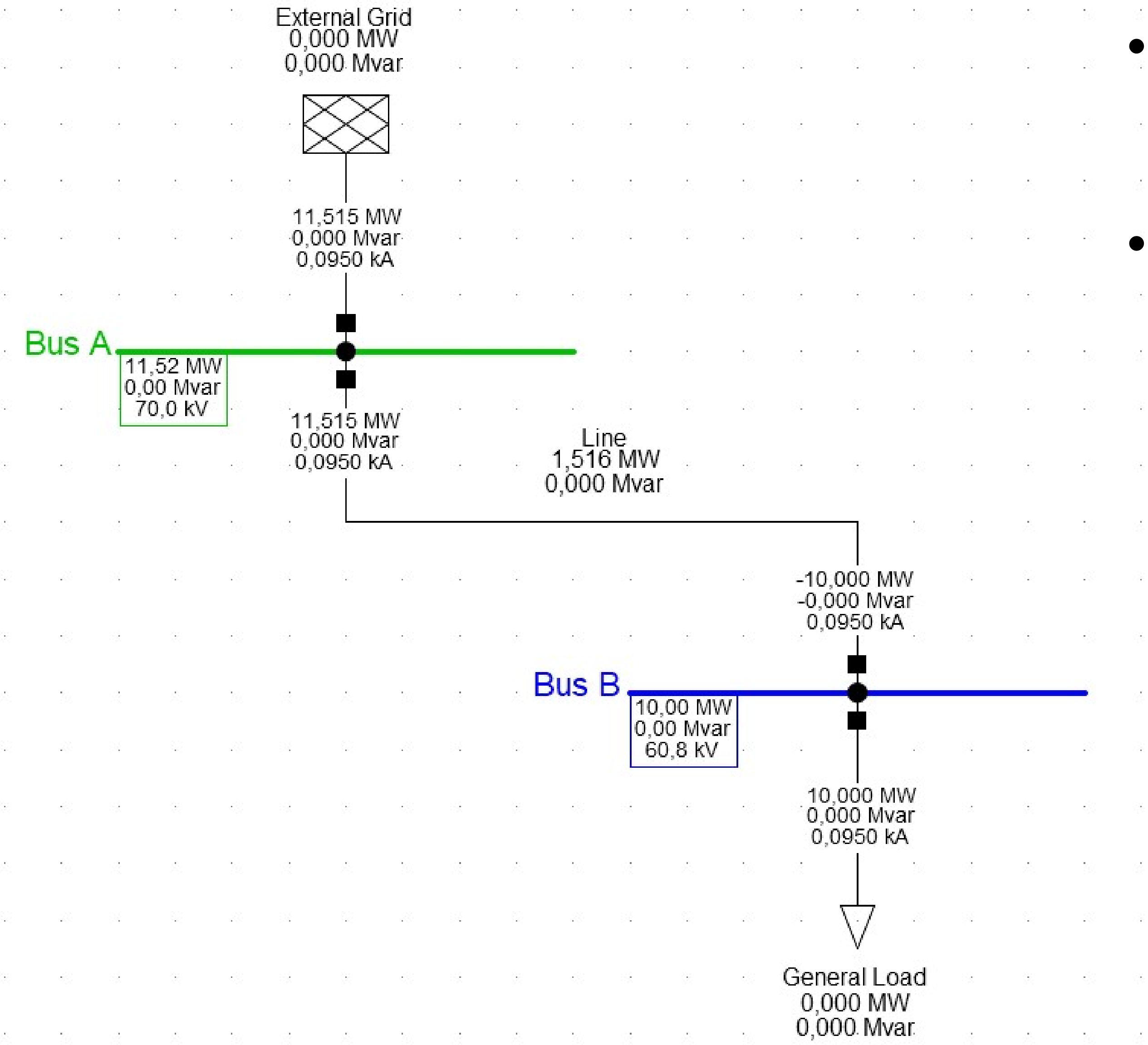
Exercise

- Example: 10 MW is to be transmitted over a 200 km, 100 mm^2 line. The resistance for a 1 mm^2 aluminum conductor is 28 Ω/km, i.e. in this example 28 · 200/100 = 56 Ω.
- In the table below the losses are compared for two line voltages by hand calculation.

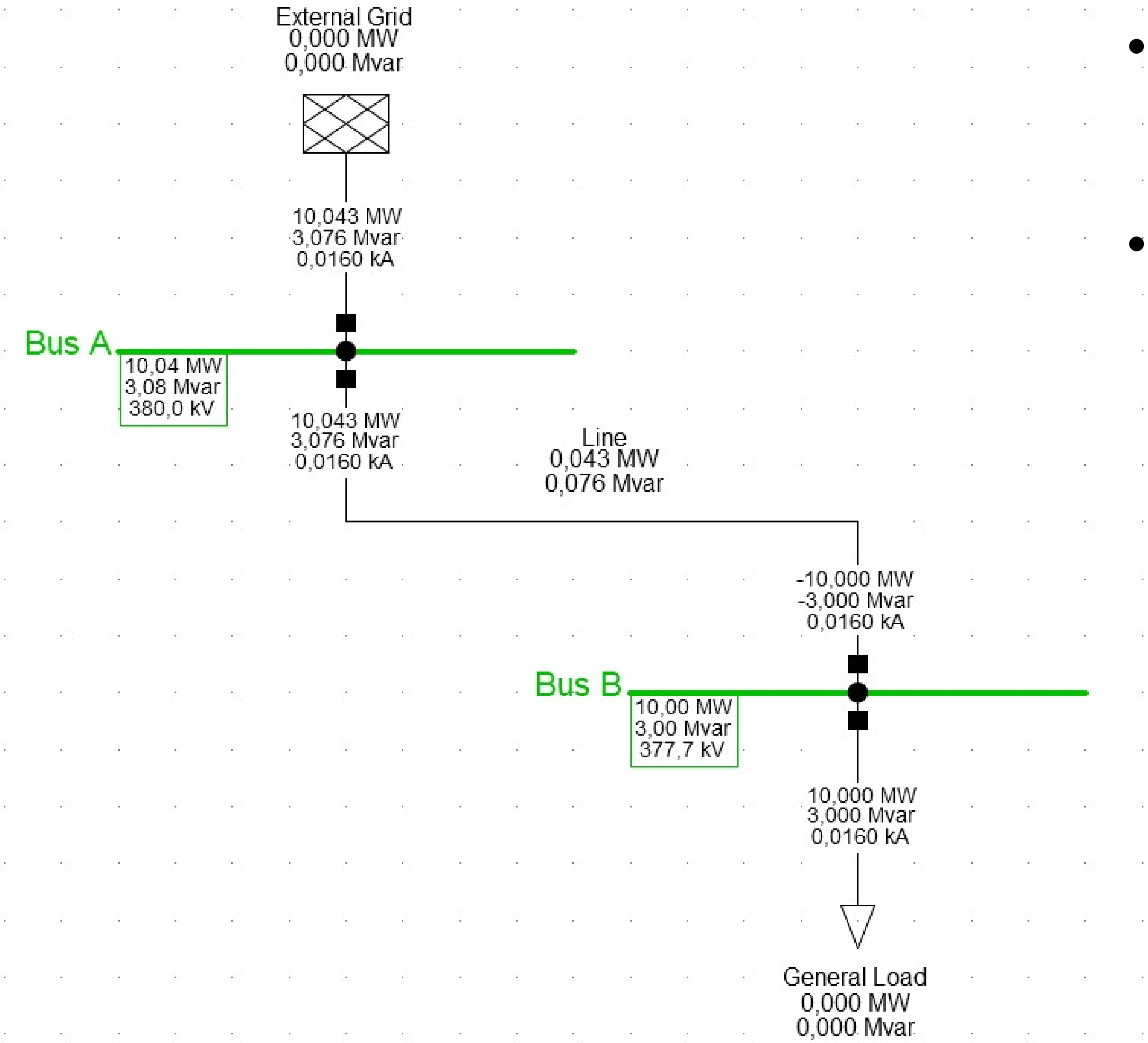
	380 kV	70 kV
Current	$I = \frac{10 \cdot 10^6}{380 \cdot 10^3 \cdot \sqrt{3}} = 15A$	$\frac{10 \cdot 10^6}{70 \cdot 10^3 \cdot \sqrt{3}} = 82A$
Power loss in line	$P = 15^2 \cdot 56 = 13\ kW$	$82^2 \cdot 56 = 377\ kW$
Loss as % of transmitted power	$\frac{13 \cdot 10^3}{10 \cdot 10^6} \cdot 100 = 0.13\%$	$\frac{377 \cdot 10^3}{10 \cdot 10^6} \cdot 100 = 3.8\%$



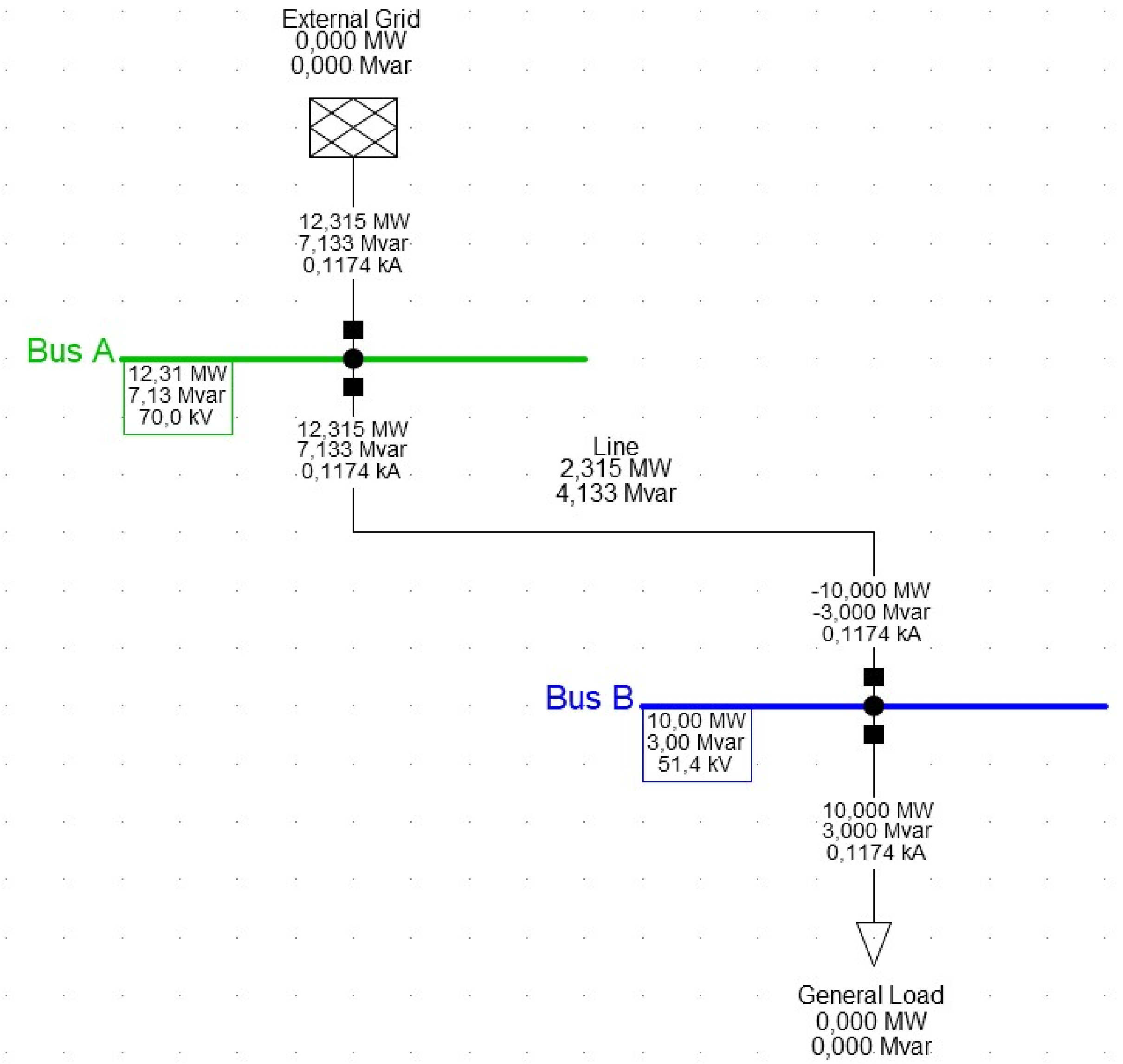
- 380 kV line
  - Only resistive, R
  - No X
- Load 10 MW
  - Only active power
  - No MVAr



- 70 kV line
  - Only resistive, R
  - No X
- Load 10 MW
  - Only active power
  - No MVAr



- 380 kV line
  - Resistance, R
  - And reactance, X
- Load 10 MW
  - Active power
  - And reactive power 3 MVAr



- 70 kV line
  - Resistance, R
  - And reactance, X
- Load 10 MW
  - Active power
  - And reactive power 3 MVAr

```
-----------------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                                              Grid Summary |
-----------------------------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence                  |    Automatic Model Adaptation for Convergence           No          |
|    Automatic tap adjustment of transformers          No       |    Max. Acceptable Load Flow Error for                              |
|    Consider reactive power limits                    No       |       Nodes                                             1,00 kVA    |
|                                                               |       Model Equations                                   0,10 %      |
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                 System Stage: Grid             | Study Case: Study Case                 | Annex:                / 1  |
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                 Summary                                                                                                |
|                                                                                                                                   |
| No. of Substations     0          No. of Busbars        2          No. of Terminals      0          No. of Lines          1       |
| No. of 2-w Trfs.       0          No. of 3-w Trfs.      0          No. of syn. Machines  0          No. of asyn.Machines  0       |
| No. of Loads           1          No. of Shunts/Filters 1          No. of SVS            0                                        |
|                                                                                                                                   |
| Generation            =      0,00  MW            0,00   Mvar        0,00  MVA                                                    |
| External Infeed       =     12,31  MW            7,13   Mvar       14,23  MVA                                                    |
| Inter Grid Flow       =      0,00  MW            0,00   Mvar                                                                     |
| Load P(U)             =     10,00  MW            3,00   Mvar       10,44  MVA                                                    |
| Load P(Un)            =     10,00  MW            3,00   Mvar       10,44  MVA                                                    |
| Load P(Un-U)          =      0,00  MW            0,00   Mvar                                                                     |
| Motor Load            =      0,00  MW            0,00   Mvar        0,00  MVA                                                    |
| Grid Losses           =      2,31  MW            4,13   Mvar                                                                     |
| Line Charging         =                          0,00   Mvar                                                                     |
| Compensation ind.     =                          0,00   Mvar                                                                     |
| Compensation cap.     =                          0,00   Mvar                                                                     |
|                                                                                                                                   |
| Installed Capacity    =      0,00  MW                                                                                             |
| Spinning Reserve      =      0,00  MW                                                                                             |
|                                                                                                                                   |
| Total Power Factor:                                                                                                               |
|   Generation          =        0,00  [-]                                                                                          |
|   Load/Motor          = 0,96 / 0,00  [-]                                                                                          |
|----------------------------------------------------------------------------------------------------------------------------------|
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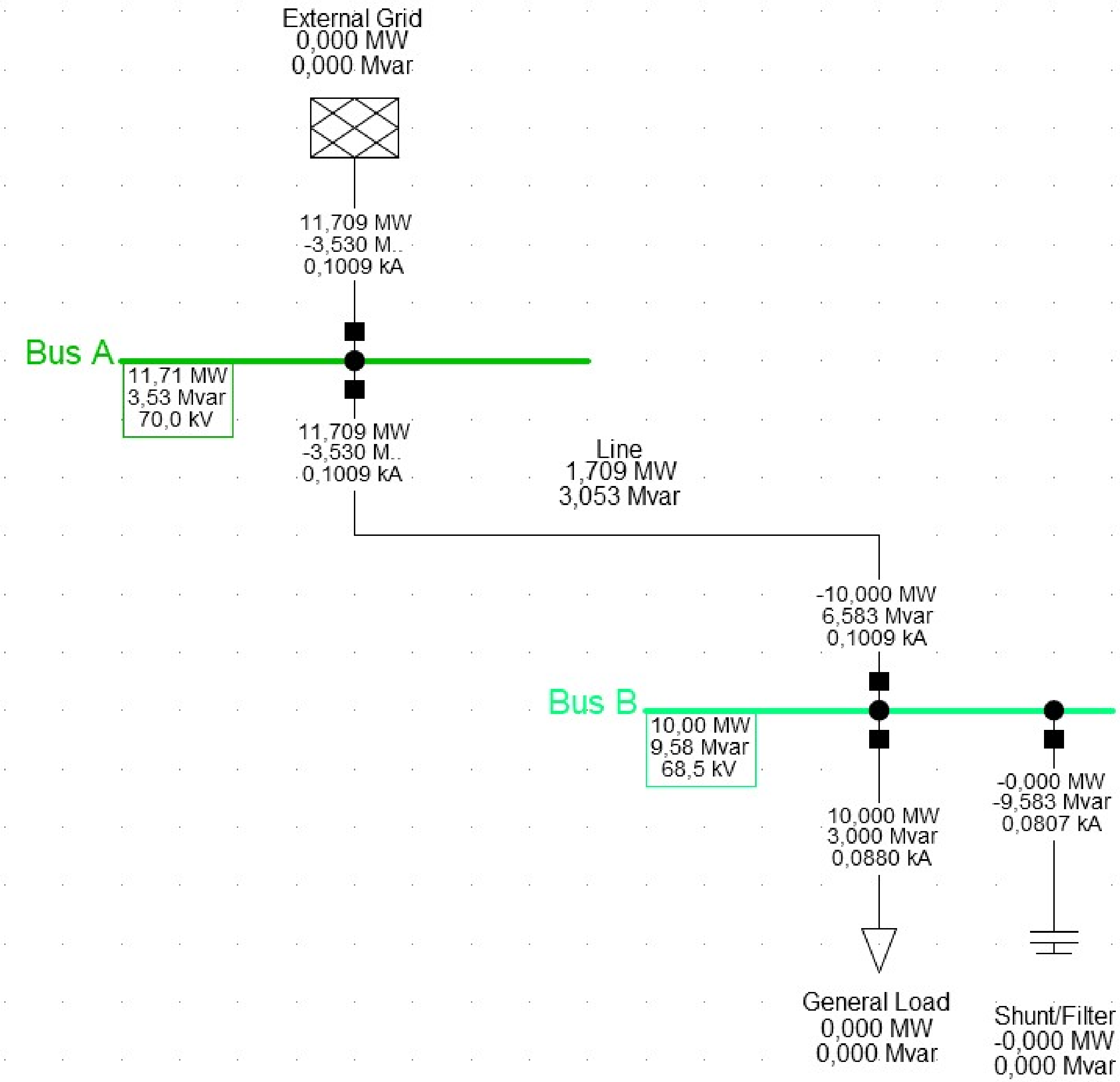

- 70 kV line
  - Resistance, R
  - And reactance, X
- Load 10 MW
  - Active power
  - And reactive power 3 MVAr
- Capacitor bank
  - 10 MVAr

```
-------------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                                           Grid Summary |
-------------------------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence            |    Automatic Model Adaptation for Convergence         No         |
|    Automatic tap adjustment of transformers      No     |    Max. Acceptable Load Flow Error for                           |
|    Consider reactive power limits                No     |       Nodes                                            1,00 kVA  |
|                                                         |       Model Equations                                  0,10 %    |
-------------------------------------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                System Stage: Grid          | Study Case: Study Case                | Annex:                 / 1  |
-------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                Summary                                                                                          |
|                                                                                                                            |
| No. of Substations     0         No. of Busbars       2         No. of Terminals      0         No. of Lines          1     |
| No. of 2-w Trfs.       0         No. of 3-w Trfs.     0         No. of syn. Machines  0         No. of asyn.Machines  0     |
| No. of Loads           1         No. of Shunts/Filters 1        No. of SVS            0                                     |
|                                                                                                                            |
| Generation            =       0,00  MW            0,00   Mvar        0,00  MVA                                            |
| External Infeed       =      11,71  MW           -3,53   Mvar       12,23  MVA                                            |
| Inter Grid Flow       =       0,00  MW            0,00   Mvar                                                             |
| Load P(U)             =      10,00  MW            3,00   Mvar       10,44  MVA                                            |
| Load P(Un)            =      10,00  MW            3,00   Mvar       10,44  MVA                                            |
| Load P(Un-U)          =       0,00  MW            0,00   Mvar                                                             |
| Motor Load            =       0,00  MW            0,00   Mvar        0,00  MVA                                            |
| Grid Losses           =       1,71  MW            3,05   Mvar                                                             |
| Line Charging         =                           0,00   Mvar                                                             |
| Compensation ind.     =                           0,00   Mvar                                                             |
| Compensation cap.     =                          -9,58   Mvar                                                             |
|                                                                                                                            |
| Installed Capacity    =       0,00  MW                                                                                     |
| Spinning Reserve      =       0,00  MW                                                                                     |
|                                                                                                                            |
| Total Power Factor:                                                                                                        |
|   Generation          =         0,00  [-]                                                                                  |
|   Load/Motor          =  0,96 / 0,00  [-]                                                                                  |
|-----------------------------------------------------------------------------------------------------------------------------|
```

Exercise

- Why is the PF calculation different to the hand calculation?
  - Three phase system – the hand task was based on a theoretic single line
  - The presented solution for the hand task does not include the voltage drop