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ENM125 Sustainable Electric Power Systems (SEPS, 7.5 credits)

- summary of lectures 2012

"The overall aim of this course is to provide an understanding of the fundamentals of the electric power system as a component of a sustainable energy system."

Lina Bertling Tjernberg
Division of Electric Power Engineering
Department of Energy and environment
Chalmers University of Technology

Acknowledgement

Welcome to this second edition of the course on Sustainable Electric Power Systems (SEPS)!

The SEPS has been developed for the Master´s Programme in Sustainable Energy Systems (MPSES) at Chalmers University of Technology during. The course has been developed at the Division of Electric Power Engineering at the Department of Energy.

The course is divided into two parts one conceptual part and one numerical part. The numerical part is trained by tutorials. The tutorial material is not included in this report. The main course book is Electric Power Systems – A conceptual introduction (2006), by Alexandra von Meier published by John Wiley & Sons. One computer lab and one experimental lab have been developed for the course, which are both based on long term experience of teaching at the Division within the Master´s Programme in Electric Power Engineering (which is recommended or further reading). The course book together with lectures and tutorials shall provide the needed theory and exercises to complete assignments in the course. The course also includes a technical study visit to show examples from practice.

This report summarizes the lecture notes and course material prepared prior to the course st(art excluding the tutorials).

Enjoy and welcome to give feed-back!

Lina Bertling Tjernberg, Professor
Course responsible and examiner
Gothenburg, January 18, 2013

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I Course program and reading instructions

Course description for

ENM125 Sustainable Electric Power Systems (SEPS, 7.5 credits)

The overall aim of this course is to provide a conceptual understanding of the fundamentals of the electric power system as a component of a sustainable energy system.

Summary introduction

The electric power system is a complex technical system with main function to deliver electricity between generation, consumption and storage. A sustainable energy system involves key components of; increasing use of renewable energy resources, increased energy efficiency and use of electricity in the transportation sector. As an effect of this some key questions for the electric power system are; integration of intermittent electricity generation e.g. from wind power, and connections of electrical vehicles to the electrical distribution system and different solutions for energy storage.

The course will give a conceptual introduction to the electric power system as a main part of the energy system. The course will start from fundamental basic concepts of the physics of electricity, basic circuit analysis. It will go through fundamental modeling of the AC system and the power flow and show on models for power system operation and planning including aspects of reliability and market. For an understanding of the dynamic behavior of the electric power system the simulator tools will be used. The course includes two laboratory exercises; one experimental in the laboratories of the Electric Power Engineering and one computer lab.

Objectives

After the course the student will be able to:

- Conceptually describe the technical fundamental characteristics and performance of the electric power system with main function to deliver electricity between generation, consumption and storage.
- Carry out basic electric circuit modeling and analysis.
- Understand the basics of synchronous generators.
- Understand the basics of the three phase transmission system.
- Perform per-unit calculations.
- Understand basic impact of different loads on the electric power system
- Formulate and solve a power flow analysis problem
- Understand the fundamental behavior of the Electric power system based on simulator tools.

- Understand the main function of the power system market
- Understand and follow safety instructions in the electric power engineering lab in the course.

Contents

The course is divided into four parts as follows:

I. Introduction with course information and presentation of the electric power system as part of a sustainable energy system.

II. Fundamental modeling and analysis of the electric power systems: from physics of electricity, basic circuit analysis to the modeling of AC system to power flow assessment.

III. Power system performance studies including aspect of; new developments with e.g. integration if renewables, operation and stability and market.

IV. Closure with course summary.

There are one experimental lab and one computer lab in the course:
1. The experimental lab gives an introduction to the electrical circuits.
2. The computer lab deals with simulation of the electric power system and the handling of stability. The simulator tool PowerWorld will be used.

Before performing the experimental lab the safety instructions must be read and understood. For each lab a laboratory report shall be submitted and approved.

Personnel

The personnel involved in the course are listed below with name and responsibility in the course.

- Examiner and course responsible: Lina Bertling Tjernberg (lina.bertling@chalmers.se)
- Lectures: Lina Bertling Tjernberg (LB), Tuan Le (market), external guest lectures
- Exercises: Pramod Bangalore (PB), Pavan Balram (PB2) (market)
- Experimental lab: Robert Karlsson (RK), Yasir Arafat (YA), Kalid Yunus (KY), Chris Saunders (CS)
- Computer lab: Kalid Yunus (KY) and Yasir Arafat (YA)

The course home page will be the primary media for communication during the course outside classes, and it also provides contact information for the involved personnel. The personnel have offices with the Electric Power Engineering Division and Hörsalsvägen 11, and e-mail addresses are given by firstname.lastname@chalmers.se.

Language

The course is given in English and all course material including the examination is in English.

Evaluation and assignments

The methods used to evaluate the work in this course are:

1. Written final examination.

2. Approved two laboratory exercises including a laboratory report for the computer lab.

Written final exam gives in total 75% of course credits, practical lab. 5 % and computer lab. 20%. Total with grades 5,4,3 or fail.

Homework tasks are provided related to the Exercises.

Literature

Main course book:

Electric Power Systems – A conceptual introduction (2006), by Alexandra von Meier published by John Wiley & Sons, ISBN-13:987-0-471-175859-0.

Additional book for further readings:

Power System Analysis Third Edition, (2010), by Hadi Saadat published by PSA Publishing, ISBN 978-0-9845438-0-9.

Complementary lecture material, exercises and laboratory preparation material will be handed out and posted on the course home page.

Schedules and organization

The course comprises of: 20 lectures, 20 exercises, one experimental laboratory exercise (4 h) and one computer lab (involving with six computer exercises) and a technical study visit (4 h). The sessions (lectures/exercises) are 45 minutes long starting 8.00 or 10.00, before noon and 13.15 and 15.15 in the afternoon.

Detailed Course Program

No	*Day*	*Date*	*Time*	*Room*	*Type and title*	*Lecturer*
1.	Tue.	30/10	13-15	ED	L1: Introduction to the course and to Electric Power Systems L2: Fundamentals of electricity	LB
2.	Tue.	30/10	15-17	ED	E1-E2: Basic circuit analysis for electrical systems	PB
3.	Thu.	1/11	13-15	ED	L3-L4: AC power	LB
4.	Thu	1/11	15-17	ED	E3-E4: AC power	PB

5.	Tue.	6/11	13-15	ED	L5-L6: Modelling of generators and loads for power system studies	LB Guest lecturer
6.	Tue.	6/11	15-17	ED	E5-E6: Generators and loads	PB
7.	Thu.	8/11	13-15	ED	L7-L8: Three Phase Transmission	LB
8.	Thu.	8/11	15-17	ED	E7-E8: Three Phase Transmission Introduction to P1 Computer Lab	PB KY/YA
9.	Fri.	9/11	13-15	MT0, MT9	P1a: Computer lab.	KY/YA
10.	Tue.	13/11	13-17	ED	L9-L12: Power Flow Analysis	LB
11.	Thu.	15/11	13-17	ED	E9-E12: Power Flow Analysis	PB
12.	Fri.	16/11	13-15	MT0, MT9	P1b: Computer lab.	KY/YA
13.	Tue.	20/11	13-17	E-Lab	P2: Experimental lab. Group 1	RK/CS/YA/KY
14.	Thu.	22/11	13-17	E-Lab	P2: Experimental lab. Group 2	RK/CS/YA/KY
15.	Fri.	23/11	13-15	MT0, MT9	P1c: Computer lab.	KY/YA
16.	Tue.	27/11	13-15	ED	L13: Power System Operation L14: Example from Svenska Kraftnät	LB Sabina Stenberg Svenska Kraftnät
17.	Tue.	27/11	15-17	ED	E13-E14: Power System Operation	PB
18.	Thu.	29/11	13-17	E-Lab	P2: Experimental lab. Group 3	RK/CS/YA/KY
19.	Fri.	30/11	13-15	MT0, MT9	P1d: Computer lab.	KY/YA
20.	Tue.	4/12	13-15	ED	L15-L16: Power System Market	Tuan Lee Chalmers

21.	Tue	4/12	15-17	ED	E15-L16: Power System Market	PB2
22.	Thu	6/12	13-17		Study visit Transmission and Distribution	Per Norberg Vattenfall
23.	Fri.	712	13-15	MT0, MT9	P1e: Computer lab.	KY/YA
24.	Tue	11/12	13-15	ED	L17: Sustainable Power System – Integration of renewables and connection of electrical vehicles L18: Future developments of Electric Power Systems with HVDC	LB Magnus Callavik ABB
25.	Tue	11/12	15-17	ED	E17-E18: Integration of renewables and connection of electrical vehicles	PB
26.	Thu	13/12	13-15	ED	L19-L20: Summary lectures	LB
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Examination dates:

Day	*Date*	*Time*	*Address*
Fri.	21/12	14-18	Hörsalsvägen

Welcome to the course and to take contact for questions!

Lina Bertling Tjernberg

Reading Instructions

ENM125 Sustainable Electric Power Systems (SEPS, 7.5 credits)

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The following reading instruction divides the content in the sections as focus material and further reading material. To complete the course objectives the material in "further reading" might be omitted.

- ***Chapter 1 The physics of electricity***
    - Focus material: 1.1-1.4
    - Further reading: 1.3.4, 1.5
- ***Chapter 2 Basic circuit analysis***
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- ***Chapter 3 AC Power***
    - Focus material: 3.1-3.4
- ***Chapter 4 Generators***
    - Focus material: 4.3
    - Further reading: 4.1-4.2, 4.4-4.6
- ***Chapter 5 Loads***
    - Focus material: 5.1, 5.4.2
    - Further reading: 5.2.-5.4, 5.5
- ***Chapter 6 Transmission and distribution***
    - Focus material: 6.1-6.6
    - Further reading: 6.7
- ***Chapter 7 Power flow analysis***
    - Focus material: 7
- ***Chapter 8 System performance***
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- ***Chapter 9 System performance***
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II Lecture notes

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  - Further reading: 9.3-9.4

ENM125: SEPS
Sustainable Electric Power Systems

Lina.Bertling@chalmers.se
Professor in Electric Power Systems
Examiner and course responsible

Course Introduction
2012-10-30, Chalmers, Gothenburg

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The electric power system

- ✓ fundamental infrastructure in the modern society
- ✓ energy conversion electricity generation and delivery

Picture: L. Bertling, Istanbul, June 2012

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Sustainable Electric Power System

Picture source http://www.oe.energy.gov/DocumentsandMedia/smartgrid_diagram.pdf

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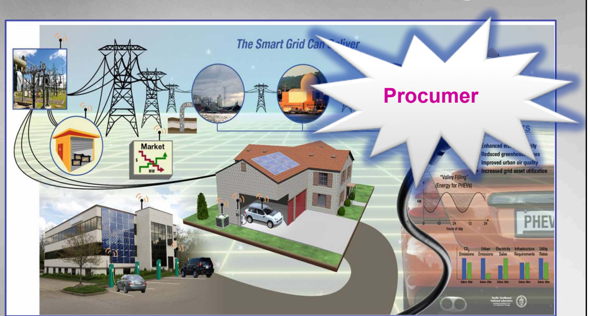
Sustainable Electric Power System



Key words: Flexibility, renewables, ac/dc, energy storage

Picture source http://www.oe.energy.gov/DocumentsandMedia/smartgrid_diagram.pdf

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ENM125 SEPS: overall aim

- *The* overall aim *of this course is to provide a conceptual understanding of the fundamentals of the electric power system as a component of a sustainable energy system.*

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ENM125 SEPS: objectives 1(2)

- Conceptually describe the technical fundamental characteristics and performance of the electric power system with main function to deliver electricity between generation, consumption and storage.
- Carry out basic electric circuit modeling and analysis.
- Understand the basics of synchronous generators.
- Understand the basics of the three phase transmission system.
- Perform per-unit calculations.
- Understand basic impact of different loads on the electric power system

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ENM125 SEPS: objectives 2(2)

- Understand basic impact of different loads on the electric power system
- Formulate and solve a power flow analysis problem
- Understand the fundamental behavior of the electric power system based on simulator tools.
- Understand the main function of the power system market
- Understand and follow safety instructions in the electric power engineering lab in the course.

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ENM125 SEPS: activities

The course includes the following activities:

- Lectures (Lina Bertling Tjernberg, guests)
- Tutorials with exercises (Pramod Bangalore)
- Laboratory work with project reports
  - Computer lab (introduction 8/11, 5 classes)
  - Experimental lab (choice of 1 of 3 groups)
- Technical study visit on 6 December
- Final written examination 21 December

✓ AND own study time!

ENM125 SEPS: lab. work

The course includes laboratory work:

- The experimental lab gives an introduction to the electrical circuits. Before performing the lab the safety instructions must be read and understood.
- The computer labs deal with simulation tools for analysis of the electric power system and the handling of stability.

✓ For each lab a laboratory report shall be submitted and approved.

ENM125 SEPS: literature

The course literature includes:

- Lecture notes and hand outs
- Tutorial exercises and notes
- Project lab instructions for Computer and Experimental lab
- Course book:
  - Electric Power Systems - A conceptual introduction (2006), Alexandra von Meier, John Wiley & Sons.
- Recommended book for further reading:
  - Power System Analysis Third Edition, (2010), Hadi Saadat, PSA Publishing.

✓ Material posted on course home page

ENM125 SEPS: examination

- Three tasks for examination with credits based on total of 100% (5,4,3 and failed):
  1. Computer Lab with lab report (20% of credit)
  2. Experimental Lab (5% of credit)
  3. Final written exam (75% of total credit)
     - Two parts: theoretical and numerical
     - Needed to pass both parts

✓ Engagements during the whole course!

ENM125 SEPS: formalia

- Course Formalia
  - *Credits: 7.5 credits*
  - *Period: second period*
  - *Exam: one written exam*
  - *Lab: one experimental and one computer lab*
  - *Credits: 5,4,3 or fail*
  - *Level: advanced*
  - *Language: English*
  - *Participants: maximum number 60*

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Explore & Good luck!

- ✓ See the Course Program with all details for the course
- ✓ Home page continuously updated with material and used for information
- ✓ Ask if any questions related to lectures or contact by:
  - ✓ Lina.bertling@chalmers.se
  - ✓ Pramod.Bangalore@chalmers.se

Lina Bertling Tjernberg Professor
Division of Electric Power Engineering
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L1 Introduction to Sustainable Electric Power Systems

Lina.Bertling@chalmers.se
Professor

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Introduction lecture ENM 125 SEPS

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Sustainable Electric Power System

Terminology and scale

- Power is a snapshot of how much electricity an appliance consumes, or a power plant produces
  - Kettle 2 000 W (2kW)
  - Wind Turbine 2 000 000 W (2 MW)
  - Nuclear reactor 1 000 000 000 W (1GW = 1000 MW)
- Energy is power over time - *how much electricity is consumed during the previous period?*
  - Kettles use a hour 2 kWh
  - Annual production from a wind turbine 6 MWh
  - Annual consumption Sweden 160 000 GWh (160 TWh)
- ✓ Smart Grid is an infrastructure for power delivery for the future sustainable energy system

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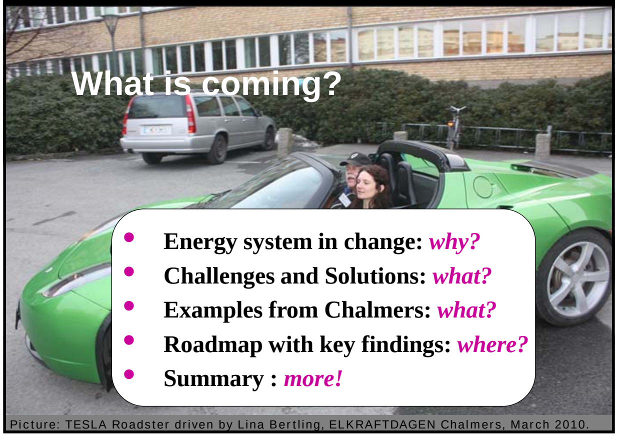

What is coming?

- **Energy system in change:** ***why?***
- **Challenges and Solutions:** ***what?***
- **Examples from Chalmers:** ***what?***
- **Roadmap with key findings:** ***where?***
- **Summary :** ***more!***

Picture: TESLA Roadster driven by Lina Bertling, ELKRAFTDAGEN Chalmers, March 2010.

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Energy system in change

- The energy system is undergoing a major global change
- Main driving forces are to meet the political climate and energy goals and to counteract the economic crisis.
- In Europe the climate and energy goals with target for 20/20/20/10 by 2020.

➢ Example Sweden with large investments in electricity generation from wind turbines, in large and small scale.

➢ The Smart Grid is a facilitator to meet these changes by "*different use of electricity*"!

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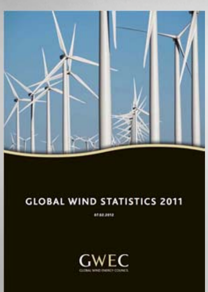
Energy system in change

Example: new capacity from wind during 2011



- ✓ Total installed 238 000 MW
- ✓ New capacity 2011, 41 000 MW
- ✓ Top 5 Countries total (new)
  - 26% (44%) China
  - 19.7% (17%) US
  - 12.2% (5%) Germany
  - 9.1% (2.5%) Spain
  - 6.7% (7 %) India
  - (1.9%) Sweden

Source: www.ewea.org

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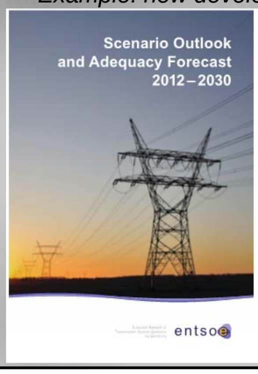
Energy system in change

Example: new developments of the grid



- ENTSO-E published 2012 ten-year network development plan
  - ✓ 80% of the identified 100 bottlenecks are related to the direct or indirect integration of renewable energy sources
  - ✓ larger, more volatile power flows, over longer distances across Europe
  - ✓ Extending the grid by 1.3% a year enables adding 3% generation capacity
- More information **www.entsoe.eu**

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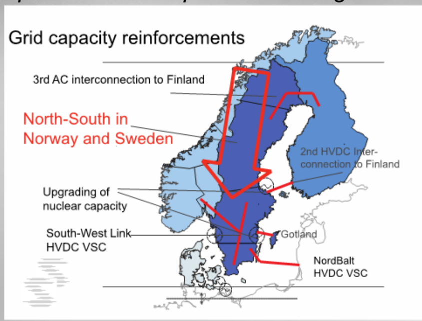
Energy system in change

Example: new developments of the grid in Sweden



Pictures: Svenska Kraftnät, Presentation Sture Larsson 2012-10

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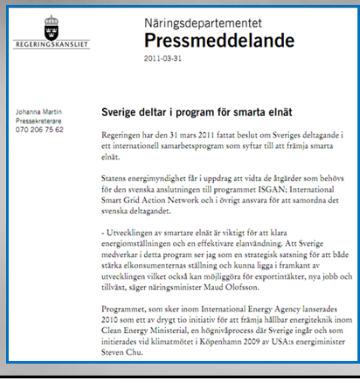
Energy system in change



REGERINGSKANSLIET

Näringsdepartementet
Pressmeddelande
2011-03-31

Johanna Martin
Pressekreterare
070 206 75 62

Sverige deltar i program för smarta elnät

Regeringen har den 31 mars 2011 fattat beslut om Sveriges deltagande i ett internationell samarbetsprogram som syftar till att främja smarta elnät.

Statens energimyndighet får i uppdrag att vidta de åtgärder som behövs för den svenska anslutningen till programmet ISGAN; International Smart Grid Action Network och i övrigt ansvara för att samordna det svenska deltagandet.

- Utvecklingen av smartare elnät är viktigt för att klara energiomställningen och en effektivare elanvändning. Att Sverige medverkar i detta program ser jag som en strategisk satsning för att både stärka elkonsumenternas ställning och kunna ligga i framkant av utvecklingen vilket också kan möjliggöra för exportintäkter, nya jobb och tillväxt, säger näringsminister Maud Olofsson.

Programmet, som sker inom International Energy Agency lanserades 2010 som ett av drygt tio initiativ för att främja hållbar energiteknik inom Clean Energy Ministerial, en högnivåprocess där Sverige ingår och som initierades vid klimatmötet i Köpenhamn 2009 av USA:s energiminister Steven Chu.

- Press release 11-03-31
- Sweden to join IEA initiative on International Smart Grid Action Network
- *Smart Grid is on the political agenda as a tool for sustainable energy system*

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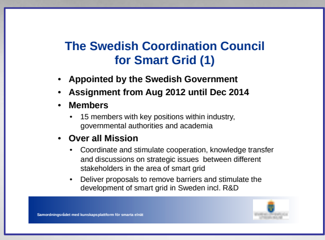
Energy system in change

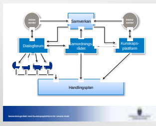
- Swedish Coordination Council for Smart Grid
  - Appointed by Swedish Government May 2012
  - Assignment until December 2014
  - 15 members with key roles and expertise
  - Overall mission

1. Coordinate, create knowledge platform
2. Proposal for Swedish Smart Grid plan



The Swedish Coordination Council for Smart Grid (1)

- Appointed by the Swedish Government
- Assignment from Aug 2012 until Dec 2014
- Members
  - 15 members with key positions within industry, governmental authorities and academia
- Over all Mission
  - Coordinate and stimulate cooperation, knowledge transfer and discussions on strategic issues between different stakeholders in the area of smart grid
  - Deliver proposals to remove barriers and stimulate the development of smart grid in Sweden incl. R&D



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Energy system in change

Smart Grid has made the electric power system visible

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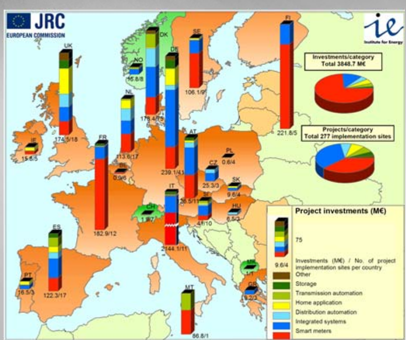
Energy system in change



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Electric power system: changes

Development phases in Sweden:

- *1950's and 1960's*
  Expansion to facilitate the large hydro power development in the far north
- *1970's and 1980's*
  Expansion in the south caused by connections of nuclear power plants
- *1990's -*
  Increased capacity for international trade.
- 2005 –
  Reinvestments and increased focus on reliability
- 2008 – Sustainable developments

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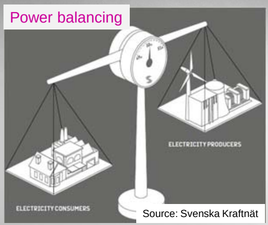
Electric power system: challenges

Power balancing



- Varying availability
- Forecast errors

Need for additional reserve capacity

Grid capacity, stability

- Good wind power sites in remote areas

Need for grid reinforcement for delivery and backup/balancing

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Electric power system: challenges

- Large disturbance in ENTSO-E (formerly UCTE) system on November 4th 2006
- System splitting in 38 minutes
- Disconnection of 17000 MW, affecting 15 millions households in two hours
- Detailed report at ENTSO-E website: http://www.entsoe.eu

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Electric power system: challenges

Challenges for the electric power system:

- need of reinforcement in the power grid
- more integration between the countries
- more intermittent power
- more large and small scale production
- plug in electrical vehicles
- active customers with more information and being both consumers and producers

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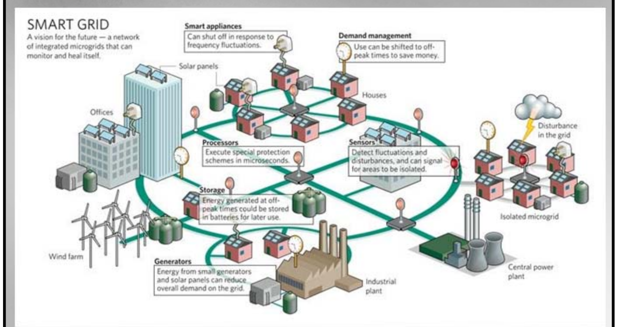
Electric power system: solutions



Source: www.nature.com/news/2008/080730/images/454570a-6.jpg

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Electric power system: solutions

Solutions for the smart electric power system:

- ✓ new standards and regulations
- ✓ techniques to control the power e.g. phase measurement units (PMUs), FACTS (Flexible AC Transmission Systems), HVDC VSC (Voltage Source Converters),
- ✓ support from Information and Communication Technology (ICT), and Digital Signal Processing (DSP),
- ✓ materials for efficient high voltage insulation
- ✓ technology for energy storage using e.g. electric cars

Smart Grid express the developments using these solutions for a sustainable electric power system!

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Electric power system: solutions

- The first IEEE PES ISGT Europe in 2010, Gothenburg
  - 420 persons, 40 countries, 150 papers
  - 60% industry and authority, 40% university
- More information: www.ieee-isgt-2010.eu

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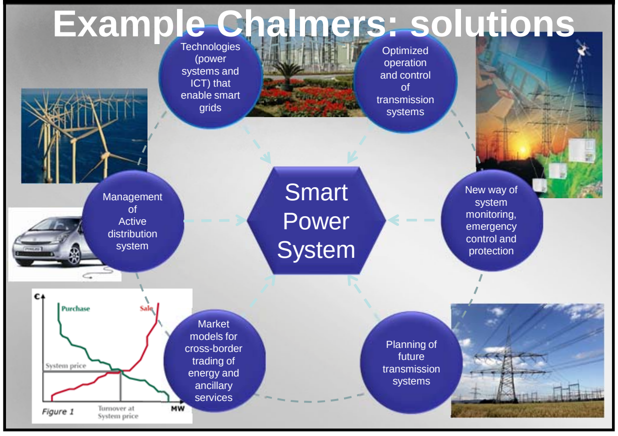
Example Chalmers: solutions



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Example: research & tests

Big Glen – demonstration site testing wind turbines

- The project develop methods, simulate and test in lab targeting wind turbines to fulfill Grid Codes.

- Full scale tests
  - 4 MW General Electric
  - More information from www.swptc.se

SWPTC board visit Big Glen, May 2012 (Picture Lina Bertling Tjernberg)

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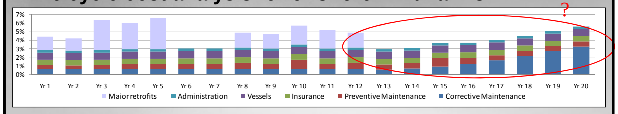
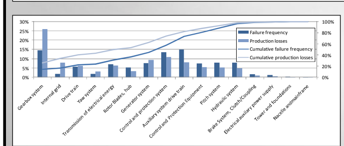
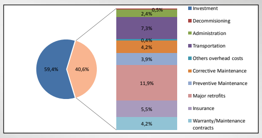
Example: research wind

Life cycle cost analysis for offshore wind farms







- ✓ Example of results from a case study based on Horns Rev (80 Vestas V80 2MW in operation since 2002)
- ✓ Recently accepted to be published in IEEE Transactions on Sustainable Energy*!

Besnard F., Fischer K., Bertling Tjernberg L. A Model for the Optimization of the Maintenance Support Organization for Offshore Wind Farms", Accepted to be published in IEEE Transactions on Sustainable Energy, 2012.

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Example: research on EV & EU

G4V™ Grid for Vehicles

- *Analysis of the impact and possibilities of a mass introduction of electric and plug-in hybrid vehicles (EV) on the electricity networks in Europe*
- FP 7 Energy 3.7 million Euro,18 months from January 2010
- RWE leader, 12 parts (Chalmers, Vattenfall from Sweden)

➢ Next step..

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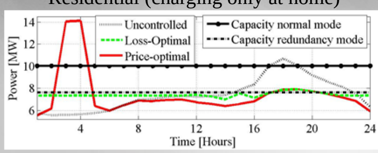
Example: research EV & grid

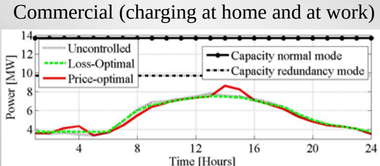
Residential (charging only at home)



Peak demand increase [%]	Residential area
Uncontrolled	21 %
Price-optimal	78 %
Loss-optimal	0 %

Peak demand increase [%]	Commercial area
Uncontrolled	3.5 %
Price-optimal	14.5 %
Loss-optimal	0 %

Commercial (charging at home and at work)



Steen D., Tuan L., Carlson O. and Bertling Tjernberg L., "Assessment of Electric Vehicle Charging Scenarios Based on Demographical Data." Published in IEEE Transaction on Smart Grid Technology, September 2012.

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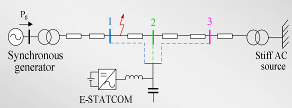
Elteknik: research grid stability

Converter for Electric Power System Stability Enhancement

- Proposing a control algorithm for the converter to provide dynamic performance to the power system with minimum active power injection



- ✓ Experimental lab setup 75kVA, 400 V, 50 Hz system
- ✓ Simulation model

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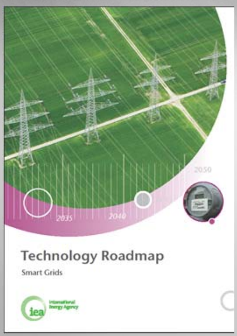
Roadmap: key findings IEA



Key points:

- *“A broad range of product and service providers who have not worked together in the past will have to collaborate”*
- *“Smart grid deployment can reduce the peak electricity demand associated with the charging of electric vehicles and contribute to reducing overall peak demand by enabling V2G.”*

Source: www.iea.org

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Roadmap: key findings IEA

Key findings from IEA roadmap: Smart Grid

✓ Smart Grid is essential if the global community is to achieve shared goals for energy security, economic development and climate change mitigation.

✓ Smart Grid enable increased demand response and energy efficiency, integration of variable renewable energy resources and electric vehicle recharging services, while reducing peak demand and stabilising the electricity system.

✓ The physical and institutional complexity of electricity systems makes it unlikely that the market alone will implement smart grids on the scale that is needed.

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Roadmap: key findings IEA

Key findings from IEA roadmap:

✓ The “smartening” of grids is already happening; it is not a one-time event. However, large-scale, system-wide demonstrations are urgently needed to determine solutions that can be deployed at full scale, integrating the full set of smart grid technologies with existing electricity infrastructure.

✓ Current regulatory and market systems can hinder demonstration and deployment of smart grids. Regulatory and market models – such as those addressing system investment, prices and customer participation – must evolve as technologies offer new options over the course of long-term, incremental smart grid deployment.

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Roadmap: key findings IEA

Key findings from IEA roadmap:

✓ Regulators and consumer advocates need to engage in system demonstration and deployment to ensure that customers benefit from smart grids. Building awareness and seeking consensus on the value of smart grids must be a priority, with energy utilities and regulators having a key role in justifying investments.

✓ Greater international collaboration is needed to share experiences with pilot programmes, to leverage national investments in technology development, and to develop common smart grid technology standards that optimise and accelerate technology development and deployment while reducing costs for all stakeholders.

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Roadmap: key findings IEA

Key findings from IEA roadmap:

✓ Peak demand will increase between 2010 and 2050 in all regions. Smart grids deployment could reduce projected peak demand increases by 13% to 24% over this frame for the four regions analysed in this roadmap.

✓ Smart grids can provide significant benefits to developing countries. Capacity building, targeted analysis and roadmaps – created collaboratively with developed and developing countries – are required to determine specific needs and solutions in technology and regulation.

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Summary: Power Systems

- Driving forces: sustainability and cost-efficiency
- Smart Grid – infrastructure for energy delivery
  - flexibility with new technologies & new usage
- Key features:
  - communication, ICT and standards
  - electricity from renewables
  - electrical vehicles and storage
- Challenges:
  - Process for developments and incentives
  - System solutions and change in behavior
  - Availability and low maintenance costs

Chalmers create solutions for smart energy systems!

More: Electricity system

- Further information
  - Energy: Svensk Energi, IEA – statistics on power production, Solar at Chalmers.
  - Grid:
    - Svenska Kraftnät – large projects like South West Link with DC 3 terminal and AC
    - ENTSO-E with a 10-year development plan
- Courses for further reading at Chalmers
  - Masters program in Electric Power Engineering courses in power planning and generation

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L2 Fundamentals of electricity

Lina.Bertling@chalmers.se
Professor

Introduction lecture ENM 125 SEPS
2012-10-30, Chalmers, Göteborg

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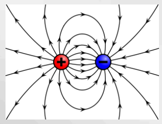
Introduction: Electricity

Electricity is a physical phenomena

- associated with the presence and flow of electric charge
- examples
  - ✓ lightning
  - ✓ static electricity



Source: wickipedia

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Introduction: Electricity physics

Electricity occurs due to several types of physics

- *Electric charge* - a property of subatomic particles which determines their electromagnetic interactions, which produce electromagnetic fields
- *Electric current* - a movement or flow of electrically charged particles, measured in amperes
- *Electric field* - an especially simple type of electromagnetic field produced by an electric charge even when it is not moving
- *Electric potential* – the capacity of an electric field to do work on an electric charge (volts)
- *Electromagnets* –electrical currents generate magnetic fields and changing magnetic fields generate electrical currents.

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Introduction: Electricity invention

Electricity as a great invention

- Electrical phenomena have been studied since antiquity but advances in science first until seventeenth and eighteenth centuries.
- Practical applications first until late nineteenth century
- Providing energy in applications for transport, heating, lightning, communications, and computation
- Electrical power is the backbone of modern industrial society
- The word electricity is from the new latin ēlectricus "amber-like" and Greek ήλεκτρον meaning amber

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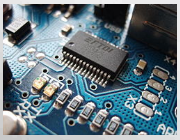
Introduction: Electricity

In electric engineering the electricity is used for

1. Electric power where electric current is used to energise equipment

2. Electronics which deals with electrical circuits that involve active electrical components (transistors, diods) and associated passive interconnection technologies



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The physics of electricity

- Basic quantities essential for understanding of electricity
  - ✓ Charge, voltage, current, resistance, electric and magnetic fields
- Hard to get an intuitive appreciation of these quantities
- Electric phenomenon a fundamental force of nature
- Electric charge is one of the five basic dimensions of physical measurements together with mass, distance, time and temperature

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The physics of electricity

Electrical processes

- like cell metabolism or nervous impulses, are vital to our body but we do not usually conceptualize these as electricity
- Electric chock – presence of charge send a strong wave of nervous impulses through the body
- Hair that stands on end
- Zap from a door knob
- Static cling in the laundry
- Electric power – the effect of electricity glowing light bulb or a rotating motor – silence happenings concealed within metals

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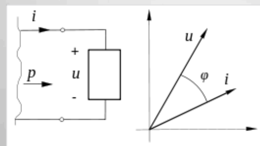
The physics of electricity

- Electricity remains as an abstraction and we rely on numerical and geometric representations



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The physics of electricity: charge

- Major scientific accomplishment to integrate electricity with fundamental concepts about the microscopic nature of matter.
- Observations of static electricity where explained by Benjamin Franklin in the late 1700s like
  - ✓ *There exist in nature two types of property called charge "positive" and "negative". Opposite charge attract each other and like repel.*
- When certain material rub together one type of charge can be transferred by friction and "charge up" objects that subsequent repel objects of same kind (hair), or attract objects of different kind (polyester and cotton e.g.)

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The physics of electricity: charge

- Scientists arrived at a model of the atom being composed of smaller individual particles with opposite charges held together with their electrical attraction
- Nucleus of an atom, constitutes the vast majority of its mass, contains protons with positive charge and is enshrouded by electrons with a negative charge
- The nucleus also contains neutrons which resembles protons except they have no charge
- The electric attraction between protons and electrons balance the electrons natural tendency to escape, which result from their rapid movement, or kinetic energy, and their mutual electric repulsion

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The physics of electricity: charge

- Electrical neutral – the atom with balance i.e. same amount of protons and electrons
- This model explains why most material exhibit no obvious electric properties and how they can be "charged" under certain circumstances
- Individual electrons can escape from their atoms and travel elsewhere. Friction can cause electrons to travel from one material to another.
- Material with excess electrons becomes negatively charged and the material with deficit of electrons becomes positively charged.
- The ability of electrons to travel explains the phenomenon of electric current.

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The physics of electricity: charge

- Some atoms or groups of atoms (molecules) naturally occur with a net charge because they contain an imbalance number of protons and electrons, they are called *ions*
- The propensity of an atom or molecule to become an ion i.e. to release electrons or accept additional ones – results from peculiarities in the geometric pattern
- These electrical phenomena within molecules determine most of the physical and chemical properties of all substances we know

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The physics of electricity: charge

- The practical unit of charge in the context of electric power is the Coulomb (C)
  - One coulomb corresponds to the charge of $6.25 \cdot 10^{18}$ protons
  - One proton has the charge of $1.6 \cdot 10^{-19}$ C.
  - One electron has the negative charge of $-1.6 \cdot 10^{19}$ C
- In equations charge is typically denoted by Q or q.

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The physics of electricity: voltage

Voltage (Potential)

- Charge has a natural tendency to “spread out”. A local accumulation or deficit of electrons causes a certain “discomfort” or “tension”, these charges will tend to move in such way to relieve the local imbalance. This discomfort level is expressed as level of energy.
- This energy - electric potential energy – is said to be “held” or “possessed” by a charge
  - Analogue with mechanical potential energy possessed with a massive object when it is elevated above ground
  - A state of lower energy – closer to the ground – or farther away from like charges – represent a more “ comfortable” state, with a smaller potential fall.

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The physics of electricity: voltage

- Potential energy held by an object or charge in a particular location can be specified in two ways that are physically equivalent:
  1. It is the work that would be required in order to move the object or charge to that location
     - e.g. it takes work to lift an object, it also takes work to bring an electron near an accumulation of more electrons
  2. The potential energy is the work the object or charge would do in order to move from that location, through interacting with the objects in its way
     - e.g. a weight suspended by a rubber band in order to move downward from higher to lower gravitational potential.

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The physics of electricity: voltage

- A charge moving toward a more comfortable location might do work by producing heat in the wire through which its flow.
- The notation of work is crucial because it represent the physical basis of transferring and utilizing electrical energy. In order to make this “work” a useful measure some proper definitions are necessary
- The contribution of charge and potential to the total amount of work or energy transferred.
  - The amount of work in either direction (higher or lower potential) depends on the amount of mass or charge involved

The physics of electricity: voltage

- The electric potential is the potential energy possessed by a charge at the location in question, relative to a reference location divided by the amount of its charge
- A potential/voltage can be positive or negative

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The physics of electricity: voltage

- Reference location – the place where the object or charge was moved to or from.
  - Mechanical context the height above ground level
  - Electricity – refer to an electrically neutral place, with zero or ground potential
- Theoretical the neutral place is a place where no other charges are present to exert any forces
- In practice the neutral place/ground potential is any place where positive and negative charges are balanced and their influences are cancel.
- When describing the potential at a single location, it is implicitly the potential difference between this and the neutral location.

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The physics of electricity: voltage

- Because electric potential or voltage equals energy per charge, the units are equivalent to units of energy divided by units of charge . These units are *volts* (v).
- One volt is equivalent to one joule per coulomb, where joule is a standard unit of work or energy.
- Note how the notion of a difference always remains implicit in the measurement of volts.
  - *"this wire is at voltage of 100 volts" means "this wire is at a voltage of 100 volts relative to ground"*
- In equations voltage is conventionally denoted by *E,e, V, v*

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The physics of electricity: ground

- The term ground has a very important and specific meaning in the context of electric circuits
  - It is an electrically neutral place. It has zero voltage/ potential
  - It has the ability to absorb excesses of either positive or negative charge and to disperse them so as to remain neutral regardless of what might be electrically connected to it

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The physics of electricity: ground

- The literal ground outdoors has this ability since the Earth as a whole acts as a vast reservoir of charge and is electrically neutral, and because most soils are sufficient conductive to allow charge to move away from any local accumulation.
- A circuit ground is constructed simply by creating a pathway for charge to ground.

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The physics of electricity: conductivity

- In certain material some numbers of electrons are always free to travel. As a result the material is able to conduct electricity
- When a charge (excess/deficit of electrons) is applied to one side of a conductive material, the electrons throughout will realign themselves, spreading out and thus conduct the charge to the other side.

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The physics of electricity: conductivity

- Metals are the most important conducting material
- Other material; water, or any fluid with dissolved ions
- Air can be temporary conductive through ionization
  - Electric spark across an air gap, an arc between power lines, or a lightning bolt.
- Plasma a gas in conductive state

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The physics of electricity: conductivity

- It is typically important to predict when ionization might occur, namely how great a potential difference over how short a distance will cause “arcing”.
  - For air this depends of the temperature and humidity, presence of e.g. salt.
- Some material can become superconducting generally at very low temperatures.
  - Electrons travel with extreme ease and do not work on anything in their path and therefore lose no energy
  - Ceramic material attain superconductivity at minus 319F
  - Costly as applications in power systems e.g. superconducting magnetic energy storage

The physics of electricity: current

- When a charge travels through a material, an electric current, is said to flow
- Current is quantified as number of electrons (or equivalent charge, in the case of ions) moving past a given point in the material in a certain period of time. Current *is a flow rate of charge*
  - Electric current is analogous to a flow rate of water or natural gas.
  - Noted by I, I units of amperes (A) often called “amps”
  - Units of charge divided with units of time.
  - 1 ampere = 1 coulomb/second

The physics of electricity: current

- Positive current generally defined as in the direction from positive to negative potential
- In power systems with alternating current (AC). The relationship between two currents is described using phase or relative time.
- Current travels at the speed of light approx 300 M m/s
- It is the pulse or signal that is travelling
- Propagation speed becomes only relevant over long distances – so that the time it takes for a current pulse to travel from one point to another is significant compared to other timing parameters.

The physics of electricity: Ohm´s law

- It is intuitive that voltage and current are related. E.g. if the potential difference between two ends of a wire is increased, we expect a greater current to flow.
- For most materials, including conducting metals, this relationship is linear and expressed in Ohm´s law as:.

V = IR

  - V the voltage
  - I the current
  - R the proportionality constant resistance.

The physics of electricity: resistance

- Resistance vary with temperature. It depends on an objects material composition and it shape.
- The resistance depends of resitivity, length of the object and cross-sectional area: $R = \rho \cdot l / A$ (unit ohms, Ω)
- To say that Ohm´s law is true for a certain conductor is to say that the resistance is constant with respect to current and voltage.

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The physics of electricity: conductance

- Conductivity is the inverse of resistivity and denoted as σ (sigma); $\sigma = 1/\rho$
- Conductance $G = \sigma A/l$ (mhos/m=1/Ω)
- For the special case of an insulator the conductance is zero and the resistance consequently infinite
- For the special case of superconductor the resistance is zero and the conductance consequently theoretically infinite (which implies infinitely large current).

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The physics of electricity: insulation

- Insulating material have infinite resistance (zero conductance)
- They are used in electric devices to keep current from flowing where it is not desired. Also called dielectric material.
- Typical material of; plastic or ceramic.
- The thicker insulation material the higher voltage difference it can sustain.

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The physics of electricity: static charge

- A current can only flow as long as a potential difference is sustained
- When charge is accumulated in one place it is called static charge.
- It lacks a conducting pathway enables to move towards opposite charge.

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The physics of electricity: electric circuits

- To produce a sustained flow of current the potential difference must be maintained which is obtained by a pathway to “recycle” charge – an electric circuit.
- Simple example Battery with two wires to a light bulb
- Closed circuit and open circuit

The physics of electricity: voltage drop

- Typically it is of interest to specify voltage at particular points along the way.
- Difference in voltage between two points in a circuit is referred to voltage drop across the wire
- The magnitude of the current also determines the voltage drop E.g. at times with high electric demand, i.e. high current flow, the voltage drop over the lines are greater

The physics of electricity: electric shock

- To be at a potential above ground, like birds sitting on a single power line is harmless
- Harm is done when a current flows through our body for which a voltage drop is needed (in contact with two sources of different potential)
- It is the current that causes damage.

The physics of electricity: resistive heating

- Heat is created whenever an electric current flows through a material that has resistance
- The heat is result from “friction”.
- The heat can be used in appliances like toaster, electric blanket this
- In power lines this heat it undesired and typically referred to as resistive losses. The heating make thermal expansion of the conductors making them sag.
- For power lines the current is determined by the load or power consumption at the end of the line (the resistance of the line is insignificant)
- P = I^2*R – doubling of resistance doubling of losses.
- Examples on the black board.

The physics of electricity: resistive losses

- Given a certain demand on power it is a choice on what voltage level and current to use.
- Higher voltage level corresponds to less current flow.
- Resistive heating is related to the square of the current.
- To reduce resistive losses is a main reason to increase voltage level for electricity transportation.

Basic Circuit Analysis - circuits

- Circuit is an interconnection of electric devices that interact with electric voltages and currents
  - e.g. power source, conductors, load
- Analysis performed to predict the circuits electrical behavior
  - depends on nature of the devices and how these are connected
  - assume that the devices are ideal e.g. follow Ohm´s rule, linear elements
- Basic elements for power system analysis
  - resistors, capacitors, inductors, ac or dc power sources
  - generally the conducting wires are assumed negligible impedance however this is only valid for short distances

Basic Circuit Analysis – series and parallel circuits

- Two basic ways to connect circuits i.e. in:
  1. series – the currents through elements are equal - conserved flow of charge
  2. parallel – two or more alternative paths for the current – conservation of charge implies that the sum of the currents remains constant

Basic Circuit Analysis – resistance in series

Resistance in series

- To find the resistance of a series combination of resistors add their individual resistance

Basic Circuit Analysis – resistance in parallel

Resistance in parallel

- Decreasing the overall resistance of the combination by providing alternative paths for the current
- Convenient to consider the inverse property if resistance i.e. conductance
- The total resistance of a parallel combination will always be less than any of the individual resistance
- The conductance of the parallel combinations equal the individual conductance

Basic Circuit Analysis – network reduction

- Any network of circuit elements is composed of series and parallel combinations
- Network reduction is an approach to deduce an equivalent network with combinations of series and parallel combinations

Basic Circuit Analysis – connection of loads

- E.g. loads in a house with different appliances these are connected in parallel which allows them to be operated independently of each other using different currents but with the same voltage
- In a system with with constant voltage source the resistive loads in parallel are essentially unaffected by each other
- The series connection in power system are typically when elements represent steps between power generation and consumption. i.e. loads are in series with distribution line and generator
- Minimum elements in series that constitutes the path from power sources to load

Basic Circuit Analysis – Kirchhoff´s voltage law

Kirchhoff´s voltage law (KVL)

- The sum of voltages around any closed loop in a circuit must be zero
- Analogue with flowing water
- Note that it is irrelevant which point is chosen as zero point

Basic Circuit Analysis – Kirchhoff´s current law

Kirchhoff´s current law (KCL)

- The current entering and leaving any branch point or node in the circuit must add up to zero
- Follows directly from conservation property *electric charge is neither created, destroyed or stored*
- Analogue with flowing water

L3-L4 alternating current

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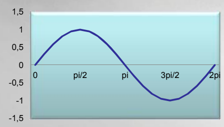
L3 & L4: AC - Summary

Alternating Current



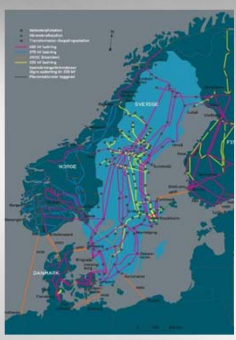
- Basis for power system analysis: solving load flow calculations.

- Alternating current and voltage
  - ✓ Historical note
  - ✓ Mathematical description
  - ✓ Root Mean Squared value
- Reactance
  - ✓ Inductance
  - ✓ Capacitance
- Power
  - ✓ Electric power definition
  - ✓ Complex power
  - ✓ Reactive power
- Phasor notations

Example: AC power in Sweden

Electric Power Grid in Sweden

- Electrification of Sweden began early and in the late 1800s prompted some cities electric lighting.
- Hydro power was built into the 1900s and grew a backbone for electricity to be transported from power plants.
- The Swedish grid is today ~ 54 500 mil equivalent to 13.6 times around the world.
  - 60% underground cables
  - 40% overhead lines
- The availability in power delivery to the customer is 99.98%.



Example: AC power in Sweden

Example electricity usage in Sweden

- Total electricity usage including transmission losses and large electric boilers in industries and heating plants during 2011 139.7 TWh (147.0 TWh in 2010).
  - Sweden has a relatively high proportion of electrical heating, (around 30 TWh)
- The average system price on Nord Pool Spot was SEK 0.42 per kWh, compared to SEK 0.50 per kWh in 2010.

Source: www.svenskenergi.se

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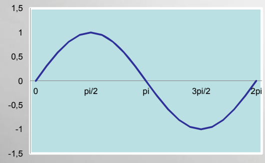
AC: current and voltage

- In AC circuits the current and voltage continuously change polarity and the speed at which this change occurs depends on the frequency.
  - Common frequencies used in electric power systems are 50 Hz (Europe) and 60 Hz (United States).



✓ The figure shows an sinusoidal oscillating wave with a frequency of 50 Hz

  - This alternating nature of wave gives rise to the properties of inductance and capacitance

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AC: reactance

- Reactance is the property of a device to influence the relative timing of an alternating voltage and current.
- It is related to the internal geometry of a device
- Physically unrelated to resistance
- Two types of reactance:
  1. inductive reactance
  2. capacitive reactance

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AC: reactance: inductance

- An alternating current is passing through a conductor
  - ➢ a magnetic field is induced,
  - ➢ this magnetic field produces an effect which opposes the change in the current.
- A pure inductive circuit produces an effect of phase lag in the current, so that the current lags the voltage in phase by 90 degrees.
- Definition: $X_L = \omega L$

  where
  - X_L =inductive reactance Ω
  - L = inductance in Henry (H)
  - $\omega = 2 \cdot \pi \cdot frequency$

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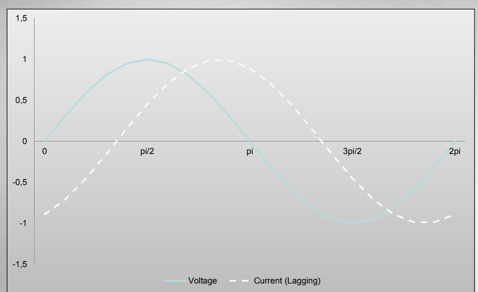
AC: reactance: inductance

- Example Current lagging voltage by a 90 degree phase difference in purely inductive circuit



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AC: reactance: capacitance

- Capacitance is the ability of a body to store an electrical charge.
- A capacitor essentially resists a change in voltage.
- A pure capacitive circuit produces an effect of phase lead in the current, so that the current leads the voltage in phase by 90 degrees.
- Definition: $$X_C = -\frac{1}{\omega C}$$

  where
  - $X_L =$ capacitive reactance Ω
  - C = capacitance in Faraday (F)
  - $\omega = 2 \cdot \pi \cdot$ *frequency*

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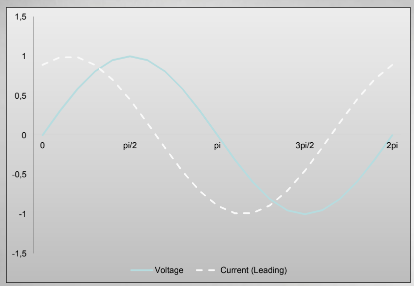
AC: reactance: capacitance

- *Example* Current leading the voltage by 90 degree in purely capacitive circuit



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AC: impedance

- The combination of reactance and resistance that describes the overall behavior of a device in a circuit is called the impedance and is often denoted by Z.
- Impedance Z is a vector sum of resistance and reactance in a complex plane.

  $$Z = R + jX$$

  where
  - Z = impedance
  - R = resistance capacitive reactance Ω
  - X= reactance (inductive or capacitive)
- Depending on the impedance is inductive or capacitive it causes the current to lag or lead the voltage in a circuit
- This <u>phenomenon gives rise to the concept of reactive power.</u>

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AC: impedance

- The phase difference between current and voltage called angle ϕ (uppercase Phi) can be calculated as follows:

  $$\phi = \cos^{-1}\left(\frac{R}{|Z|}\right)$$

  where
  - $|Z| = \sqrt{R^2 + X^2}$
- Another quantity of practical use is the admittance

  $$Y = \frac{1}{Z}$$

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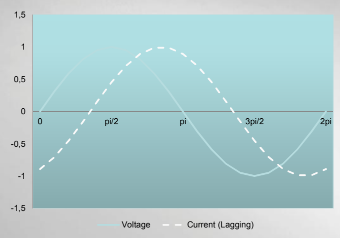
AC: impedance

- Example Current lagging voltage



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AC: power

Definition of electric power

- Power is a measure of energy per unit time
- Unit for power generally watts [W]
  - Watt rating of an appliance is the wattage multiplied by the amount of time during which it was used- commonly expressed in kilowatt-hours
- The power dissipated by a circuit element is given by the product of its resistance and the square of the current through it: $P = I^2 R$
  - dissipated indicates that energy is converted to heat
  - the heat could be part of the function, like heater, or considered as a loss

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AC: power

Definition of electric power

- From Ohm´s law: $P = IV = I(IR) = I^2 R$
- Example light bulb 60W

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AC: power

- In AC power circuits there are three different power values that are calculated:
  1. active power $P = |V| \cdot |I| \cdot \cos\phi$ Watts [W]
  2. reactive power $R = |V| \cdot |I| \cdot \sin\phi$ VAR
  3. apparent power $S = |V| \cdot |I|$ VA
     - complex expression $S = V \cdot I^*$

  where
  - $|V|$ = RMS value of voltage
  - $|I|$ = RMS value of current
  - ϕ = power factor – angle between voltage and current

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AC: power

Direction of the power

- Active power is always positive (as cosine)
- Reactive power can be negative.
  - Negative reactive power means that the reactive power is flowing in the opposite direction of the active power.
- For example in a generator both active and reactive power are positive when they are flowing out of the generator, but when the reactive power starts flowing in to the generator then it is assigned a negative sign.

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AC: power

Definition of electric power

- In electrical systems the voltages and currents are always expressed in RMS quantities.
  - For example “The electrical distribution system voltage level in Sweden is 230 V”; this statement means that the RMS value of the distribution system voltage is 230 V.

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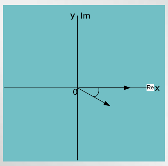
AC: phasor notation

- Average values are typically of interest in practical situations in ac circuits
  - i.e. what happens over the course of many cycles?
  - therefore RMS values are typically used which provide a measure of each sine wave´s amplitude (scaled by factor $\sqrt{2}$) but with no information about the timing – frequency and phase – of the wave
- To keep track at all times of both magnitude and phase of every variable – phasor notation is used



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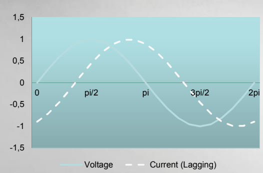
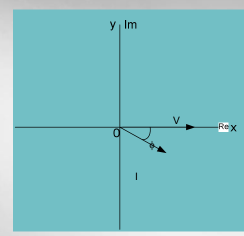
AC: Summary

- Example Impedance with current lagging voltage current phasor





L5-L6 generators and loads

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L5&L6: generators & loads

Summary

- ✓ fundamentals of generated electricity and loads
  - synchronous generator
  - asynchronous generator
- ✓ be able to model generator and loads for load flow studies.

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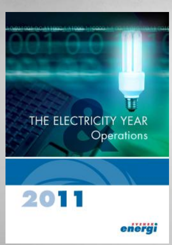
Example: AC power in Sweden

Example electricity generation in Sweden



- Total electricity generation 2011 146.9 TWh (2010)
  - Hydro 66 (66.8)
  - Nuclear 55.6 (58)
  - Wind 6 (3.5)
  - Other thermal 10.6 (19.1)

Source: www.svenskenergi.se

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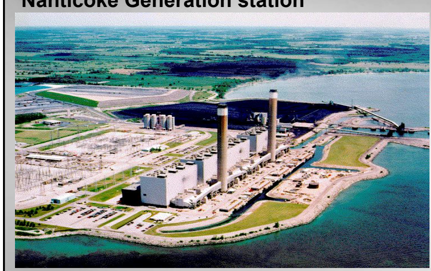
Generator: Example

Nanticoke Generation station



Facts:

- Largest coal fired plant in north America
- Commissioned 1972-1978, max 3964 MW today 2760 MW
- Switching into biomass and natural gas finished by 2014

Picture: Nanticoke Generation station, 2003 Lina Bertling associated with Kinectrics Inc.

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Generator: Example

Picture: Nanticcoke Power station, 2003 Lina Bertling associated with Kinectrics Inc.

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Generator: flow of current

- An electric generator is a device designed to take advantage of *electromagnetic induction* in order to convert movement into electricity
  - Induction – an electric charge in the presence of magnetic field in relative motion to it – e.g. by changing intensity – experiences a force in a direction perpendicular to the relative motion & magnetic field
  - Acting on the charges contained in the conducting material – i.e. electrons in a wire – this force becomes an electromagnetic force (emf) that produce voltage along the wire and thus cause an electric current to flow

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Generator: induction

- A generator is designed to obtain an induced current in the conductor as a result of mechanical movement
  - ✓ achieves a conversion of energy : energy of motion is converted into electrical energy
  - ✓ the opposite of an electrical motor which converts electrical energy into mechanical energy of motion
- Electrical generators and motors are similar devices and a generator could be operated as a motor and vice versa
  - *Example:* pumped hydroelectric storage or tidal plants where large water pumps are operated reversible as turbine generators
  - Design parameters: geometry – how wires are arranged, choice of material

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Generator: focus

In this course the focus on

- AC synchronous generator which is the standard type of generator in the electric power system with main issues of:
  - operation in system context and means to control variables like frequency, voltage, real and reactive power
  - interaction among generators which is fundamental for power stability of an ac power system
- Induction generator which is used in some specific applications like wind turbines

Generator: magnetic flux

- The simple generator is created by:
  - ✓ rotation of a bar magnet
  - ✓ induced current in wire loop
- Magnetic flux = magnetic field * area
  - total magnetic flux from the magnet does not change
  - the induced current is direct proportional to the flux linking – going through the loop
  - the induced current or voltage is given by the rate of change of the flux

Generator: energy conversion

- Energy is transferred from the generator to the load:
  - where to the energy come from how did it get to the wire?
  - the magnet must offer some resistance to being spun; there must be something to push against

The magnetic field of a rotating magnet
is pushing against a second magnetic field
that is the result from the induced current in the wire

Generator: in summary

i. An external force spins the bar magnet resulting in a magnetic field or flux which changes over time.
ii. This changing magnetic field induces an alternating voltage/current in a loop of wire surrounding the space
iii. The ac in turn produces its own magnetic field, which acts to retard the motion of the spinning magnet.
iv. The interaction of magnetic fields mediates the transfer of energy from mechanical movement into electricity

✓ If the generator is operated in reverse as a motor the wire field, the armature field is produced by an external supplied current

Generator: ac/dc

- In the simplest case an electric generator produces ac
- The ac output could be rectified/converted into dc
  - in this case easier to hold the magnet still and rotate the armature
  - contact with the load with sliding contacts (brushes or slip rings) that reverse the connection with each half turn
  - Since the magnitude of the current still oscillates its direction in the terminals going out of the lead always remains the same

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Generator: overall

- An electric generator is a device used to convert mechanical energy to electrical energy
- There are different kind of generators for example;
  - DC generator
  - AC synchronous generator
  - AC asynchronous (induction) generator.

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Generator: AC synchronous generator

Nomenclature

- Rotor is the rotating assembly in the center of the generator
- Stator is the stationary part outside

✓ Typically the rotor contains the magnet and the stator of the armature that is electrically connected to the load

✓ Permanent magnet is typically not used since it is weak compared to size and weight

✓ Instead a coil of wire – inductor/solenoid that is adjustable in strength and allows geometric configurations to get more magnetic poles

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Generator: AC synchronous generator

The standard generator has three conductors

- the windings are not electrical connected to each other but constitutes three phases of a power circuit that corresponds to the three wires as in the transmission lines. A, B, C (Lecture 7 & 8 more details on three phase T&D)
- Each phase carries ac and av shifted by 120°
- It takes the rotor 1/3 cycle to pass a given point on the armature
- Three phase main advantage for generator/motor
  - ✓ It gives a uniform force - *torque* - on the generator rotor

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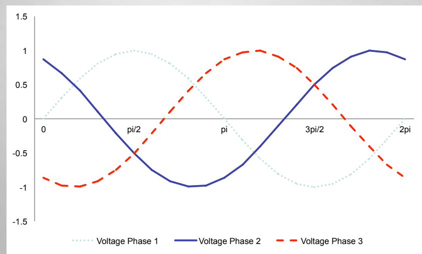
Generator: AC synchronous generator

- A three phase synchronous generator produces three phase voltages with a phase lag of 120° as shown in the figure.



Generator: AC synchronous generator

- The armature reaction of a three-phase generator appears as a steady rotating field called *stator field.*
- The stator field spins at the same frequency as the rotor, meaning that the two fields move into synchronicity and maintain a fixed position relative to each other as they spin
  - This is why this type of generator is called synchronous

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Generator: AC synchronous generator

- The rate of the rotation of the rotor and the frequency of the ac in the synchronous generator is the same, but they are typically specified in different units
  - ✓ ac frequency hertz (Hz) – *cycles per second*
  - ✓ rotor rotation in revolutions per minute (rpm)

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Generator: AC synchronous generator

- The frequency of voltage, which the generator produces, depends on the number of poles in the generator and the speed at which it rotates and is given by the following equation.

$$f = \frac{np}{120}$$

where,
- f = frequency in Hz
- n = speed of rotation in RPM
- p = number of magnetic poles

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Generator: size

- The terminal voltage of most utility generators is on the order of 10 kV. The size (voltage level) balancing
  1. high voltage requires more insulation between terminals and the generator, and can give a hazard of arcing and flashover and requires larger space
  2. low voltage efficient for large amount of power due to higher losses
  - ✓ Highest practical voltage level!
  - The conductors to be designed to safely being able to carry high currents

Generator: design

- Large conductor diameter for lowering the resistance and cooling the conductor
- Larger generators need cooling media
  - ✓ hydrogen gas development in 1940s 1950s lead to development of larger size generators
  - ✓ the temperature tolerance of the insulation material sets the limit
- Geometry of generator design to utilize the magnetic fields most efficient e.g. the air gap between rotor and stator is studied in detail, fringe effects (like leaking flux), distortions, *eddy currents*

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Generator: dc

- There are several options for providing dc field current to the generator rotor.
- For larger synchronous generator this is typically done with an auxiliary dc generator called *exciter*
  - it require its own field current e.g. from self excitation or from a permanent magnet – to overcome losses in the generator rotor
- Alternatives are that the synchronous generator draw its field current from a battery, or directly from the ac grid *rectifying* from ac to dc

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Generator: AC synchronous generator

- A synchronous generator has a set of windings - stator windings which carry the generated current and is connected to the electric power system.
- These winding have very less resistance as they are made up of copper in most cases and have short length.
- However, they have a significant amount of reactance as they are wound in a fashion that creates a lot of inductance in the windings. The reactance depends on the frequency.

  - ➢ In generator specification the reactance is specified as synchronous reactance, which means the reactance of the generator when it is rotating at the synchronous speed.

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Generator: example

- Figure of a single phase equivalent electrical representation of a 3-phase generator.

where
- V_{in} = *internal* voltage of the generator
- V_T = *terminal* voltage of the generator
- L_S = internal winding inductance
- R = internal winding resistance

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Generator: operational control

- The operational control of interconnected synchronous generators in a power system can be understood in terms of the interactive behavior of the generators.
- Basic variables to control a generator:
  1. rotational frequency of the generator - related to the real power it supplies
  2. voltage at the terminals – referred to as the generator bus voltage – related to the reactive power is supplies
- The bus bar (bus *omnibus* – for all) provides a reference point for measurements of voltage, current and power flows - how the generator is interacting with the grid

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Generator & loads: single phase representation

- In this course we will perform load flow study on single phase equivalent circuit.
- This simplifies the calculation without affecting so much on the accuracy as it is assumed that the loads in the system are balanced across all the three phases, which means that the current in all the three phases are equal.
  - ➢generator and loads will be represented by their single phase equivalent circuits.

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Generator: induction generator

- An induction generator *asynchronous generator*
  - ✓operates without a dependent source for its rotor field current
  - ✓the rotor field current appears by electromagnetic induction from the field of the armature current
- The rate of the rotation is not fixed – but varies depending of the power delivered
  - slip speed is the difference with synchronous speed
- Important application for wind turbines, with advantages of
  - can absorb fluctuations of mechanical power delivered by the wind resource
  - typically cost less than synchronous generators

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Generator: inverter

- An inverter is a device that changes from dc to ac meaning that it change - *invert*- the direction of the current
- Typically used when dc is the electrical source e.g. battery, photovoltaic, fuel cell and ac is needed for the usage
- Dc sources are typically at low voltages and therefore also include transformers components
  - e.g. connecting electrical vehicles to the house hold and grid
- Key criterion: wave form – how closely the ac out put are to a sinusoidal wave *harmonic content*

✓Development area for sustainable energy systems!

Loads: induction motor

- Induction motors are the most common loads in the electric distribution system and are used to convert electrical energy to mechanical energy.
- Induction motors are robust appliances with simple construction and are available in single phase and three phase versions.
  - The windings in a three phase induction motor are arranged so that when a three phase voltage is applied to the motor a rotating magnetic field is created. This rotating magnetic field induces current in the rotor, which in turn produces the force on the rotor which makes it rotate.

Loads: induction motor

- The electrical rating of an induction motor is given in Watts or Kilowatts and the mechanical output is measure in terms of torque Neuton-Meter. The relation between the electrical power and the mechanical output power can be given by the following equation.

$$P_{out} = \omega \cdot T$$

where
- P_{out} = output electrical power (W)
- ω = angular frequency (rotation per second)
- T = output torque of the machine in Neuton-Meters

Loads: induction motor

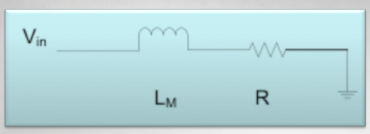
- For any machine the input and output power are related by a factor *efficiency* - depending on the losses in the system
  - For induction motors there are losses in the electrical system in the form of resistive and inductive losses and in the mechanical system in the form of frictional losses.

$$\eta = \frac{P_{in} - P_{out}}{P_{in}}$$

where
- η = efficiency in %
- P_{in} = input electrical power
- P_{out} = output electrical power

Load: example

- For the purpose of load flow study it is sufficient to model the induction motor as shown below.



where
- V_{in} = *internal* voltage of the generator
- L_m = internal winding inductance
- R = internal winding resistance

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Example: EU project G4V

G4V™ Grid for Vehicles

– *Analysis of the impact and possibilities of a mass introduction of electric and plug-in hybrid vehicles on the electricity networks in Europe*
– FP 7 Energy 3.7 million Euro,18 months from January 2010
– RWE leader, 12 parts (Chalmers, Vattenfall from Sweden)
➢ Results presented at final seminar June 30, in Brussels.

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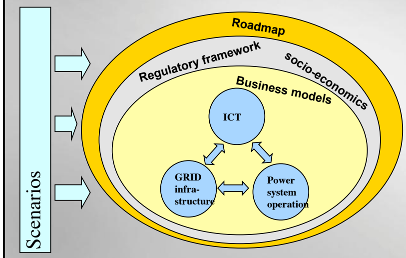
G4V: overall project

Key question: What must we start doing today to enable a mass market for e-vehicles?

Time horizon: 2030 and beyond



- Technical aspects
- Legal framework
- Business models
- Customer satisfaction
- Environmental aspects

Recommendations

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G4V: three scenarios

Investigated Features	1 Conservative World	2 Pragmatic World	3 Advanced World
Charging control	No	Yes, simple charging control	Yes, complex charging control
Prices	As today	Dynamic tariffs	No limitation
Regulation	Conservative	Some liberalization	Optimal situation for EVs
Services	Unidirectional, no services	Unidirectional, all services can be provided	Bidirectional, all services can be provided
Grid infrastructure	Conventional development	Smart grids	Advanced smart grids, virtual power plant etc.
ICT	As today	Innovative	Advanced
Stakeholders	Traditional stakeholders	Traditional stakeholders with new roles	New stakeholders

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G4V: conclusions

Controlled charging

*“**Charging control systems** should be **adjustable flexibly** to suit the market penetration of electric vehicles. Controlling of electric vehicles should take such a form that the needs and restrictions relevant to distribution system operators are also accounted for. DSOs need a detailed picture of all electric vehicles active within the grid. The DSOs must be given the possibility in the event of an emergency (grid congestions) to intervene and control electric vehicles.”*

*“Vehicle-to-Grid (**V2G**) still appears **not to be a profitable business** at the moment. **Uni-directional charging** should therefore be pursued and **promoted** first. Bi-directional (de-) charging should be analysed further and looked at again with higher numbers of electric vehicles.”*

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G4V: conclusions

Charging infrastructure

As regards charging infrastructure, ***home charging*** *represents the* ***most cost-effective*** *solution. This should be pushed (up to charging ratings of 3.7kW) and augmented by a* ***network of public (fast) charging stations****.*

ICT

ICT represents no hurdle *to integration of electric vehicles into the power grids. No fundamentally new technologies are needed. Application of ICT as a means to implement charging control systems* ***may reduce the (negative) effects*** *of electric vehicles* ***on the grids****. Potential synergies with SmartGrid functionalities should be considered in further development of ICT.*

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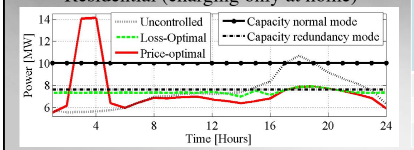
Example: PEV study*

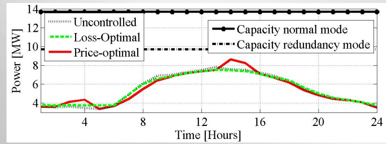
Residential (charging only at home)



Peak demand increase [%]	Residential area
Uncontrolled	21 %
Price-optimal	78 %
Loss-optimal	0 %

Commercial (charging at home and at work)

Peak demand increase [%]	Commercial area
Uncontrolled	3.5 %
Price-optimal	14.5 %
Loss-optimal	0 %



[1] D. Steen, T. Le, O. Carlson and L. Bertling, "Assessment of Electric Vehicle Charging Scenarios Based on Demographical Data." Accepted to be published in IEEE Transaction on Smart Grid Technology.

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Closure: energy in move no electricity energy

What is this?

Picture: Lina Bertling , ..., February 2003.

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L7-L8 Transmission and distribution

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Lecture in ENM125 SEPS
2012-11-08, Chalmers, Göteborg

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L7&L8: transmission and distribution

Summary T&D:

- Repetition AC – power factor
- System structure
- Three Phase Transmission
- Transformers
- Power Lines
- Loading
- Voltage control

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AC: power – repetition

- Power $P = IV = \{Ohm\acute{}slaw\} = I(IR) = I^2 R$
- Power with current and voltage varying over time with a sinusoidal function with the angular frequency ω (rad/s) with possible phase shift ϕ (cosϕ = power factor)

$$I(t) = I_{\max}\sin(\omega t + \phi_I) \quad V(t) = V_{\max}\sin(\omega t + \phi_V)$$

  - The root mean square (rms) value

$$I_{rms} = 1/\sqrt{2}\cdot I_{\max} \quad V_{rms} = 1/\sqrt{2}\cdot V_{\max}$$

  - Impedance $Z = R + jX$ where the conductance consists of capacitance and inductance

$$X_C = -\frac{1}{\omega C} \qquad X_L = \omega L$$

  - Admittance $Y = 1/Z$ with $Y = G + jB$

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AC: power – repetition

- For a transmission line
  1. dissipated power – *a resistive wire* - $P = I^2 R$
  2. transmitted power – *extended terminals* - $P = IV$
- Here V refers to the voltage drop – *between two ends not the same as the* line voltage – *voltage to ground or between conductors*

AC: power – repetition

$$P = IV$$

voltage is a measure of energy per unit charge
"how many electrons that are passing through"
*
current is the flow rate of charge
"amount of energy the electrons are carries"
=
Energy is carried in the sense that an electron that has been propelled to a higher voltage level has the potential to do more work as it returns to the ground

*(charge/time*energy/charge=energy/time)*

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AC: power – repetition

- Complex power $S = I^* \cdot V$ with S= apparent power
- Power relationship $P(t) = I(t)V(t)$
- Average power is typically of interest P_{av} (watts)
  - purely resistive load $P_{av} = I_{rms}V_{rms}$
  - with reactance - current lagging Φ after voltage
    $P_{av} = I_{rms}V_{rms}\cos\phi \Leftrightarrow \frac{1}{2}I_{\max}V_{\max}\cos\phi$
  - the power actually transmitted or consumed by the load – *real power, active power, true power*
- Apparent power $S = I_{rms}V_{rms}$(VA)
- Reactive power - *difference between the real and apparent power –* $Q = I_{rms}V_{rms}\sin\phi$ *(VAR)*
  - *The component of power that oscillates back and forth through the lines not getting dissipated*

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AC: power – repetition

- The most loads are inductive rather than capacitive
  - Different power factors of individual loads are combined into an aggregated power factor, typically a total value of 0.9 lagging
- All reactive power "consumed" in a grid has to be "supplied" by generators or capacitive devices – *improve the power factor*- how these are located is related to operational control of synchronous generators (L5&L6) and voltage control (L7&L8)
- Reactive power with property occupying the lines without doing useful work "the cholesterol of power lines"

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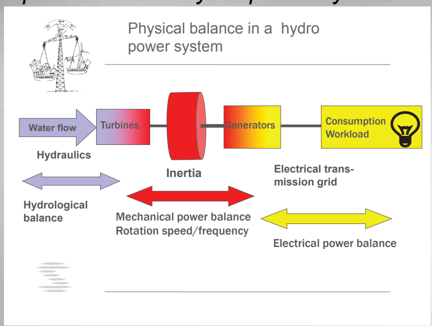
L7&L8: Balance

Example: balance in hydro power system



Pictures: Svenska Kraftnät, Presentation Sture Larsson 2012-10

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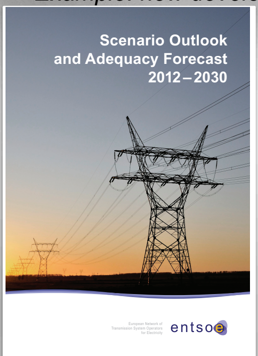
T&D: Example planning

Example: new developments of the grid



- ENTSO-E published 2012 ten-year network development plan
  - ✓ 80% of the identified 100 bottlenecks are related to the direct or indirect integration of renewable energy sources
  - ✓ larger, more volatile power flows, over longer distances across Europe
  - ✓ Extending the grid by 1.3% a year enables adding 3% generation capacity
- More information **www.entsoe.eu**

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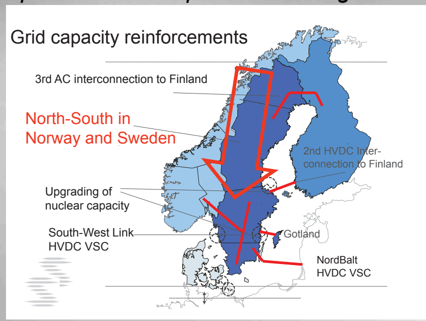
T&D: Example planning

Example: new developments of the grid in Sweden



Pictures: Svenska Kraftnät, Presentation Sture Larsson 2012-10

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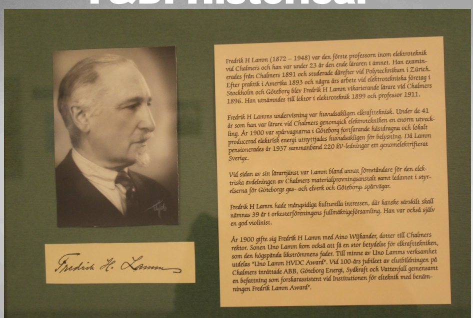
T&D: Historical



- Fredrik Lamm the first Professor in Electric Engineering at Chalmers, 1911 and the father of Uno Lamm who is the *father of HVDC*

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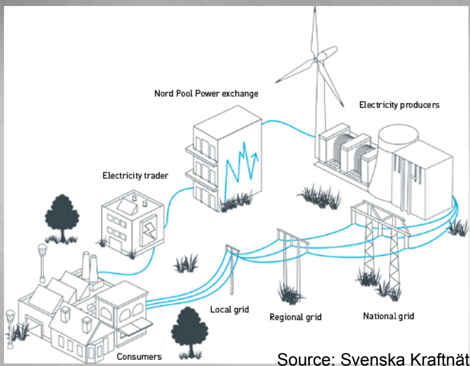
T&D: Yesterday & today

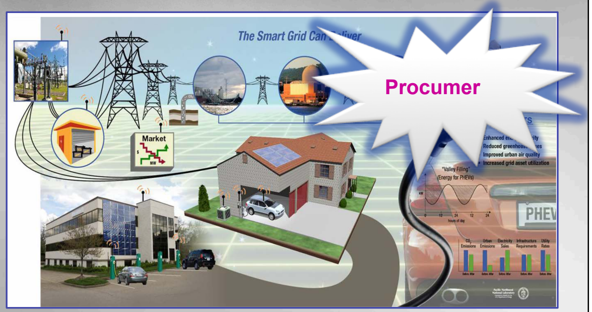
- "The purpose of the electric energy system is to generate electric energy in sufficient quantities to the load centers, and then distribute it to the individual customers in proper form and quality and that the lowest possible ecological and economic price" (*Electric Energy Systems Theory: An Introduction, Olle Elgerd, McGraw-Hill, Electrical and Electronic Engineering Series, 1971*)
- "Electric energy is the most popular form of energy, because it can be transported easily at high efficiency and reasonable cost" (Hadi Saadat, Power System Analysis, Third Edition PSA publishing, 2010)

T&D: Traditional outlook



Source: Svenska Kraftnät

T&D: Future outlook



Key words: Flexibility, renewables, ac/dc, energy storage

Picture source http://www.oe.energy.gov/DocumentsandMedia/smartgrid_diagram.pdf

T&D: system structure

Historical note

- Since beginning of the commercial power system in 1880s the trend has been towards lager and interconnected systems and expanding geographical into large synchronous grid
- Motivations
  - ✓Economics of scale – towards larger units
  - ✓Reliability enhancement – pooling reserves
  - ✓Improvement of Load factor – large customer areas
- However – long transmision lines introduce problem of stability, more interdependence means greater vulnerability to disturbances far away

T&D: system structure

Enhancement of Load factor

- The load factor relates to the ratio of a load´s actual energy consumption over a period of time to the maximum amount of power it demands at any one instant.
- Cost of building the supply infrastructure is related to the maximum amount of power (i.e. capacity of generators and transmission lined) whereas the revenues from electricity sale are related to the amount of energy (kilowatt-hours) consumed.
- Smooth consumption profile by aggregating loads

T&D: system structure

Structural features

- High voltages crucial for power transmission over long distances, however safety prohibits use of equipment at high voltages
- Use of transformer makes it possible to operate different parts of the system at different voltages
- This result in the dividing into Transmission and distribution systems (T&D) – e.g. high voltage, medium voltage and low voltage
- Normally one-line diagram representation

T&D: system structure

Topology

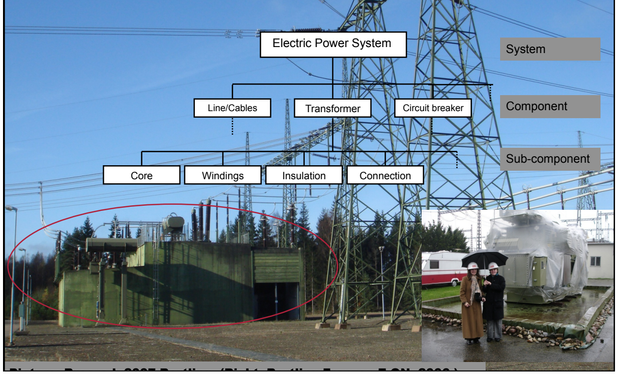
- T&D system: topology *how the lines are connected*
  - ✓ power flow from high to low voltage
- Radial configuration
  - ✓ power flow one direction
  - ✓ typically used for distribution systems
- Network configuration
  - ✓ more interconnected
  - ✓ power flow several directions
  - ✓ redundancy with several paths
  - ✓ more challenging for isolation and protection
  - ✓ typically for transmission systems

T&D: system structure

Differences

- There are major differences in system design in different countries. Europe compared with US with typically:
  - ✓ in Europe fewer and larger transformers than in US placed in separate locations rather than mounted in the poles like in US
  - ✓ underground cables in cities in Europe compared to over head lines in US – related to voltage level and cost
  - ✓ generally in more populated areas higher voltage levels used and system optimized around load level, compared rural areas (location of customers and size of are in focus) system lay out

System structure – stations and substations



T&D: system structure

Stations and substations

- Transmission and distribution stations
  - ✓ interface between different levels or sections of the power system
  - ✓ capability to switch or reconfigure connections
- Central components of a substation
  - ✓ transformer – interface between high and low voltage parts of the system
  - ✓ circuit breakers – automatic protection device in event of failure
  - ✓ switches – control devices opened or closed to establish or break a connection under normal conditions
  - ✓ capacitor banks – to provide voltage support

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T&D: system structure

Reconfiguring the system

- Operating a T&D system involves switching connections among high voltage circuits. These can be made remotely from the computer screen at a switching center through a supervisory control and data-acquisition (SCADA) system
- Reasons for switching - contingencies, work clearance, restoration following outage
- Restoring load – reconnect sections of load one at a time in a given order to keep stability
- Under extreme over load conditions load can be selectively disconnected – shed
- Load balance – redistribute loads – to increase the operating efficiency by minimizing losses

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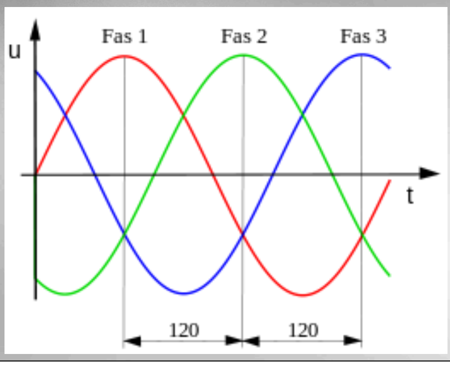
T&D: example three phase



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T&D: three phase

Rationale

- Power generators having three sets of outgoing windings or phases, each carrying an a.c. of same magnitude but separated in timing by one-third of a cycle, 120 degrees from the other two-
  - ✓ Rationale for this system is that it result in <u>constant torque on its rotor</u> as opposed to pulsating torque (that is the case for one or two phase systems)
- Economy in transmission using a.c.
  - ✓ three phase permits use of less wires – no return conductor needed
  - ✓ less conductor capacity compared to one phase.

T&D: three phase

Rationale

- Generally an electric circuit requires two conductors between the power source and the load: one for the current flow out and one for it to return. In principle this is true both for a.c. and d.c.
- For d.c. sometimes one conductor is enough and the ground could be used for return current – ground return
- For multiphase a.c. the return conductors of each of the three circuits can be combined into a single and the current would be zero (three phases are exactly 120 degree, maxima)

T&D: three phase

Balancing loads

- Balancing loads among individual phases is needed to adjust to fulfill
  - ✓ the assumption that the impedance or total load connected to each phase is identical, making the amplitudes of the three phases equal, needed for the non need of ground return conductor
- The challenge is to distribute the customers among the phases as evenly as possible so that the combined load on each phase is about the same
- Imbalances of above 10% . Typically greater close to customers and reduce with aggregation
- When imbalances are expected a return conductor is introduced – a neutral wire.

T&D: three phase

Per-phase analysis

- Based on the assumption that the voltages and currents in the three phases are equal the analysis of the three-phase circuit can be simplified to a single phase that is representative of what happens in all three.
- One-line diagram are often used.

T&D: three phase

DC transmission

- In some situations it is beneficial to use d.c. transmission despite having to convert between a.c.
- Conversion between a.c. and d.c. is made by thyristors which are normally costly
- D.c. eliminate the problem of stability limit which occurs for transmission on long lines with a significant inductance like in a.c.
- Thermal limitations due to resistance
- Also use of d.c. to connect two a.c. systems which are not synchronous

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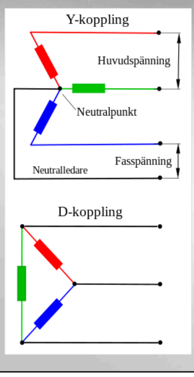
T&D: transformers



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T&D: transformer

- An individual load generally require two conductors to connect to. When power is delivered in three phases there are two choices for connection: A load can be connected between
  - ✓ one phase and ground - wye
  - ✓ one phase and another phase – delta
- In each case three phases will supply three separate loads
- The magnitude of the phase-to-phase voltage is greater than the voltage to ground by a factor of about 1.73 (root of 3)

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T&D: conductors

- Conductors of overhead lines
  - typically of aluminum (light, relatively inexpensive)
  - often reinforced with steel for strength
  - weight is a concern
- Conductors of underground lines
  - cables with insulation are used
  - heat dissipation is an issue but not weight
  - copper is used as main material (more expensive but lower resistance than Al)

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T&D: conductors

- From L1 Resistance is given by R=ρl/A. The electrical resistance of a power line thus increases linearly with distance and decreases with the conductor cross section.
  - ➢ larger conductors give lower resistance (line losses)
- Note however that the resistance is less important in context of power flow and stability. For the line in overall it is the inductive reactance which dominate the impedance.
  - E.g. approximations made that lines have zero resistance and only reactance – *lossless line*
- Conductors also have capacitance. Especially for coaxial cables.

T&D: conductors

- In summary a line can be characterized in terms of an equivalent resistance and inductance (in series), (in parallel with) a capacitance on a per-length basis.
- The ratio of series impedance (resistance+reactance) and shunt admittance (capacitance) is called the characteristic impedance. If resistance is negligible it reduces to include capacitance and reactance and is called *surge impedance* of a line
  - A voltage signal can be transmitted with minimal loss if the resistance connected to the end of a line is equal in magnitude to the lines surge impedance – this is used in telecommunications
- *Surge impedance loading* (SIL) used in power system

T&D: conductors

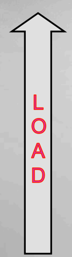
- *Surge impedance loading* (SIL) used for power transmission
  - an amount of real power in MW that is given by the square of transmission voltage divided by the surge impedance. The SIL states the amount of real power transmission in the situation where the line´s inductive and capacitive properties are completely balanced.
- To system operators the SIL provides a benchmark
  - if the power transmitted along a line (at unity power factor)
  - is less than the SIL; the line appears as a capacitance that injects reactive power (VARs) into the system;
  - exceeds the SIL (more common situation);the line appears as an inductance that consumes VARs and consequently contributes to reactive losses

T&D: conductors

- Conductors on transmission lines are sometimes bundled, meaning that that the electrical conductor is made of several wires.
- One reason for bundling conductors is to reduce so called *corona* losses and reducing inductance

T&D: loading

- The loading of the lines is as follows:



  - Heavy load
    - Inductive behaviour
    - Consumes reactive power
  - Surge load impedance
    - Ohmic behaviour (resistive)
    - Balanced reactive power (zero)
  - Light loads
    - Capacitive behaviour
    - Generates reactive power

T&D: loading

- The power flow through the line can be limited by three main factors:
  - ✓Thermal overload
  - ✓Voltage instability
  - ✓Transient instability

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T&D: loading

Thermal overload

- Cause: excessive current flowing in the circuit (I^2R)
- Thermal expansion → conductor sags
- Two limits are usually specified:
  1. Nominal rating: flows on a continuous basis
  2. Emergency rating: flows on extreme circumstances (e.g. Contingencies of parallel circuits) for a limited amount of time (e.g. 30 min)
- Factors:
  - Conductor construction (diameter, core, strands, etc)
  - Conductor resistance
  - Conductor surface condition
  - Location
  - weather

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T&D: loading

Voltage instability

- Occurs when the reactive power required to maintain voltages within acceptable thresholds is larger than that available at one or more buses
- Reasons:
  - Increase in the reactive demand
    - ✓I^2X_L are to be considered
  - Decrease in reactive power supply
    - ✓Generator
    - ✓Synchronous condenser
    - ✓Shunt capacitor
    - ✓Static VAr compensator (SVC)

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T&D: loading

Transient instability

- Dynamic problem that arises after faults on:
  - Transmission lines
  - Generators
  - Substations
- During fault $V \rightarrow 0$; therefore $P_e = 0$; however the mechanical power on the shaft of the generating units remains constant
- The generating units accelerate

T&D: voltage control

- Voltage in power system is controlled both at generators and along the T&D
- There are two methods for controlling or supporting the voltage in the T&D
  1. Transformer taps
     - load tap changer (LTC)
     - voltage regulator
  2. Reactive power injection (typically capacitance)
     - capacitors (shunt (parallel) capacitance,
     - static VAR compensators (SVCs)
     - synchronous condensors

T&D: voltage control

Reactive power injection

- The effect of voltage control through capacitors can be understood in terms of a reduction in the line drop as a result of injecting reactive power.
- Compensating for the inductive load with nearby capacitance brings the power factor of the area closer to unity
- This means a reduction in current, since a smaller apparent power is needed to deliver the real power demand by the load, which in turns causes a reduction in the voltage drop along the line according to Ohm´s law

T&D: voltage control

Reactive power injection

- In terms of the circulating current required to serve a reactive load which has to travel between where reactive power is “generated” and “consumed”, effectively swapping stored energy between electric or magnetic fields during certain portions of the cycle.
- If reactive power is injected at a generator bus to match the reactive demand this circulating current must travel throughout the transmission system to reach any give load which is not needed if the reactive power is injected locally

AC power: complex power

Reactive power injection

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L9-L12 Power flow analysis

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Lecture in ENM125 SEPS
2012-11-13, Chalmers, Gothenburg

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L9-L12: power flow analysis

✓ *What is the present operating state of the system given certain known quantities?*

- *Chapter 6 from* Power System Analysis, Hadi Saadat (1999) – for further reading and exercise.

- The PF problem
  - network and choice of variables
  - three type of buses
    1. generator bus
    2. load bus
    3. slack bus
- The PF equations
- The PF solution methods
  1. Newton-Raphson
  2. Gauss-Seidel
  3. Decoupled PF

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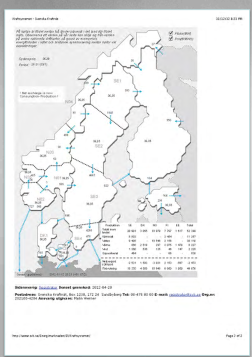
Power flow: Example



- *The current power system balance and power flow*
  - *updated every minute* *www.svk.se*
  - *the flow between countries*
  - *elspotpris - electricity trade in the Nordic countries - Nord Pool Spot.*
  - *Example Sweden (MW)*
    - *total production* 20 901
    - total export 18 370
    - average 36.38 €/MW

Source: Svenska Kraftnät, 121112, 20.23

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PF: introduction

- Power flow analysis describes the operating state of an entire power system - Load flow analysis
  - ✓ *Given the amount of power delivered and where it comes from power flow analysis tells how it flows to its destination*
- Given certain known quantities power flow analysis is used to determines other unknown quantities
  - ✓ the equation systems can not be solved analytically – no closed-form solution
  - ✓ experimental solutions by simulations of the system and successive approximations – iterations are made

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PF: introduction

- Mathematical algorithms of successive approximation by iteration or repeated application of calculation steps
- The steps represent a process of trial and error
  1. assuming initial numbers for the whole system,
  2. comparing the relationships with the laws of physics
  3. repeatedly adjusting the numbers until the entire array is consistent with both physical law and conditions stipulated by the user

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PF: introduction

- Variations on what types of information that are chosen as input and output
- Different computational techniques used by different programs
- More advanced programs analyze multitude of hypothetical situations/system conditions, and rank them according to some criteria *optimal power flow* (*OPF*)
- This course aims to answer:
  - ✓ What is power flow analysis?
  - ✓ How is it useful?
  - ✓ What can it and what can it not do?
  - ✓ AND to make simple own calculations

PF: power flow problem

Network

- For analyze of any circuits - references are those points which are electrically distinct
- These reference points are called *nodes* in larger power systems called *busbar* – physical bus bar where components meet.
- The buses are connected by transmission lines. A one-line diagram is representing the power system.
- The impedance of the line is typically assumed to be constant – no need for geographical accuracy
- The network topology is different with change in switching operations, power flow analysis of a fixed topology

PF: power flow problem

Choice of variables

- Two basic quantities that describes the flow of electricity
  - ✓ voltage and current.
- For d.c. both voltage and current vary from one location to another in a circuit and they are everywhere related. Generally assumed that impedances of the circuit are known.
- For a.c. more complicated – time added as dimension. An ongoing oscillation is described in power flow analysis: *root-mean-squared* (rms) and *phase angle* are used.
- It may be impossible to find one unique solution.

PF: power flow problem

Choice of variables

- In practice current is unknown at all buses
- Voltage would be known for some buses
- The amount of power going into or out of a bus is known
- Power flow analysis consists of
  - taking all the known real and reactive power flows at each bus, and those voltage magnitudes that are known, and from this information calculate the remaining voltage magnitudes and voltage angles.
  - to calculate the current magnitudes and angles from the voltages.

PF: power flow problem

- Different types of buses based on their actual, practical and operating constraints
  - real (P) and reactive power (Q)
- Three types:
  1. Generator bus - P-V bus
  2. Load bus
     - P-Q bus
     - Assumed power consumption is given
  3. Slack bus – P is specified for all than one generator

PF: power flow problem

- Balancing power means that all generators in the system collectively must supply exactly the amount demanded by the load, plus the amount lost on transmission lines.
- A mismatch of
  - real power lead to that the system loses synchronicity
  - reactive power lead to voltage collapse

PF: power flow problem

Balancing active

- How can we know ahead of time what the transmission losses are going to be?
  - ✓ after performing PF we know the current flows, this combined with the line impedances gives the losses.
  - ✓ the amount of losses will depend on the dispatch, or amount of power coming from each generator

PF: power flow problem

Active balancing - in practice:

- knowing the total demand P by the load, we begin by assuming a typical percentage of losses say e.g. 5%. We now dispatch all the generators in the system in the way so that the sum of their output matches the expected total real power demand.
- We make the assumption that this uncertainty in losses constitutes a sufficient small amount of power that a single generator could provide it – so we choose one generator whose output we adjust depending on the systems needs
  - it "takes up the slack" – slack bus or swing bus.

PF: power flow problem

Reactive balancing

- Analogous problem: how much total Q our generators should produce, not knowing ahead of time what the total reactive losses for the system will turn out to be
- Here the generator is instructed to maintain a certain voltage magnitude at its bus. The voltage is continually and automatically adjusted through the generator´s field current and is therefore a straight forward variable to control.
  - when the combined generation of reactive power by all generators in the system matches the amount consumed, their bus voltage holds steady.
- P and Q are defined for each generator buses except for one slack bus assigned the voltage regulation where Q are adjusted as needed but in practice V is the control variable

PF: power flow problem

Slack bus

- Real power balance result in steady frequency e.g. 50Hz
- A constant frequency is indicated by an unchanging voltage angle, which for this reason also is called power angle, at each generator.
- When more power is consumed than generated the generators rotation is slowed down and their electrical frequency drops, and their voltage angles falls farther and farther behind.

PF: power flow problem

Slack bus

- In power flow analysis the slack bus is the bus mathematically assigned to do the load following
- Physically it means to hold the voltage angle constant
- Assign to the slack bus a voltage angle θ
  - θ is the power angle
  - the numerical value has no physical meaning but the implication that this angle will not change as the system operates
  - physically corresponds to the phase differences between voltage curves
  - gives a reference point and the choice of value is a matter of convenience: e.g. "zero"

PF: power flow problem summary

Variables in the power flow analysis

Type of bus	Knowns	Unknowns
Generator	Real power (P) Voltage magnitude (V)	Voltage angle (θ) Reactive power (Q)
Generator/ load	Real power (P) Reactive power (Q)	Voltage angle (θ) Voltage magnitude (V)
Slack/ reference	Voltage angle (θ) Voltage magnitude (V)	Real power (P) Reactive power (Q)

PF: power flow problem summary

- In summary three different buses in power flow analysis:
  1. P,V (generator bus)
  2. P,Q (load bus)
  3. Θ, V (slack bus)
- Given input data: these two input variables per bus, knowing all fixed properties of the system (e.g. impedances, a.c. frequency) – the operating state of the system can be decided.
- The unknown variables can be decided. Then the currents can be calculated using Ohm´s law.

PF: power flow equations

- The *power flow equations* state how the variables in the different buses are related
  - one equation for each node/branch in the network referred to as bus
  - the complex power injected or consumed is the product of the voltage and the current flowing into or out the bus *i*

$$S_i = V_i I_i^*$$

  - The power is choosen positive either going into or coming out of a node – just be consistent

PF: power flow equations

- Make use of the information we have of the network – impedances of the transmission links between the nodes
  - ➤ Ohm´s law $V = IZ \Leftrightarrow I = VY$

    where $Y = 1/Z$ admittance
- The admittances of all the links in the network are summarized by the admittance matrix Y where the lower case indicates the matrix element that connects nodes i and k $y_{ik} = g_k b_{ik}$
  - ➤ total currents coming out of any node $I_{ik} = V_k y_{ik}$

PF: power flow equations

- The resulting complete statement of the complex power for node i can then be written as:

$$S_i = V_i I_i^* = V_i \left(\sum_{k=1}^{n} y_{ik} V_k \right)^* = V_i \sum_{k=1}^{n} \left(g_{ik} - j b_{ik} \right) V_k^*$$

$$\Leftrightarrow \sum_{k=1}^{n} |V_i||V_k| e^{j(\theta_i - \theta_k)} \left(g_{ik} - j b_{ik} \right)$$

$$\Leftrightarrow \sum_{k=1}^{n} |V_i||V_k| \left[\cos\left(\theta_i - \theta_k\right) + j \sin\left(\theta_i - \theta_k\right) \right] \left(g_{ik} - j b_{ik} \right)$$

PF: power flow equations

- The resulting complete statement of the complex power for node i can then be written in the real and imaginary part as:

$$P_i = \sum_{k=1}^{n} |V_i||V_k| \left[g_{ik} \cos\left(\theta_i - \theta_k\right) + b_{ik} \sin\left(\theta_i - \theta_k\right) \right]$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_k| \left[g_{ik} \sin\left(\theta_i - \theta_k\right) - b_{ik} \cos\left(\theta_i - \theta_k\right) \right]$$

PF: power flow solutions

- There is no analytical, closed-form solution, for the power flow equations, numerical approximations must be used ”trial and error” approach
- Assume certain values for the unknown variables
  - e.g. a *flat start* assuming initial values of all voltage angles to be zero and the voltage magnitude to be 100% of the nominal value or 1 p.u.
- Input variables i the power flow equations. There will be a discrepancy between reality and calculated values - mismatch . Repeat iterations until required degree of precision.
  - direction of error needs to be decided

PF: power flow solutions

- There are several standard techniques of iterative methods to solve power flow equations
  - Newton-Raphson (NR) – *most common.*
  - Gauss-Seidel (GS)
- The choice of technique is a trade off between
  - number of iterations required to reach solution
  - amount of required computational time for each iteration
  - degree of certainty with which the solution is found

PF: power flow solutions

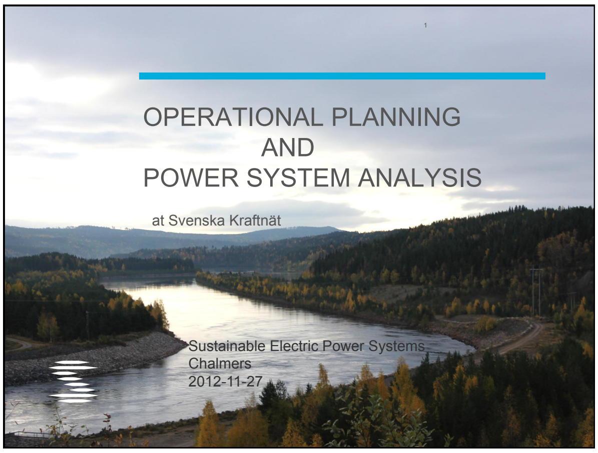
- To get information about the direction of the error *partial derivatives* of the power flow equations are used – their rates of change with respect to individual variables
  - e.g. real and reactive power respect to voltage angle or magnitude
  - each of these combinations is a matrix - Jacobian matrix

$$\frac{\partial P}{\partial \theta}, \frac{\partial P}{\partial V}, \frac{\partial Q}{\partial \theta}, \frac{\partial Q}{\partial V}$$

CHALMERS Chalmers University of Technology

PF: power flow solutions

- Decoupled power flow
  - ”decoupling” refers to separation of the two pair of variables
    1. P and θ
    2. Q and V
  - assuming small derivatives to be zero the Jacobian matrix can be simplified and needed computations are reduced
- Fast-decoupled power flow are methods using
  - additional assumption that the voltage magnitude profile is flat



About the lecturer

- Sabina Stenberg
- Civil Engineering in Energy Systems
  Uppsala University, graduated Feb 2012
- Working at SvK since March 2012
- Operational Planning Department
  Power System Analysis

AIM OF THE LECTURE

A grasp on…

- The role of Svenska Kraftnät in the energy system
- Operation of the national grid

Agenda

Introduction to Svenska Kraftnät

The Swedish power system

The control center and its functions

Operational planning

Power system analysis

Examples of power system analysis using the simulator ARISTO

SVENSKA KRAFTNÄT

> Public utility

> Mission

SVENSKA KRAFTNÄT

> Established in 1992

> State owned utility

> Financed through fees for the use of the grid

SVENSKA KRAFTNÄT'S MISSION

> **Maintain the grid**

> **Expand the grid** if and where more power is consumed or produced
Example: Strengthen the grid for wind power connections

> **Operate the grid**
Balance frequency
Balance voltages

THE SWEDISH POWER SYSTEM

> National, regional and local grid

> Synchronous area in Scandinavia

> Distribution of production and consumption

> Bidding areas in Sweden

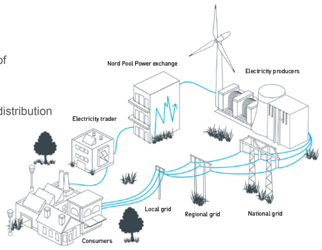
> Tie lines and congestion

National grid

> **National grid**
> Transmission of electricity

> **Regional grid**
> Transmission/distribution

> **Local grid**
> Distribution



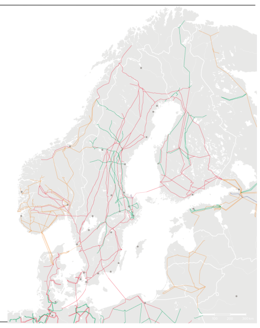
Nordel system

> **Synchronous system:**
> Same frequency throughout the system

> **Nordel system:**
> Sweden
> Norway
> Finland
> Sealand (Denmark)

> Within the system: AC

> Between synchronous systems: HVDC

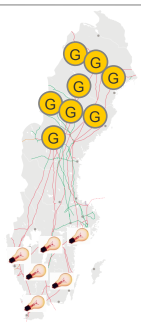


The Swedish national grid

> Production up north

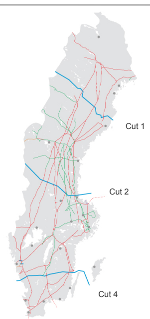
> Consumption in the south

> Challenge to transmit the power from north to south



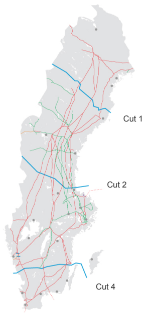
Cuts in the grid

> Cut = part of the grid over which a limited amount of power can be transmitted



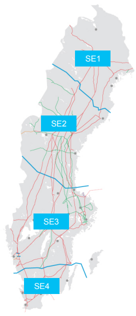
Cuts in the grid

- Dynamic limits
- Thermal limits
- Cut 1: 3300 MW
- Cut 2: 7300 MW
- Cut 4: 5400 MW



Bidding areas in Sweden

- Since November 2011
- Congestion in the grid leads to different price in the different areas
- Same price in the country 80% of the time

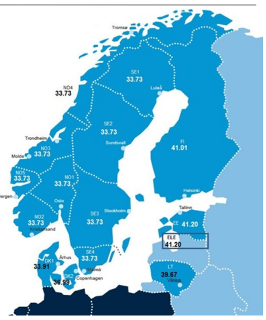


Price in Scandinavia

2012-11-20

€/MWh

Why is the price higher in Finland?

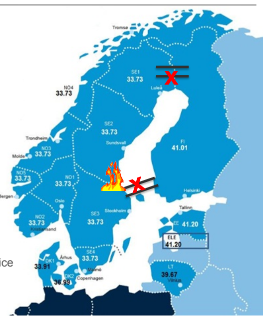


Source: nordpoolspot.com

Price in Scandinavia

2012-11-20

- Outage of one of two northern tie lines
- Outage of one of the HVDC links
- Congestion leads to price difference!



Source: nordpoolspot.com

THE CONTROL CENTER

> The different functions in the control center

> Frequency regulation

> Voltage regulation

Control centers at Svenska Kraftnät

> Two control centers:
Sollefteå
Sundbyberg

> Operating the grid 24/7

Functions in the control center

Dispatchers

Operating Balance Service

Grid Supervisor

System analyst

IT

BTI Operating Balance Service

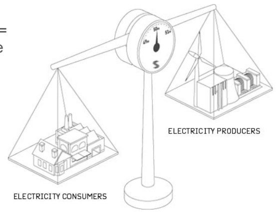
> Maintaining the frequency at 50 Hz

> Balancing production and consumption

Frequency regulation

> Loss of production = frequency decrease

> Loss of load= frequency increase



http://www.svk.se/Start/English/About-us/Our-Activities/System-Responsibility/

Dispatchers

> Maintaining the voltage

> Performing the switching of objects in the grid

Voltage regulation = Balancing reactive power

> Inserting reactive power to the system increases the voltage

> Removing reactive power from the system decreases the voltage

Voltage regulation

> Synchronous generators are the pillars of voltage stability!
>
> > Rotational energy
>
> > Excitation system

> Shunt capacitors and reactors help manage the deviations

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Voltage regulation

Shunt capacitors → Produce reactive power → Increase of voltage ↑

Reactors → Consume reactive power → Decrease of voltage ↓

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Power system analyst

> Back office for the grid supervisor
> Calculating the transfer capacities over cuts and tie lines
> Analyzing any urgent outages

27

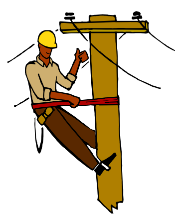
OPERATIONAL PLANNING

> Outage Planning
> Power system analysis

28

Maintaining the grid

> Planned outages in the grid for maintenance and projects are necessary
> Most work on the grid is performed during the summer



Outage Planning

> Finding a date for the job to be done
  > Distribution in time of outages
  > Entrepreneurs available
  > Co-planning in the Nordic countries

> Analysis of the outage
  > Safe to take the outage?
  > Will it lead to reduction of the transfer capacity?

POWER SYSTEM ANALYSIS

> n-1

> Dimensioning fault

> PV curves

> Tools for analyses

Deterministic mindset

> n-1

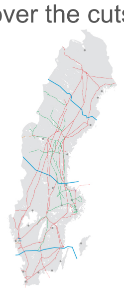
> Dimensioning fault

Deciding capacities over the cuts

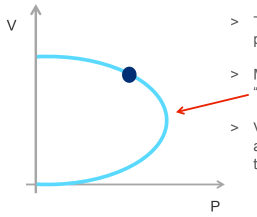
> Overload limits

> Dynamic limit

> Voltage collapse limit



Voltage stability



PV curve

> The relation between power and voltage

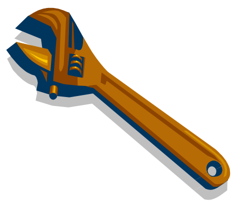
> Maximum power transfer at "the knee" of the curve

> Voltage falls uncontrollably after the knee = collapse of the system

Tools

> Spica - static

> ARISTO - dynamic



Spica

> Static load flow program
  > Newton Raphson iteration

> Estimates
  > Snapshot of the grid from the SCADA system
  > Data on flows, voltages, currents etc.
  > Every 15th minute

Voltage collapse calculations

> PV curves for each cut
  > Intact grid
  > Contingencies

> Result:
Dimensioning fault and the limit of transfer through the cuts

> Spica calculates the voltage collapse limits in the control room every 15th minute

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ARISTO

= Advanced Realtime Interactive System for Training and Operation

> A real time power system simulator

> Used for training and for studying transients

ENM125: Sustainable Electric Power Systems

Lectures L15-L16
An Overview of Markets Operation: Nordic Perspectives

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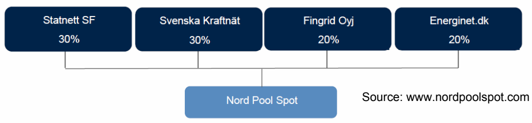
Content

- Markets for electricity
  - Physical trading
  - How spot market works
- Keeping the market to function:
  - Network management
    - Power flow management principle
    - Market-based congestion management
  - Keeping the system in balance
    - Generation and load balance
    - The balancing market

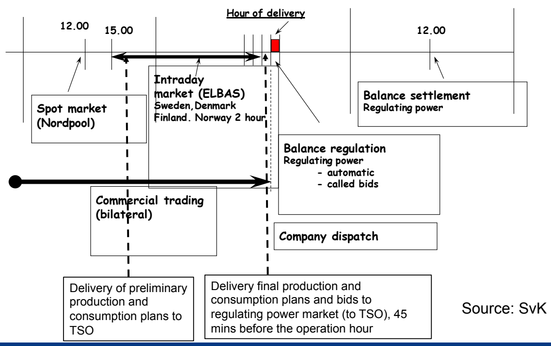
Market for electricity: Nordic power exchange

- Market place for sellers and buyers of electricity
- Nord Pool Spot operates the leading power market in Europe
  - Day-ahead and intraday markets
  - 350 companies trade on the market
- In 2010 the group had a turnover of 311 TWh
  - 74 % of the total consumption in the Nordic countries were traded on NordPool Spot
- Owned by Nordic transmission system operators (TSOs)



Source: www.nordpoolspot.com

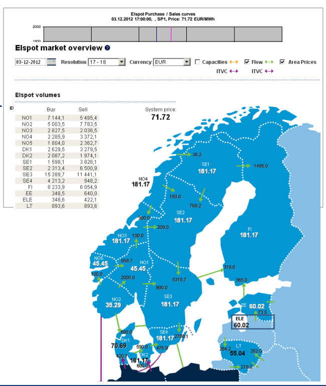
Physical trading of electricity



Source: SvK

How does the spot market work?

- Trade in hourly contracts for the 24 hours of the coming day
- Every morning, submit bids (sells and buys) for each hour of the following day
- Market closes for bids at 12:00 hours. Selling curve and buying curve are constructed (by Nord Pool): system price and market volume cleared (determined)
- Players are informed about preliminary price and volume by 12:45 hours



Content

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  - Physical trading
  - How spot market works
- Keeping the market to function:
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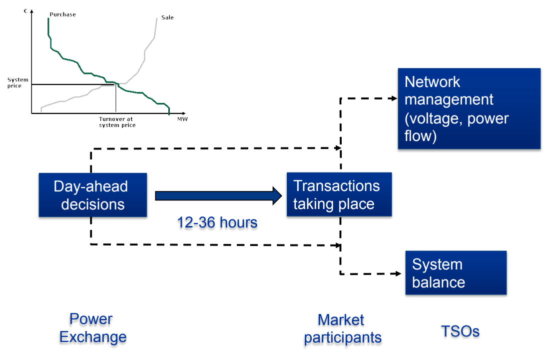
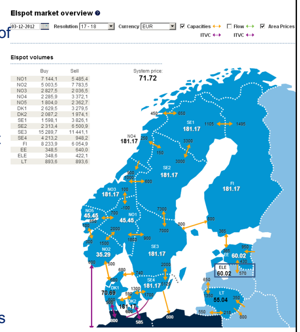
Keeping the market to function



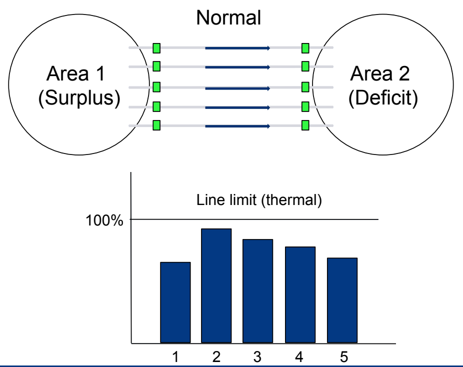
Power Flow Management/Control

- A major problem with the AC power system operation is the limited capacity of the transmission system
  - lines/transformers have limits
    - Thermal limit
    - Voltage stability limit
    - Transient (angular) stability limit
- Control the power flow in an AC transmission system
  - ensure to meet system operational objectives (e.g., min loss, min cost, etc.)
  - to bring the actual line flows below limits under normal condition
  - change power flow under dynamic conditions (subjected to disturbances such as sudden increase in load, line trip or generator outage) to ensure system stability.

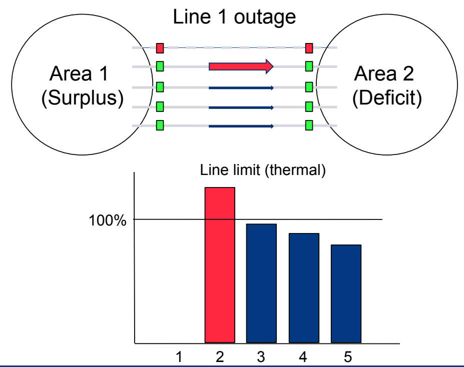


nordpoolspot.com

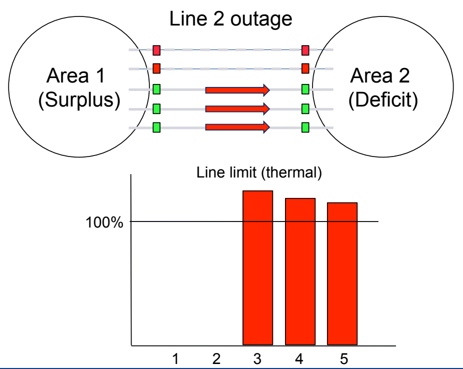
Power Flow Management: Example



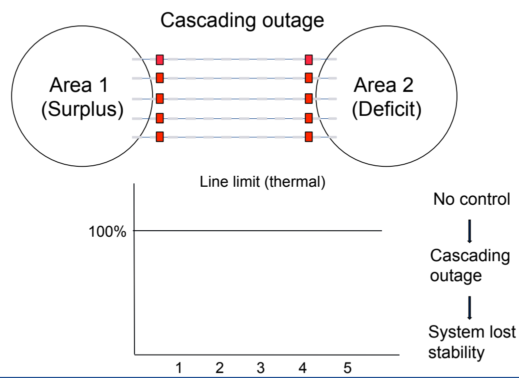
Power Flow Management: Example



Power Flow Management: Example

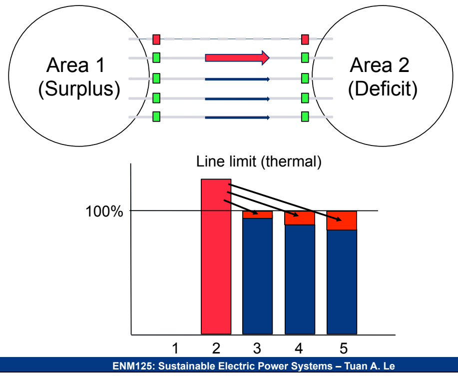


Power Flow Management: Example



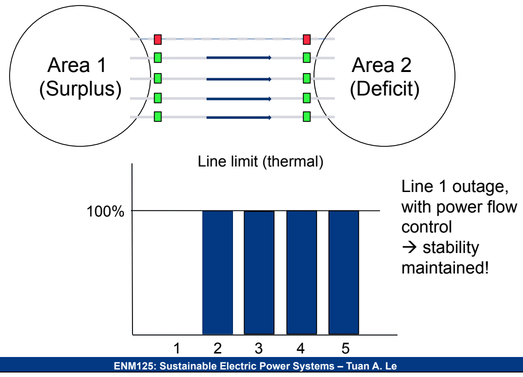
Power Flow Management: Example

Line 1 outage, with power flow control



Power Flow Management: Example

Line 1 outage, with power flow control



Power Flow Management Methods

- A major problem with the AC power system operation is the limited capacity of the transmission system
  - lines/transformers have limits
  - no direct way of controlling flow on a AC transmission line (e.g., there are no valves to close to limit the flow)
- Control methods:
  - a) Indirectly control transmission line flow by changing the generator outputs, or change the load demand
  - b) Modify the network parameters by using compensation → Flexible AC Transmission System (FACTS)
- Apply market principles to a) to manage the network flow → Market-based solutions:
  - Market splitting (or price-area) method: used in the planning phase → **manage well in advance before it happens!**

Congestion: What is it and why does it happen?

- In a restructured electricity market, when the producers and consumers of electric energy desire to produce and consume in amounts that would cause the transmission network to operate at or beyond one or more transfer limits, the system is said to be congested.
- This could happen if the market settlement process does not take into account the physical flow of electricity in the transmission network.
- Taking the transfer capacity between areas in the market settlement process could solve part of the problems → **Price area method**

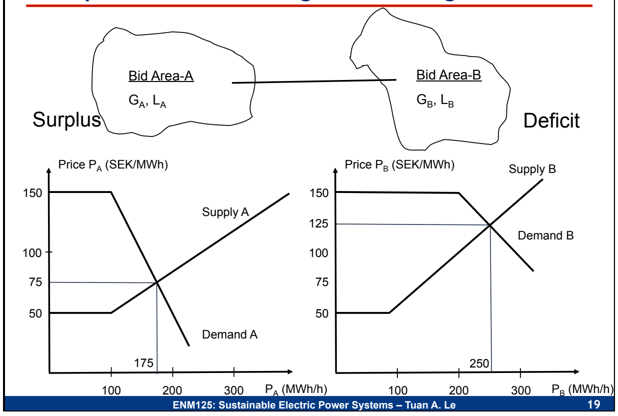
Price Area Congestion Management

- Applied in e.g. Nordic market
- Used in the planning phase (day-ahead)
- Also known as "**market splitting**"
- When congestion is expected to appear, the system is divided into ***bid areas*** separated by corridors
- Each bidder submits separate bid for each area

Price Area Congestion Management

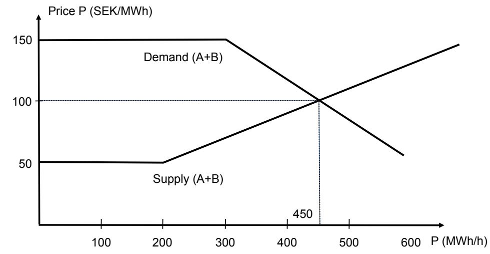
- Market is first resolved as un-congested, and generation and load in each bid area is determined. If transfers between areas **do not exceed** limits, then this solution, with **one system wide market price,** is used.
- If transfers exceed limits, then **each area is separately settled** using only the bids for that area and the transfer constraint
- In effect, the TSO purchases energy equal to transfer limit at low price area price, and sells it at high price area price (since he owns the transmission capacity and "offer" to the market)
  - The TSO received "congestion income", or "congestion rent"

Example: Price Area Congestion Management



Example: Price Area Congestion Management

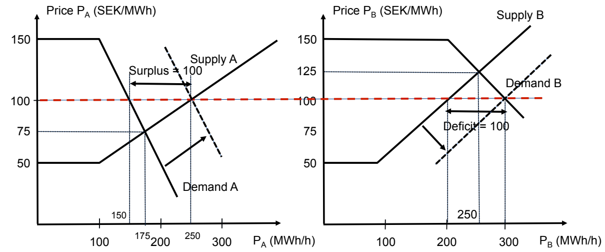
Unconstrained market settlements (unlimited transfer capacity)



Reference: I. Wangensteen, "Power System Economics - the Nordic Electricity Market", 2007.

Example: Price Area Congestion Management

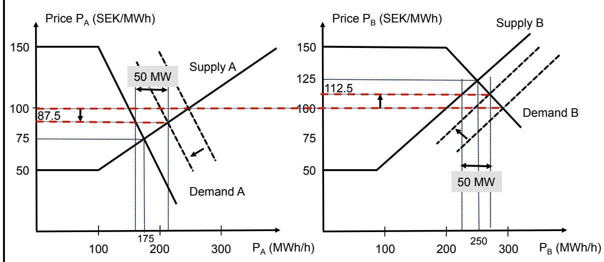
Unconstrained market settlements (unlimited transfer capacity)



Power transfer between A and B is 100 MW, prices are equal in both areas.
→If this transfer is above the available transmission capacity → Congestion occurs → Settle the market by area taking into account transmission capacity. The idea is to use the transmission capacity to the maximum level to take the benefit of interconnection.

Example: Price Area Congestion Management

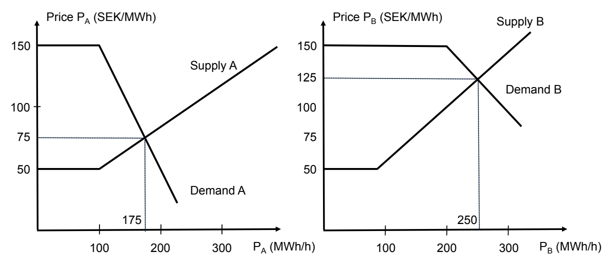
Market settlement: Limited transfer capacity (50 MW)



Area generation and load "automatically adjust" with price such that the transfer between area is equal to max tranfer capacity

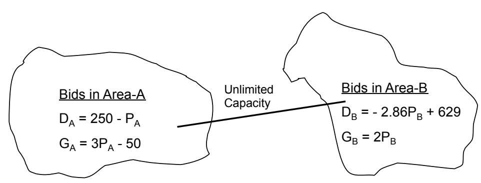
Example: Price Area Congestion Management

Market settlement: No interconnection available (most congested)



The lesser the transmission capacity → the higher the price difference!

Example: Price Area Congestion Management



D_A is the demand bid in Area-A
G_A is the supply bid, in Area-A
P_A is the price in area-A

D_B is the demand bid
G_B is the supply bid, in Area-B
P_A is the price in area-A

Generation in MWh (sell bids) and demand in MWh (buy bids) as linear functions of price in SEK.

Example: Price Area Congestion Management

Market settlement

Without transmission constraint

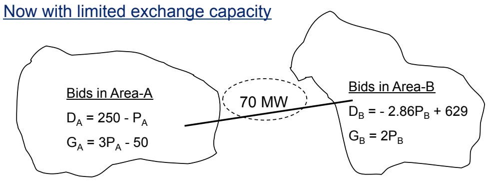
- $P_A = P_B = P$ (price of Area-A = price of Area-B = system price)
- $G_A + G_B = D_A + D_B$ (system generation = system demand)

- Solution:
  - System price = 104.85 SEK/MWh
  - G_A = 264.56 MWh
  - D_A = 145.15 MWh
  - G_B = 209.71 MWh
  - D_B = 329.12 MWh

  – Transfer (exchange) = 119.41 MWh (from A to B)

Example: Price Area Congestion Management

Now with limited exchange capacity



D_A is the demand bid in Area-A

G_A is the supply bid, in Area-A

P_A is the price in area-A

D_B is the demand bid

G_B is the supply bid, in Area-B

P_A is the price in area-A

Generation (sell bids) and demand (buy bids) as linear functions of price. It can be in the forms of block bids

Example: Price Area Congestion Management

Settlement

With transmission constraint (areas are settled separately)

- G_A - Transfer Capacity (export) = D_A
- G_B + Transfer Capacity (import) = D_B

- Solution:
  - P_A = 92.5 SEK/MWh (Generation surplus area price decreases, compared to the unconstrained case)
  - G_A = 227.5 MWh
  - D_A = 157.5 MWh

  - P_B = 115.0 SEK/MWh (Generation deficit area price increases, compared to the unconstrained case)
  - G_B = 230.0 MWh
  - D_B = 300.0 MWh

  - Transfer = 70 MWh (From A to B)

Example: Price Area Congestion Management

Congestion rent (income)

- The TSO purchases 70 MWh from the low price area (A)
  – at the price prevailing at Area-A: 92.5 SEK/MWh

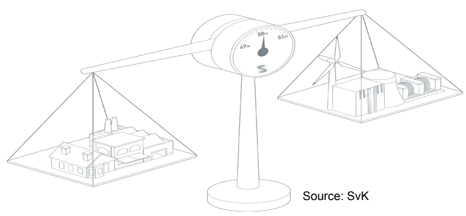
- Then sells this power to the high priced area, Area-B
  – at the price prevailing at Area-B: 115.0 SEK/MWh

- Income for TSO: (115.0 - 92.5)x70 = 1575 SEK

Content

- Markets for electricity
  – Physical trading
  – How spot market works
- Keeping the market to function:
  – Network management
    - Power flow management principle
    - Market-based congestion management
  – Keeping the system in balance
    - Generation and load balance
    - The balancing market

Keeping the system in balance



Source: SvK

- If active power produced = active power consumed → frequency remains constant
- Imbalance between active power produced and active power consumed will lead to frequency deviation:
  – Excess load causes a drop in frequency
  – Excess generation causes an increase in frequency
- Reserve power must be used to correct the imbalance

Keeping the system in balance

- Imbalances due to:
  - Constant fluctuations in the load
  - Inaccurate control of the generation
  - Sudden outages (disturbance) of generators and inter-connectors
- Generators can only operate within a narrow range of frequencies
  - Protection system disconnects generators when frequency is too high or too low
- System operator must maintain the frequency within limits (±0.1 Hz)
- Market mechanism for power balancing → The balancing market

Disturbance example

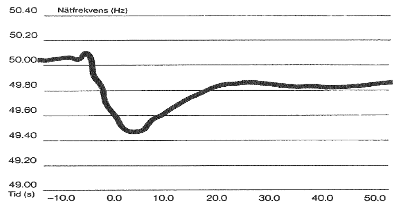


Figure 14.4. The transient frequency response after a production loss. The diagram is a recording from the Nordic system at a loss of a 1000 MW unit on the 24 November 1983.

Source: G. Andersson, "Dynamics and Control of Electric Power Systems", Lecture notes, 2007, ETH-Zurich

Regulating power market

Managed by TSOs → Regulating Power Market

Regulating power trading (real-time) → Balance settlement (balancing power market) (after delivery)

- On the regulating power market, TSO buys/sells power (**regulating power**) from/to the players in the delivery hour on the basis of bids for upward and downward regulation.

- In the balance settlement, TSO settles (or "buys/sells") power (im) balancing power from/to the players in order to neutralize imbalances incurred by them.
- **Settlements for balancing power** (difference between actual and scheduled) are calculated based on the price determined by **regulating power market**
- These trades are not "settled" till after the delivery hour when metered data is available and the imbalances

Regulating resources

- Automatic reserve
  - Acquired separately by TSO through agreements with generators
- Manual reserve
  - Acquired through Regulating Power Market

Automatic reserve

Primary response divided into two products:

- Frequency controlled normal operation reserve (FNR)
- Frequency controlled disturbance reserve (FDR)

Frequency controlled normal operation reserve

- Nordic requirement is 600 MW (6000 MW/Hz)
- Has to be activated within 3 min if frequency deviates with +- 0,1 Hz from 50.00 Hz.
- Devided between the Nordic TSO´s due to last year annual load
- Sweden 231 MW, Norway 207 MW, Finland 139 MW and Denmark 23 MW.

Frequency controlled disturbance reserve (FDR)

- Nordic requirement depended on N-1 security standard, normally 1000 MW
- Has to be activated with 50% within 5 sec. and in total after 30 sec if frequency drops to 49.5 Hz.
- Decided on a weekly basis due to current N-1. Normaly a nuclear power plant (Forsmark 3 or Oskarshamn 3 or a tie-line)

Secondary response (manual reserve)

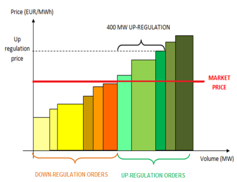
- Manual reserve that has to be activated within 10-15 minutes
- Regulating bids submitted to area TSO 45 minutes before actual operation hour
- TSOs forward bids to common Nordic regulating market (NOIS - is the common TSO information system for regulation power)
- Requirements for bids are: minimum 10 MW, marked with price and area
- Restore primary

- Norway and Sweden has the responsibility for frequency in the Nordic synchronous system.

Regulating power market

Regulating bids (volume-price-area)
- generators willing to quickly (max 15 minutes) increase /decrease
- consumers willing to increase/decrease consumption

Bids arranged in price order- "staircase" for each hour
- When regulation needed, TSO activates most favourable bid
- TSO is said to buy/sell "regulating power"



NOIS merit-order list and price setting

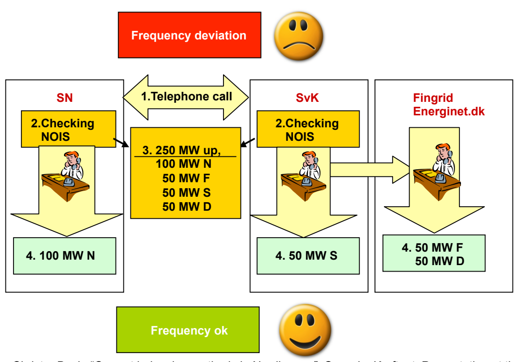
Regulating power market

At the end of each hour, regulating price is fixed as:
- price for most expensive regulating up
- least expensive regulating down

- All selected/activated bids get paid uniform price for up regulation and pay uniform price for down regulation.

NOIS (Nordic Operational Information System) merit-order list and price setting

Activation of Manual Reserve



Source: Christer Bäck, "Current balancing methods in Nordic area", Svenska Kraftnät, Presentation at the Nordic Project Meeting on Spinning Reserve, DTU, Denmark, 2011

More about power markets?

Welcome to the course:
EEK201: Power Market Management
Study Period 2 – 2012/2013

Dr. Magnus Callavik, ABB Power Systems – Grid Systems

High voltage grid system technologies for the future onshore and offshore grid

CTH, Dec 11, 2012

Power and productivity
for a better world™

Outline

- What could a chemical engineer know about HVDC
- Introduction
- ABB Grids systems
- HVDC Technology and Applications
  - VSC, LCC and Grids
  - HVDC breakers
- Skill set of a future engineer in companies targeting to be #1 in their business
- Discussions
- See also: www.abb.com/hvdc; new.abb.com /hvdc-breaker

Magnus Callavik. CV

Education

MBA Executive Master of Business Administration
2009. Stockholm School of Economics

PMP Project Management Professional
2008. Project Management Institute

Ph.D. Chemical Technology
1998. KTH – Royal Institute of Technology

M.Sc. Chemical Engineering
1994. KTH – Royal Institute of Technology

Var. Law, English 1.5 semesters
1989-94, Stockholm University

Phone: +46 21 32 32 26
Fax: +46 21 32 32 12
E-mail: magnus.callavik@se.abb.com

Employment

2012-	BU Technology Manager Grid Systems	ABB Power Systems, Sweden
2010-2012	Program manager HVDC Grids	ABB Power Systems, Sweden
2001-2010	R&D Manager & Program manager	ABB Corporate Research, Sweden
2000	Senior Researcher	ABB Lummus Global, New Jersey, USA
1999	Executive Trainee	ABB, Sweden
1994-99	PhD student & Research Ass.	KTH, Stockholm, Sweden
1993-94	Research Fellow	Stanford Research Institute, California, USA
1988-89	Military Service	I1, Sweden

Board of SEK Elstandard (Swedish national committe for electrical standardization, IEC & Cenelec), vice chairman. Since 2011
Board of KIC Innoenergy (one of Europes new flagships for innovation in a new university collaboration industry - academia). Since 2011
Convenor Friends of the Supergrid Technology Working group, 2012-

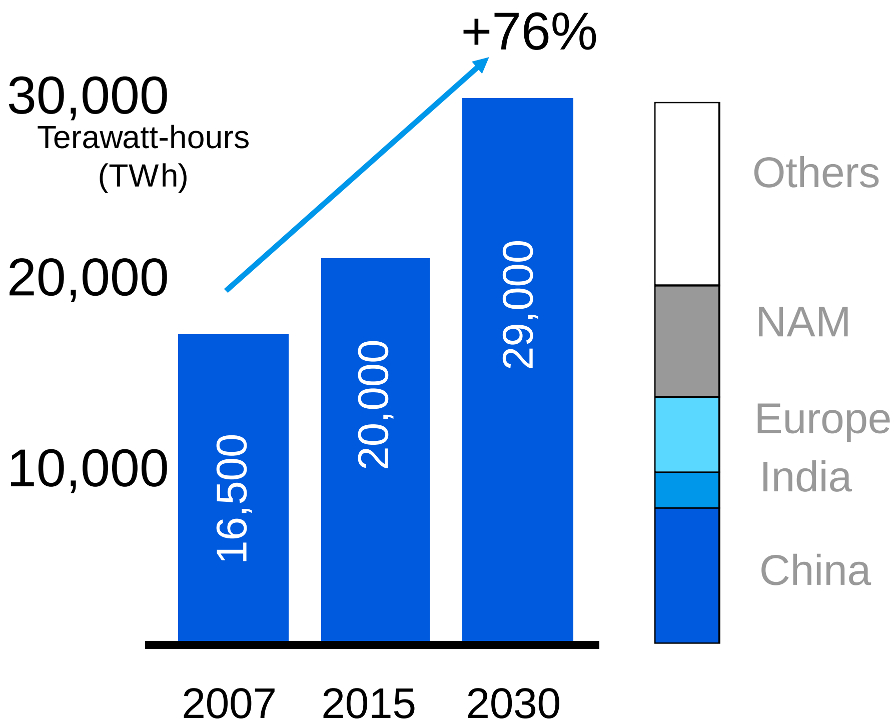
Electric Power Systems

- What is the purpose of the electric power system?
- Why is the system based on AC power?
- When is DC power preferred or needed?

Tackling society's challenges on path to low-carbon era means helping utilities do more using less

Forecast rise in electricity consumption by 2030

▪Source: IEA, World Energy Outlook 2009



Solutions are needed for:

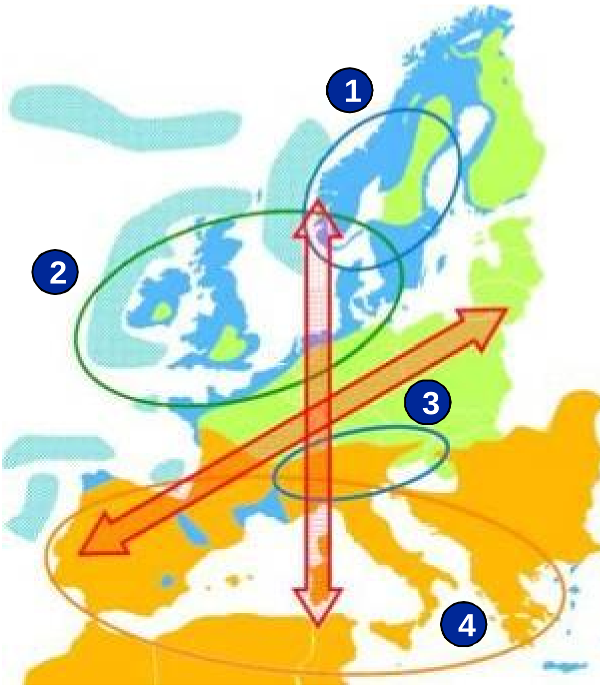
- Rising demand for electricity – more generation
- Increasing energy efficiency - improving capacity of existing network
- Reducing CO_2 emissions – Introduce high level of renewable integration

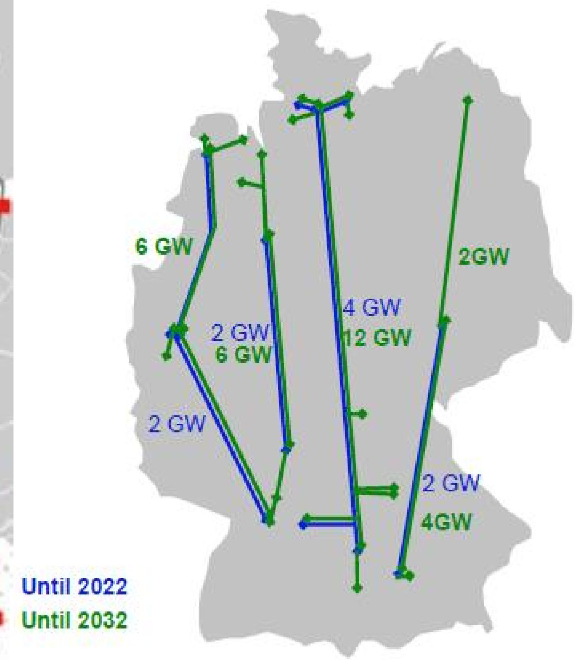
Meeting the rise in demand will mean adding a 1 GW power plant and all related infrastructure every week for the next 20 years

IEA World Energy Outlook 2012 - 2035

- **5 890 GW of capacity additions (> the total installed capacity in 2011) is required**
- One-third of this is to replace retiring plants; the rest is to meet growing electricity demand.
- Renewables represent half : 3000 GW. Gas 1400 GW.
- The power sector requires investment of $16.9 trillion, ca. half the total energy supply infrastructure investment
- Two-fifths of this investment is for electricity networks, while the rest is for generation capacity.
- Investment in generation capacity, > 60% is for renewables: wind (22%), hydro (16%), solar PV (13%).

The evolution of grids: Connect remote renewables
Europe & Germany are planning large scale VSC-HVDC





Source: DG Energy, European Commission

European Visions

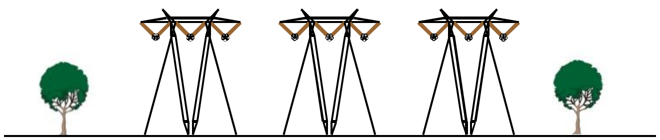
1. Hydro power & pump storage -Scandinavia
2. >50 GW wind power in North Sea and Baltic Sea
3. Hydro power & pump storage plants - Alps
4. Solar power in S.Europe, N.Africa & Middle East

Germany (draft grid master plan)

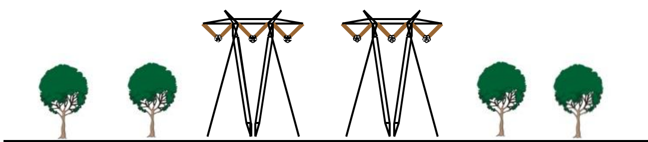
- Alternatives to nuclear-distributed generation
- Role of offshore wind / other renewables
- Political commitment
- Investment demand and conditions
- Need to strengthen existing grid

The transmission grid becomes increasingly important
Continued development of AC and DC technologies

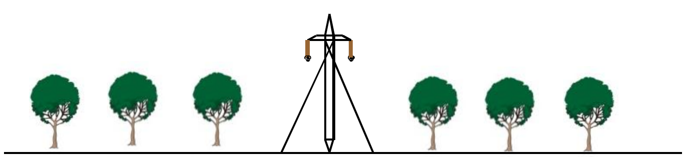
Different technologies :Same power transmitted



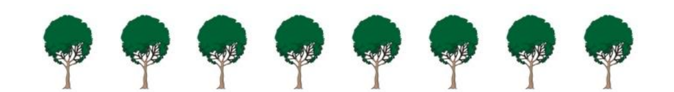
Traditional overhead line with AC



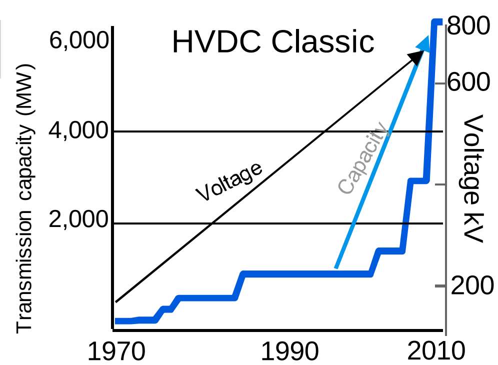
Overhead AC line with FACTS*



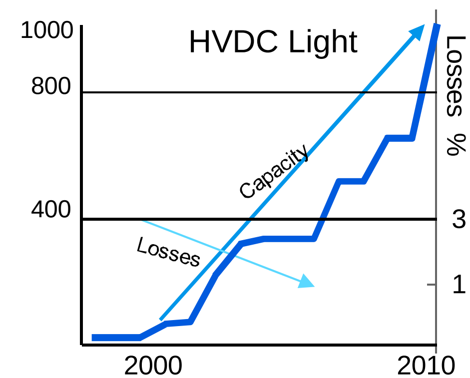
HVDC (high voltage direct current) Classic overhead line



Underground line with HVDC Light or AC cable



Capacity up 6x since 2000; Voltage up from +/- 100kV to +/- 800kV since 1970



Capacity up 10x ; losses down from 3% to 1% per converter station since 2000

- Longer transmission distances
- More power - lower losses - reduced cost per megawatt (MW)
- Development of power electronics, cable and semiconductor technology

More than 50 years ago ABB broke the AC/DC barrier Gotland 20 MW subsea link 1954

2012: New cable ship AMC Connector

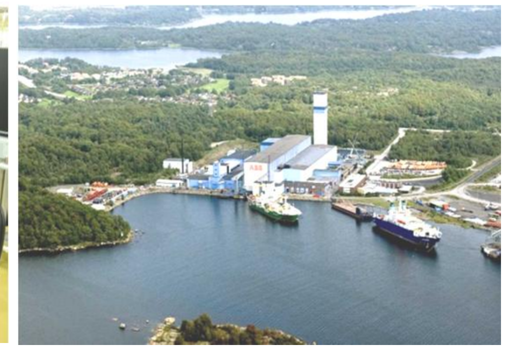
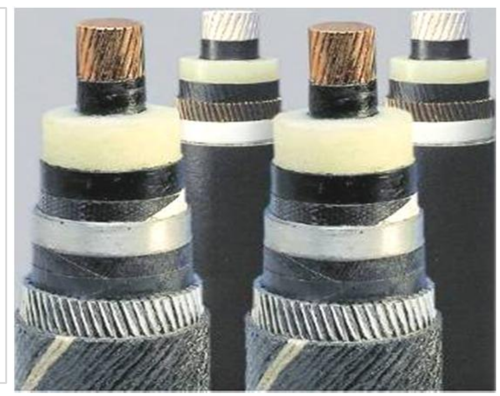
East West Interconnector Project

EWIP 500 MW world record transmission VSC-HVDC

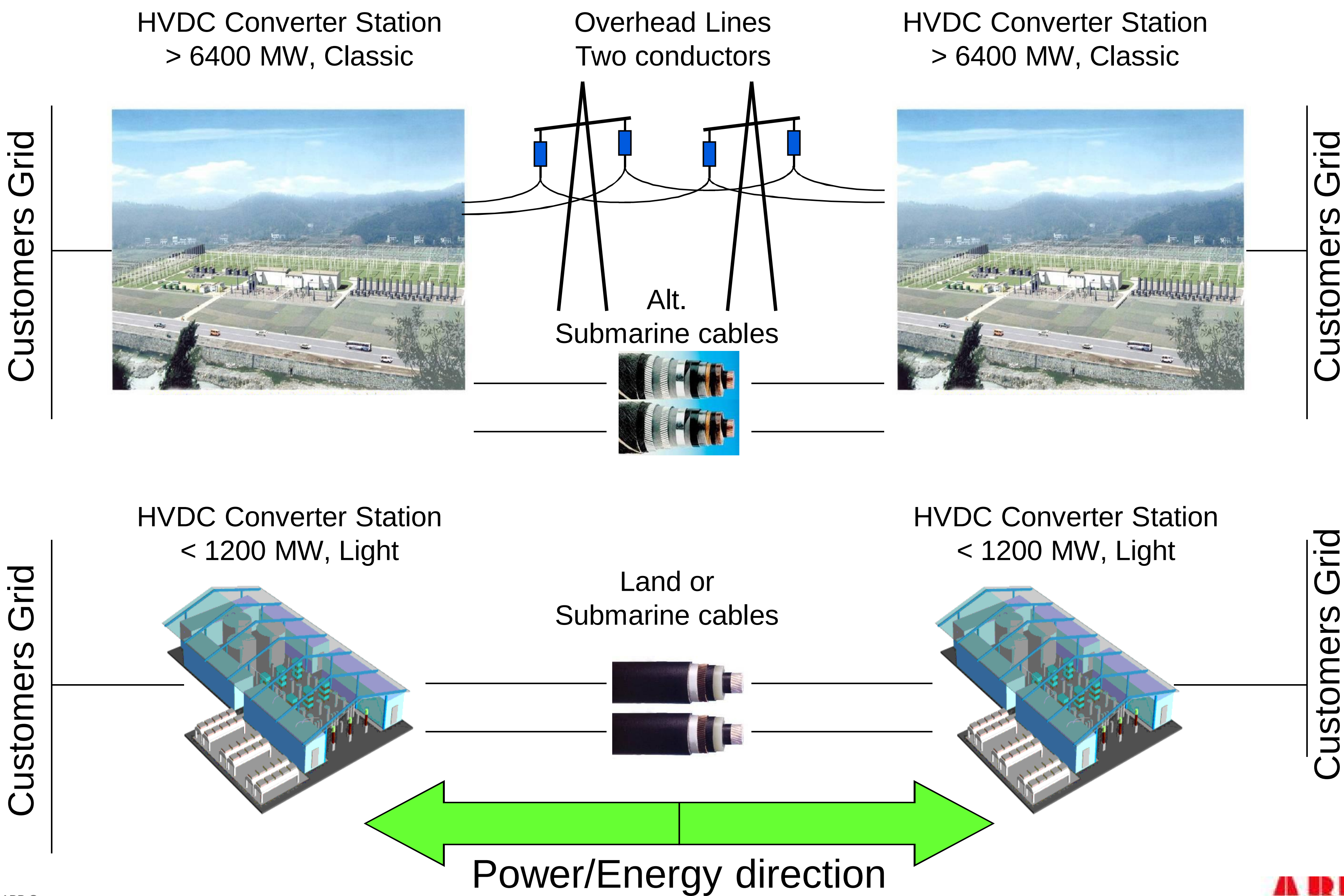
+/- 200 kV XLPE cable pair covering 75 km underground and 186 km sub sea

ABB's unique position in HVDC
In-house converters, semiconductors, cables

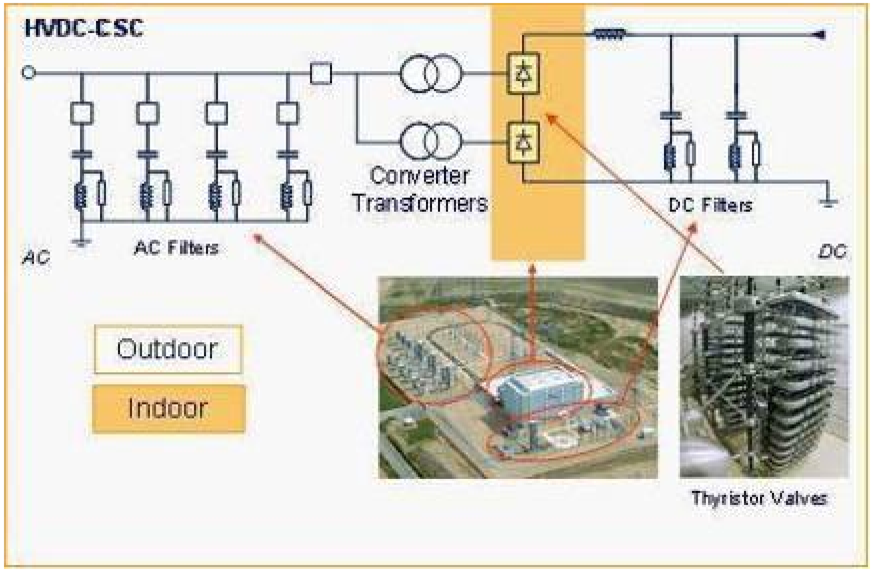
Key components for HVDC transmission systems

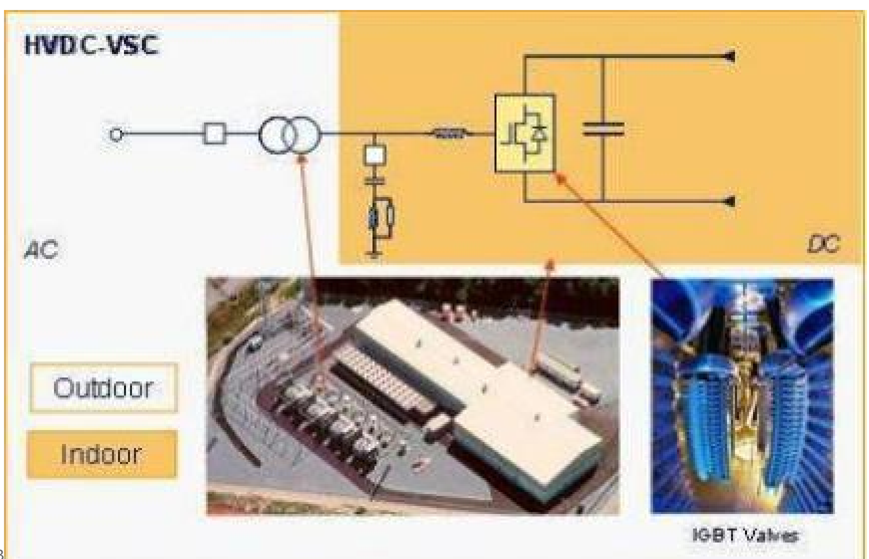
Converters	High power semiconductors	HV Cables
		
		
Conversion of AC to DC and vice versa	Silicon based devices for power switching	Transmit large amounts of power- u/ground & subsea

What is an HVDC Transmission System?



HVDC Technologies





HVDC Classic
- Current source converters
- Line-commutated thyristor valves
- Requires 50% reactive compensation
- Converter transformers
- Minimum short circuit capacity > 2x converter rating

HVDC Light
- Voltage source converters
- Self-commutated IGBT valves
- Requires no reactive power compensation
- “Standard” transformers
- No minimum short circuit capacity, black start

Grid Systems portfolio
HVDC Classic

Applications

- Connecting remote generation
- Interconnecting grids
- Connecting remote loads
- Upgrades

Portfolio

- Turnkey HVDC transmission systems
- Power range 250 – 9,000 MW
- System retrofit through upgrading, uprating & major retrofit of converter stations

Longquan, China
HVDC Classic

Grid Systems portfolio
HVDC Light

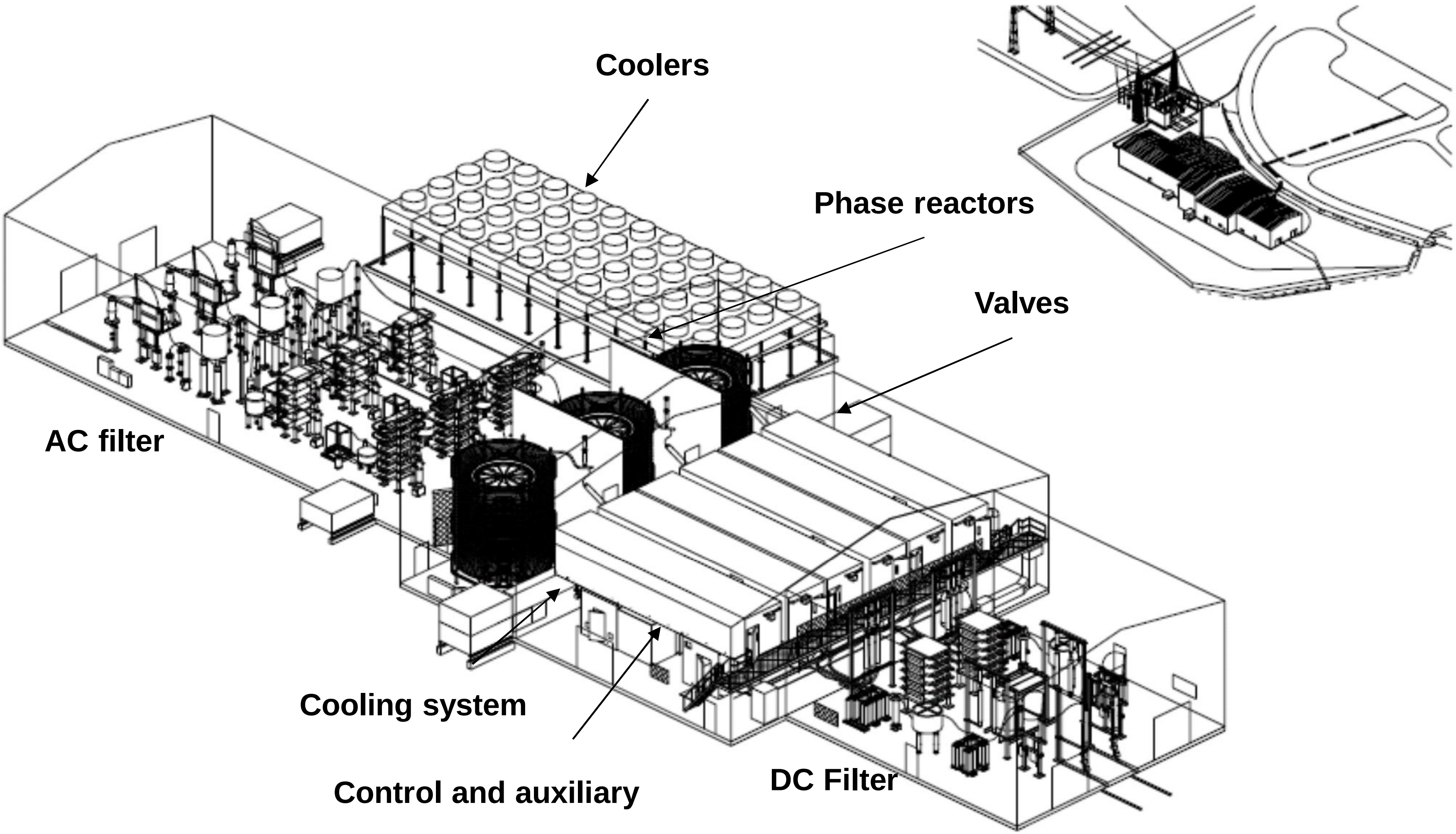
Applications

- Connecting remote generation
- Interconnecting grids
- Connecting remote offshore wind
- City center infeed
- Power from shore
- AC grid enhancement
- Connecting remote loads
- Upgrades

Portfolio

- Turnkey HVDC Light® transmission systems
- Land cable, OH line or sea cable connections
- Power range 50 -1,200 MW

HVDC Light
±150 kV, 175- 555 MW



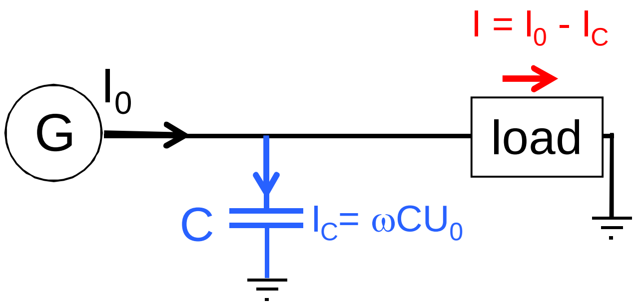
40 x 110 meters

The converter at Harku
Estonia

Converter building

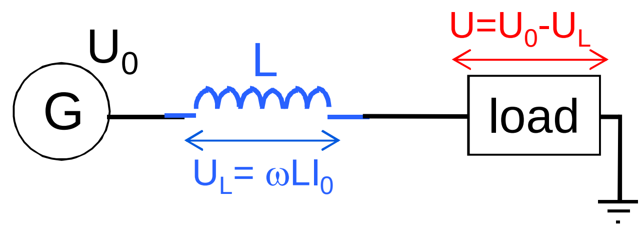
Why HVDC is ideal for long distance transmission?
Capacitance and Inductance of power line

Cable



In cable > 50 km, most of AC current is needed to charge and discharge the “C“ (capacitance) of the cable

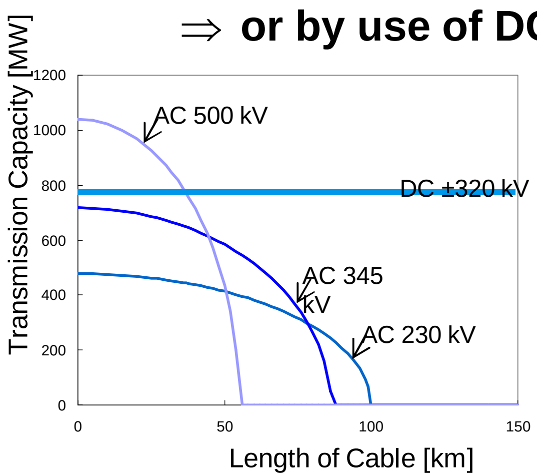
Overhead Line



In overhead lines > 200 km, most of AC voltage is needed to overcome the “L” (inductance) of the line

$\Rightarrow$ C& L can be compensated by reactors/capacitors or FACTS

$\Rightarrow$ **or by use of DC, which means $\omega = 2\pi\nu = 0$**



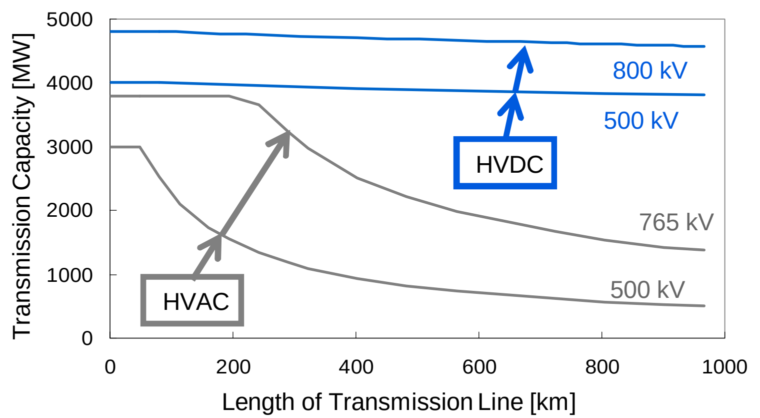
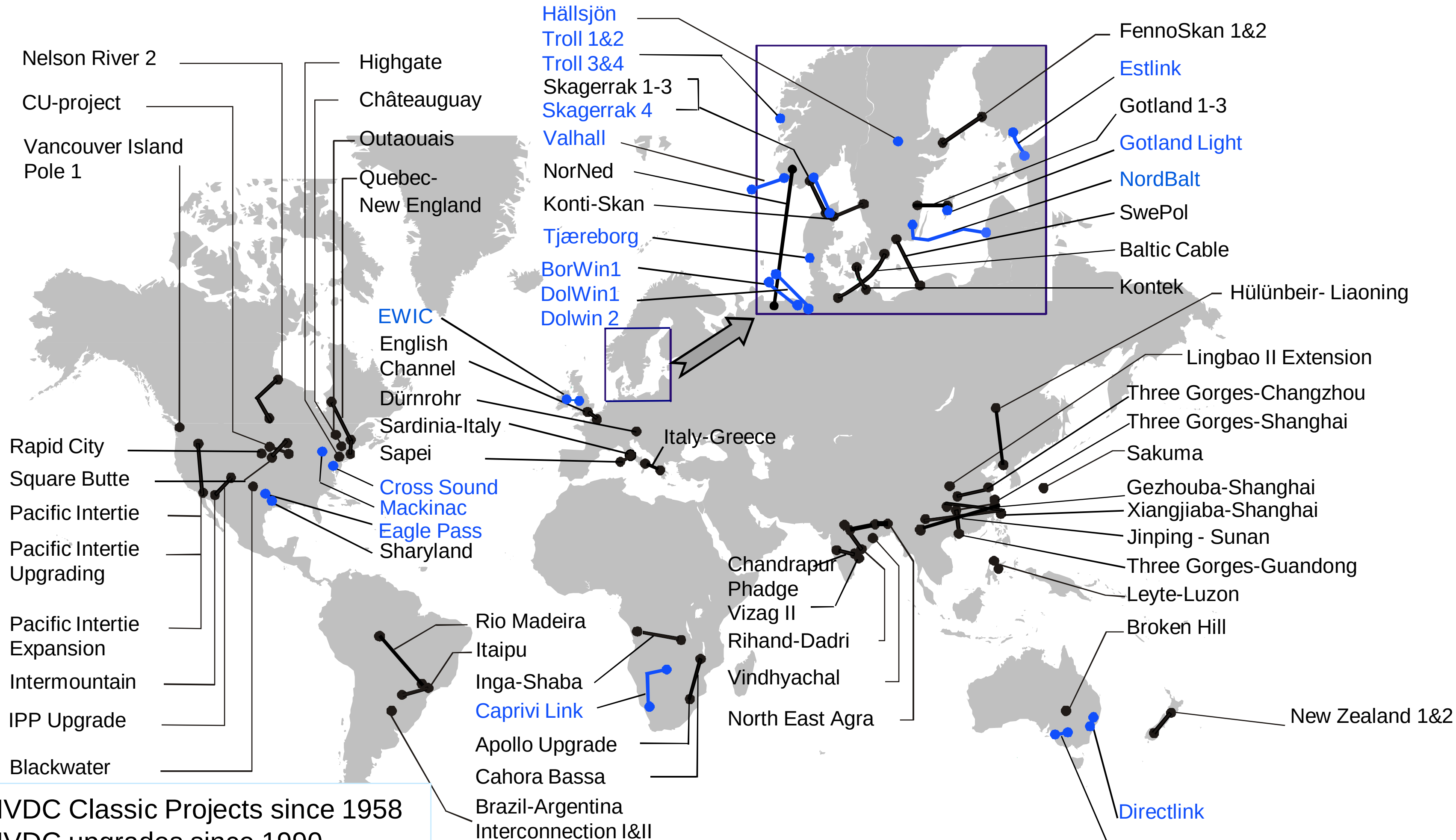
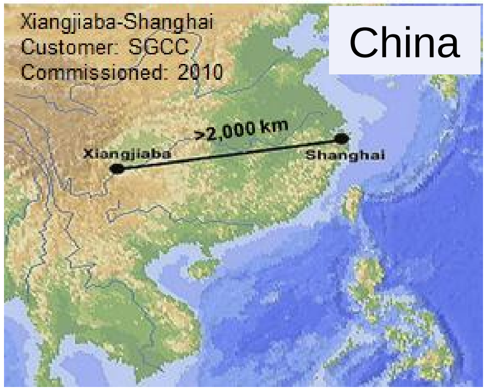


ABB has more than half of the 145 HVDC projects
The track record of a global leader



58 HVDC Classic Projects since 1958
14 HVDC upgrades since 1990
19 HVDC Light Projects since 1997

ABB’s track record of HVDC innovation
Many firsts – some examples



World’s longest / highest power capacity - first 800 kV commercial link -

Integrating the world’s most remote offshore wind farm

World’s longest underwater power link

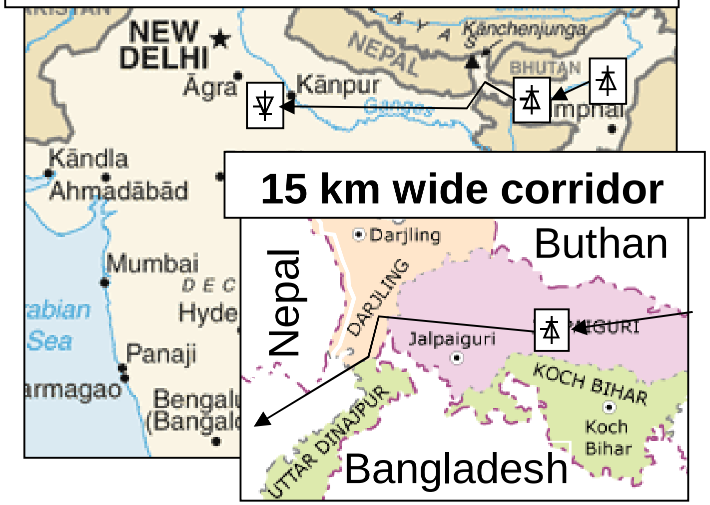
World’s first offshore platform connected to shore power

World’s longest underground cable link

World’s first HVDC Light on an overhead line

2014: North East – Agra: Multiterminal Classic UHVDC 8 000 MW Power Transmission

NEA800: 1 728 km transmission



800 kV Converter Valve, Shanghai

HVDC connection of multiple remote hydro power regions in NE India

- Low losses, reliability, flexibility

North East - Agra (NEA 800)

- Hydro resources NE locally
  13 m of rainfall per year
- 15 km wide “Chicken Neck” Transmission Corridor
- Electricity to 90 M people

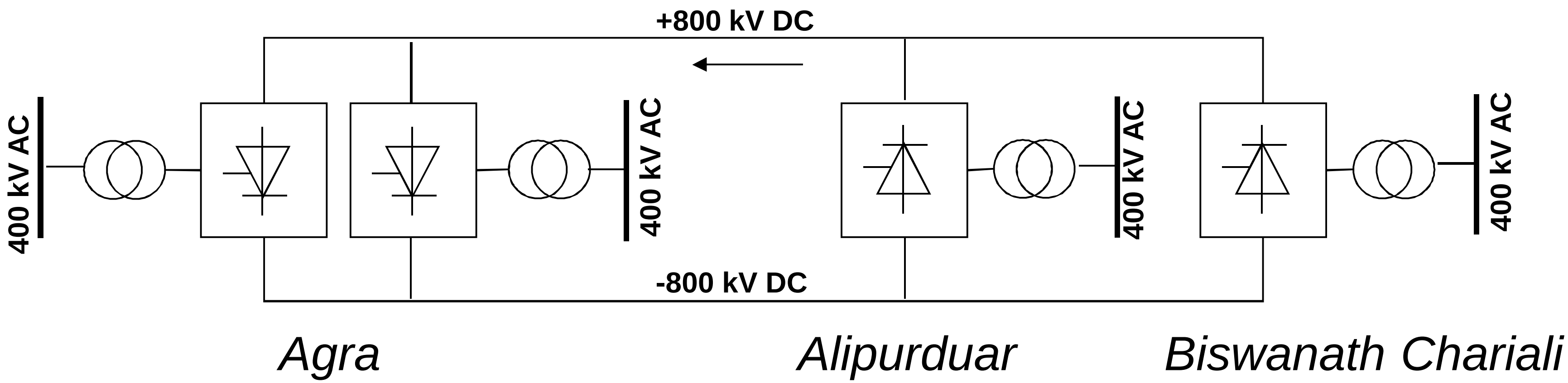
Not the first Multiterminal HVDC

1. New England – Hydro Quebec 1992
   Three terminal, 2000 MW

Not the first 800 kV HVDC

1. Xiangjiaba – Shanghai 2010
   2000 km, 6400 MW UHVDC

NEA800
Four station Multiterminal HVDC
Simplified Single Line Diagram



Customer	India Power Grid Corp.
Distance	1 728 km
Power	8 000 MW
Terminals	Four (2x2 bipoles)
Voltage	±800 kV
In operation	2014 - 2015
Delivery time	39 - 42 months

ABB

Zhundong- Chengdu 1100 kV UHVDC Project

Zhundong-Chengdu First 1100 kV UHVDC Project

10.450 MW, +/- 1100 kV OHL transmission

Customer: SGCC

Customer

SGCC, State Grid Corporation of China

ABB Scope

1100 kV , 10.450 MW bipolar HVDC Link (2100 km OHL)

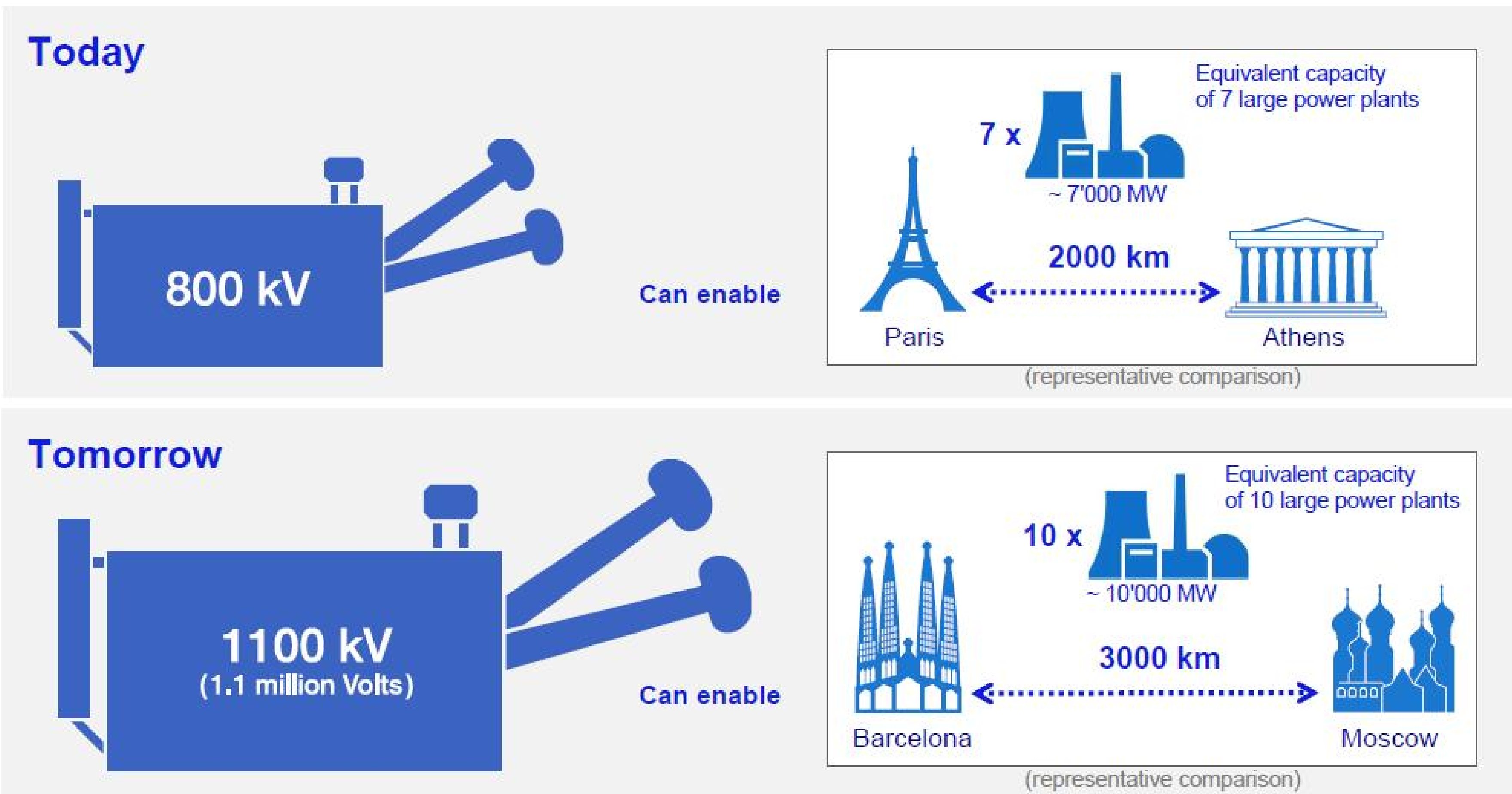
- System support, Valve, C & P, DC Yard
- Transformers (including site manufacturing support)

Status

- Development of 1100 kV technology ongoing
- Transformers, transformer bushing and wall bushing have passed the required qualification tests
- 10 transmission lines at 1100 kV in SGCCs 20-year plan

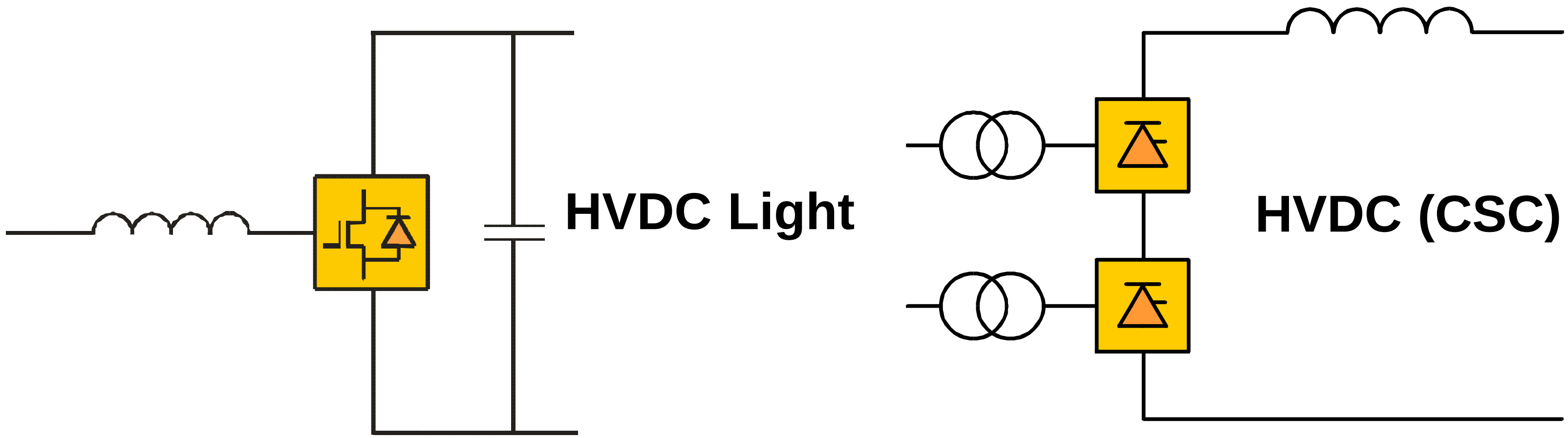
24 m Wall Bushing in Ludvika during transportation to Test Hall, Apr 2012

Highlights 2012: 1100 kV UHVDC* converter transformer
New world record – highest DC voltage ever



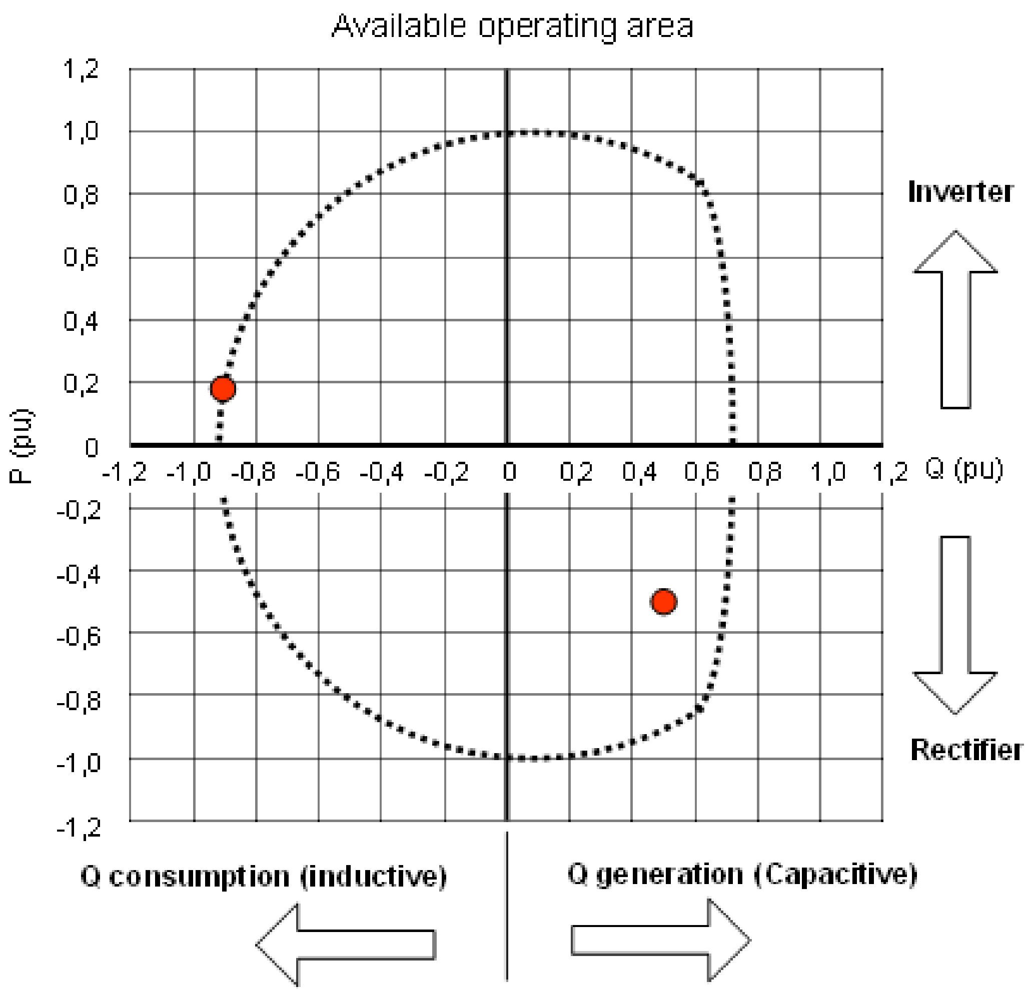
* Ultra high voltage direct current

Why use HVDC Light (Voltage Source Converter)?



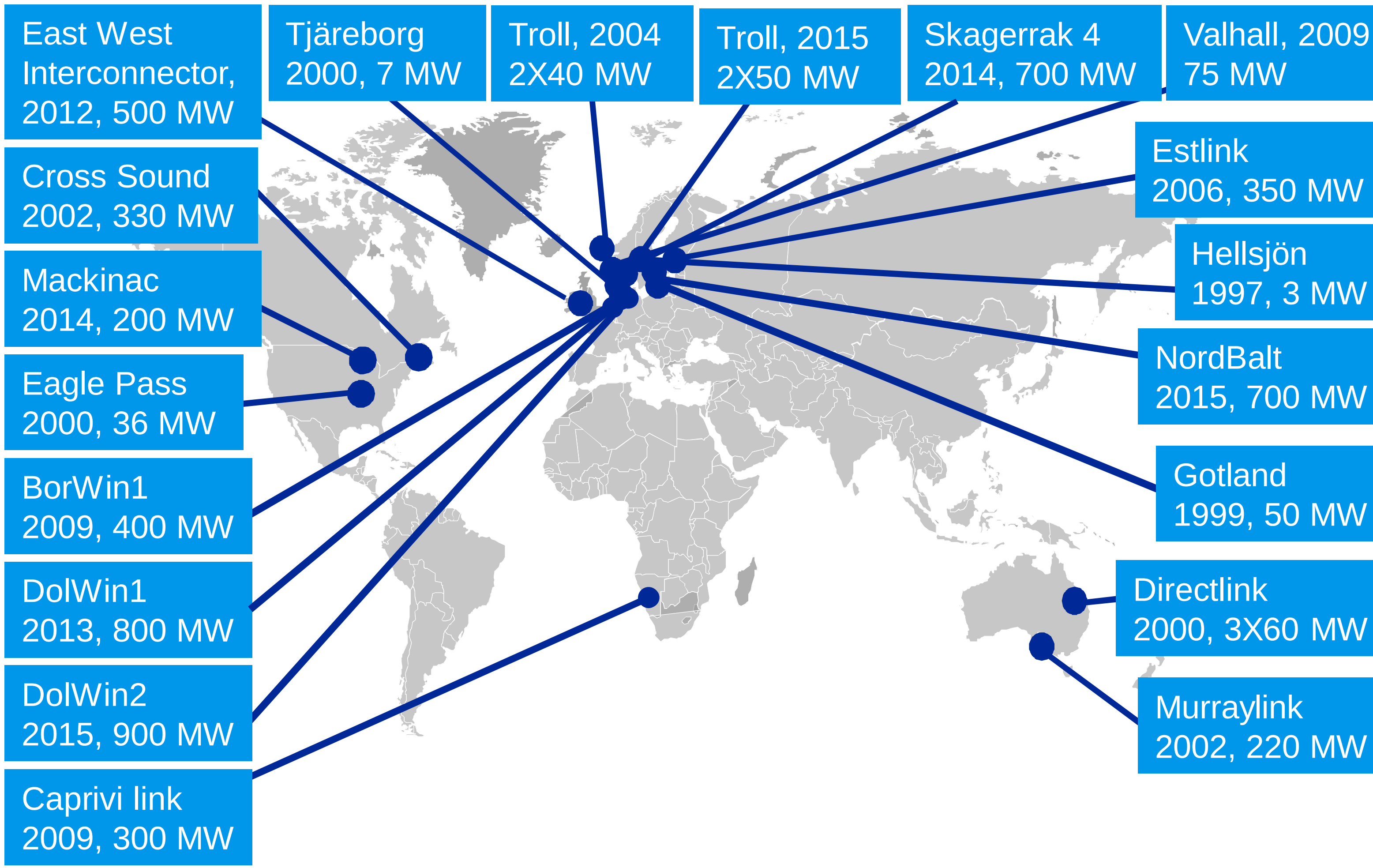
- Fault ride-through capability.
- Connection to electrically weak AC-network.
- Integrated reactive power compensation.
- Independent active and reactive power control.

HVDC Light: Active and Reactive Power Compensation Voltage Source Converter (VSC)



The operating area limits active (MW) & reactive (MVar) power

Project references
HVDC Light technology matures



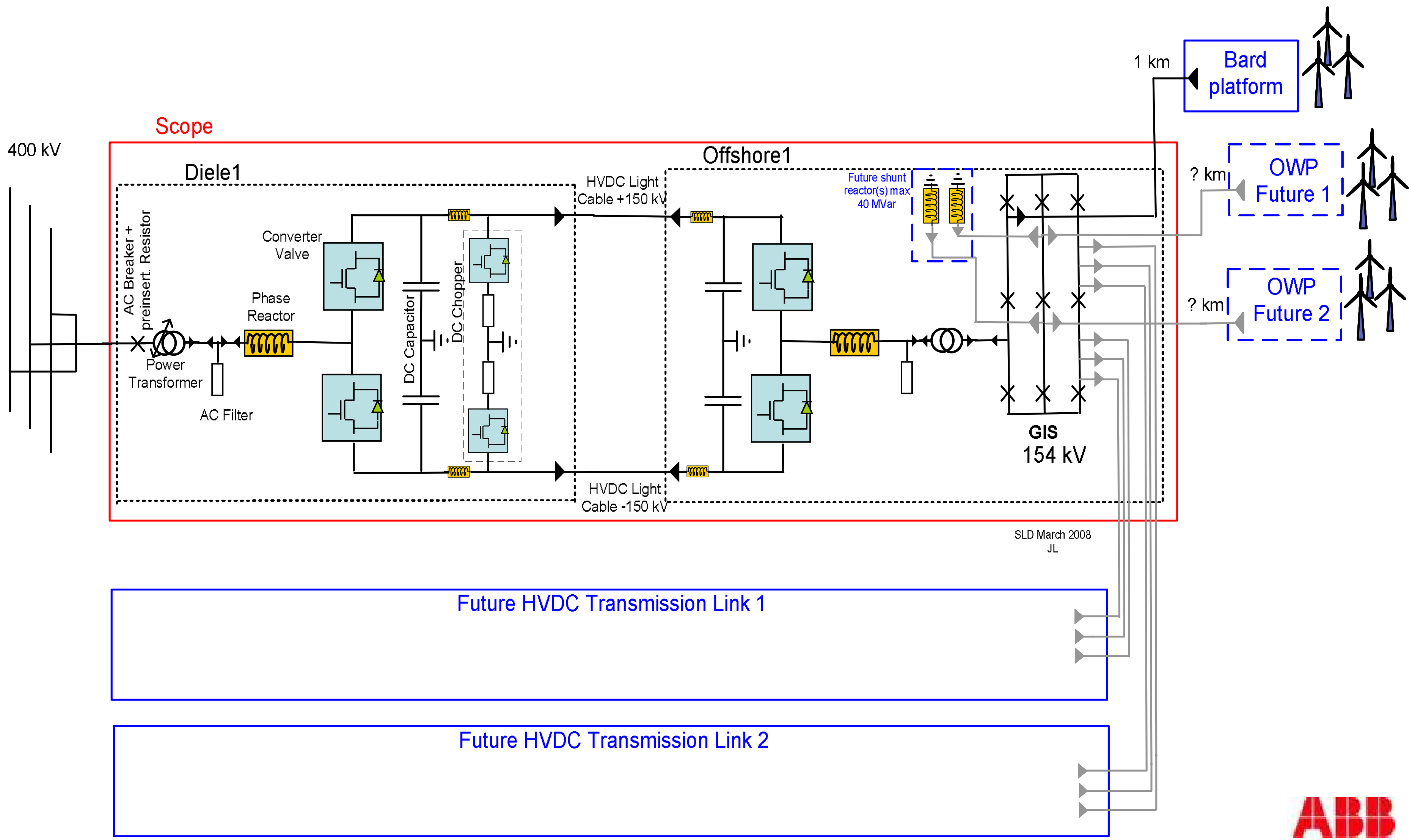
Offshore wind connections
Borwin 1 & Dolwin 1-2

Main data	Borwin 1	Dolwin 1	Dolwin 2
Commissioning year:	2012 *	2013	2015
Power rating:	400 MW	800 MW	900 MW
AC Voltage:	170 kV (Platform) 380 kV (Diele)	155 kV (Platform) 380 kV (Dörpen W)	155 kV (Platform) 380 kV (Dörpen W)
DC Voltage:	±150 kV	±320 kV	±320 kV
DC underground cable: DC submarine cable:	2 x 75 km 2 x 125 km	2 x 75 km 2 x 90 km	2 x 45 km 2 x 90 km

Main reasons for choosing HVDC Light: Length of land and sea cables

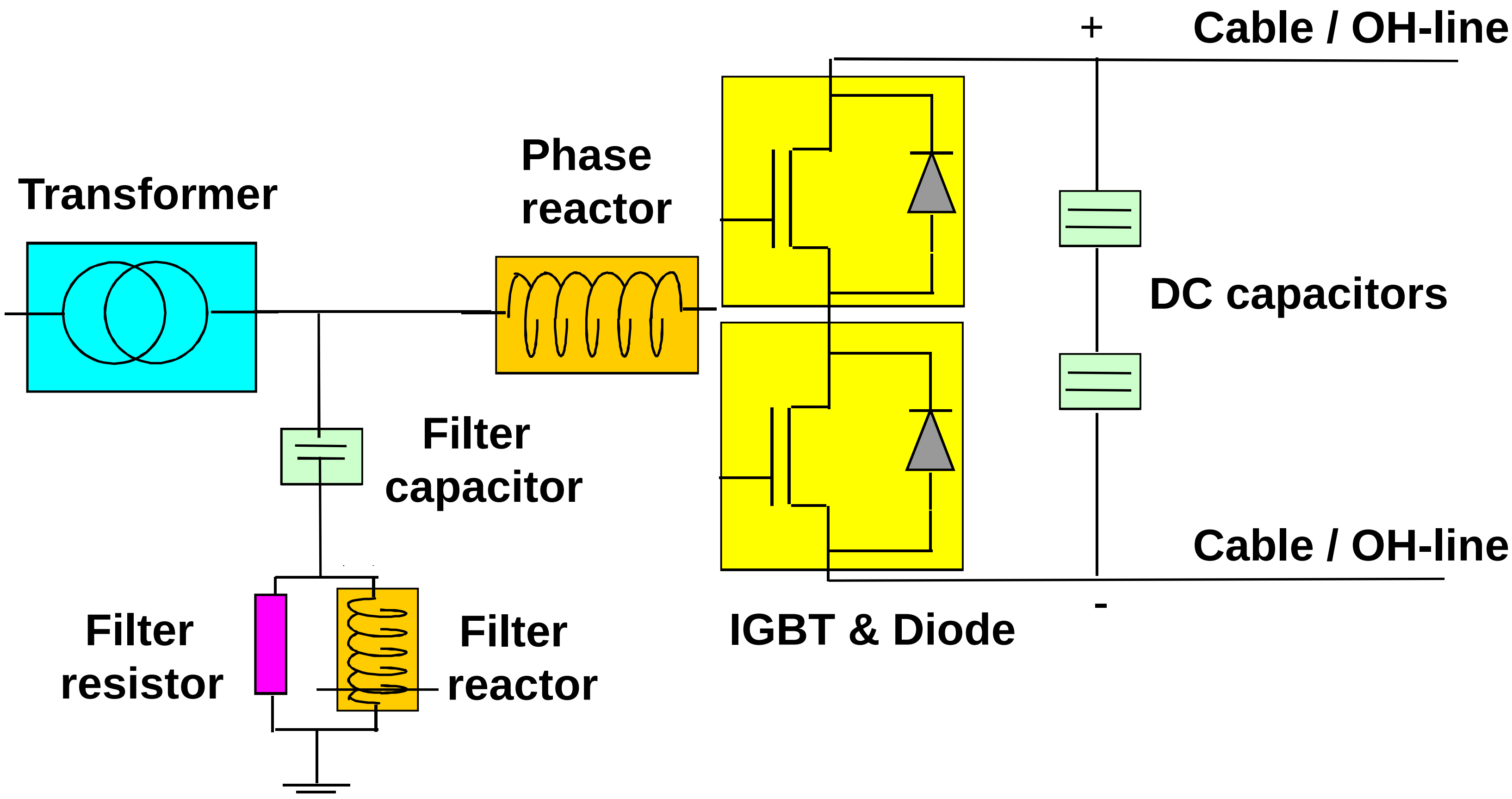
*) when all Bard 1 wind generation is in operation. Transmission since 2010

BorWin1
Example Simplified Single Line Diagram



ABB

Overview of core components

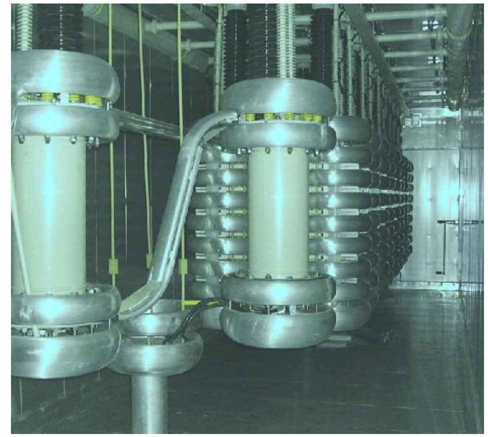


HVDC Light core components

Transformer

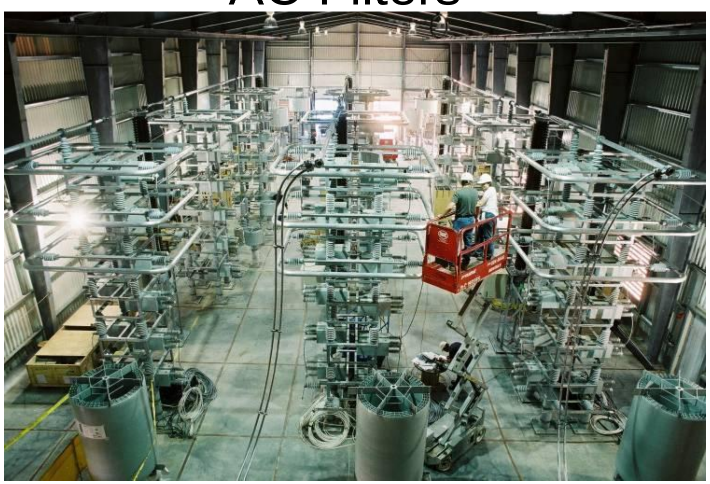
Phase Reactor

IGBT Valves



Capacitors

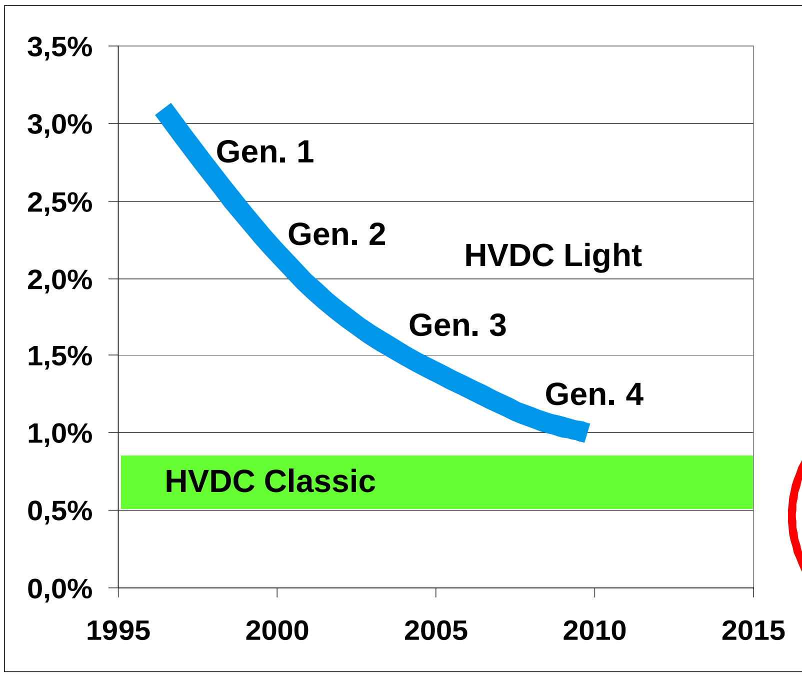
AC Filters



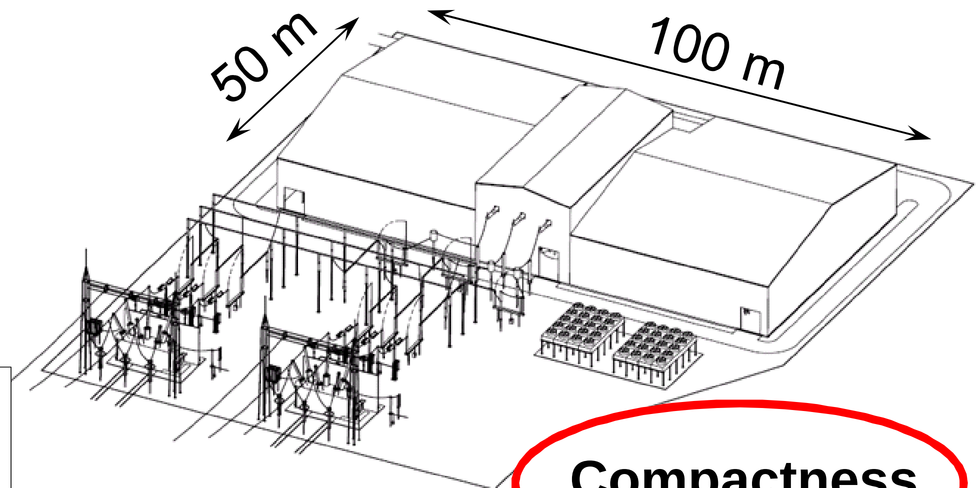
Extruded cables

Generation 4
Main features

Lower losses



1000 MW



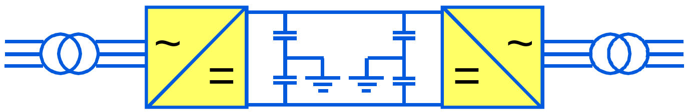
Compactness

Maintained functionality

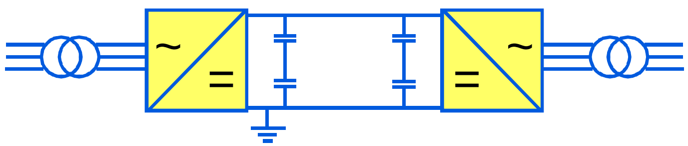
Maintained availability and reliability

Converter Configurations and operation modes

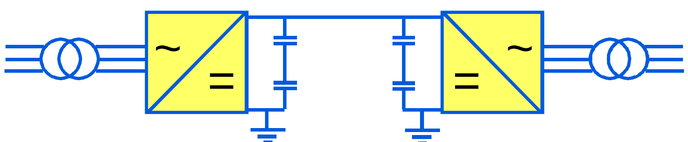
Symmetric monopole



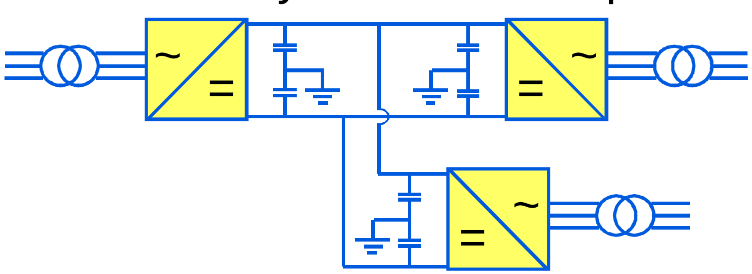
Asymmetric monopole, metallic return



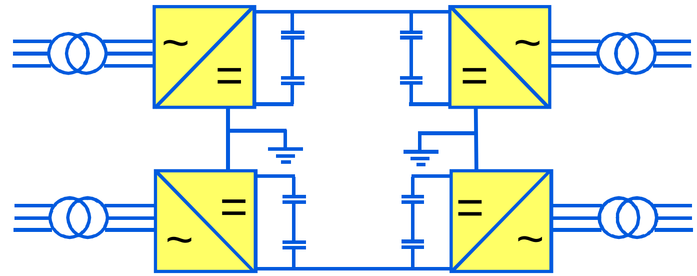
Asymmetric monopole, ground return



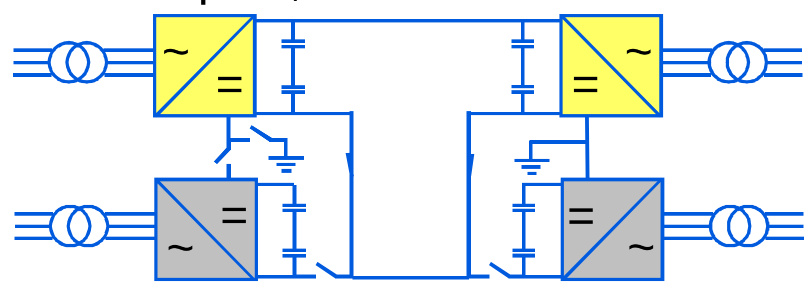
Multiterminal Symmetric monopole



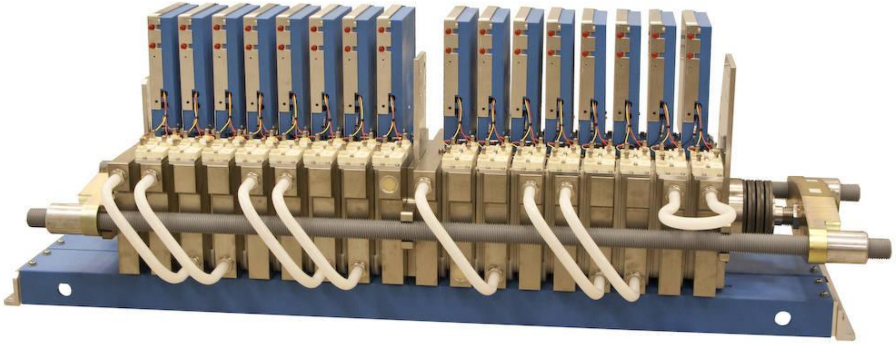
Bipole

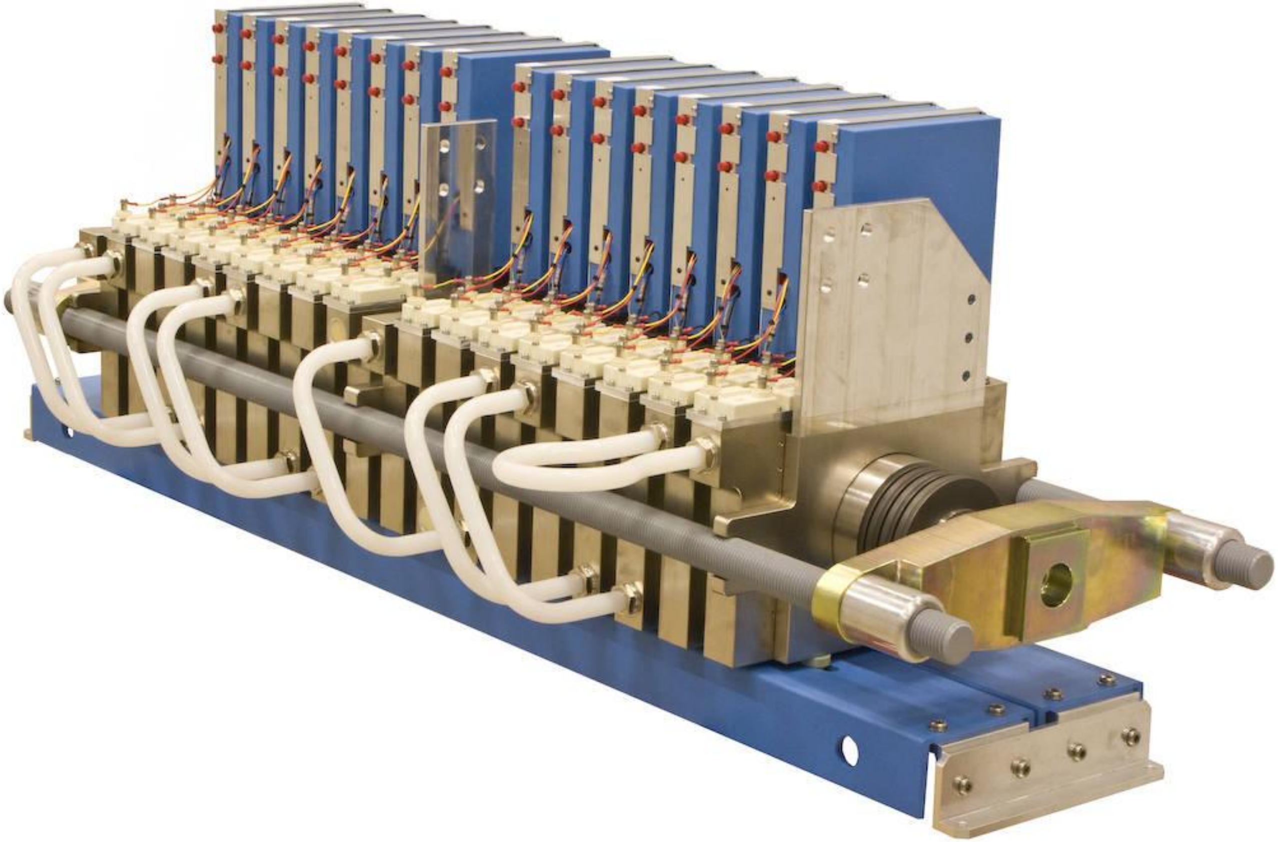


Bipole, metallic return



IGBT Module





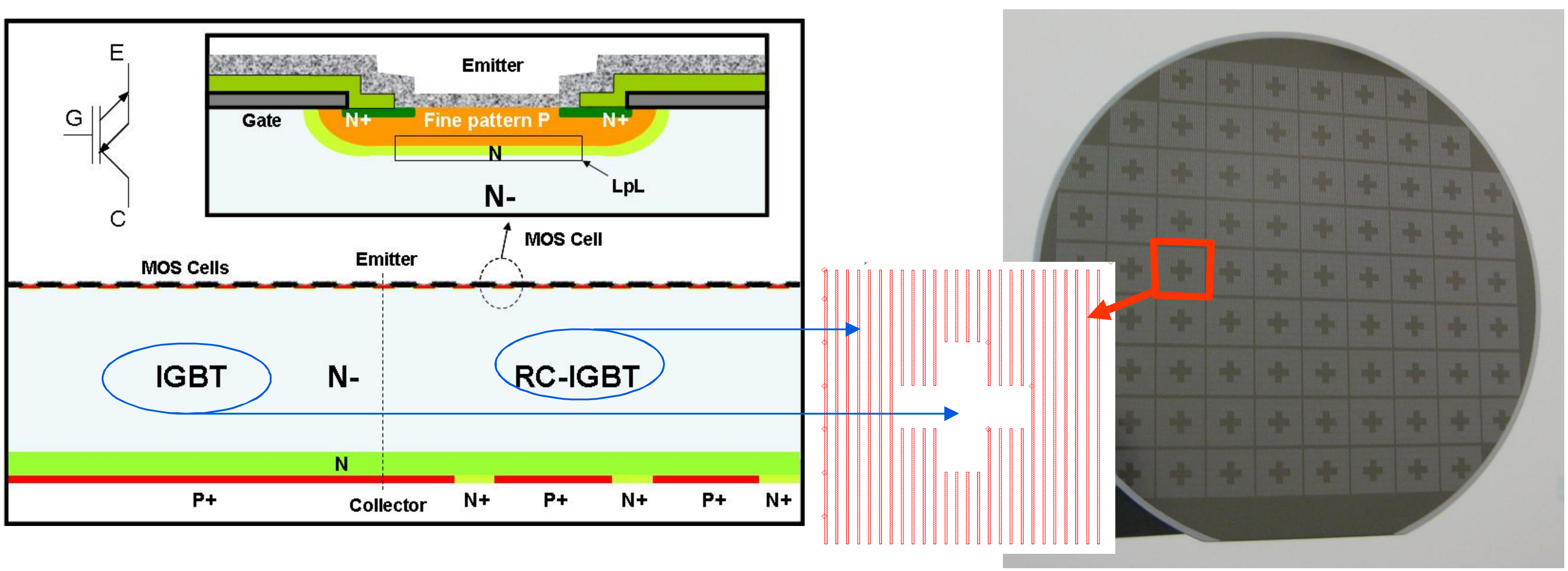
IGBT inner structure

Control system in Factory System Test phase

Advancements in MV-Drive Switching Technologies
Outlook BIMOS technology

The Bi-mode Insulated Gate Transistor (BIGT) :
integrates an IGBT & diode in one structure
=> Reverse Conducting (RC) IGBT

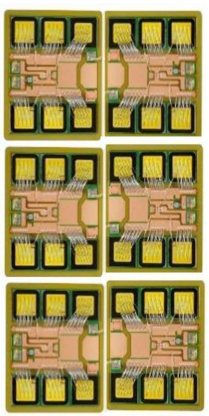
BIGT Wafer Backside



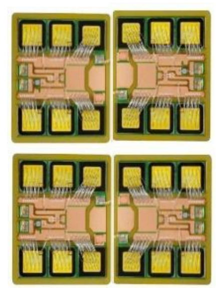
Technology Value for Customer
Decreased Module Size for Similar Power

Example: 3.3 kV IGBT module

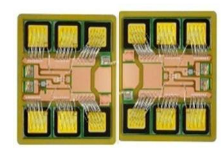
1998: 800A



2010: 1000A

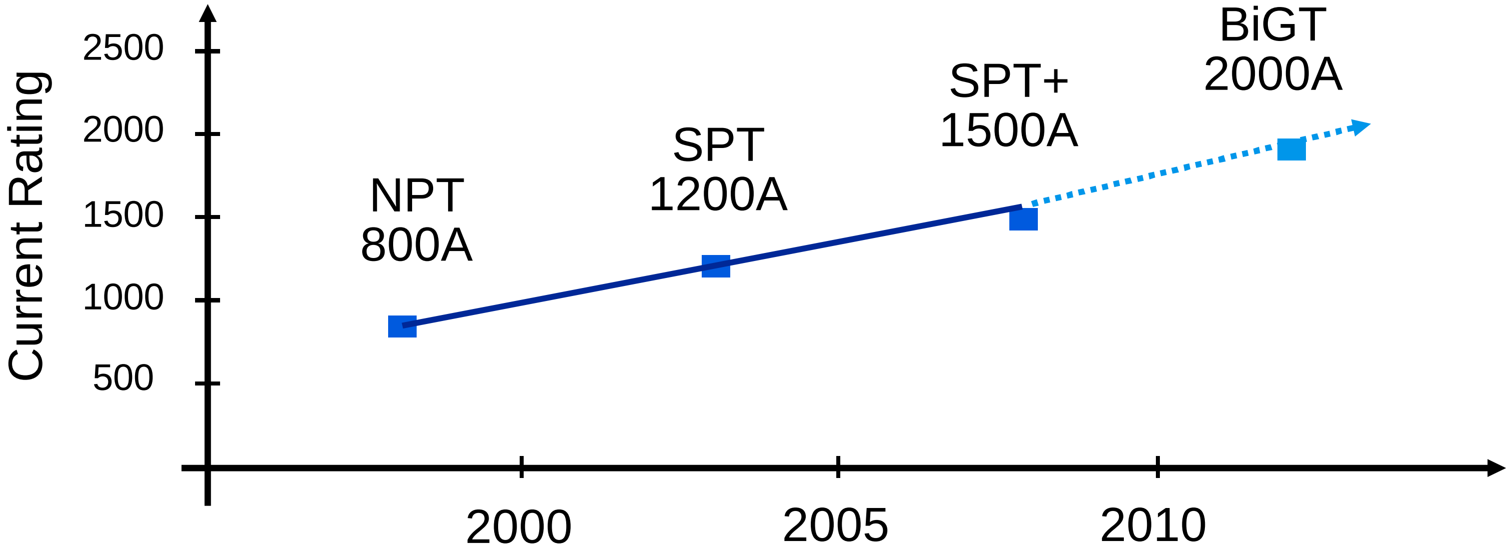


2016?: 800A

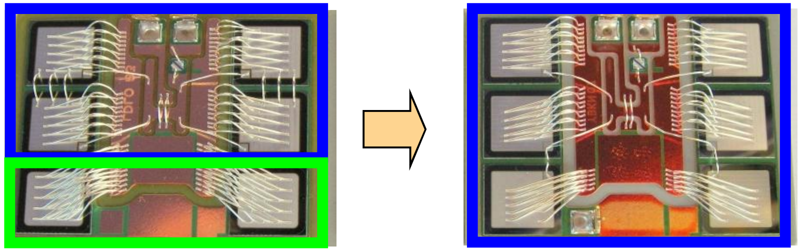


Technology Value for Customer
Increased Power per Module

Example: 3.3 kV HiPak2



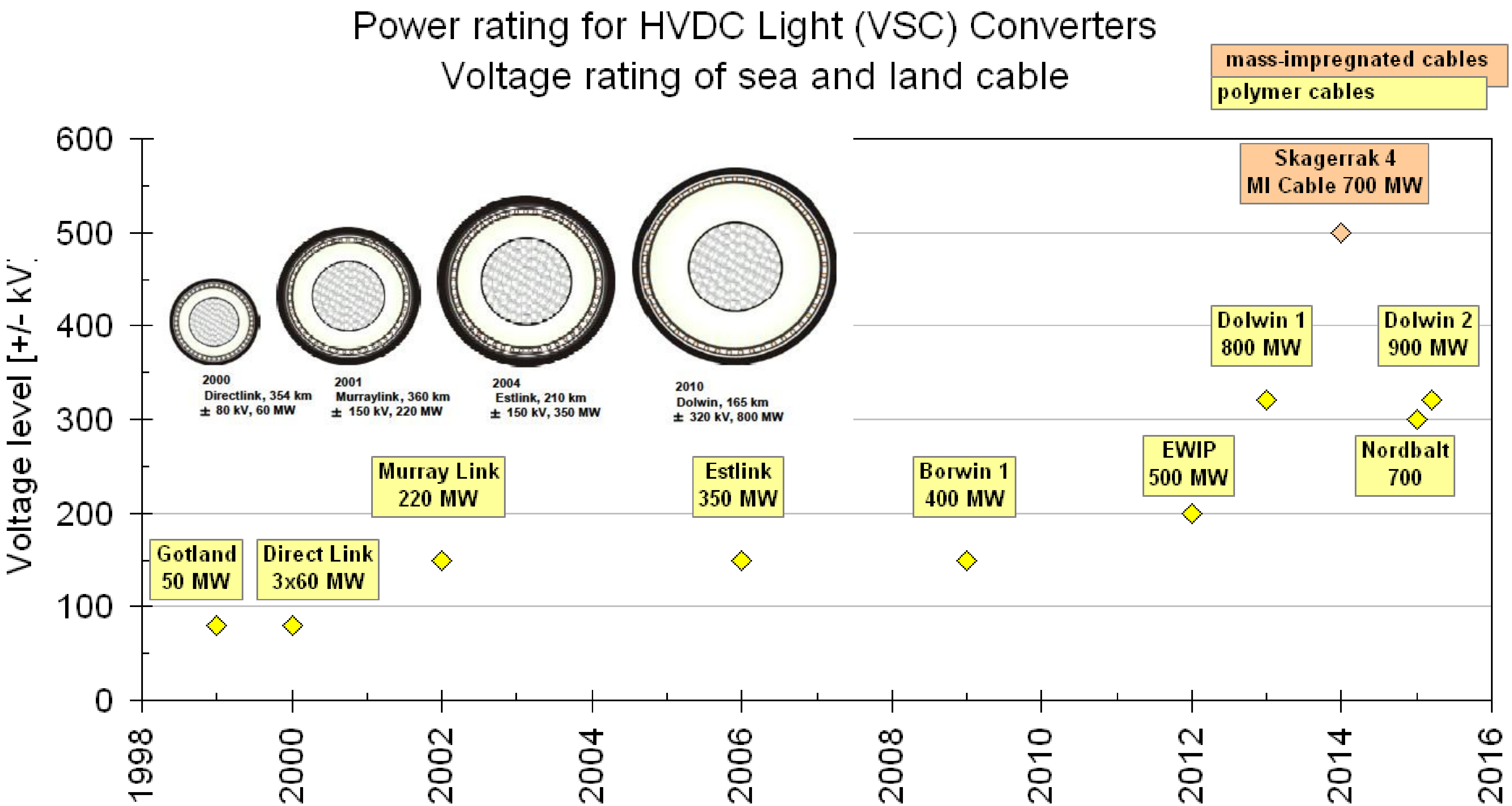
4 x 62.5A **IGBT**
2 x 125A **Diode**
250A



6 x 62.5A **BIGT**

375A

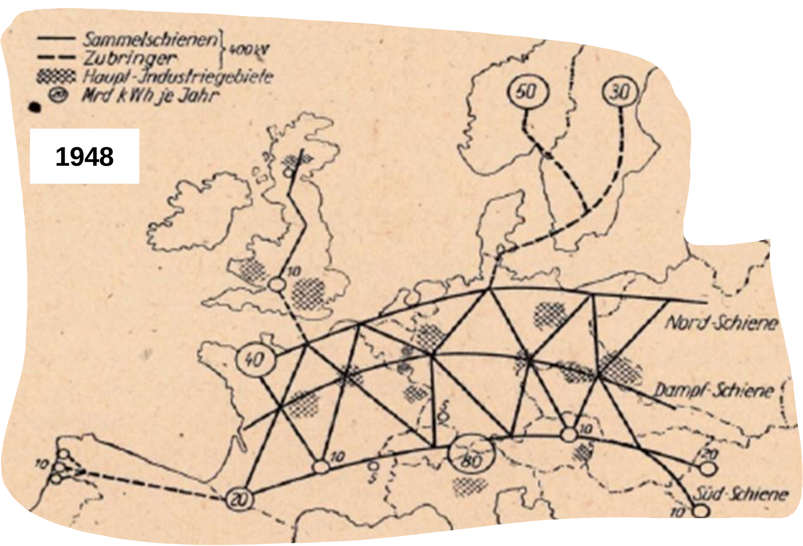
Polymer cable systems for HVDC
Increase in voltage and power by new insulation materials and processing methods



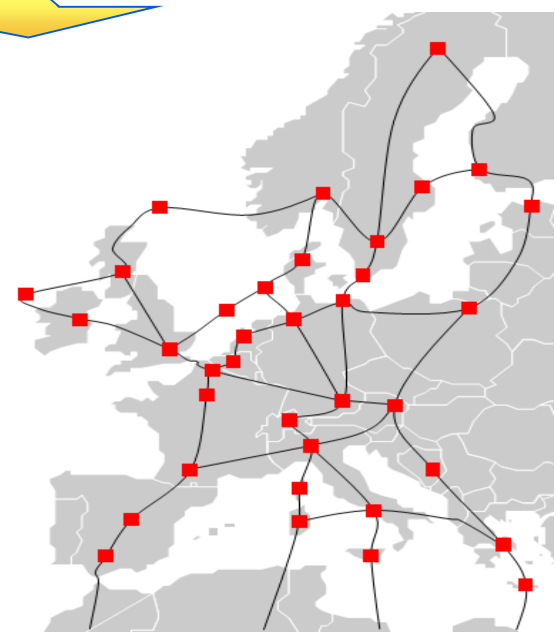
ABB

The Vision – Pan Continental HVDC Grids

Challenge



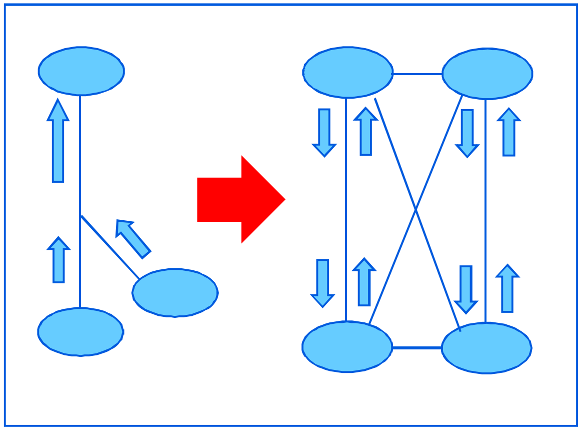
AC Grid plan 1948

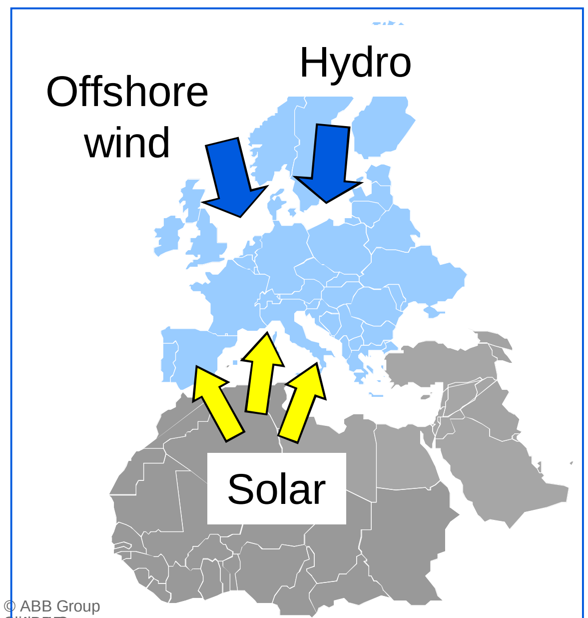


Overlayed DC-grid

This vision is now a shared vision
MoU European Energy Ministers Round the North Sea

HVDC Grids – Why?
Regional to continental HVDC Grids





Why DC Grids *vs* DC single links or AC

- Only relevant offshore solution
- Loss reduction
- Increased power capacity vs. AC
- Less visual impact

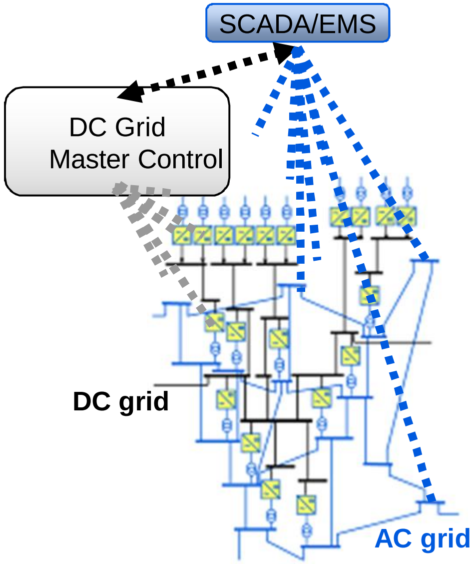
Why now:

- Offshore wind, remote solar, grid constraints
- HVDC Light systems and components mature

Challenges:

- DC Breakers & DC/DC Converters
- Regulatory framework

Regional Grids can be delivered today - We are working on the missing gaps for the full realization



- Control & Protection Systems for multi-terminal operation and grid master control
  - **ABB:s response:**
    State-of-the-art real time digital simulation center for hardware-in-the-loop verification of control and protection methods
  - Interaction of converter control, DC Grid control & SCADA EMS

The fault current – Sets requirements on breaker

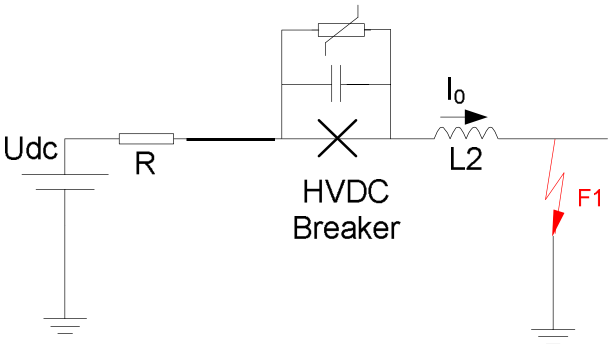
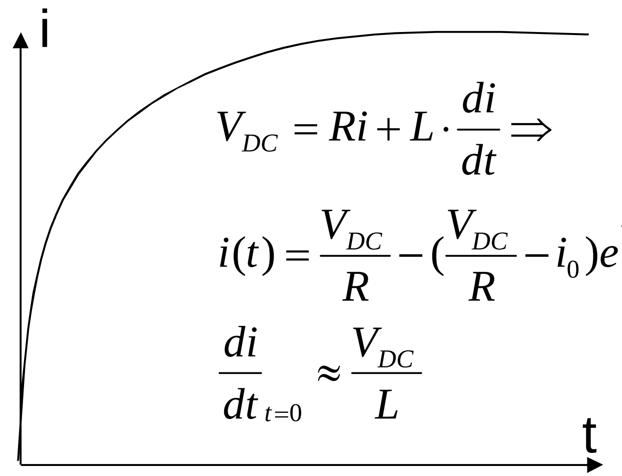


Figure 1: Simplified circuit for fault clearance



$$V_{DC} = Ri + L \cdot \frac{di}{dt} \Rightarrow$$

$$i(t) = \frac{V_{DC}}{R} - \left(\frac{V_{DC}}{R} - i_0\right)e^{-\frac{R}{L}t}$$

$$\left.\frac{di}{dt}\right|_{t=0} \approx \frac{V_{DC}}{L}$$

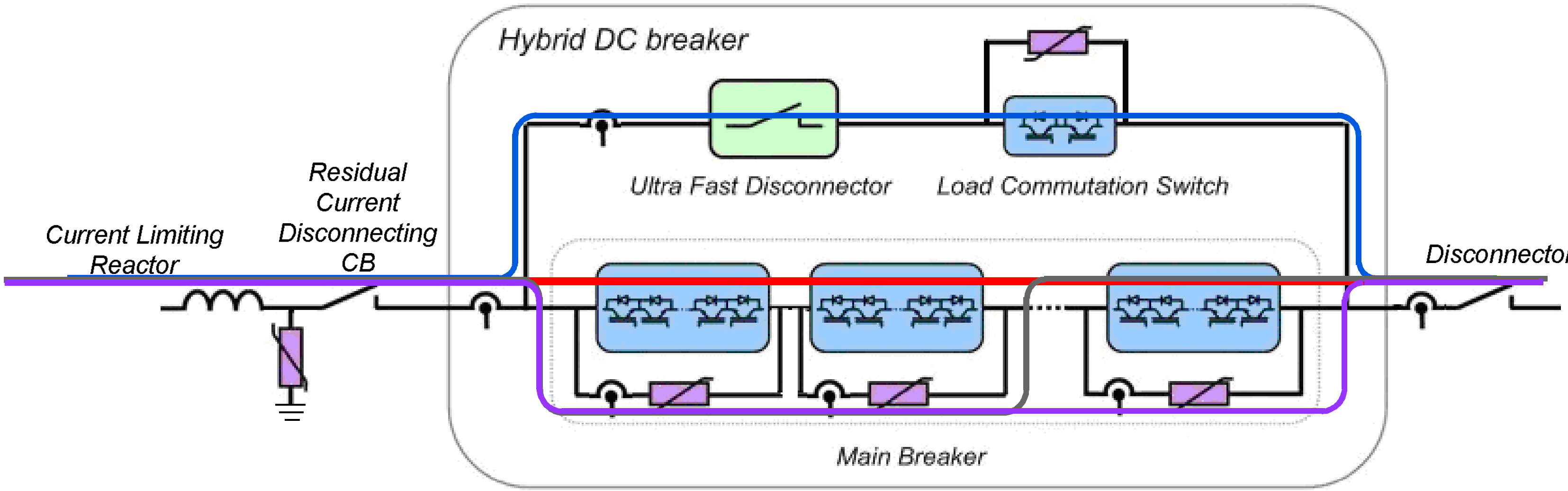
- Low inductive + low resistive circuit
  ➔ high rate of rise currents to high values, e.g. 3 kA/ms

$$\frac{di}{dt} \approx \frac{U}{L} = \frac{320\,\mathrm{kV}}{100\,\mathrm{mH}} = 3.2\,\mathrm{kA/ms}$$

- DC breaker with limited capacity breaking

  ➔ fast fault detection

Hybrid DC Breaker
Basic Functionality



- Normal operation: Current flows in low-loss bypass
- Proactive control: Load Commutation Switch opens and commutates current into Main Breaker; the Ultra Fast Disconnector opens with very low voltage and current stress
- Fault clearance: Remaining Main Breaker Modules open and commutate fault current into corresponding arrester banks

Conclusions and take-aways

- Massive investment in electricity generation and transmission & distribution foreseen
- Generate renewable electricity where it is most suitable and transmit with low loss to load centers
- LCC for bulk transfer
- VSC for wind, undergrounding and embedded transmission with P&Q capability

Power and productivity
for a better world™

Assessment of Electric Vehicle Charging Scenarios Based on Demographical Data

David Steen, Le Anh Tuan, *Member, IEEE*, Ola Carlson, *Member, IEEE*, and Lina Bertling, *Senior Member, IEEE*

***Abstract*—A massive introduction of plug-in electric vehicles (PEVs) in the transportation sector would likely increase the total electricity consumption. Depending on how and when the PEVs are charged, the effects on the power demand will vary. Previous studies have shown that uncontrolled charge of PEVs can cause problems for the distribution system in some areas. This paper proposes an approach to control PEVs charging based on the charging behavior estimated from the demographical statistical data. In this approach, three different charge strategies are designed and the impacts of PEVs charging on the distribution system is assess using standard load flow calculations. A case study using the proposed approach examines the real situation in Gothenburg, a city on the west coast of Sweden. The results from the study show that the impacts on the distribution system due to PEVs vary between different areas. By controlling the charging, the impacts can be reduced but the choice of control methods must be chosen carefully. Furthermore, the results indicate that a well-developed public charging infrastructure could reduce the stress on the residential distribution systems since part of the charging can be done in commercial areas.**

***Index Terms*—Electric distribution system, electric vehicle (EV), open loop radial distribution system, plug-in electric vehicle (PEV), plug-in hybrid electric vehicle (PHEV).**

List of Nomenclatures and Symbols

EPS	Electric power system.
DSO	Distribution system operator.
DS	Electrical distribution system.
OLR-DS	Open loop radial distribution system.
EV	Electric vehicle.
PHEV	Plug-in hybrid electric vehicle.
PEV	Plug-in electric vehicle.
DG	Distributed generation.
DES	Distributed energy storage.
V2G	Vehicle To grid.
$\mathrm{PEV}_{\max}$	Maximum number of PEVs.
$\mathrm{PEV}_{\mathrm{share}}$	PEV penetration share ($1 = 100\%$ PEVs).
i	Bus index.
h	Hour index.
n	No. of buses.
VH_h^W	No. of vehicles stopping at work at hour h.
VH_h^H	No. of vehicles stopping at home at hour h.
$\mathrm{VH}_h^{\mathrm{SL}}$	No. of vehicles used for shopping and leisure journeys stopping at hour h.
CP_P	Active charge power.
CP_Q	Reactive charge power.
CT	Charge time.
$\mathrm{P}_{\mathrm{PEV}_{i,h}}$	Active PEV load at bus i at hour h.
$\mathrm{P}^W_{\mathrm{PEV}_{i,h}}$	Active PEV load, charging at work, at bus i at hour h.
$\mathrm{P}^H_{\mathrm{PEV}_{i,h}}$	Active PEV load, charging at home, at bus i at hour h.
$\mathrm{P}^{\mathrm{SL}}_{\mathrm{PEV}_{i,h}}$	Active PEV load, for PEVs used for shopping and leisure journeys, at bus i at hour h.
$\mathrm{Q}_{\mathrm{PEV}_{i,h}}$	Reactive PEV load at bus i at hour h.
Dist	Average driving distance.
Cons	Average energy consumption [kWh/km].
η	Charge efficiency (*"Grid to Battery"*).
$\mathrm{P}_{i,h}$	Active power at bus i at hour h.
$\mathrm{Q}_{i,h}$	Reactive power at bus i at hour h.
$\mathrm{P}_{D_{i,h}}$	Base load active power demand at bus i at hour h.
$\mathrm{Q}_{D_{i,h}}$	Base load reactive power demand at bus i at hour h.
$\cos\varphi$	Power factor.
$\mathrm{P}_{\mathrm{loss}}$	Losses in the distribution system.
$\mathrm{G}_{i,j}$	Conductance of cable (i,j).
$\lvert\mathrm{Y}_{i,j}\rvert$	Element of the network admittance matrix.
$\theta_{i,j}$	Angle associated with $\mathrm{Y}_{i,j}$.
$\lvert\mathrm{V}_{i,h}\rvert$	Voltage magnitude at bus i at hour h.
$\delta_{i,h}$	Angle associated with $\mathrm{V}_{i,h}$.
$I_{i,j,h}$	Current in cable (i,j) at hour h.

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

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$I_{i,j}^{\max}$	Maximum current capacity in cable (i,j).
$S_i^{\max}$	Maximum apparent power capacity in transformer at bus (i).
$\mathrm{Cost}_{\mathrm{PEV}}$	Average charge cost for one PEV.
Price_h	Electricity price per kWh at hour h.
$\mathrm{VH}_h^{\mathrm{HP}}$	No. of vehicles parked at home at hour h.
$\mathrm{VH}_h^{\mathrm{WP}}$	No. of vehicles parked at work at hour h.
$\mathrm{VH}_h^{\mathrm{SLP}}$	No. of vehicles used for shopping and leisure journeys parked at home at hour h.
$\mathrm{WP}_{\mathrm{City}}$	No. of workplaces in the city.
$\mathrm{WP}_{\mathrm{DS}}$	No. of workplaces in the DS.
WP_D	No. of workplaces in the district where the DS is located.
$\mathrm{EP}_{\mathrm{DS}}$	No. of employed persons living in the DS area.
EP_D	No. of employed persons living in the district where the DS is located.
F_{DS}	No. of customers (families) connected to the DS.
F_D	No. of families living in the district where the DS is located.
$\mathrm{VCS}_{\mathrm{City}}$	Vehicle commuting share in the city or country.
$\mathrm{VCS}_{\mathrm{DS}}$	Vehicle commuting share in the DS.
$\mathrm{VH}_{\mathrm{City}}$	No. of vehicles registered in the city.
$\mathrm{VH}_{\mathrm{DS}}$	No. of vehicles registered in the DS.
$\mathrm{VH}_{\mathrm{City}}^{\mathrm{SL}}$	No. of vehicles used for shopping and leisure journeys in the city.
$\mathrm{P}_{f,c}$	Power capacity for the system in case of a failure in feeder f, for reconfiguration c.
$\mathrm{P}_f^{\max}$	Maximum power capacity for the system in case of a failure in feeder f, for the optimal reconfiguration.

I. Introduction

The plug-in electric vehicle (PEV), including plug-in hybrid electric vehicle (PHEV) and electric vehicle (EV), can, as they are using electricity as the energy carrier, be energized by power sources based on e.g., hydro, nuclear, coal, wind and solar etc. It is considered as one of the promising options to reduce the oil dependency, energy usage and CO_2-emissions. A massive introduction of PEVs will, however, likely increase the total electricity consumption and may put higher stress on the electrical infrastructure.

Several studies have been conducted regarding PEVs and their impact on the electric power system (EPS) on a national level, e.g., [1]–[3]. The results vary for different countries, although most of the studies conclude that the impact will be reduced if the charging is controlled to take place during off-peak hours. A study from Sweden [1] showed that the increased energy needed to charge 80% of the vehicle fleet in Sweden corresponds to about 6% (about 9 TWh) of the total electricity consumption in Sweden, which can be compared with the goal off the Swedish government to produce 30 TWh (about 20% of the electricity produced today) of electricity from wind power by 2030 [4]. Although the energy problem seems to be manageable for Sweden, it may be a problem regarding the capacity in the EPS. According to [1], the power needed to charge 80% of the vehicle fleet is about 3 GW, which is about 10% of the installed generating capacity in Sweden. If charging is conducted during peak hours, this can result in a need to install more generating and transmission capacity into the EPS. The EPS in Portugal will experience a power demand increase by 30% for a PEV penetration level of 17% if uncontrolled charging is conducted, although the energy demand is only increased by 3% [2]. The EPS in USA could, on average, provide 73% of the vehicle fleet with electricity if charging was conducted during off-peak hours. However the number varies from 18%–127% between the states [3].

On an electric distribution system (DS) level, the impacts could be even more severe if the charging is uncontrolled. Several studies have been conducted for different regions and countries, e.g., Portugal [5], Germany [6], Belgium [7], USA [8], and Canada [9], among others. All of these studies pointed at the need to coordinate the charging in some way to be able to accommodate a large number of PEVs in the DS. However, only [9] considers that the PEVs can be charged at different locations and that the charge behavior will vary between different areas, although the place of the charging is discussed in [6]. In [9], the PEV charging can be conducted both at home, at work or at a retail location. The number of vehicles charging at the retail location is estimated based on traffic volume data, but it is not described how the number of PEVs charging at the work location is estimated.

In [10], the maximum number of simultaneously charged vehicles were estimated for two different 10-kV DS in Gothenburg, one commercial and one residential, during a peak hour. The study showed that without any control, it could be a problem to charge high penetration of PEVs, especially for the residential area. As a continuation of that study, an optimal charge strategy, aiming at minimizing the losses, was proposed in [11]. The results showed that the possible reduction in losses was small and the main advantage of coordinating the charging of the vehicles was that the number of vehicles that could be handled without any violation was increased substantially.

The present paper proposes an approach to estimate the impact of PEVs charging on a real open loop radial distribution system (OLR-DS) based on demographical data and a travel survey in order to obtain realistic results. Three different charge strategies are proposed in this paper: uncontrolled, loss-optimal and price-optimal, to evaluate the possible advantages of controlling the charging. The uncontrolled and loss-optimal charge strategies are based on the strategies presented earlier in [11] but include two different charge scenarios, one scenario only allowing charging at home, which represents a future where the public charge infrastructure is limited, and the other one allowing charging both at home and at work, which represents a future with a public charge infrastructure in place. In addition, shopping and leisure journeys are considered in this study. The price-optimal charge strategy is based on the assumption that the PEVs are subject to obtaining hourly electricity prices at the Nordic day-ahead spot market [12]. To predict where the vehicles are located during the day, demographical data, such as number of workplaces and employees, have been used. Data from a national travel survey [13] are used to obtain usage patterns for the vehicles.

The paper is organized in five main sections. Section II gives an overall presentation of the proposed approach. Section III presents the detailed formulation of the models. Section IV presents the data used for the case study while Section V presents the results from the case study. The conclusions are presented in Section VI.

II. Proposed Approach

An approach is proposed to evaluate the impacts of PEVs charging on an electrical distribution system (DS) as illustrated in Fig. 1. The first step in this approach is to gather the data needed for the study. From the data, three key parameters can be processed for further analysis: 1) the locations of the vehicles (i.e., where can they be charged); 2) when they are parked (i.e., when can they be charged) and 3) technical limitations in the DS. The second step in this approach is to formulate and implement the optimization models for different charge strategies. The final step is to use the data in the models developed to evaluate the impacts of different PEVs charge strategies on the DS. The models just mentioned above are based on an ac optimal power flow framework which is described in, e.g., [14], with the objective functions being: maximization of the number of PEVs, minimization of the network losses, minimization of the electricity cost paid by PEVs owners, respectively. These models are implemented in a general algebraic modeling system (GAMS), a high-level modeling system for mathematical programming and optimization [15].

The majority of the vehicles are used for transportation purposes and can, with a developed charge infrastructure, be charged at different locations. The proposed approach uses demographical data to estimate the number of vehicles during different hours of the day, for different areas. The demographical data provides information such as number of workplaces, vehicle density and number of employees, etc. for an area. By solely using information such as the number of customers connected to the DS, the estimated number of vehicles may be inaccurate due to differences between different locations. In addition to where the vehicles are charged, it is also important to know when and for how long they are charging. As in [7] and [11], the approach in this study is to use data from a national travel survey to estimate when the vehicles are actually used. The case study includes only privately owned passenger vehicles and no commercial vehicles are included, and are hereinafter referred to as vehicles.

An open loop radial distribution system (OLR-DS) is designed as a meshed system but is normally operated radially using the tie and sectionalizing switches. The system configuration can be modified by changing the status of the switches [16]. This will enable the possibility to improve the operation

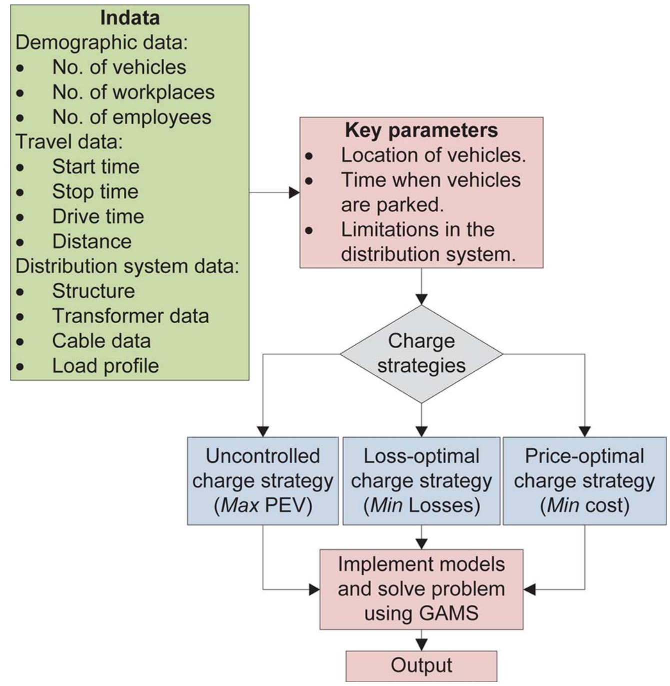

Fig. 1. Flowchart of the proposed approach.

condition, such as minimizing the losses, but also to improve the reliability of the DS. The reliability is improved if the DS is operated in such a way that if a failure occurs in one of the feeder the load can be supplied by the remaining feeders with minimum interruption time. The proposed approach can analytically find the optimal reconfiguration and the capacity of the DS when one of the feeders is disconnected.

Three charge strategies were analyzed in two different future scenarios which are described below:

1) Scenario A: Charging is only conducted at home, i.e., limited charge infrastructure is available.
2) Scenario B: Charging is conducted both at home and at work, i.e., a well-developed charge infrastructure.

Additionally, the results were compared with a reference scenario without any PEVs.

III. Formulation of Charge Strategies

This section presents the formulation of the proposed charge strategies developed within this work.

A. Uncontrolled Charge Strategy

The uncontrolled charge strategy assumes that the charging is conducted immediately after each journey or immediately after the last journey of the day. For both scenarios, it is assumed that the charging is conducted on a daily basis.

1) Objective Function: The objective is to maximize the number of PEVs which can be charged in the DS. This is shown in (1), where the decision variable is the penetration level, $\mathrm{PEV}_{\mathrm{share}}$:

$$\mathrm{PEV}_{\max} = \sum_{h=1}^{24} \left(\mathrm{VH}_h^H + \mathrm{VH}_h^W + \mathrm{VH}_h^{\mathrm{SL}}\right) \cdot \mathrm{PEV}_{\mathrm{share}}. \quad (1)$$

The total number of vehicles consist of all vehicles that are making a stop in the area, i.e., the vehicles commuting to the area in the morning (VH_h^W), i.e., commuting to work, and in the afternoon (VH_h^H), i.e., commuting home, and the vehicles that conduct a shopping or leisure related journey during the day $(\mathrm{VH}_h^{\mathrm{SL}})$.

2) Constraints: The total power drawn from the DS by the PEVs depends on the active charge power (CP_P) and the charge time (CT) and is calculated from (2)–(4). As can be seen in the last fraction in (2)–(3), the PEVs are assumed to be distributed between the buses according to the base load power demand of each bus, and during the day according to the stop time given by [13]. For scenario A, where only charging at home is available, no PEVs will be charged at work, i.e., $\mathrm{VH}_h^W = 0$, and the charge time for the PEVs charging at home will be increased since the interval between the charges is increased:

$$P_{\mathrm{PEV}_{i,h}}^H = \sum_{k=h-\mathrm{CT}_H+1}^{h} \left(\mathrm{VH}_k^H \cdot \mathrm{PEV}_{\mathrm{share}}\right) \cdot \mathrm{CP}_P \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^n P_{D_{i,h}}} \quad (2)$$

$$P_{\mathrm{PEV}_{i,h}}^W = \sum_{k=h-\mathrm{CT}_W+1}^{h} \left(\mathrm{VH}_k^W \cdot \mathrm{PEV}_{\mathrm{share}}\right) \cdot \mathrm{CP}_P \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^n P_{D_{i,h}}} \quad (3)$$

$$P_{\mathrm{PEV}_{i,h}}^{\mathrm{SL}} = \sum_{k=h-\mathrm{CT}_{\mathrm{SL}}+1}^{h} \left(\mathrm{VH}_k^{\mathrm{SL}} \cdot \mathrm{PEV}_{\mathrm{share}}\right) \cdot \mathrm{CP}_P \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^n P_{D_{i,h}}}. \quad (4)$$

The total power drawn from the DS to charge the PEVs is calculated from (5) and (6):

$$P_{\mathrm{PEV}_{i,h}} = P_{\mathrm{PEV}_{i,h}}^H + P_{\mathrm{PEV}_{i,h}}^W + P_{\mathrm{PEV}_{i,h}}^{\mathrm{SL}} \quad (5)$$

$$Q_{\mathrm{PEV}_{i,h}} = P_{\mathrm{PEV}_{i,h}} \cdot \tan\varphi. \quad (6)$$

The CT depends on the active charge power (CP_P), the efficiency of the charger and battery (η), the energy consumed per km (Cons) and the distance driven (Dist), which vary between commuting journeys and shopping and leisure journeys and is given by (7):

$$\mathrm{CT} = \frac{\mathrm{Dist} \cdot \mathrm{Cons}}{\mathrm{CP}_P \cdot \eta}. \quad (7)$$

It is assumed that the distance to/from work is equal but different from the distance for shopping and leisure journeys, i.e., $\mathrm{CT}_W = \mathrm{CT}_H \neq \mathrm{CT}_{\mathrm{SL}}$.

The standard power flow constraints are given by (8) and (9) [14]:

$$P_{i,h} - \left(P_{D_{i,h}} + P_{\mathrm{PEV}_{i,h}}\right) = \sum_{j=1}^{n} |Y_{i,j}| \cdot |V_{i,h}| \cdot |V_{j,h}| \cdot \cos(\theta_{i,j} + \delta_{j,h} - \delta_{i,h}) \quad (8)$$

$$Q_{i,h} - \left(Q_{D_{i,h}} + Q_{\mathrm{PEV}_{i,h}}\right) = -\sum_{j=1}^{n} |Y_{i,j}| \cdot |V_{i,h}| \cdot |V_{j,h}| \cdot \sin(\theta_{i,j} + \delta_{j,h} - \delta_{i,h}). \quad (9)$$

Further the voltage is limited according to (10):

$$0.9 \leq |V_{i,h}| \leq 1.1\,\mathrm{p.u} \quad (10)$$

the current limitations in the cables according to (11):

$$I_{i,j,h} \leq I_{i,j}^{\max} \quad (11)$$

and the transformer capacity according to (12):

$$\sqrt{\left(P_{\mathrm{PEV}_{i,h}} + P_{D_{i,h}}\right)^2 + \left(Q_{\mathrm{PEV}_{i,h}} + Q_{D_{i,h}}\right)^2} \leq S_i^{\max}. \quad (12)$$

The total loss in the DS during one day is calculated by (13), [14]:

$$P_{\mathrm{Loss}} = \frac{1}{2} \sum_{h=1}^{24} \cdot \left(\sum_{j=1}^{n} \cdot \sum_{i=1}^{n} G_{i,j} \cdot (|V_{i,h}|^2 + |V_{j,h}|^2 - 2 \cdot |V_{i,h}| \cdot |V_{j,h}| \cdot \cos(\delta_{j,h} - \delta_{i,h})) \right). \quad (13)$$

The average cost of charging one PEV during one day is calculated according to (14):

$$\mathrm{Cost}_{\mathrm{PEV}} = \frac{\sum_{h=1}^{24} \mathrm{Price}_h \cdot \sum_{i=1}^{n} P_{\mathrm{PEV}_{i,h}}}{\mathrm{PEV}_{\max}}. \quad (14)$$

It can be noted that the loss and cost can be calculated for any given PEV penetration. The time step of the simulations in this study is one hour. It can be reduced if desired to gain more detailed results.

B. Loss-Optimal Charge Strategy

Compared to the uncontrolled charge strategy where the charging starts immediately when the vehicle is parked, the loss-optimal charge strategy seeks to conduct the charging when it is most favorable from the DSO's point of view. The objective of the loss-optimal charging is to minimize the losses in the DS for a given penetration of PEVs. The objective function is given by (13). The decision variables for the loss-optimal charge strategy are the total charge power at hour h, i.e., when the charging is conducted.

1) Constraints: The objective function is subjected to the number of PEVs given by (1) and, as for the uncontrolled charge strategy, to the total charge power, power flow constraints and network constraints given by (5)–(12). However, the total charge power will be limited by the number of PEVs that are parked according to (15)–(17):

$$P_{\mathrm{PEV}_{i,h}}^H \leq \mathrm{VH}_h^{\mathrm{HP}} \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^n P_{D_{i,h}}} \cdot \mathrm{PEV}_{\mathrm{share}} \cdot \mathrm{CP}_P \quad (15)$$

$$P_{\mathrm{PEV}_{i,h}}^{W} \leq \mathrm{VH}_h^{\mathrm{WP}} \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^{n} P_{D_{i,h}}} \cdot \mathrm{PEV}_{\mathrm{share}} \cdot \mathrm{CP}_P \quad (16)$$

$$P_{\mathrm{PEV}_{i,h}}^{\mathrm{SL}} \leq \mathrm{VH}_h^{\mathrm{SLP}} \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^{n} P_{D_{i,h}}} \cdot \mathrm{PEV}_{\mathrm{share}} \cdot \mathrm{CP}_P. \quad (17)$$

In addition, all PEVs connected to bus i need to be charged over 24 h, according to (18)–(20):

$$\sum_{h=1}^{24} P_{\mathrm{PEV}_{i,h}}^{H} = \sum_{h=1}^{24} \mathrm{VH}_h^{H} \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^{n} P_{D_{i,h}}} \cdot \mathrm{PEV}_{\mathrm{share}} \cdot \mathrm{CP}_P \cdot \mathrm{CT}_H \quad (18)$$

$$\sum_{h=1}^{24} P_{\mathrm{PEV}_{i,h}}^{W} = \sum_{h=1}^{24} \mathrm{VH}_h^{W} \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^{n} P_{D_{i,h}}} \cdot \mathrm{PEV}_{\mathrm{share}} \cdot \mathrm{CP}_P \cdot \mathrm{CT}_W \quad (19)$$

$$\sum_{h=1}^{24} P_{\mathrm{PEV}_{i,h}}^{\mathrm{SL}} = \sum_{h=1}^{24} \mathrm{VH}_h^{\mathrm{SL}} \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^{n} P_{D_{i,h}}} \cdot \mathrm{PEV}_{\mathrm{share}} \cdot \mathrm{CP}_P \cdot \mathrm{CT}_{\mathrm{SL}}. \quad (20)$$

The maximum penetration can be found by iteratively increasing the penetration level until any of the limitations in the DS is violated.

C. Price-Optimal Charge Strategy

Although the losses can be reduced by charging according to the loss-optimal charge strategy, the incentive for the customer may be limited [11]. The introduction of smart meters enables the possibility to pay the electricity on an hourly basis [17]. In the price-optimal charge strategy, it is assumed that the electricity price for the customer is based on the spot price at Nordpool spot. The price-optimal charge strategy seeks to minimize the electricity cost for the customers for charging PEVs according to (14). Similarly to the loss-optimal charge strategy, the decision variables for the price-optimal charge strategy are the total charge power at each hour.

1) Constraints: The objective function is subjected to the number of PEVs given by (1) and to the total charge power, power flow constraints and the distribution of the PEVs according to (5)–(9) and (15)–(20).

Since this control strategy is customer oriented (i.e., the customer decides when to charge) and the customers are unaware of the limitations in the DS [(10)–(12)], these limitations will not affect when the charging is conducted although it will limit the penetration level of PEVs. Therefor these constraints are not included in the price-optimal charge strategy. However, the maximum penetration of PEVs is found by iteratively increasing the penetration level until any of the limitations in the DS [(10)–(12)] is violated.

IV. Data and Assumptions for the Case Study

The following section presents the data and assumptions used in the case study. For the case study, the different charge strategies proposed in Section III are applied to examine the impact of PEV charging for two parts of the real DS in Gothenburg, Sweden.

A. Capacity of an Open Loop Radial Distribution System (OLR-DS)

The power capacity in a DS is either limited by the thermal limit of cables and transformers or by the voltage drop in the DS. The same holds for the open loop radial DS (OLR-DS). To maintain high reliability, the maximum loading of the cables is reduced, since the remaining feeders must be able to supply all loads in case of a failure in one of the feeders. Several studies, e.g., [16], [18], [19], have been conducted to find the optimal reconfiguration of a OLR-DS. However, the focus of these studies has been on minimizing the losses and the restoration time, not on maximizing the capacity or reliability of the system, although these could be included [16]. With an introduction of PEVs, the peak demand may increase, which will increase the importance of maximizing the power capacity of the DS.

Due to the nonlinear nature of the power flow problem and the large number of reconfiguration possibilities, it is difficult to find the solution that provides highest capacity. To find the reconfiguration option with highest power capacity in case of a disconnected feeder, an analytic approach is proposed. Fig. 2 presents the proposed approach. Firstly, all reconfigurations possibilities (c) in case of the most severe fault [i.e., a fault located at one of the main feeders (f)] are identified. Secondly the total maximum power of the DS $(\mathrm{P}_{f,c})$ is calculated for each reconfiguration (c) by increasing the load at every substation until the DS is overloaded, either by the thermal limits of the cables and transformers or by the voltage drop in the system, and the reconfiguration with highest power capacity $(\mathrm{P}_f^{\max})$ is found. The load is assumed to be increased linearly between the substations, i.e., a substation with high load today is assumed to have a higher increase than that of a substation with less load. The power capacity is found when each of the feeders is disconnected, one at a time. The disconnected feeder with lowest power capacity found $(\mathrm{P}_f^{\max})$ corresponds to the most severe fault in the system.

The DS simulated in the case study is situated in the city of Gothenburg, Sweden. Two areas of the DS are simulated, one residential and one commercial. The residential part consists of three 10-kV feeders and 26 10/0.4-kV substations and the load consist mostly of small houses. The commercial part consists of four 10-kV feeders, nine 10/0.4-kV substations, and three 10-kV custom stations. The commercial area consists mostly of office buildings and apartments. Figs. 3 and 4 present the one-line diagram of the DS, where the tie switches are open in normal operation.

By using the proposed approach described in Fig. 2, the optimal reconfiguration option with regards to the capacity is found for the case with one of the feeders disconnected. The sectionalizing switches shown in Figs. 3 and 4 indicate the optimal reconfiguration for the DSs in case of a disconnected feeder.

The total capacity in the DS is, as stated before, limited by the thermal limits of the cables and transformers or by the voltage

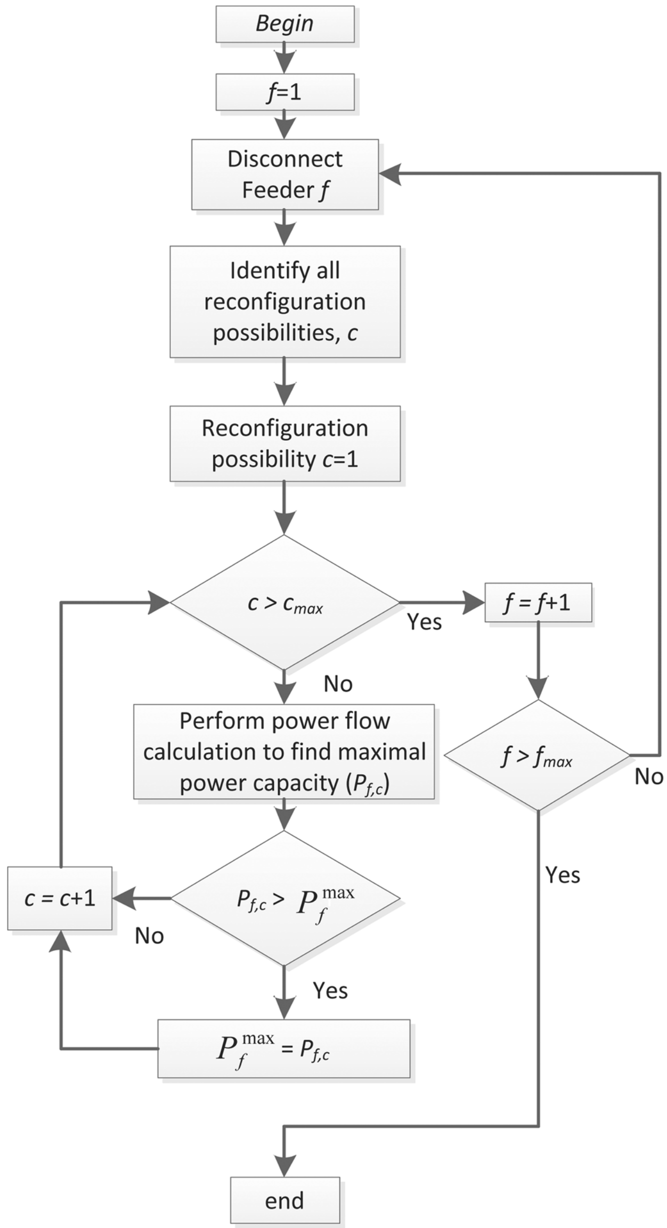

Fig. 2. Flowchart of the process to identify the reconfiguration possibility with highest power capacity.

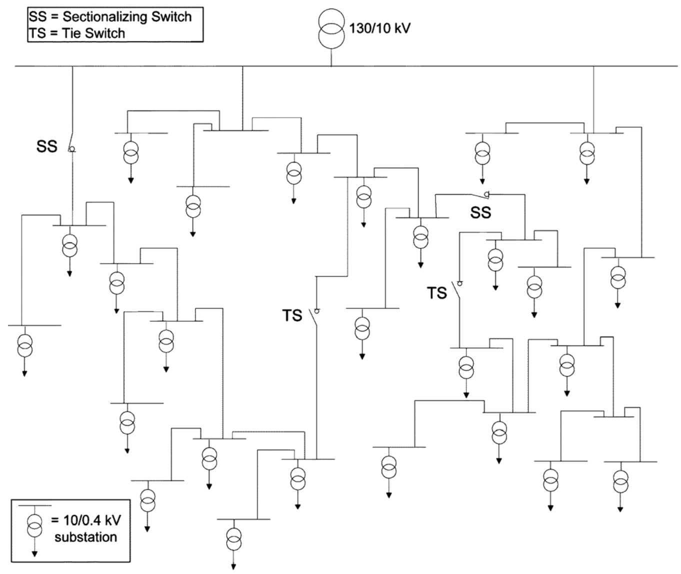

Fig. 3. One-line diagram of the residential distribution system.

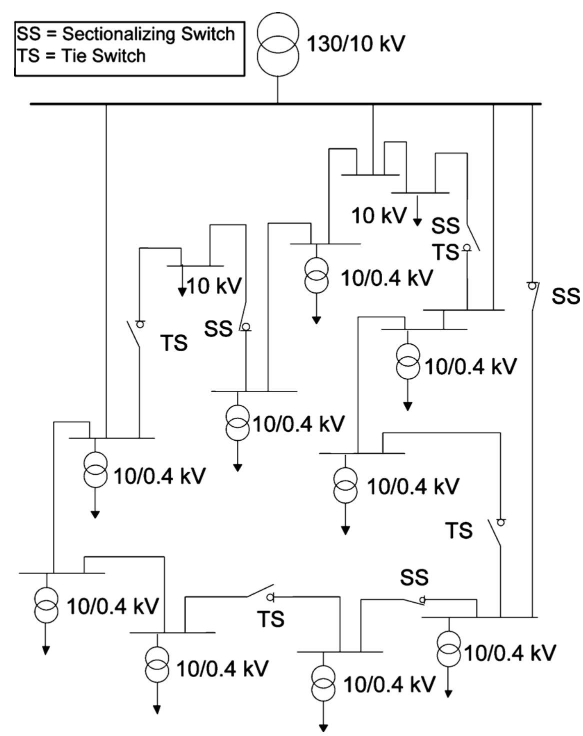

Fig. 4. One-line diagram of the commercial distribution system.

drop in the DS and will in turn depend on how the loads are distributed between the substations. Table I presents the calculated maximum total capacity for the DS's for the situation when the load increases linearly between the substations, both for normal operation and for contingency operation (i.e., when one of the feeders is disconnected, hereinafter referred to as "redundancy mode"). Additionally, the number of customers connected to the DS, provided by Göteborg Energi, is presented in Table I and is used when calculating the number of vehicles for the different areas, which is further described in the following subsection.

Furthermore, the hourly load profile for 2008 was obtained from Göteborg Energi. Since the grid should be designed to withstand the highest demand during the year, the day with highest demand was chosen as a reference case for the case study. Fig. 5 presents the load profiles for the 10-kV DS in the residential and the commercial area without any PEVs. Obviously, the profiles differ between the areas.

B. Estimation of Number of Vehicles and Their Usage

The number of vehicles in an area depends mainly on the number of people living in that area, but also on the type of area. Similar to the load profiles, the number of vehicles varies during the day for the different areas. In the residential area, there are only a few workplaces, which means that during day time there will only be a limited number of vehicles parked in this area and the number is highest during the evening when people return home from work. The opposite holds for the commercial area.

TABLE I
MAXIMUM CAPACITY, PEAK LOAD, AND NO. OF CUSTOMERS

	Residential	Commercial
No. of customers	1932	635
Peak demand [MW]	7.91	7.76
Max capacity normal mode [MW]	10.04	13.66
Max capacity redundancy mode [MW]	7.63	9.68

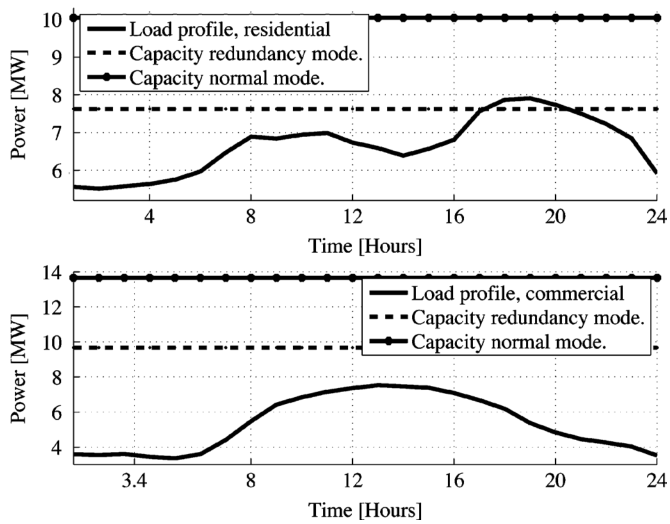

Fig. 5. Load profile for the DS in the residential and in the commercial area.

To make realistic assumptions regarding the impacts of PEVs on a DS, it is important to know in what kind of area the DS is located. For this study, the number of household customers connected to the DS $(\mathrm{F}_{\mathrm{DS}})$ and the location of the DS is known. In addition, demographical data, such as number of vehicle (VH_D), number of workplaces (WP_D), number of families (F_D), etc., are available for the district where the DS is located.

The number of persons working in the DS area $(\mathrm{WP}_{\mathrm{DS}})$ and the number of employed persons living in the DS area $(\mathrm{EP}_{\mathrm{DS}})$ can be calculated according to (21) and (22), respectively:

$$\mathrm{WP}_{\mathrm{DS}} = \frac{\mathrm{WP}_D \cdot F_{\mathrm{DS}}}{F_D} \tag{21}$$

$$\mathrm{EP}_{\mathrm{DS}} = \frac{\mathrm{EP}_D \cdot F_{\mathrm{DS}}}{F_D}. \tag{22}$$

However, some commuting journeys to work are conducted by other means than with a vehicle (i.e., a privately owned personal vehicle), e.g., public transport, bicycle, etc. If the vehicle commuting share (VCS), i.e., the percentage of all work related journeys that are conducted by a vehicle, is known for the city or country, the number of vehicles commuting to work in an area can be calculated according to (23), and the vehicles commuting back home to the area according to (24):

$$\mathrm{VH}^W = \mathrm{WP}_{\mathrm{DS}} \cdot \mathrm{VCS}_{\mathrm{City}} \tag{23}$$

$$\mathrm{VH}^H = \mathrm{EP}_{\mathrm{DS}} \cdot \mathrm{VCS}_{\mathrm{DS}}. \tag{24}$$

TABLE II
DEMOGRAPHICAL DATA

	Residential district	Commercial district	City of Gothenburg
No. of families (F_D)	2 381	3 967	286 195
No. of employees (EP_D)	3 409	3 301	241 450
No. of Workplaces (WP_D)	581	13 408	293 509
No. of vehicles (VH_D)	2 842	1 587	148 547
Vehicle Commuting Share (VCS)	39.4%	22.7%	29.1%
No. of vehicle used for leisure $(\mathrm{VH}_{city}^{SL})$	—	—	89 867

Due to differences in vehicle density (i.e., number of vehicles/persons) between the districts, it is assumed that VCS varies for the districts and also for the DS, i.e., the number of persons commuting with a vehicle will probably be higher for a district with a high vehicle density than for a district with a lower vehicle density. The VCS for the DS $(\mathrm{VCS}_{\mathrm{DS}})$ is calculated according to (25):

$$\mathrm{VCS}_{\mathrm{DS}} = \mathrm{VCS}_{\mathrm{City}} \cdot \frac{\mathrm{VH}_{\mathrm{DS}} \cdot \mathrm{EP}_{\mathrm{City}}}{\mathrm{EP}_{\mathrm{DS}} \cdot \mathrm{VH}_{\mathrm{City}}}. \tag{25}$$

Although many journeys are work related, there are journeys conducted for other purposes, such as shopping and leisure journeys. The number of vehicles used for these journeys can be calculated according to (26). With a developed charge infrastructure, these vehicles could be charged while they are parked, e.g., at the shopping center. However, due to limited data, it is assumed that they are charged at home for both scenarios, as described earlier in Section III:

$$\mathrm{VH}^{\mathrm{SL}} = \frac{\mathrm{VH}_{\mathrm{City}}^{\mathrm{SL}} \cdot \mathrm{VH}_{\mathrm{DS}}}{\mathrm{VH}_{\mathrm{City}}}. \tag{26}$$

Table II presents the number of vehicles, families, employees, workplaces, etc. for the districts where the DSs investigated in the case study are located and for the city of Gothenburg [20]. From (22)–(26) and from the data in Table II, the same information can be calculated for the DSs investigated. Table III presents the data for the DSs investigated in this case study.

As can be seen in Table III, the total number of vehicles registered in each DS $(\mathrm{VH}_{\mathrm{DS}})$ is lower than the total number of vehicles used for shopping and leisure journeys $(\mathrm{VH}^{\mathrm{SL}})$ plus the vehicles commuting home (VH^H). The reason for this is that some vehicles conduct both a commuting journey and a shopping and leisure related journey during the same day.

Commonly, all vehicles are not starting their journey simultaneously. Fig. 6 presents the start and stop time for the different journeys and can be extracted from the national travel survey [13].

Since the number of vehicles commuting to/from an area varies for different areas, the stop time for the commuting journeys are divided into two parts, one for vehicles going home from work (VH^H), i.e., the vehicles that are staying in the area during the night, and one for vehicles going to work (VH^W), i.e., the vehicles that are staying in the area during the day. Fig. 7

TABLE III
DATA FOR THE DISTRIBUTION SYSTEM AREAS

	Residential DS	Commercial DS
No. of customer (F_{DS})	1 932	635
No. of employees (EP_{DS})	2 766	528
No. of workplaces (WP_{DS})	471	2 146
No. of vehicles (VH_{DS})	2 306	254
Vehicle Commuting Share (VCS_{DS})	39.4%	22.7%
No. of vehicle used for leisure (VH^{SL})	1 395	154
No. of vehicles commuting to work in the DS (VH^{W})	137	624
No. of vehicles commuting home to the DS (VH^{H})	1 091	120

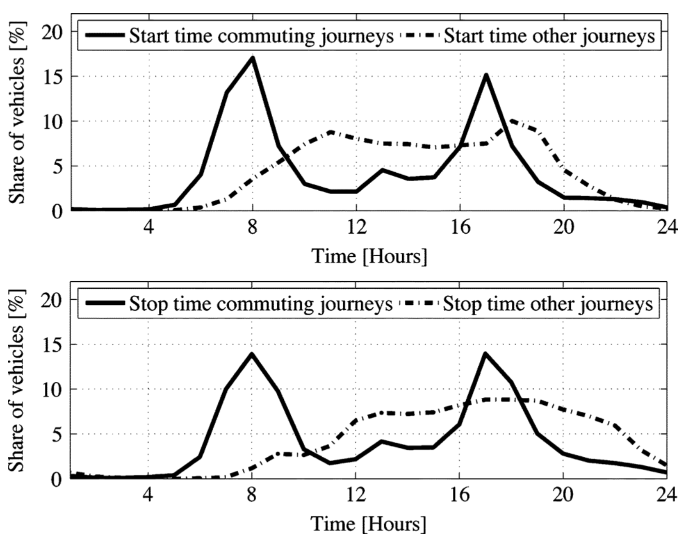

Fig. 6. Start and stop time for the different journeys conducted by vehicles [13].

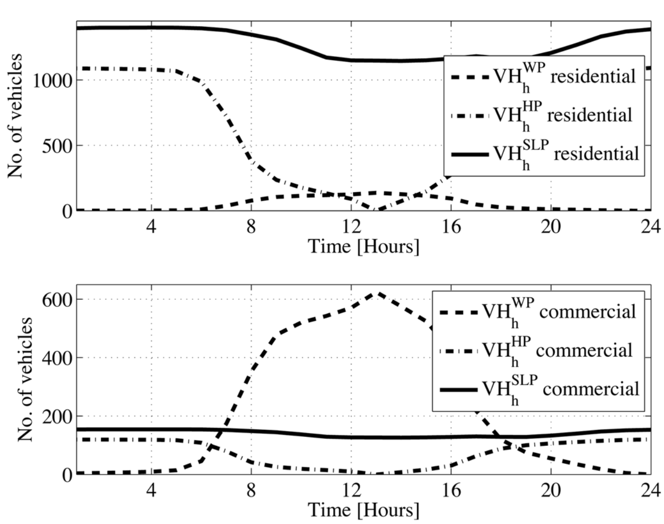

Fig. 7. Stop time for the vehicles for the simulated areas.

presents the stop time of the journeys conducted to the DSs investigated in this study.

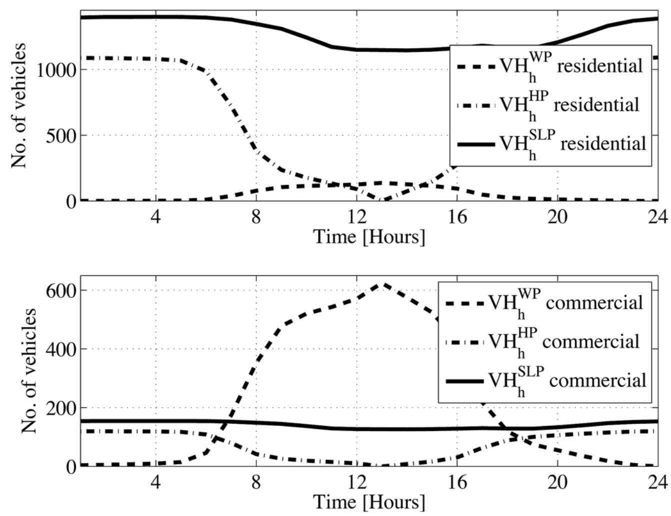

Fig. 8. Number of used vehicles that are parked.

A vehicle only stays in a location for a certain time period and can only be charged during that period. From the start and stop time, the distribution in time for when the vehicles are parked is found. Fig. 8 presents the distribution of the parked vehicles.

Table IV presents the assumptions made, regarding PEV charging, etc., for the case study. Although the travelled distance varies between the vehicles, the average distance has been used in this study. The average distances can be found in [13]. Similarly, an average energy consumption of 0.2 kWh/km has been used for the PEVs, although the energy consumption varies for different vehicle classes, driving styles, etc. The charge power varies with the state of charge (SOC) of the batteries [21]. For low SOC, the charge power is more or less constant but decreases as the battery becomes more and more charged. However, for a fully discharged battery, most of the energy is delivered to the battery during the constant charge power period [21]. The most common rating of the charge stations available in Sweden today is 3.68 kVA (16 A at 230 V, single phase) [22] and a constant charge power of 3.68 kVA is assumed in this study. Transferring power from the grid to the batteries involves losses both in the charge equipment and in the battery itself. As discussed in [21] and [23], the charge efficiency varies for different operating points of the charger. However, since the operating point is assumed to be constant (constant charge power), the efficiency is also assumed to be constant. As in [7], an overall efficiency of 88% is assumed in this study.

C. Nordpool Day-Ahead Spot Market

Although the electricity in Sweden is traded on an hourly basis at the Nordic electricity market (Nordpool spot), most small customers have their electricity price based on either monthly average price or fixed yearly contracts. There is an ongoing discussion among the electricity trading companies to implement time based electricity tariffs and a few companies provide time based electricity tariffs, usually as a dual tariff system [17].

TABLE IV
VEHICLE PARAMETERS AND DATA

Distance/day commuting	24 km
Distance/day leisure	30 km
Energy consumption	0.2 kWh/km
Charge power	3.68 kVA
Power factor	0.95
Charge efficiency	88%

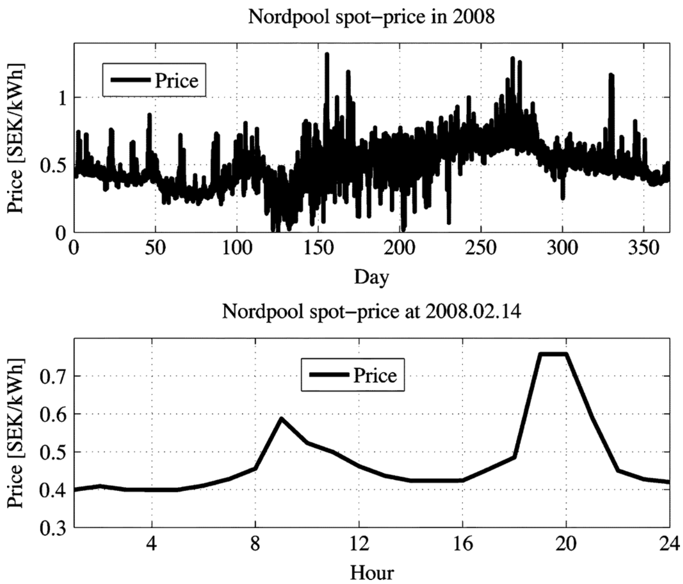

Fig. 9. Spot-price at Nordpool in 2008, and 14/2 2008 [12].

The customer is also obliged to pay a network tariff. Usually this is a fixed price per kWh but a few companies include a power tariff to reduce the peak power consumption [17].

In addition to the electricity and network cost, the price for electricity certificate (around 0.06 SEK/kWh) and an electricity tax (0.283 SEK/kWh) is added and above that a value-added tax (25%) [24].

As stated, there is an ongoing discussion to implement a time based pricing system in Sweden [17]. In this study, it is assumed that the electricity price is based on the hourly day-ahead spot-prices at Nordpool spot [12]. The price at Nordpool spot depends both to the consumption and the production. The introduction of PEVs will increase the electricity consumption and the electricity price at Nordpool spot could be affected. However, changes in the electricity price are not considered in this study.

In Fig. 9 the spot price on Nordpool's day-ahead market is presented for the whole 2008 and for the day simulated in the case study. As can be seen in the figure, the price varies both during the year and during the day. This means that the charge profile for the price-optimal strategy would vary for every day accordingly. Similarly, the cost of charging the PEVs would vary for every day for all charge strategies if the customers are to pay market hourly electricity price.

V. RESULTS FROM THE CASE STUDY

This section presents the main results from the case study.

TABLE V
MAXIMUM PENETRATION LEVEL

		Residential		Commercial	
		Normal	Redund.	Normal	Redund.
Uncontrolled charging	Scen. A	76%	0%	>100%	>100%
	Scen. B	>100%	0%	>100%	>100%
Loss-optimal charging	Scen. A	>100%	0%	>100%	>100%
	Scen. B	>100%	0%	>100%	>100%
Price-optimal charging	Scen. A	49%	0%	>100%	>100%
	Scen. B	49%	0%	>100%	>100%

A. Maximum Penetration Level

Table V presents the maximum penetration possible without overloading the DS's for Scenario A, only charging at home, and Scenario B, charging both at home and at work. As can be seen, no PEVs can be charged in the residential area with maintained redundancy since the system is overloaded even in the reference scenario (without any PEVs). For the price-optimal charge strategy, the maximum penetration level decreases as compared to that of the uncontrolled charge strategy, which indicates that solely using the hourly spot-price can be a poor measure of controlling the PEV charging. For the commercial area the impacts of PEVs are limited and a full penetration could be supported for all proposed charge strategies.

Fig. 10 presents the charge profiles for a 100% penetration level of PEVs under the different charge strategies for the DS located in the residential area, although, as shown in Table V, the DS will be overloaded. As can be seen in Fig. 10, the peak power varies both in time and size between the different charge strategies. In the residential area, most PEVs will be charged during the afternoon for the uncontrolled charge strategy while for the loss-optimal charge strategy, the charging will be spread out during the night to achieve a flatter load profile. For the price-optimal strategy most PEVs will charge simultaneously since all PEVs react on the same price signals, resulting in a high total charge power. As stated earlier, since the electricity price varies for every day the charge profile will also vary for the price-optimal charge strategy.

For the uncontrolled charge strategy, the maximum charge power is found higher for Scenario A (with only home charging) than for Scenario B (with charging conducted both at home and at work). This is due to the fact that the increased charge time leads to more simultaneous charging for Scenario A as compared to Scenario B and due to the low number of workplaces in this area. The same holds for the loss-optimal charge strategy although the difference is smaller. For the price-optimal strategy, the maximum charge power is limited by the total number of vehicles and the power is therefore equal for both scenarios, although the duration of the peak period is longer for Scenario A due to the increased charge time in Scenario A.

For the commercial area, the total charge power is less than for the residential area since there are fewer PEVs to be charged in this area. Fig. 11 presents the charge profiles for a 100% penetration of PEVs under the different charge strategies for the DS in the commercial area. As can be seen in the figure, the maximum charge power is higher for the loss-optimal than for the

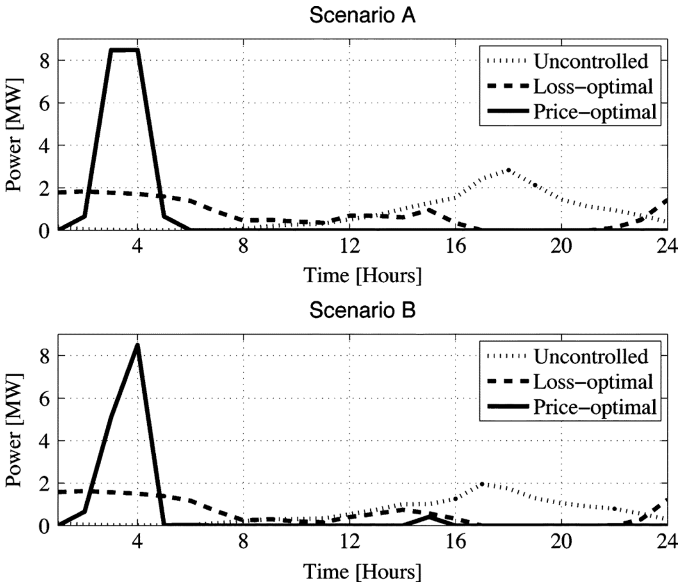

Fig. 10. Charge profiles for the different charge strategies and scenarios in the residential area.

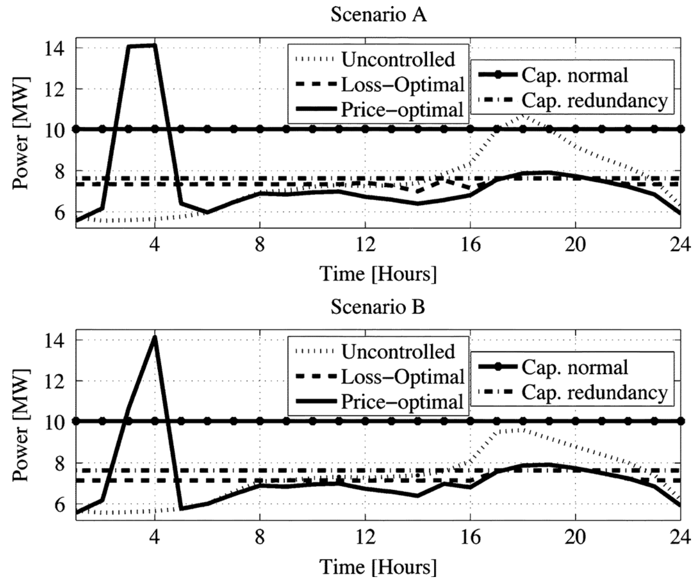

Fig. 12. Load profile of the residential area.

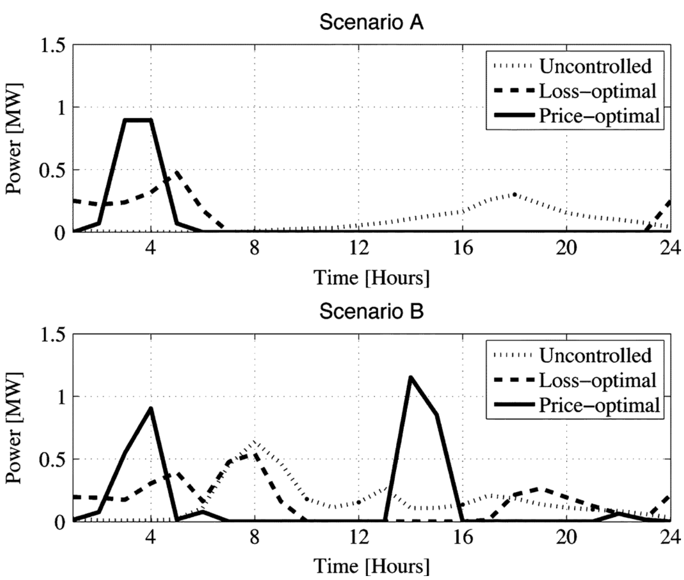

Fig. 11. Charge profile for the different charge strategies in the commercial area.

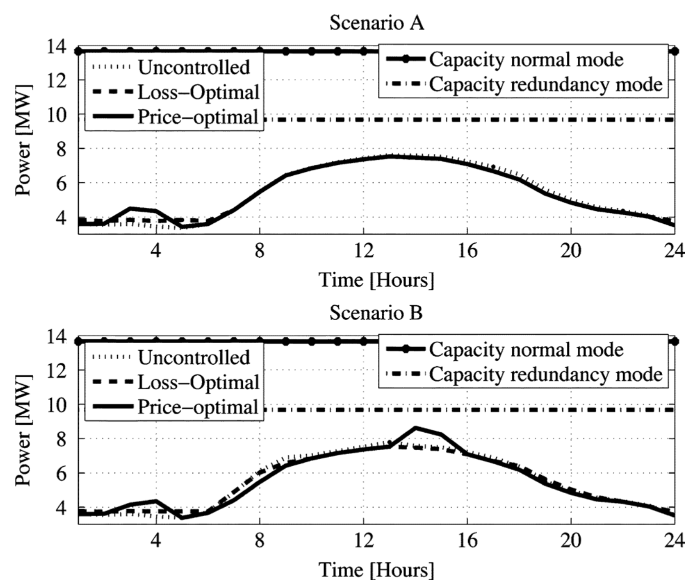

Fig. 13. Load profile of the commercial area.

uncontrolled charging in Scenario A. For Scenario B, the maximum charge power occurs in the morning for the uncontrolled strategy since the majority of the PEVs charging in this area is charging at work. For the price-optimal charge strategy, two peaks are visible, one during the night and one during the day. The reason for this is due to the two low price periods shown in Fig. 9, and due to that the PEVs are able to charge at two different locations, i.e., at work and at home. For the loss-optimal charge strategy, the maximum charge power occurs during the morning hours, although the maximum power is lower than for the uncontrolled strategy.

B. Resulting Load Profiles

Fig. 12 presents the resulting load profiles including PEV charging for a full penetration (100%) of PEVs for the residential area. As can be seen, the uncontrolled charging will occur simultaneously with the ordinary peak load. Although the price-optimal strategy will shift the charging to off-peak hours, the increased total charge power will result in a new peak during the early morning hours. The DS will be overloaded for both strategies in Scenario A while the DS can handle a full penetration of PEVs in Scenario B if the charging is conducted according to the uncontrolled charge strategy. With the loss-optimal charge strategy, the DS will be able to cope with a full penetration without increasing the peak load. However, since the redundancy in the system is violated for the reference scenario without any PEVs, the DS must be reinforced to be operated with maintained redundancy.

Fig. 13 presents the load profile including PEV charging for a full penetration (100%) of PEVs for the commercial area. As

TABLE VI
LOSSES AND MINIMUM VOLTAGE IN THE RESIDENTIAL 10-kV DS

		Losses [kWh]	Voltage[pu]
Uncontrolled	Scen. A	3411.9	0.96
charging	Scen. B	3243.6	0.97
Loss-optimal	Scen. A	3279.2	0.97
charging	Scen. B	3133.5	0.97
Price-optimal	Scen. A	3559.7	0.95
charging	Scen. B	3348.3	0.95

TABLE VII
LOSSES AND MINIMUM VOLTAGE IN THE COMMERCIAL 10-kV DS

		Losses [kWh]	Voltage[pu]
Uncontrolled	Scen. A	696.58	0.98
charging	Scen. B	716.12	0.98
Loss-optimal	Scen. A	687.72	0.98
charging	Scen. B	705.06	0.98
Price-optimal	Scen. A	688.77	0.98
charging	Scen. B	716.36	0.98

can be seen, the charging of PEVs will have a limited impact on the DS in Scenario A. However, due to the high number of workplaces and thereby PEVs charging in Scenario B, the impact will be more severe in Scenario B, where the PEVs can be charged both at home and at work, especially for the price-optimal charge strategy.

C. Total System Loss and Voltage Variation

Tables VI and VII present the total system loss and minimum voltage for the different scenarios and charge strategies under normal operation for the simulated day and a 100% penetration. The total system loss for the reference scenario, without any PEVs, is 2673.2 kWh for the residential area. As can be seen in Table VI, the loss increases from 460 kWh to 890 kWh (18% to 33%) due to charging of PEVs. The loss increase is, as expected, lowest for the loss-optimal charge strategy and this strategy decreases the loss by more than 100 kWh (about 4%) as compared to the uncontrolled strategy. Although the DS would be overloaded, the price-optimal strategy would increase the loss by more than 100 kWh (about 4%) as compared to the uncontrolled strategy and is not preferred from a loss point of view. The voltage drop is however within the limit for all strategies considered.

For the commercial area the total system loss for the reference scenario is 674.8 kWh. As shown in Table VII, the losses increase for all strategies. However, the increases are small (between 2%–6% increase compared to the reference scenario) compared to the residential area, due to the lower number of PEVs charging in this area. In contrast to the residential area, the losses decrease for the price-optimal charge strategy compared to the uncontrolled in Scenario A. The voltage drop is small for all strategies.

TABLE VIII
COST/CHARGE FOR 100% PEVS [SEK/CHARGE]

		Residential	Commercial
Uncontrolled	Scen. A	7.51	7.51
charging	Scen. B	5.67	4.36
Loss-optimal	Scen. A	6.61	6.35
charging	Scen. B	5.02	4.19
Price-optimal	Scen. A	6.29	6.29
charging	Scen. B	4.82	3.85

D. Charge Cost

One of the main purposes of the price-optimal charge strategy is to reduce the electricity cost for the customer. Table VIII presents the average cost per charge for the customer. For the residential area, the cost of charging according to the price-optimal strategy is reduced by about 15% compared to the uncontrolled strategy, for the simulated day. For the commercial area, the cost is reduced with between 11%–16%. Even for the loss-optimal strategy, the cost is reduced compared to the uncontrolled strategy (about 11% for the residential and 4%–16% for the commercial area). The reason for the increased cost in Scenario A is due to the fact that the cost is presented as cost/charge and fewer, but longer, charge occasions are conducted in Scenario A. In terms of money, the savings are found to be between 0.9–1.2 SEK/charge for the residential area and between 0.5–1.2 SEK/charge for the commercial area, provided that the charging is conducted according to the price-optimal strategy compared to the uncontrolled strategy.

As shown in Fig. 9, the electricity price varies for every day. This will result in different charge profiles for every day, but also that the savings will also vary for different days. The cost presented in Table VIII, is the average cost per PEV for this specific day. Similarly, the individual savings will vary between the PEVs, depending on the charge time but also on the usage of the PEVs.

VI. CONCLUSION

This paper presents an approach to estimate the impact of PEV charging on an open loop radial distribution system. The approach uses demographical data and travel surveys to estimate when and where the PEVs can be charged. A case study from two parts of the DS in Gothenburg is performed. The result shows a large difference in when the charging is performed for the two areas indicating the importance of considering the location of the DS, e.g., by using demographical data. Furthermore, it was found that the peak power in the DS can increase and the maximum penetration can decrease if the customers are exposed to the hourly spot price and seek to minimize their electricity costs (price-optimal strategy), as compared to the case when the customers have flat electricity tariffs (uncontrolled strategy).

The loss-optimal charge strategy would limit the impact on the DS and increase the number of PEVs that can be served by the DS. However, the reduction in losses was limited, even for a full penetration of PEVs (about 4% of the total losses in the system) and the main advantage of the strategy is to reduce the need for reinforcement of the DS.

Furthermore, it was found that the impact on the residential DS would be reduced if a charge infrastructure was in place, while the impact on the commercial DS would be increased.

ACKNOWLEDGMENT

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IV Material and instructions for laboratory work

Computer Lab. Instruction for

ENM125 Sustainable Electric Power Systems (SEPS, 7.5 credits)

Distributed: Thursday, November 8, 2012
Due: Thursday, December 20, 2012 (5:00PM)
Note: This project is compulsory. The project can be done in groups of five students.

The aim of the project is to design an electric power transmission system having 10-buses; a number of generations and loads in the system and taking the following factors into account:-

- the cost of the system (both investment cost and cost of power loss), design a system with minimum cost as possible
- the effects of contingencies on the system design
- the effects of a remote wind farm generation unit and plug-in hybrid electric vehicle (PHEV) loads on the designed system

The geographical map is shown in Figure 1, and distances between each bus (in km) are presented in Table 1.

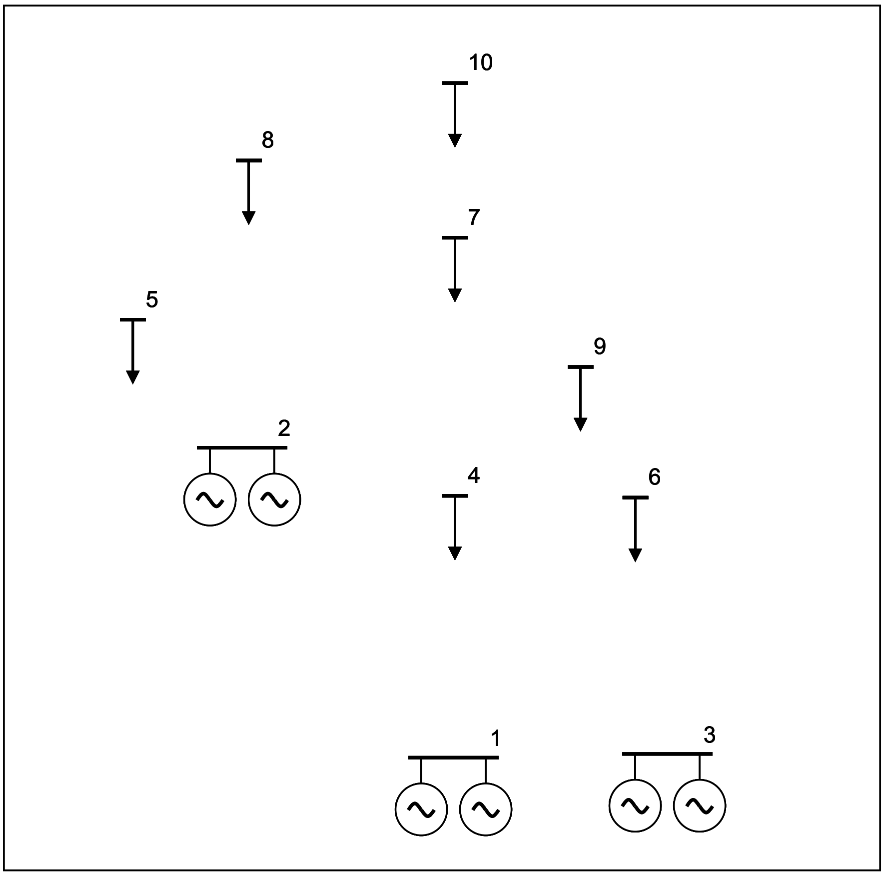


Figure 1: Geographical arrangement of the generators and load buses (**not** to scale)

Table 1
Distance between buses of the 10 bus system [in km]

		To Bus									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
From Bus	**1**	0	121	68	80	169	98	161	196	129	209
	2	121	0	169	74	48	130	97	89	116	134
	3	68	169	0	105	216	80	174	227	126	219
	4	80	74	105	0	114	56	80	122	58	129
	5	169	48	216	114	0	166	105	61	142	126
	6	98	130	80	56	166	0	98	159	45	140
	7	161	97	174	80	105	98	0	69	56	48
	8	196	89	227	122	61	159	69	0	122	69
	9	129	116	126	58	142	45	56	122	0	97
	10	209	134	219	129	126	140	48	69	97	0

As can be seen in Figure 1, there are six generating units in the system, having identical specification. Table 2 shows the specifications of each generator.

Table 2: Generator data

S (MVA rating)	35 MVA
$P_{G,min}$ (minimum active)	10 MW
$P_{G,max}$ (maximum active power)	30 MW
$Q_{G,min}$ (minimum reactive power)	-5 MVar
$Q_{G,max}$ (maximum reactive power)	10 MVar
$U_{G,min}$ (minimum terminal voltage)	1.00 pu
$U_{G,max}$ (maximum terminal voltage)	1.05 pu

There are seven constant power loads. The nominal load at each bus is presented in Table 2. All loads have 0.8 pf (lagging).

Table 2: **Nominal Load at Different Buses**

Location	**Size (MW)**
Bus 4	20
Bus 5	20
Bus 6	24
Bus 7	30
Bus 8	10
Bus 9	16
Bus 10	20

All lines used for the transmission system are of the same conductor, with the following parameters:

z1 = 0.1 + j 0.45 Ω/km, b = 3x10-6 mho/km, where z1 is the impedance, b is the susceptance of the line. The transfer capacity of the line is 100MVA.

Students are expected to design and simulate the transmission system by using Power World Simulator. The simulator can be downloaded for free from http://www.powerworld.com .

The Tasks

1. **Design a transmission system in such a way that six generating units can supply seven loads with the following objective and operating constraints (10 points).**

Objective:

Determine the best alternative transmission system design which seeks to reduce the investment cost of transmission lines and the power loss cost for 30 years. Assume that:

1. The investment cost of transmission line can be calculated according to the formula:
   Cost of one line = (1+0.1*length) / M€, where 1 km OHL costs 0.1 M€, and connection cost for both ends is 1 M€ for each line.
2. The cost of power losses can be calculated using the equation below (assuming that the energy price is 0.05 € / kwh, operation duration is 30 years, the equivalent operation hours at the peak load level each year is 4000 hours, the interest is 5% each year)
   $$PV(A) = \frac{A}{i} \cdot \left[1 - \frac{1}{(1+i)^n}\right]$$
   Where, *PV (A)* is the present value of total cost of power losses for 30 years; *A* is the cost of power losses each year; *i* is the interest; *n* is 30 years. (For more information, refer:
   http://en.wikipedia.org/wiki/Time_value_of_money#Present_value_of_an_annuity_for_n_payment_periods
3. If required, shunt capacitors or reactors can be installed. Use a unit size of 10MVAr in both cases. Assume a shunt device costs is about 0.1 M€ for one bank.

Operating Constraints:

1. Generator constraints:
   $P_{G,min} \leq P_G \leq P_{G,max}$
   $Q_{G,min} \leq Q_G \leq Q_{G,max}$
   $U_{G,min} \leq U_G \leq U_{G,max}$
   for all generators
2. Bus voltage constraints:
   0.95 pu $\leq U_B \leq 1.05$ pu, for all load buses
3. Power transfer constraints
   $S_{i,j} \leq 100$ MVA, for all lines
4. Islanding constraints
   There will be no part of the system in islanding operation.

All system operating constraints should also be satisfied in N-1 contingency conditions.

Assumptions:

1. The term of "N-1 contingency" refer to losing one of either the transmission lines, shunt devices, or generating units.
2. For simplicity, transformers are not used in the network.

You should present two "best" alternatives. Justify any assumptions and planning decisions that you make in arriving at your final design. This is **very** important as the process is as important as the outcome.

2. **Study the effects of the wind farm and PHEV on one of the 'best' alternative designs in task 1 (10 points, 5 points for each sub tasks (wind farm and PHEV)).**

   Assume that there is a remote wind farm generation unit with the same specification as the generation units except power range that is:
   P = 16 MW
   $P_{G,min}$ = 5 MW and $P_{G,max}$=15 MW

   The distance of the wind farm unit to each system bus is indicated as in Table 4:

Table 4

From Bus	To Bus									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
11	220	230	195	153	210	130	131	170	93	105

   Your tasks are:
   - Find the best connection point from the wind farm to the system by using a double circuit line (the wind farm should be connected just to one bus in the system) such that the total system loss is minimized.
   - Investigate the results when the wind farm is producing 30%, 60% and 100% its rated active power output.
   - Describe the changes that the wind farm brings to the systems (e.g., voltage, line overload, generation levels of the existing units, etc.).

   Assume now that there are PHEV loads, with constant-power characteristics and unity power factor, connected to the residential areas (in buses No. 7, 8 and 10). The maximum amount of PHEV load at each bus is 6 MW.

   - Perform power flow and contingencies analyses for this new situation to find possible network problems.
   - Propose any network reinforcement needed to improve the situation.

The Final Report

Each group should write a project report. The report and all related simulation files shall be emailed to the project supervisor (kalid.yunus@chalmers.se, yasir.arafat@chalmers.se) and the course examiner (lina.bertling@chalmers.se) by Thursday, 20 December 2012, at 05.00 PM the latest. Send the report in Word format to enable the supervisor to comment on the submitted file. Note that it is not necessary to submit a hardcopy of the report.

The report should cover the following:
1. Transmission system design (10 points)
   - Design process: steps to the design and comparison of the two alternatives to arrive at the final selection.
   - A single line diagram of the system with load flow simulation results (voltages, active and reactive power generated by each generator, power flow

on each line and reactive power support from shunt devices) for the two best alternatives.

- N-1 contingency report of the two systems
- The number and length of transmission lines and shunt devices used for each alternative.
- The investment cost and the cost of the loss of the system
- Analysis and justification that the design is best alternative amongst those studied.

2. Wind farm and PHEV integration studies (10 points)

Wind farm integration

- Design process for the integration of the wind farm
- One line diagram and load flow simulation results (voltages, active and reactive power generated by each generator, power flow on each line and reactive power support from shunt devices).
- N-1 contingency report, which shows all possible N-1 contingencies.
- Analysis and justification of the proposed solutions

PHEV Integration

- Illustrate the impacts of PHEV integration in the system
- Propose any network reinforcement needed to improve the situation
- Analysis and justification of the proposed solutions

Simulating Three-Bus System Using Power World Simulator

A Brief Tutorial

I. Introduction

The goal of this tutorial is to introduce you to a user-friendly power flow programs, **Power-World** (from PowerWorld Corp.) to solve power flow and explore N-1 contingency of the system shown in Figure 1.

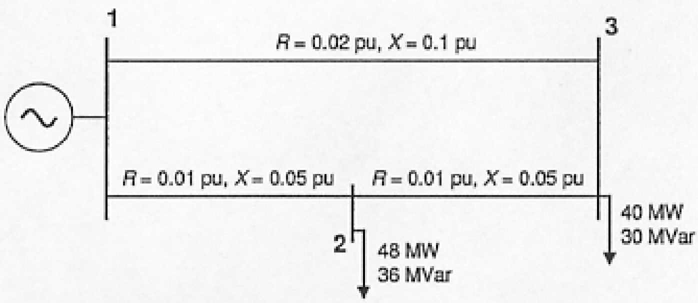
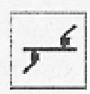


Figure 1. One-line diagram of a three-bus system

II. Building a Simple Three Bus System

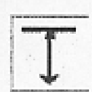
1. Once PowerWorld is up and running ... Begin by starting the program and choosing "File" then "New Case".

2. To place a new bus on the workspace, click on the bus icon, then click in the workspace at the place you want the new bus to be. Repeat this and place the second and the third bus according to Figure 1.

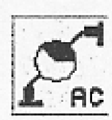


3. Next, we need a power source in the system. Click on the generator icon, then click on bus one. The field called MW Output needs to have a value. For this system, type in the number "100"

4. To insert a load, click on the load icon from the toolbar, and click on Bus-2. Under the heading of Constant Power, type 48 for MW and 36 for MVar. Repeat this for the load at Bus-3.



5. Finally, we need to connect the generator to the loads. Click on the AC transmission line icon. Click once on Bus-1 and then double click on Bus-2.



Set the per unit series resistance (R) and series reactance (X) to 0.01 and 0.05, respectively. Repeat this for lines between Bus-2 and Bus-3, and between Bus-1 and Bus-3.

6. Click the Line/Transformer Flow Pie Chart in the lines. Set the MVA rating to 100 and thick on square for Always Show Value (Percent).

7. Now, the one-line diagram of the system is ready.

III. Solving the Power Flow

Select "Run Mode". There are several new icons that appear on the right side, most notably are ones that look like play and pause. Press "Play". The one line diagram will be as shown in Figure 2.

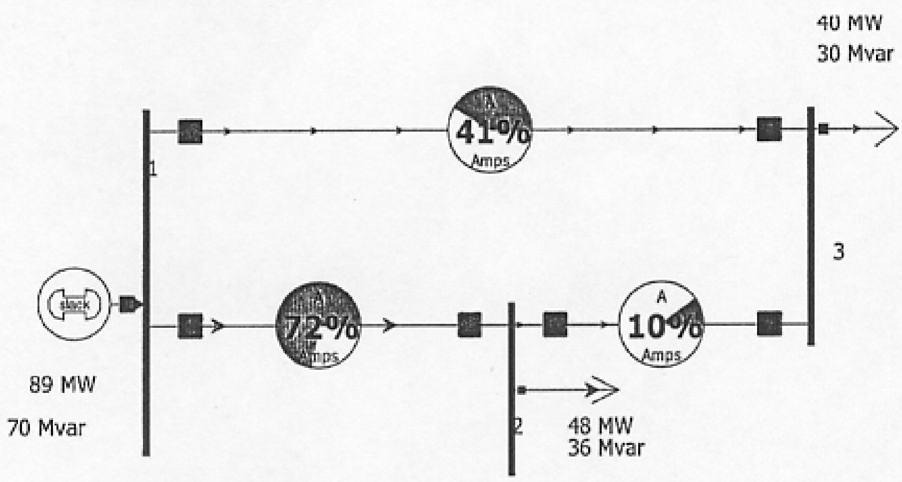


Figure 2. One-line diagram with solved power flow.

Two things to notice, first is that the generator output is now changed to 89 MW and 70 MVar, from the entered value of 100 MW and 0 MVar. Second are the green arrows moving from the generator to the loads. Their direction is aligned with the direction of power flow, and their size is an indication of the amount of power flowing.

IV. Operating Constraints

Assume that we have following operating constraints:

- Bus voltage constraint

  0.95 pu $< U_B \leq$ 1.05 pu, for all load buses

- Power transfer constraint
  $S_{i,j} \leq 100$ MVA, for all lines

We then need to check whether the operating constraints are fulfilled.

The power transfer constraints can be seen directly from Figure 2, as we have set the MVA rating to 100, which shows that the power transfer constraint is fulfilled.
Whether the voltage constraint is fulfilled or not can be checked by clicking Case Information -> Buses and a Bus Record window will appear. Some part of the Bus Record window is Figure 3, which indicates that the voltage constraint is fulfilled.

	Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)
1	1	1	1	138,00	1,00000	138,000	0,00
2	2	2	1	138,00	0,97227	134,173	-1,40
3	3	3	1	138,00	0,96830	133,625	-1,61

Figure 3. Bus Record

V. N-1 Contingency

In order to check whether the operating constraints are fulfilled on N-1 contingencies, we need to run contingency analysis.

First, limit monitoring settings and violations need to be set.
Under Edit Mode, click Tools -> Limit Monitoring Settings and Violations.
Under Limit Group Values, select Line & Transformers and then set the percentage to 100.
Again, under Limit Group Values, Buses and then set the low and high voltage limits in pu to 0.95 and 1.05 pu, respectively.

Secondly, run the contingency analysis.
Select the run mode and play.
Click Tools -> Contingency Analysis -> Auto Insert, then select single transmission line and click Do Insert Contingencies -> Start Run.

The contingency report is shown in Figure 4, and when the first line of the report in Figure 4 is clicked on, the violation will be reported as shown Figure 5. Figure 5 shows that opening line 1-2 will cause three violations, i.e.: overload on line 1-3, and undervoltage at Bus-2 and Bus-3.

Contingencies | Lines, Buses, Interfaces | Options | Summary

	Label	Skip	Processed	Solved	Islanded Load	QV Autoplot?	Violations	Max Branch %	Min Volt	Max Volt	Max Interface %
1	L_000011-000022C1	NO	YES	YES	0,00	NO	3	124,0	0,875		
2	L_000011-000033C1	NO	YES	YES	0,00	NO	2	116,4	0,934		
3	L_000022-000033C1	NO	YES	YES	0,00	NO	0				

Figure 4. Contingency report.

Violations

Show related contingencies | Combined Tables >

	Category	Element	Value	Limit	Percent	Area Name Assoc.	Nom kV Assoc.
1	Branch Amp	1 (1) -> 3 (3) CKT 1 at 1	518,86	418,37	124,02	1-1	138,0
2	Bus Low Volts	2 (2)	0,87	0,95		1	138,0
3	Bus Low Volts	3 (3)	0,90	0,95		1	138,0

Figure 5. Violation Report

If the generator terminal is set to 1.048 pu and 30 MVAr shunt capacitor is installed at Bus-2, the contingency report will be as shown in Figure 6, where no violation is indicated.

Contingencies | Lines, Buses, Interfaces | Options | Summary

	Label	Skip	Processed	Solved	Islanded Load	QV Autoplot?	Violations	Max Branch %	Min Volt	Max Volt	Max Interface %
1	L_000011-000022C1	NO	YES	YES	0,00	NO	0				
2	L_000011-000033C1	NO	YES	YES	0,00	NO	0				
3	L_000022-000033C1	NO	YES	YES	0,00	NO	0				

Figure 6. Contingency report with generator terminal voltage alteration and shunt capacitor installation.

VI. Conclusion

We have built a simple three-bus power system. The generator default values were sufficient to meet the operating constraints on normal condition. The system was enhanced to meet the operating constraints while one line is out of service (N-1 contingency) by increasing the generator terminal voltage and installing a shunt capacitor.

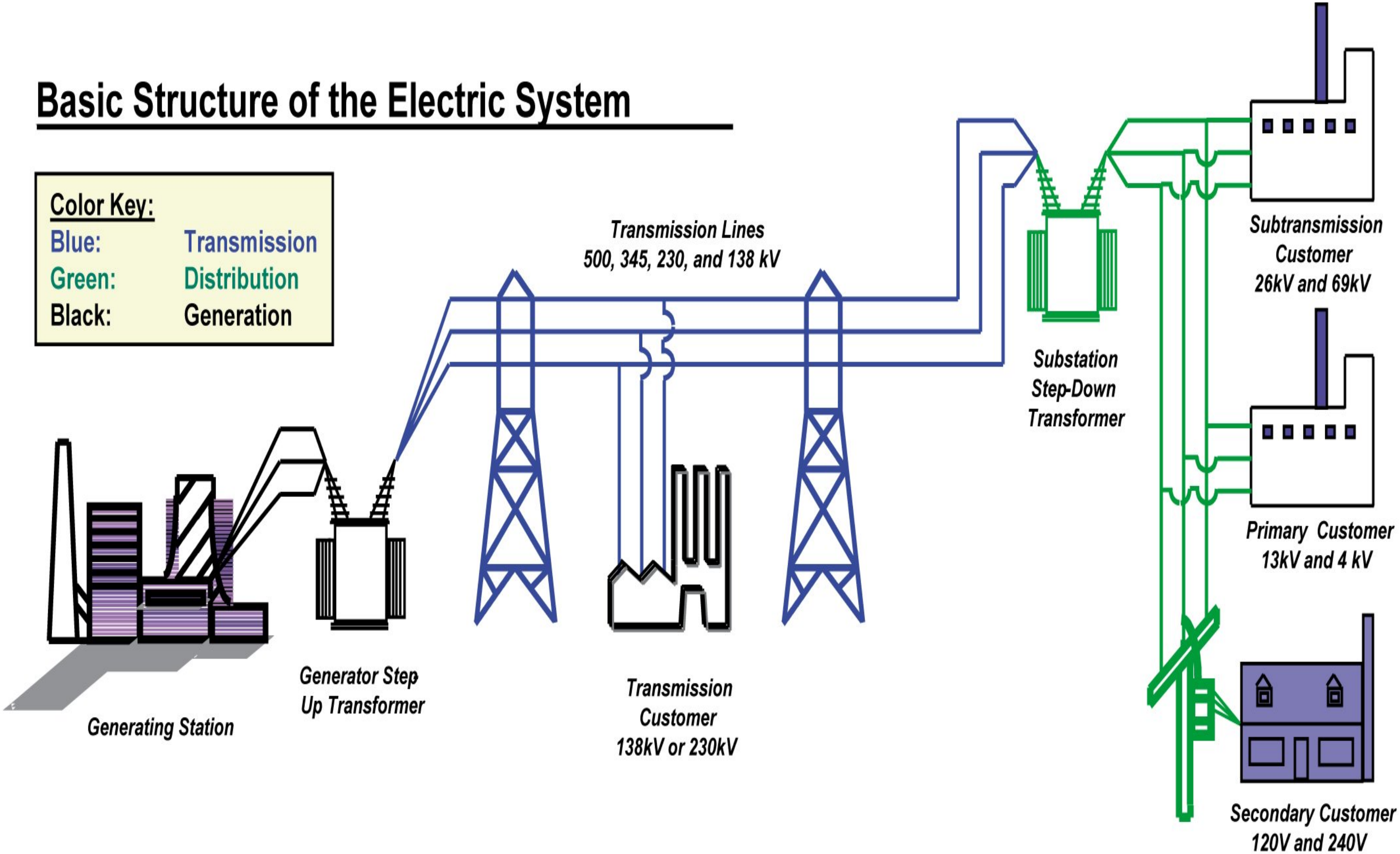
ENM125 Sustainable Electric Power Systems -Simulation Design Project- Introduction

Kalid Yunus
Division of Electric Power Engineering
Chalmers University of Technology
2012

Outline

- **Project Description**
- **Simulation Tools**
  - **PowerWorld Simulator: a Short Tutorial**

Basic Structure of the Electric System



Required Studies

1. **Technical study**
   - ➢ **Steady-state calculation**
     load flow
   - ➢ **Reliability**
     adequacy and security

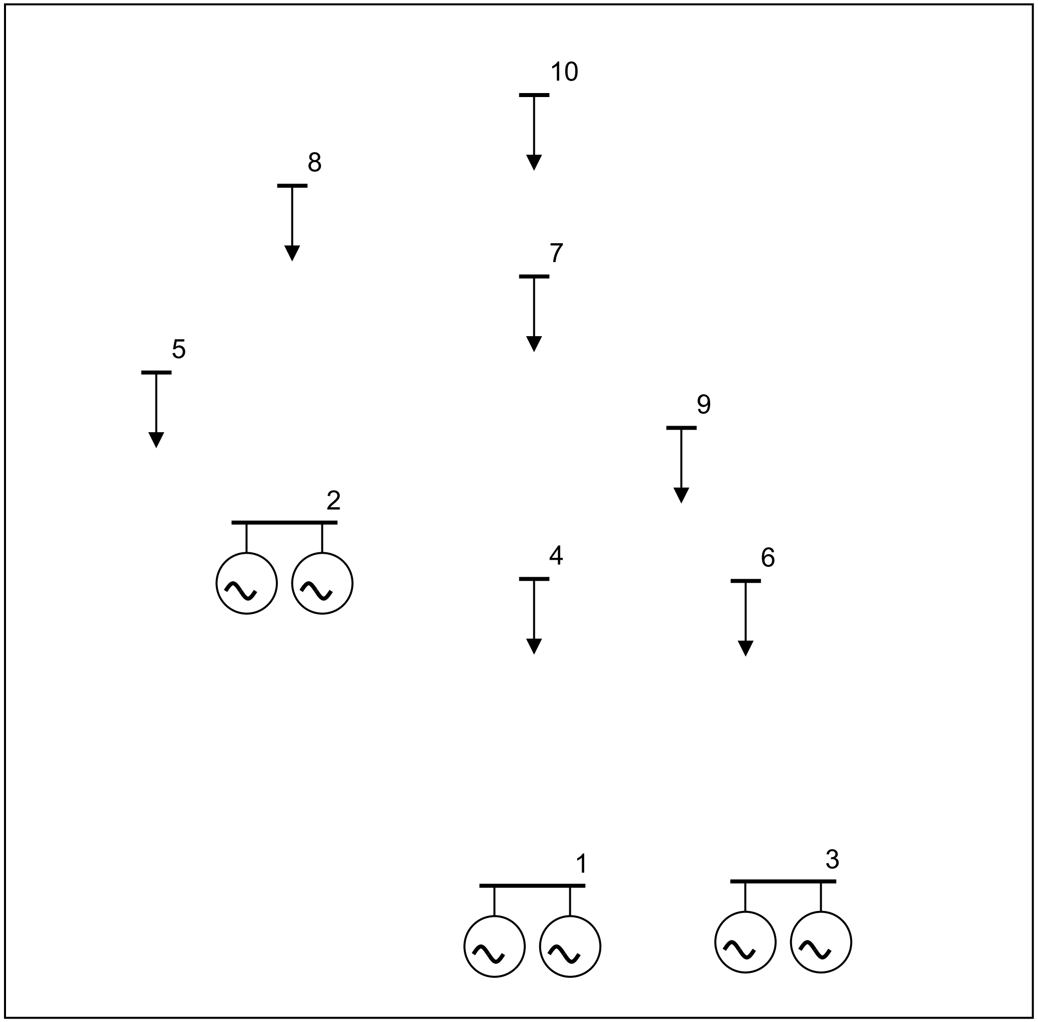
2. **Economic evaluation**
   - ➢ **Investment cost & operational cost**
     Optimal (economic) system design

Project Objective

- To design a 10-bus transmission system, so that
  - Power balance is ensured
  - Operating constraints are satistified
  - N – 1 reliability criteria are fulfilled

- To study the steady-state system impact by connecting a remote wind farm and Plug-In Hybrid Electric Vehicles (PHEV).

10-bus Transmission System



System Components

Six Generators, each having

Rated Capacity : 35 MVA

PQ limits : 10 MW ≤ P ≤ 30 MW

-5 Mvar ≤ Q ≤ 10 Mvar

Voltage limits : 1.00 pu ≤ U ≤ 1.05 pu

Reactances: $x'' = 0.12$, $x_2 = 0.14$, $x_0 = 0.05$ pu

Seven Loads

Constant power

Others

System nominal voltage : 138 kV.

Load power factor : 0.8 (inductive)

Transformers or SVCs : not considered

Shunt capacitors and reactors: 10 MVAr, and assume the cost to be the same as a 0.1 M£.

Transmission Lines

$z_1 = 0.1 + j\,0.45\ \Omega$/km

$b = 3\text{x}10^{-6}$ mho/km (pi model)

Transfer capacity: 100MVA.

Load Location	Size (MW)
Bus 4	20
Bus 5	20
Bus 6	24
Bus 7	30
Bus 8	10
Bus 9	16
Bus 10	20

System Design Criteria

Objective Function:

Minimize the total investment cost, which includes cost of transmission lines & reactive power compensators

Operating Constraints:

- Generator constraints:

$$P_{G,min} \leq P_G \leq P_{G,max}$$
$$Q_{G,min} \leq Q_G \leq Q_{G,max} \quad , \qquad \text{for all generators}$$
$$U_{G,min} \leq U_G \leq U_{G,max}$$

- Bus voltage constraints:

$$0.95 \text{ pu} \leq U \leq 1.05 \text{ pu} \quad , \qquad \text{for all load buses}$$

- Power transfer constraints

$$S_{i,j} \leq 100 \text{ MVA} \quad , \qquad \text{for all lines}$$

- Islanding constraints

No islanding operation allowed.

All system operating constraints should also be satisfied in N-1 contingency conditions (only transmission lines are considered).

Your Tasks

1. **10-bus Transimission system design**
   - Power balance (load flow calculation)
   - Analyse Power and Voltage contraints
   - N-1 contingency
   - Two best alternatives
2. **Wind farm and PHEV integration studies**
   - Select optimal wind farm connection point to minimize system loss
   - Power flow and N-1 contingency studies

Outline

- Project Description

- **Simulation Tools**
  - **PowerWorld Simulator: a Short Tutorial**

Simulation Tools

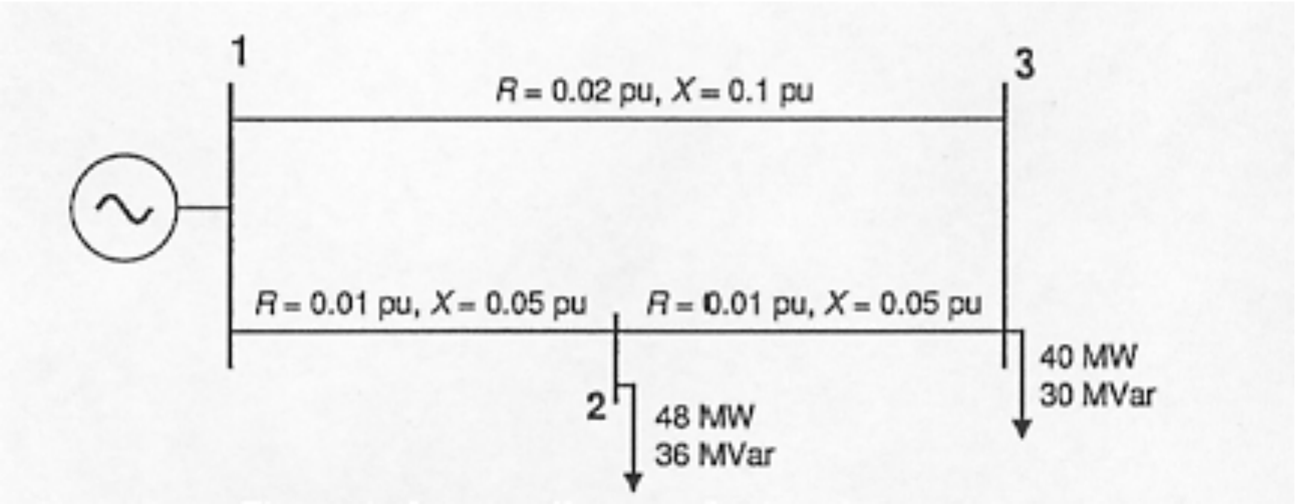
- Matlab
- DigSilent
- PSS/E
- PowerWorld Simulator
- Etc……

We use PowerWorld Simulator in this project!

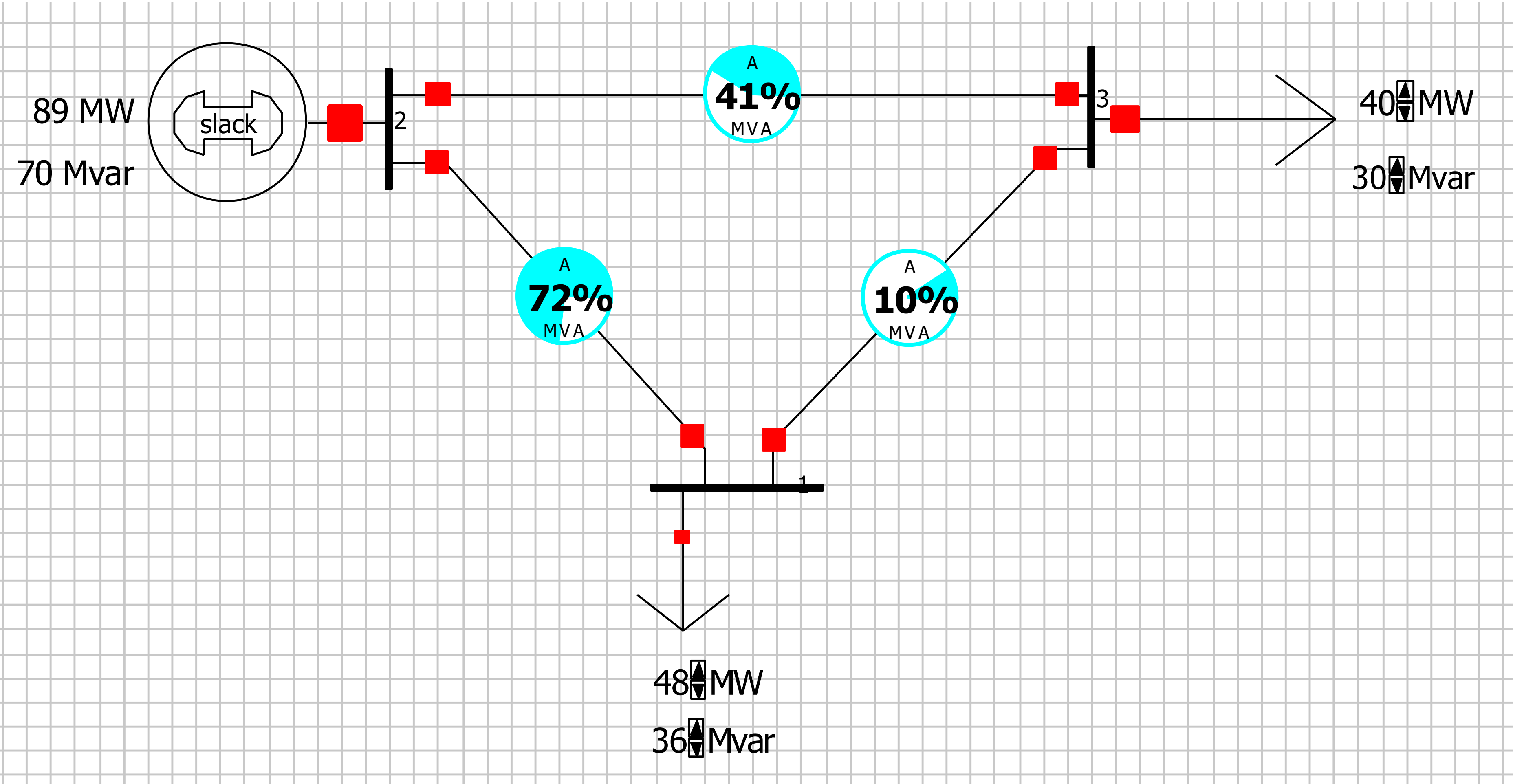
PowerWorld Simulator

- **Main Feature:**
  - interactive
  - highly visual
  - designed to simulate power system operations.
- **Software capability**
  - Claimed to be able to handle up to 100,000 buses
  - Power flow solution options: Gauss-Seidel, Newton-Raphson, Decoupled power flow, DC-power flow.
- **The free educational/demo version available at http://www.powerworld.com, limited to 12 buses.**

A Simple 3 Bus System



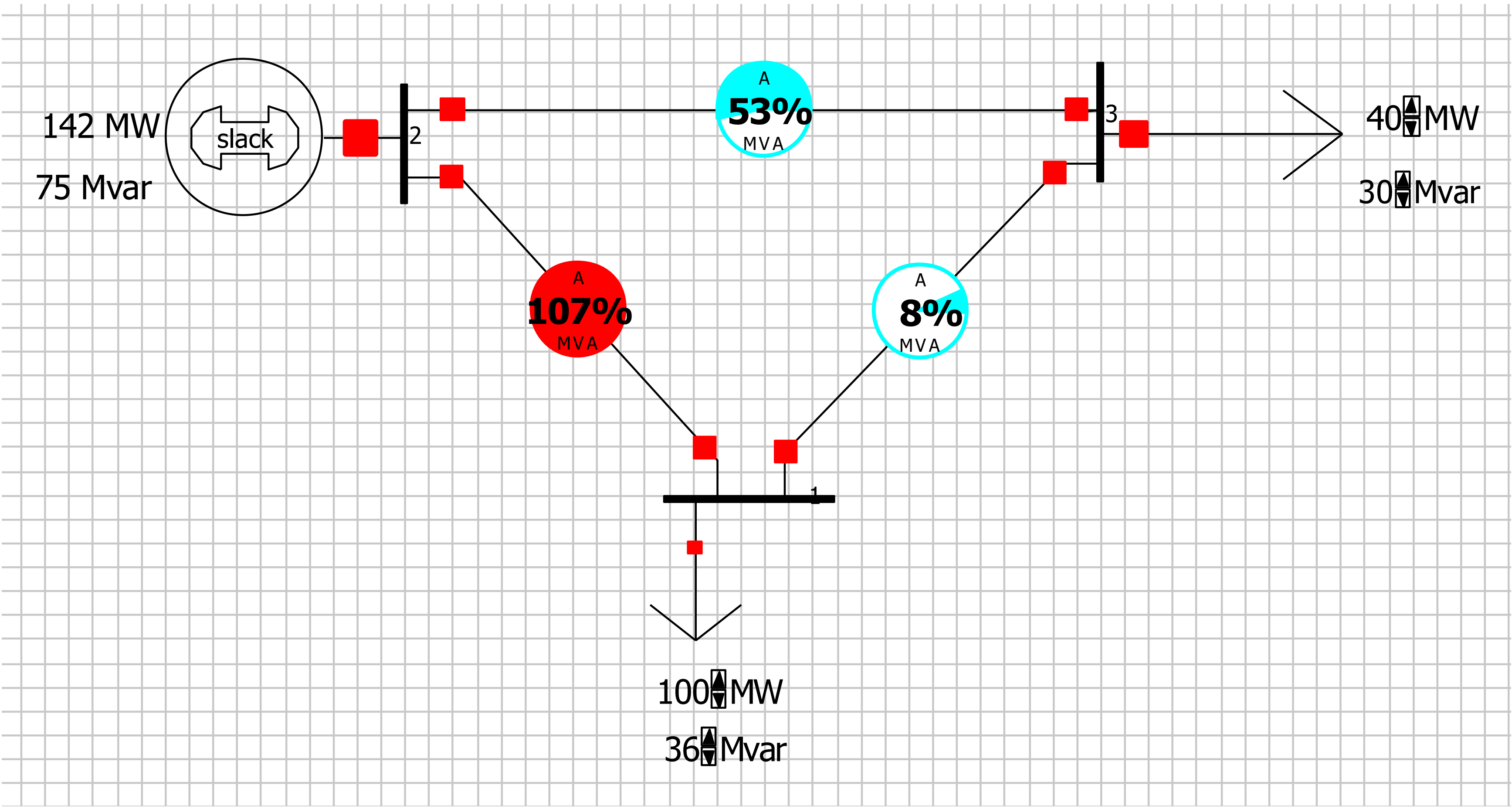
PowerWorld View



What Affect Power Flow?

- Change in load
- Opening a circuit breaker (eg. Due to fault)
- Change in generators output (P, Q) and voltage set-point
- Change in line series impedance X (using series compensation)
- Use of regulating transformers (boosters)
- Use of power-electronic control devices (FACTS)

Overloaded Transmission Line



Reactive Power

- Source of reactive power
  - generators, capacitors, transmission lines
- Sink of reactive power
  - generators (absorb), loads
  - transmission lines and transformers
- Reactive power doesn't travel well – should be supplied locally (switched shunt capacitors)

Reactive Power and Voltage

- Reactive power and voltage magnitude are tightly coupled.
  - Reactive demand decreases the bus voltage,
  - Reactive generation increases the bus voltage

- Power systems must supply electric power within a narrow voltage range, typically within ±5% of a nominal value.

- Voltage regulation/control is an important aspect in power system design and operation.

Voltage Control

- Voltage control devices
  - Generators: reactive power output is changed to keep terminal voltage constant.
  - Capacitors/reactors: switched on/off manually or automatically
  - Tap-changing transformers: regulate tap ratio
  - FACTS devices, e.g. static var compensators (SVCs):

Experimental Lab. Instruction for

ENM125 Sustainable Electric Power Systems (SEPS, 7.5 credits)

Student(s): Date:

....

....

....

....

Supervisor's signature:

Homework approved Lab approved

....

1: Introduction

In this experimental lab, the effects of phase compensation on power transfer over a transmission line are investigated, as well as studying how a transformer is used and how its parameters can be measured.

This lab procedure includes exercises that the students should have completed before the lab. You should also have read through the whole lab procedure before the conducting the lab experiments.

H *The homework is marked with H and written in Italics.*

The purpose of the homework is for you to have a basic understanding of how the system you will be measuring operates prior to conducting the lab. You will be then be able to relate the measured results to a theoretically-derived understanding. Additionally, preparation for the lab allows the lab experiments to be completed more rapidly and more safely.

1.1: Objectives

At the end of this lab, you will be able to:

- Understand how the voltage in an inductive grid can be controlled by local production of reactive power
- Implement the phase compensation using a shunt capacitor, and understand what it does and how it improves the situation for the electric grid
- Measure and evaluate the transformer performance

1.2: Prerequisites

Prior to performing this lab, you should:

1. Read and sign the Laboratory Safety Instructions;
2. Study the theoretical background about the transformer and phase compensation;
3. Read the lab procedure and understand how you will perform the experiments;
4. Complete the homework portions of the lab procedure.

1.3: General Information

When plotting the results of your lab experiments, you may find it useful to use a software tool such as Excel or Matlab. If you choose to use plot your results by hand instead, take care to select your axes appropriately and be precise in your plotting. Using graph paper for manual plots is recommended. Look for the highest and lowest value of the plotted quantity before you select the scale for axes, as small but important variations may be difficult to see in your plots.

You have access to two measuring programs in Lab View which are designed to measure all the necessary quantities in the experimental lab procedure. When using the program, you are required to make sure that you measure the correct quantities and connect their measurement signals to the proper input channels of the computer, according to the signal list on the computer screen of the measurement program. Refer to Appendix A as a guide for the physical connection points in the laboratory setup.

You should carefully document your work during the lab procedure, including measured quantities and the results found. These notes will be important when you explain your results for the supervisor at the end of the lab.

For all portions of the lab procedure, please refer to the appendices for guidance on how to physically construct the circuits being tested in the various lab procedures.

2: Phase compensation

2.1: Introduction

The most important goal of the laboratory exercise is for you to develop your own understanding of the subject material. You should focus on answering any questions you may have and make sure you understand the investigated system as well as possible. To facilitate the development of your understanding of phase compensation, rather than an exact step-by-step lab procedure, you are given a circuit to construct, and a set of open-ended questions to answer for this section of the lab procedure. The reason for structuring the laboratory exercise in this manner is so that you will be more involved in formulating the method of testing the performance of the phase compensation, as well as drawing conclusions.

After constructing the test circuit for this portion of the lab, devise a set of measurements which you can collect and use to prove your hypotheses for the four questions in this portion of the laboratory procedure. You should then collect this data and generate the appropriate graphs and tables to support your conclusions. Present this data to the laboratory instructor and discuss your results ***before*** disassembling the circuit and advancing to the next portion of the lab procedure.

2.2: Investigation

The circuit used for analyzing capacitive phase compensation is presented in Figure 1. Use a 2.2 Ω-resistance in series with a 30 mH-inductance to construct a model of a transmission line, and connect the controllable resistance (fixed at 43 Ω) in series with a 150-mH inductance to model a load. Connect a single-phase circuit with the transmission line fed from the grid (230 V) and loaded in the other end by the resistive-inductive load. Finally, connect a controllable capacitor in parallel with the load, to enable shunt compensation.

H *What are the reasons to phase compensate a load? State at least two positive effects.*

H *When setting the capacitance to zero, what will the capacitor current be?*

H *Draw a phasor-diagram for the voltage drop across the transmission line. Assume the value of the phase compensation capacitance to be zero, and the load resistance is 220 Ω.*

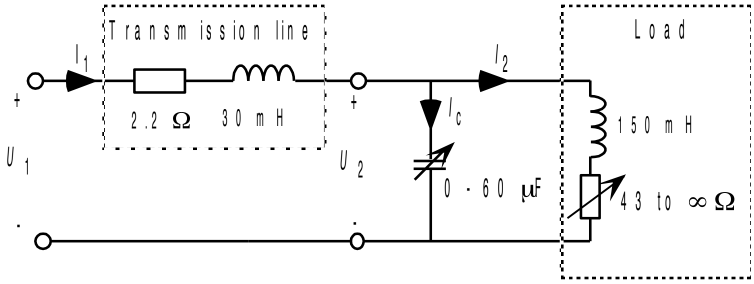


Figure 1 The circuit to be investigated. An inductive/resistive load with controllable phase compensation, fed from the grid via an inductive/resistive power-line.

Vary the capacitor value and investigate the following:

Base your answers and explanations on measured values. Write down your measured values and the conclusions. Note that these questions can have several answers.

1. Which is the best value of the phase compensation capacitors, and why? You should observe the **best** value of the phase compensation for several different load values.

Load Resistance	Capacitance Value	Load Voltage
∞ Ω		
43 Ω		

2. What happens to the load voltage as the capacitor value changes, and why?

   -Select a load resistance, and observe the voltage as the capacitance is altered.

Capacitance Value	Load Voltage

3. What happens to the losses in the system as the capacitor value changes, and why?

   -Select a load resistance, and observe the losses as the capacitance is altered.

Capacitance Value	Input Power	Load Power	Efficiency

4. What will happen with the phase compensation if the load resistance changes, and why?

If you have other questions about the behavior of this circuit, feel free to investigate these further.

3 Three phase transformer

3.1 Introduction

The transformer is a critical device in electric power systems. Transformers are used in a wide variety of applications in the electric grid, from distribution transformers (50-1000 kVA) serving one or more users to very large units (several 100 MVA) that are parts of the transmission system. Smaller transformers are also used in electronic circuits as a component of power supplies and to provide galvanic isolation for electronic devices (1-1000 VA). Thus, understanding the transformer's performance and its operational principle is a basic and essential part of the power engineer's knowledge base. Not only is theoretical understanding important, but experimental experience is important as well.

3.2 General

The transformer in this lab has three different sets of three-phase windings. Each of these sets can independently be connected in Y- or Δ- configuration. Most transformers are only designed to have a single primary and a single secondary three-phase winding, while this transformer can have two separate secondary outputs. If only one secondary is required, as in this lab procedure, one set of windings should be left open-circuited. Figure 2 shows a cross section of the transformer core and the three winding sets.

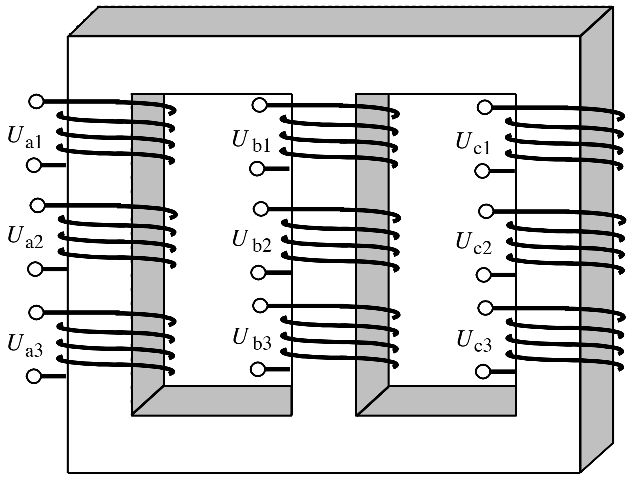


Figure 2 Cross section of the transformer core

The ratings of the transformer winding-sets are:

U_{1N} = 230 V	U_{2N} = 230 V	U_{3N} = 133 V
I_{1N} = 8.7 A	I_{2N} = 8.7 A	I_{3N} = 15 A

Since this transformer can be connected many different configurations, the ratings for the complete three-phase transformer cannot be specified until the type of connection is decided. Therefore, the ratings above apply only for the single windings.

3.3 Transformer connection

The transformer shall be used to transform from 400 V to 230 V (line-to-line). Suggest a way of connecting the transformer to achieve the required rated voltages.

H *Make a three-phase circuit diagram for how to connect the transformer windings to the 400 V grid and to the 230 V load.*

3.4 Loaded Transformer Test

In this section, the transformer performance will be evaluated with a resistive load connected. As a load, three controllable resistances are used. By varying the resistance value, the transformer load can be modified. The controllable resistors have a rated voltage of 230 V.

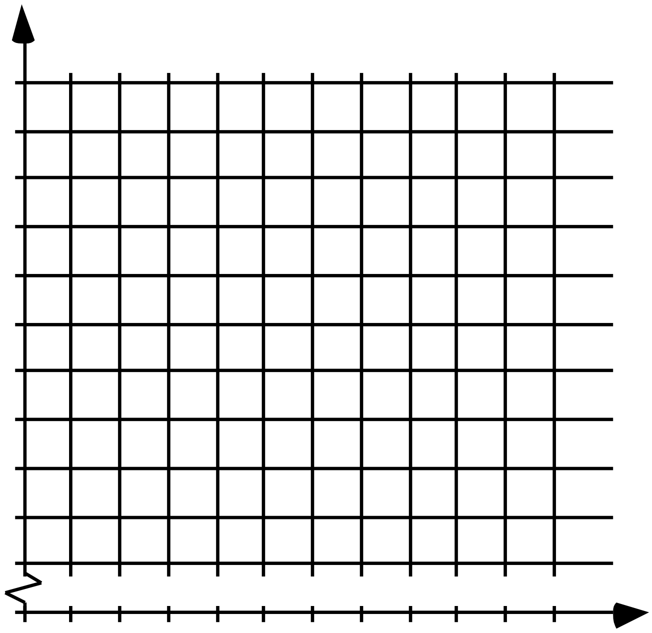
Refer to Appendix B for assistance with constructing the circuit for the no-load testing of the transformer. Note that this is the same configuration used for the no-load testing, with only the additional resistive load included.

Test the transformer performance with varying load, with the load **Δ** connected:

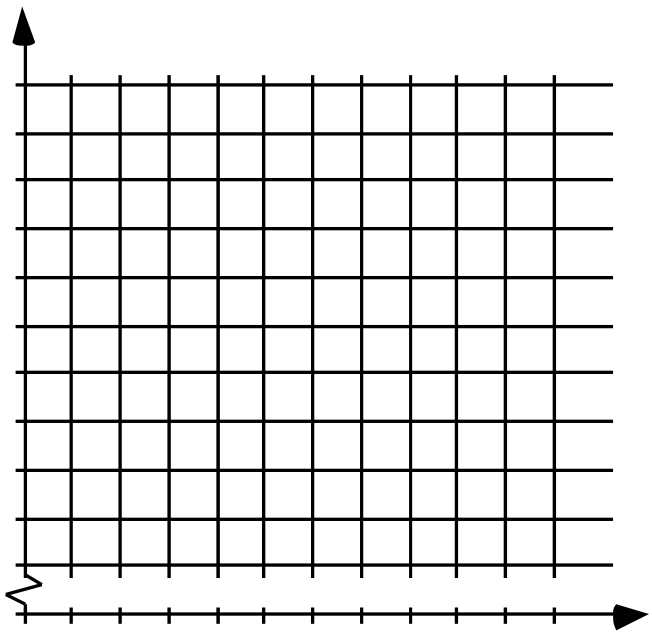
1. Measure the output voltage and the transformer active and reactive losses as functions of the load current (0-9 A)! (Write down the measured values.)
2.

Load	Vout	Pin	Qin	Pout	Qout

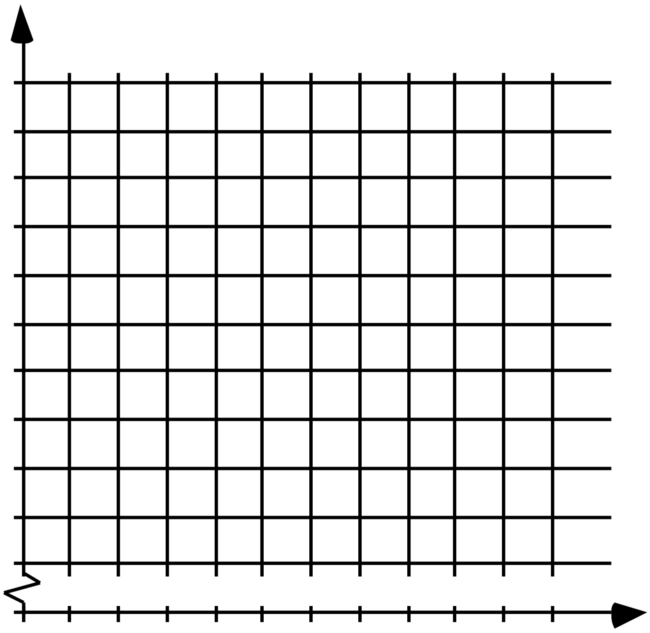
3. Plot the load voltage as a function of the load power. Is the load voltage increasing or decreasing when increasing the secondary current? Could you explain why?



4. Plot the transformer efficiency versus the load power. When does the maximum efficiency occur?

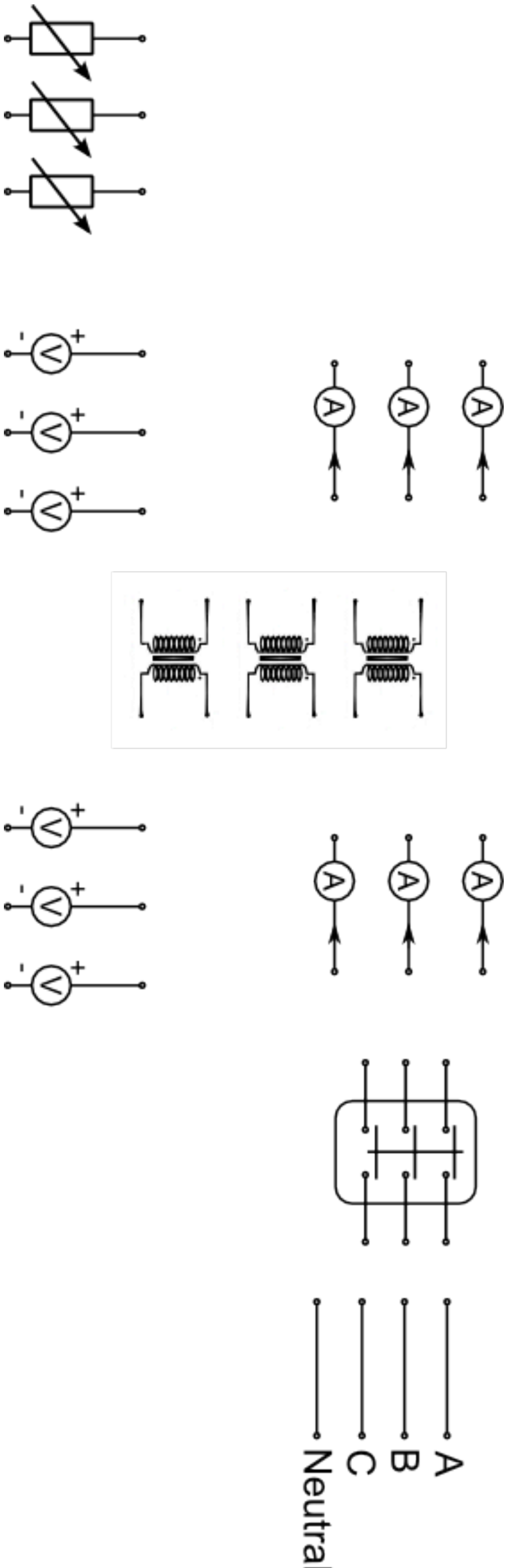


5. Plot the active losses of the transformer versus the load power. Why are the active losses of the transformer changing as they do?



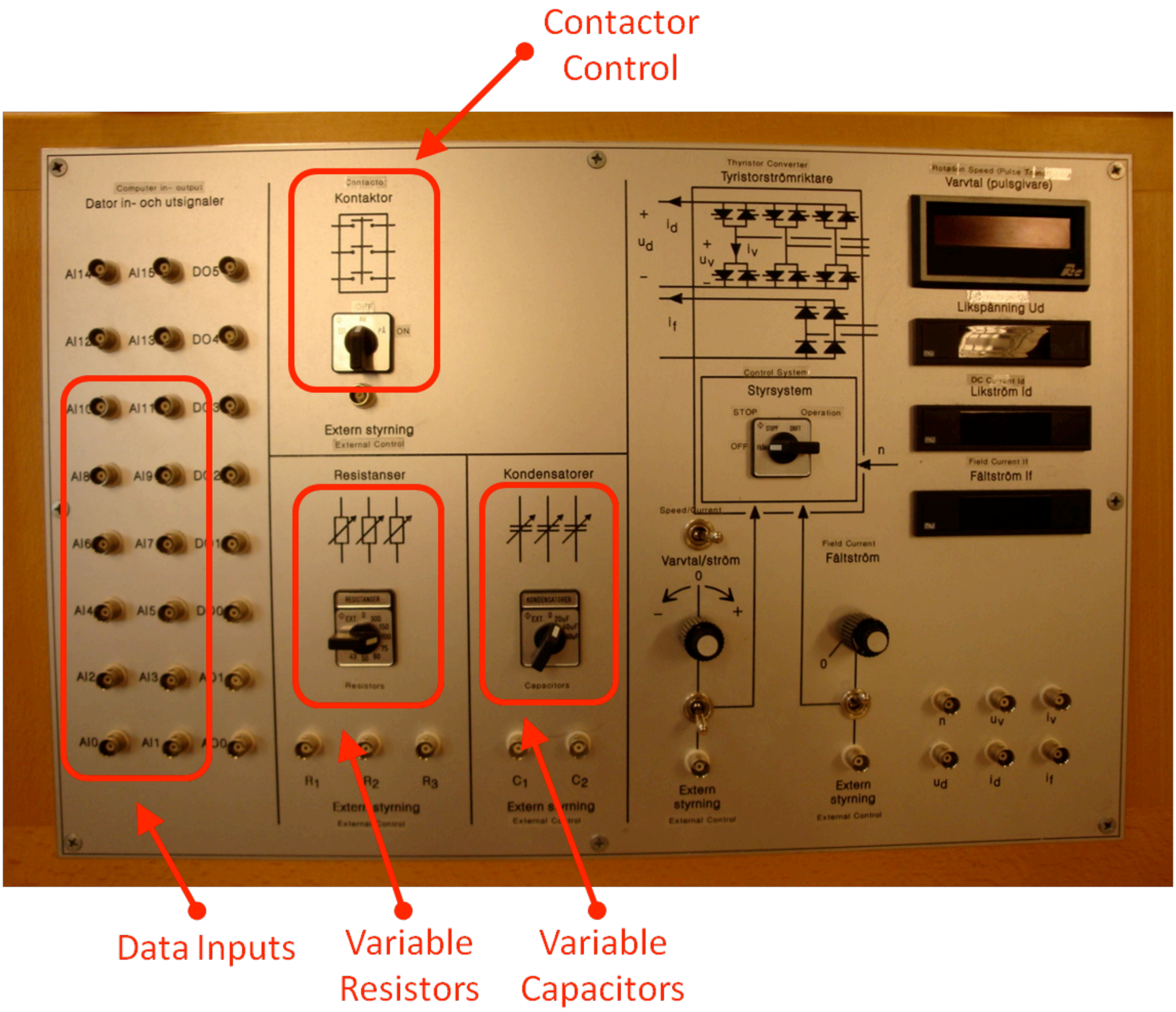
6. Is the primary voltage leading or lagging the secondary voltage? Why?
   Is the primary current leading or lagging the secondary current? Why?
   These effects will make the power factor at the input terminals different from the power factor at the output terminals. Compare the power factors.

Appendix A: Loaded Transformer Test Wiring Diagram

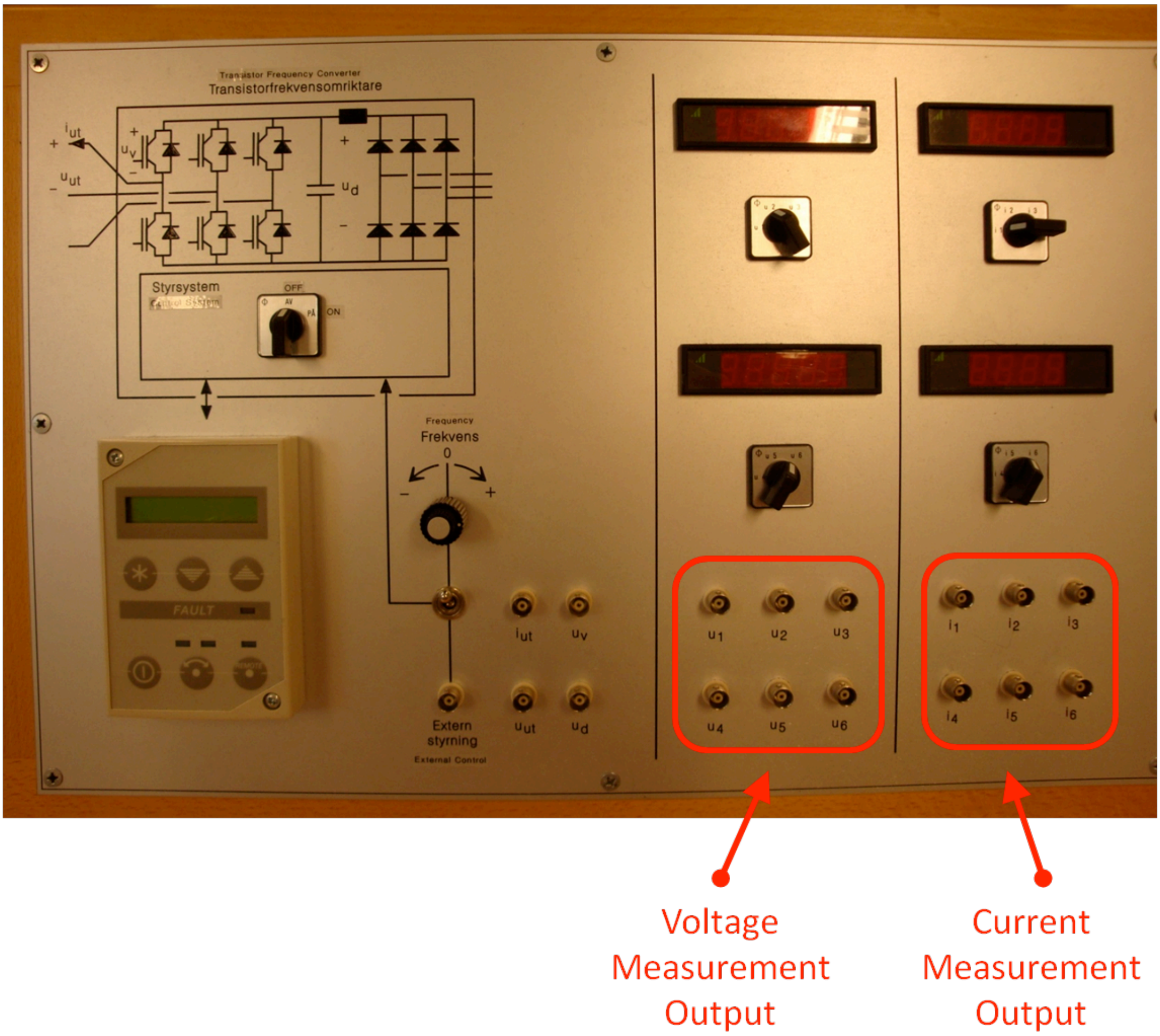


Appendix C: Component Guide

Laboratory Physical Setup – Controls and Measurements Panel

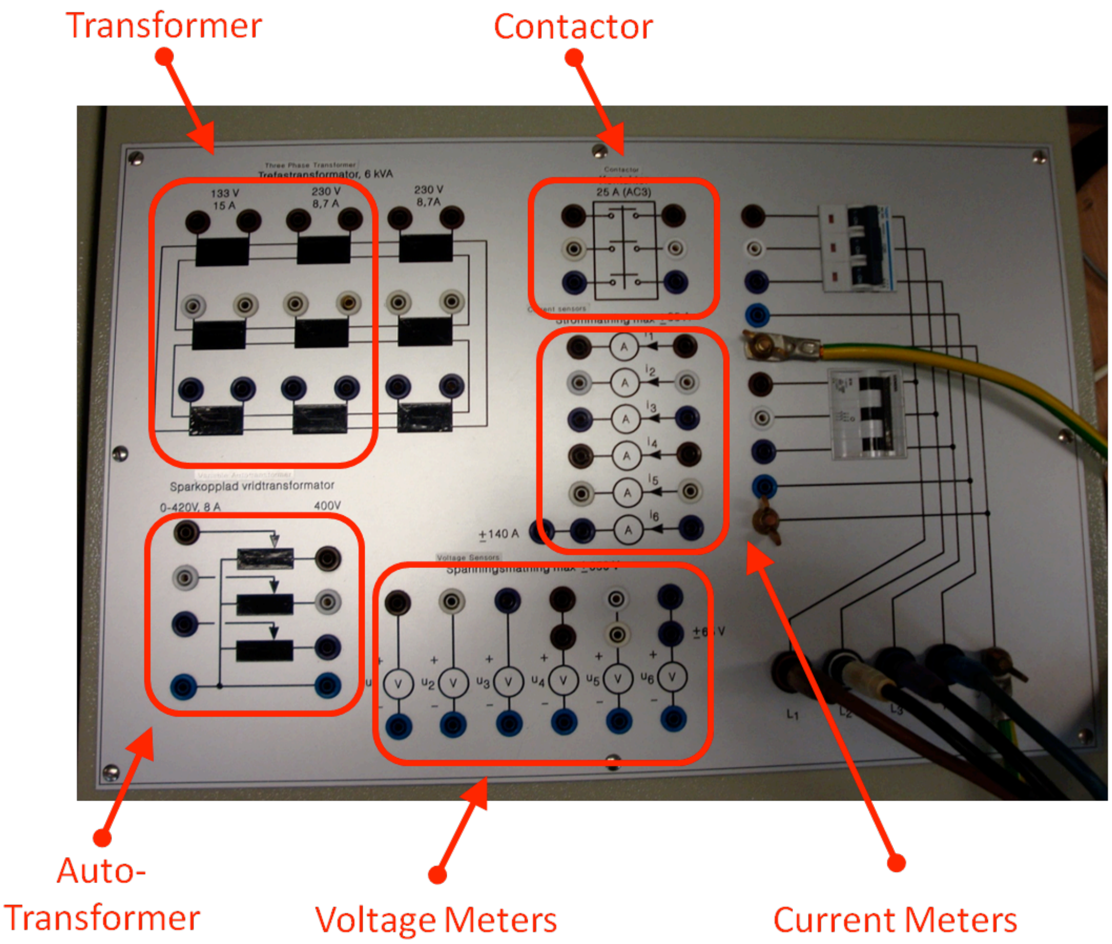


- Contactor Control - Used in all parts of the lab exercise for controlling the connection of the circuit
- Data Inputs - Used in all parts of the lab to input the measured quantities to the LabView interface
- Variable Resistors - Used to load the transmission line model and transformer in Sections **2.2** and **3.4**
- Variable Capacitors - Used to load the transmission line model for line compensation in Section **2.2**

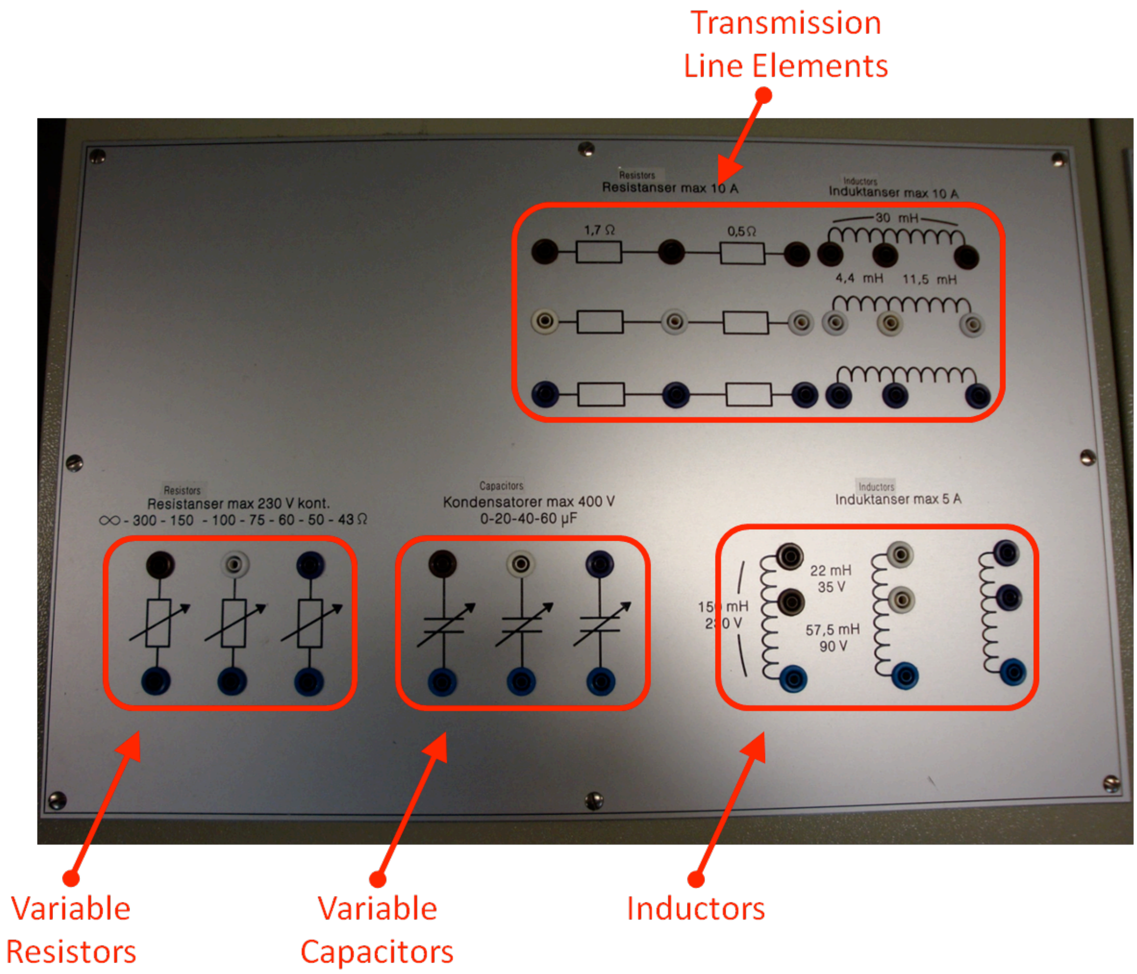


- Voltage Measurement Outputs - Used in all parts of the lab exercise to monitor voltages within the circuit; connect these to the appropriate Data Input for viewing in the LabView environment
- Current Measurement Outputs - Used in all parts of the lab exercise to monitor currents within the circuit; connect these to the appropriate Data Input for viewing in the LabView environment

Laboratory Physical Setup – Circuit Elements



- Transformer – The circuit element used to transform voltage levels; used in Section **3.4**
- Contactor – The circuit element used to open or close the electricity source from the circuit; used in all sections of the lab
- Auto-Transformer – This element is unused
- Voltage Meters– These meters measure the voltage level at whichever part of the circuit they are connected, connected in parallel to the circuit; used in all sections of the lab
- Current Meters– These meters measure the current through a part of the circuit where they are connected, connected in series to the circuit; used in all sections of the lab



- Transmission Line Elements - Used to create a model of a transmission line; used in Section **2.2**
- Variable Resistors – Used to load either the transmission line model or the transformer with a variety of resistances; used in Sections **2.2** and **3.4**
- Variable Capacitors – Used as a load of the transmission line model to subsequently compensate for the reactive load of the inductance; used in Section **2.2**
- Inductors– Inductive circuit element which serves as part of the load connected in series with the resistance for the transmission line model; used in Section **2.2**

GENERAL SAFETY INSTRUCTIONS FOR THE ELECTRIC POWER ENGINEERING and HIGH VOLTAGE ENGINEERING LABORATORIES AND WORKSHOPS

1. PURPOSE

The following procedures and regulations are intended to reduce the risk of injury to persons and damage to material during work in the laboratories and workshops. Note that these instructions alone do not constitute an exhaustive list of necessary precautions. Each person in the department is therefore urged to exercise the utmost caution and discretion at all times.

2. VALIDITY

These procedures apply to all personnel at the divisions of Electric Power Engineering and High Voltage Engineering including temporary personnel (whether the length of stay is for a short or long period of time), such as research students who are not on the staff, those working on thesis projects, guest researchers and other students.

All personnel shall indicate agreement with the procedures contained in this document by signing the agreement sheet provided. It is the responsibility of the head of each division to ensure that new personnel have received a copy of the document and signed the agreement. Signing for the safety procedures means that the person has received a copy of the procedures, has read and understood them and therefore binds him- or herself in writing to following them.

The instructions hold for all types of work carried out at the divisions.

3. GENERAL RULES

3.1 Circuit connections

3.1.1 No connections shall be attempted or carried out on a live system !

3.1.2 It is forbidden to work with dangerous voltages and machines in the laboratories and workshops if a person who is familiar with the operation of the equipment is not within sight or earshot.

NOTE: This rule applies even outside of ordinary working hours.

NOTE! A dangerous voltage is generally an alternating (ac) voltage with an effective value greater than 25 V and a direct current (dc) voltage of 60 V in dry environments. The equivalent voltages for wet environments are 6 V ac and 15 V dc.

Exceptions are work carried out at office machines and data terminals, as well as the reading of instruments during long-term testing, where the risk of coming in contact with exposed elements is considered non-existent.

3.1.3 Each connection shall be approved by the Electrical Safety Supervisor, who shall also be present when the power is switched on to the connected circuit for the first time.

3.1.4 Connections shall be made so that only necessary equipment is present in the work area. These shall be arranged as neatly and clearly as possible. Exposed parts must be grounded for protection.

3.1.5 Each connection must have an emergency cut-off switch (breaker). This must be clearly indicated, have satisfactory trip capacity and be easily accessible from the work area.

3.1.6 Before apparatus (instruments, breakers, wires, etc.) is connected and power is applied it should be ensured that each piece of equipment is suitable for the particular connection with respect to voltage rating, loading capacity, insulation, etc.

3.1.7 Work area shall be roped off and clearly marked so as to eliminate the risk of unintentional contact by unauthorised persons.

3.1.8 No unauthorised person should be allowed within the roped-off area while an experiment is in progress.

3.2 Experiment supervisor

3.2.1 The Electrical Safety Supervisor is liable to ensure that there is an Experiment Supervisor for each experiment, connection or laboratory test. This Experiment Supervisor shall, primarily, ensure that safety procedures are adhered to and shall provide personnel involved with information on the experiment. The appointed Lab Assistant has the chief responsibility during course laboratory sessions.

3.3 Special rules of caution

3.3.1 Those who work in the laboratories and workshops should be aware of the risks involved and should thus work with consideration and caution, having regard for their safety as well as that of others.

3.3.2 All persons present in the laboratories and workshops must exercise caution around connections that may be live. Never touch equipment or connections unless you have personally verified that the circuits are dead.

3.3.3 Never take automatic protective devices for granted. Always maintain a sense of personal responsibility and caution.

3.3.4 The setting-up of apparatus, connection of machines, etc., shall be done in such a manner as to prevent the possibility of unintentional contact with live or rotating parts.

3.3.5 Particular caution must be exercised with dc-motors, considering the risk for racing. Ensure that cables to the excitation circuits are whole, safely connected and drawn in a suitable manner in terms of safety. Ammeters with fuses may not be used in excitation circuits.

3.3.6 Test objects connected to condensers may not be touched until the condensers have been short-circuited and grounded as condensers can maintain charge for a long time. Series-connected condensers must be short-circuited one element at a time. For small condensers and a low voltage (less than 60 V) a careful discharge is sufficient.

3.3.7 Persons conducting electrical tests and experiments should not wear necklaces, bracelets, or similar metallic objects. These increase the risk of contact with sources of electric current. Serious burns can result if current is transmitted through the metal objects. Even strong or high-frequency magnetic fields can be hazardous in this context.

3.3.8 Each person is responsible for maintaining order at his or her workstation. Objects that are not being used, such as tools, clothing and instruments should not be allowed to clutter the work area.

3.3.9 Power should be switched off at the breaker when one is leaving the laboratory. The person in charge of a specific connection should check that voltage, gas, water supplies, etc., are turned off when work is completed.

3.3.10 Additional safety and work instructions apply for work in the high-voltage laboratory and outdoor test plants. Refer to Appendix 1.

3.4 Measurements

3.4.1 When conducting measurements with equipment that have a large short-circuit power the measurement cables should be supplied with special current limiters.

3.4.2 Extreme caution should be exercised when carrying out measurements with an oscilloscope. The ground rule is that the chassis of the oscilloscope should be connected to zero potential (neutral) and that voltage probes be used with voltages exceeding 250 V.

In the case of special measurements where the oscilloscope is subjected to high voltages (with respect to ground) it shall be clearly marked with warning signs and be mechanically isolated so as to prevent any unintentional contact with the apparatus.

3.5 Variable voltages

3.5.1 When using variable voltages the connection instructions for each additional voltage source shall be scrupulously followed.

3.5.2 Connections to the main switchboard for the distribution of variable voltages may only be carried out by the Electrical Safety Supervisor or someone appointed by the Supervisor.

3.5.3 Motor terminal boards for variable voltages are equipped with blade fuses for 16, 63 and 200 A respectively. A fuse box shall be used in cases where these fuses are deemed to be too large.

3.5.4 Fuses may only be re-set after the cause of the fault has been certified. This procedure may only be carried out by the Electrical Safety Supervisor.

3.6 Long-term testing

3.6.1 Automatic monitoring which trips all sources of electricity in the event of a fault, overheating or other disturbance should be arranged wherever possible. In other cases a clearly visible sign with instructions as to how the experiment can be interrupted shall be displayed. The sign should also contain the name of the person responsible for the experiment as well as how that person can be contacted. If an experiment is to be carried out for a period of time in a locked room then the sign should be posted on the door of the room. Such a sign should also state the location of the nearest emergency breaker.

The lighting in an area where a long-term experiment is being carried out shall always be on. Provisional lighting can be arranged.

The test area shall be fenced off with railings, lines, plastic-cable barriers or similar material. The appropriate warning signs (previously mentioned) should be displayed at the site.

3.7 Obligation to report

3.7.1 Everyone has a duty to report to the Electrical Safety Supervisor if it is observed that there may be a fire hazard, risk to personnel or material damage due to the placement or connection of equipment.

4. ACCIDENTS

Each person should be aware of the First Aid supplies which are available in each room and where they are located. Notices outlining action to be taken in the event of an accident should be carefully read and with such an occurrence, closely followed.

All electrical accidents and near accidents (“narrow escapes”) shall be immediately reported to the department’s Electrical Safety Supervisor, the Head of the Department, the work environment representative and the safety engineer in the work environment unit.

5. FIRE EXTINGUISHING

Each person working in the laboratories and workshops should be aware of the existing fire extinguishing equipment and become familiar with how they are used.

Water must never be used in attempts to extinguish a fire in a laboratory set-up that is powered. Carbonic acid or powder should be used instead.

In the case of a fire in a live circuit the power to the circuit should first be disconnected, if possible. The fire can then be more easily handled, and with less risk, with ordinary fire-extinguishing agents, such as water.

Call the fire department. The owner of the property will be notified directly by the emergency service.

Göteborg, 20 januari 2007

Lennart Vamling
Head of Department
Energy and Environment

Aleksander Bartnicki
Electrical Safety Supervisor

Lars Nyborg
Head of Department
Materials and Manufacturing Technology

APPENDIX 1

ADDITION TO GENERAL SAFETY INSTRUCTIONS CONCERNING OPERATIONS AND TESTING IN HIGH-VOLTAGE LABORATORIES AND AT OUTDOOR TEST PLANTS.

1. Protective measures shall be taken to ensure that live parts are not accessible. In order to fulfil this requirement the test area must be clearly defined and marked off through the use of painted railings, barriers or similar apparatus. With respect to the size of the defined area, the distance from the live parts to the separation shall be at least:

Voltage U (kV)	**Distance through air D (m)**
< 20	1.8
30 – 50	2.3
70	3.1
130	3.6
220	4.5
400	5.5

   The general rule for tests with impulse voltages is that the distance from the live parts of the system to the separation (barrier) shall be at least 1.5 m plus 1.5 times the shortest flashover distance through air to earth.

2. Warning signs, together with a double warning lamp shall be mounted in a prominent location. The lamp should automatically switch on and off to coincide with the switching (on or off) of a circuit breaker or disconnector located between the voltage source and the system.

3. At least two persons shall be present each time a high-voltage test is run. These persons shall be familiar with the nature of the test, the extension of the live sections of the circuit, as well as the procedures for regulating and discontinuing the voltage. One of these persons must always be in close proximity to the emergency switch or circuit breaker.

4. Persons may enter the test area only when the system has been de-energised through the opening of a circuit breaker and if possible, through total disconnection of the system from the power supply. The test system shall be immediately grounded when a person enters the test area. The grounding apparatus should be located sufficiently close to the work station that one can immediately see if the test system is grounded through a metal conductor. In addition, the earth point should be located between the voltage source and the workstation.

   The circuit shall be de-energised and grounded before the test area is left unattended.

5. The entire high voltage laboratory should be treated as a hazardous area during experiments involving switching impulses, extremely high voltage or the risk of explosion. No-one may enter the area before the voltage supply has been discontinued. Protective railings shall be used as needed.

6. Warning lamps shall be illuminated above the entrance to the high-voltage laboratory during high-voltage tests.

7. Special caution must be exercised during tests with condensers which can maintain charge and which, under certain conditions, may also be charged through air. A condenser which is not short-circuited or connected in parallel with a suitable discharge resistor shall therefore be considered to be current-carrying. This applies to condensers in impulse generators and high-voltage rectifiers as well as separately mounted condensers at any location in the laboratory. Therefore the condensers should either be short-circuited or connected in parallel with a discharge resistor when they are not in use.

8. The risk of induced voltages must be taken into consideration during tests on systems which contain long conductors. This implies that each conductor should be considered to be live if it is not grounded in a satisfactorily safe manner: either directly grounded or through a suitable low-ohm resistor.

External switchgears

9. An enclosed switchgear shall have the necessary space and be installed such that supervision, service and transportation can be carried out without hindrance or hazard.

   Current-carrying wires should either be arranged on overhead trays, on a permanent platform or similar apparatus at a height equivalent to 2.5 m plus phase-to-ground air clearance for the isolation class in question in accordance with Swedish standards; the overall height should be no less than 3 m above the ground in sections that are normally in use by personnel. The area around these sections should also be furnished with barriers to prevent unintentional entry.

   Isolators may be placed so that the distance from the ground to the lowest part of the isolation or permanent platform is at least 2.5 m.

   Other clearances are to be observed for outdoor switchgears which are not enclosed in order to prevent unintentional contact with live parts of the circuits. The following guidelines shall be observed:

   The risk of unintentional contact is generally considered non-existent when the distance from the ground surface to unshielded live circuits is at least 4.5 m at system voltages up to and including 25 kV and at least 5 m for voltages above 25 kV, up to and including 55 kV. The distance shall be increased by 0.5 cm for each kV when the voltage exceeds 55 kV. All clearances should be increased by 0.5 m when there is considerable snowfall.

   NOTE !

   An isolator that supports a live part is itself considered to constitute part of the live section of the circuit.

Other potential hazards

Work in high voltage laboratories also implies certain other potential risks, for which it is more difficult to draw up general safety rules. Thus caution, common sense and due consideration must guide the laboratory procedures to an even greater degree. The following points are intended to be examples:

10. Safety belts shall be worn for work at great heights above the floor surface.

11. One should first and foremost assure oneself that lifting devices and parts thereof (hooks, blocks, lines, etc.) are strong enough before attempting to use them to move heavy equipment. Most of the hooks in the ceiling of the high-voltage laboratory are not intended for heavy loads. The “Safety Regulations for Lifts” which is posted in the high-voltage laboratory should be observed and followed.

12. All persons entering the central test area in the high-voltage laboratory, as well as the outdoor test plants should, as a rule, wear protective helmets. This primarily applies during ongoing work.

13. Ear protection should be used during tests with large surge generators as large discharges or many repeated discharges typically occur.

14. The eyes should be protected during the use of ultra-violet lamps. Not only direct light, but even indirect light, for example in the form of reflections, can cause irritation and pain which first occur some time after exposure.

Göteborg, 20 januari 2007

Lennart Vamling
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Electrical Safety Supervisor

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Head of Department
Materials and Manufacturing Technology

Per Norberg November 2012

Study visit to Lindome substation

Summary

The substation, Lindome, was commissioned in the middle of 1970:s as a single 400/132 kV transformer station to supply the southern Gothenburg area with electricity. Until 1986 the station had one 750 MVA 400/132 kV unit and 3 outgoing 132 kV lines. At 1986 the Kontiskan 2 (KS2) HVDC converter station was placed at Lindome. At the same time another 750 MVA unit was installed.

The original Kontiskan 1 (KS1) HVDC project commissioned in the middle of the 1960:s was the first big scale commercial HVDC installation in the world. The first was the cable to Gotland ten years before. KS1 connected the Swedish/Nordic synchronous grid with central Europes by a cable to Jutland. In KS1 mercury valves was used for the conversion of AC to DC (see more below) – a technique that became obsolete in the 1970:s with the introduction of the thyristor.

KS1 originated in Stenkullen substation east of Gothenburg and the DC overhead line passed close to Lindome. That was the main reason to put KS2 in Lindome instead of Stenkullen. About 10 years ago it was decided to scrap the old KS1 because of high costs and the environmental risks in handling tons of mercury. So the new KS1 was placed together with KS2 in Lindome.

The new KS1 is connected to 400 kV and can transmit 350 MW at 285 kV DC, the older KS2 from 1986 connected to 132 kV AC can transmit 300 MW at 285 kV DC.

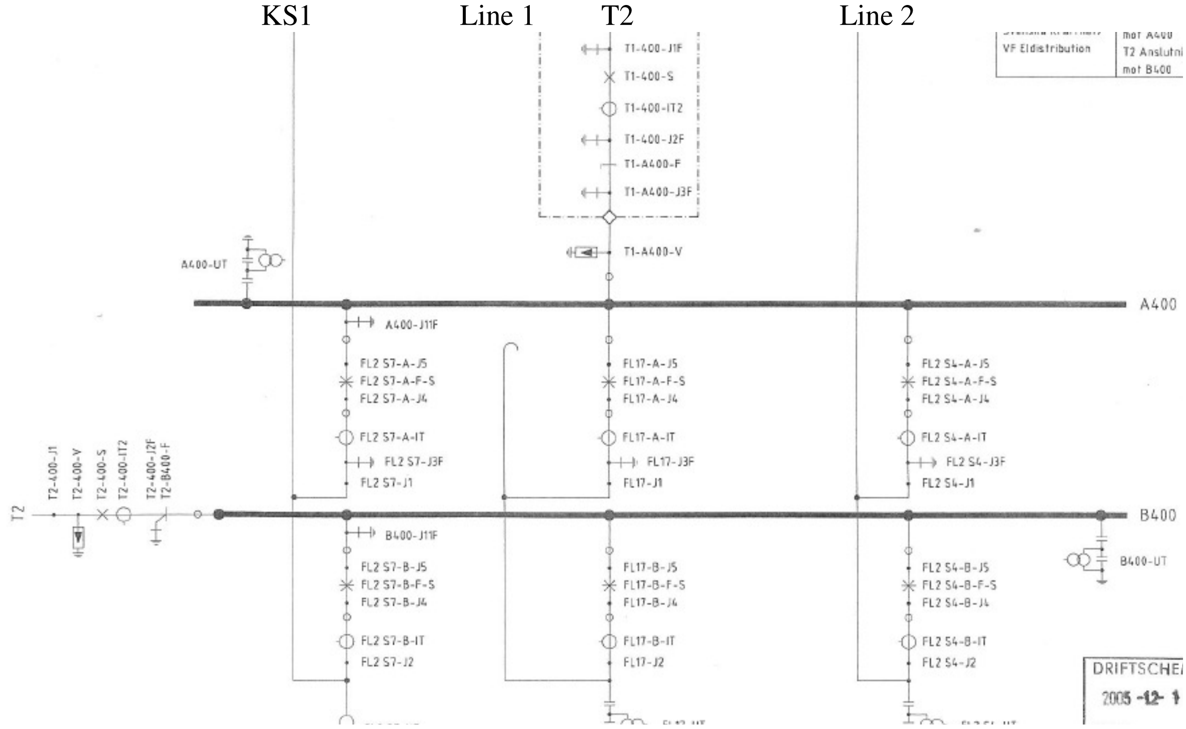
The AC transformer station.

400 kV switchyard
Until this summer 2012 the station has been radial connected to the 400 kV system. A second line in the same right of way as the old HVDC line between Stenkullen and Lindome was delayed for many years because of local impact. The 400 kV switchyard was built when KS1 was connected. It's Svenska Kraftnäts (the Swedish TSO) standard double breaker layout. A double breaker switchyard is characterized that a fault on a busbar (A or B) leads to disconnection of the faulted part without disturbing the system operation. Ie all lines connected with two breakers will be in service. Since the transformers are reserve for each other they have a more simple connection – T2 to A and T1 to B. See below.

Transformers
Usually system transformers of this size, 750 MVA, are auto-coupled. That means that the primary and secondary windings share turns up to secondary voltage. This saves costs and weight. But for different reasons the transformers in Lindome are full coupled YN/yn/Δ . T2 with rating 400/140.9/21.2 kV 750/750/150 MVA is the most heavy transformer that is owned by Vattenfall. Both T1 and T2 have fixed ratios so for voltage regulation we have two regulating units RT1 and RT2. They work in different ways. RT1 is a separate auto-coupled transformer 140.9/140.9 kV +- 9*1.67 %. RT2 is a so called booster regulator. It takes voltage from the main units 21.2 kV winding and adds a voltage ≤ 21.2 kV in series with the 140.9 kV winding.

X = breaker. All connected items are taken in/out of service by breakers.
— = disconnector. Are used to change operation modes. Can only be operated without load.

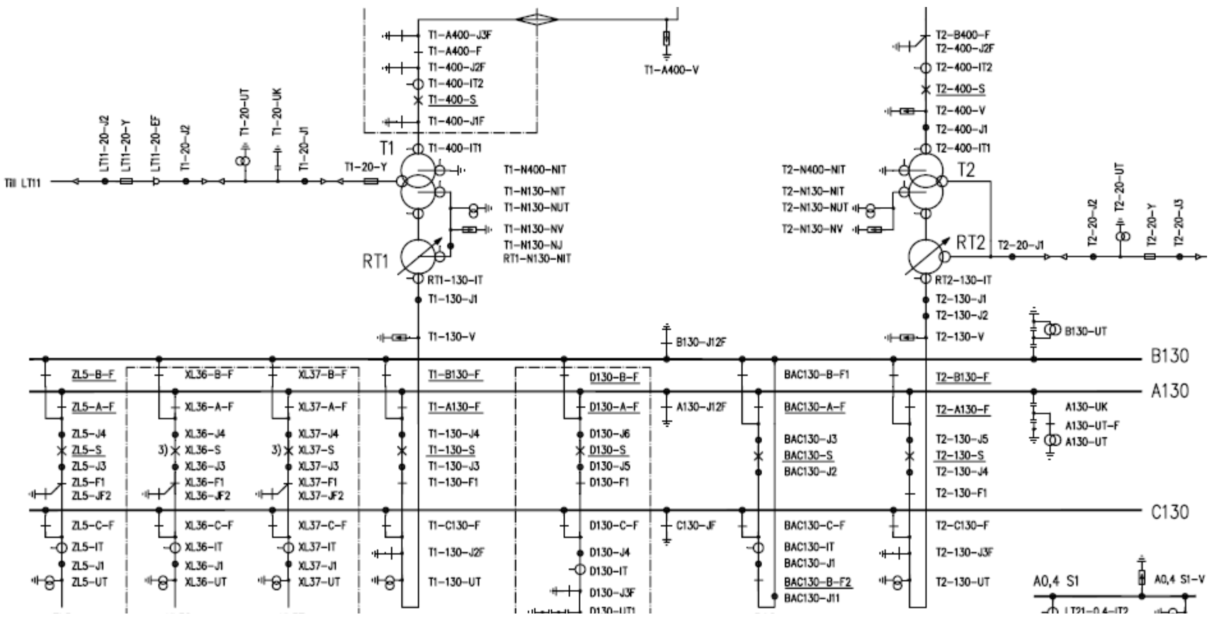
KS1 Line 1 T2 Line 2



400 kV layout.

132 kV switchyard

From start the 132 kV switchyard had two busbars, one main A and a so called help-busbar C.



Line 1 Line 2 Line 3 T1 KS2 Help T2

Later a second main B busbar was added. In normal operation T1 is feeding the outgoing lines from A busbars and T2 serves KS2 via B busbar.

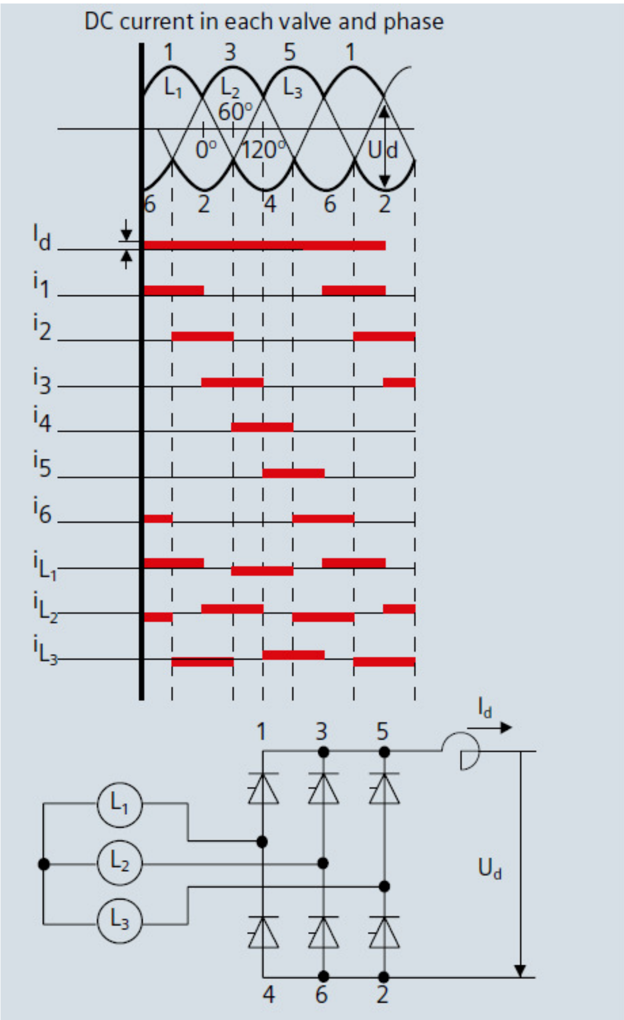
A help-busbar is used when equipment fails or it's time for maintenance. If we need to work on Line 1 breaker (the X) the following is done. All disconnectors (—) connecting to C busbar should be open. The help-breaker should be open. Close c-f for line 1. Close c-f for the Help bay. Close the disconnector connecting the help bay to busbar A. Close the help-breaker. Now the load at line bay is split between its own bay and the help bay. By opening line 1 breaker the whole load is handled by the Help bay and the line breaker is non-energized.

HVDC converters.

As mentioned above Lindome has two converter stations, KS1 and KS2. They are both so called classical HVDC to differ them from the new so called Voltage Source Converters (VSC).

A classic HVDC must be connected to existing AC networks since the DC voltage is created from the existing 3-phase AC system. How it works can be described from the two pictures below.

RSTRSTRS....



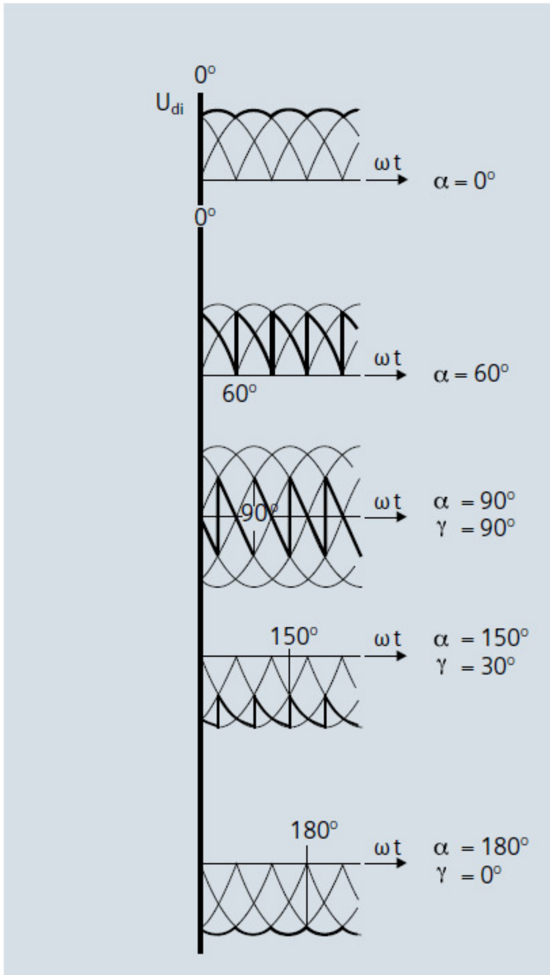


Figure 1 Basic principle for a 6 pulse converter (from Siemens brochure). Figure 2

L1, L2 and L3 symbolize the 3 phase AC voltages – in Sweden we call them R, S and T phases. In fig 2 the thin lines shows the 3 phase voltage as a function of time. α is the so called firing angle that starts the thyristor to lead current. At α = 0˚ the thyristor acts like a diod.

With the coupling in fig 1 the resulting DC voltage U_d will be nearly constant with a small distortion. In fig 1 we can see how the dc current I_d is distributed through the thyristors and phases. It's always two thyristors that is active the others are blocking. At $\alpha = 60^\circ$ we will have a positive but very fluctuating DC voltage and at $\alpha = 90^\circ$ the resulting DC voltage will be 0. For At $\alpha > 90^\circ$ we will see a negative DC voltage. In practice the DC voltage is stabilized by filters.

A HVDC classic can be either monopolar or bipolar. The original KS1 was a monopolar converter. The common practice is to ground one of the DC poles and use earth as return conductor. A bipole converter is two converters that work opposite each other. One gives + voltage and the other – voltage so a bipole must have both DC phases at full insulation. Very common is to have the midpoint grounded to earth so if one pole fails you can run the other with ½ power by ground current return. The installation of KS2 led to that it together with KS1 could be operated as a bipole.

III . One example paper

IV Material and instructions for laboratory work

V Material for technical study visit at substation Lindome

Per Norberg November 2012

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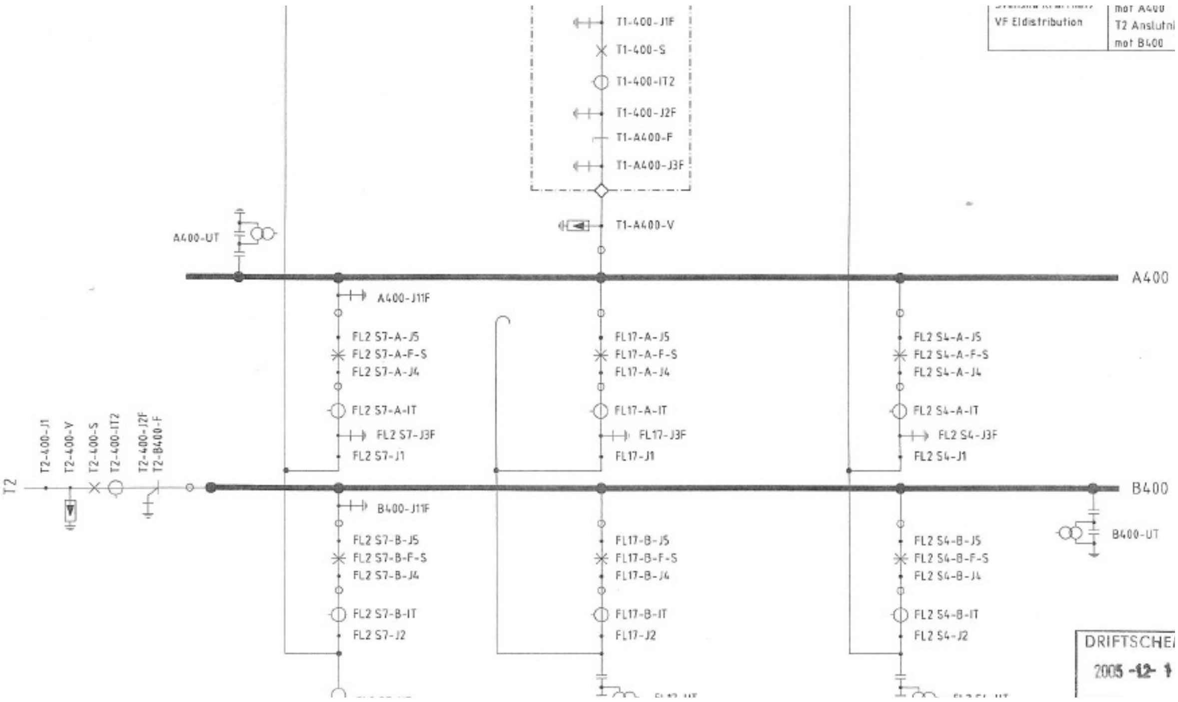

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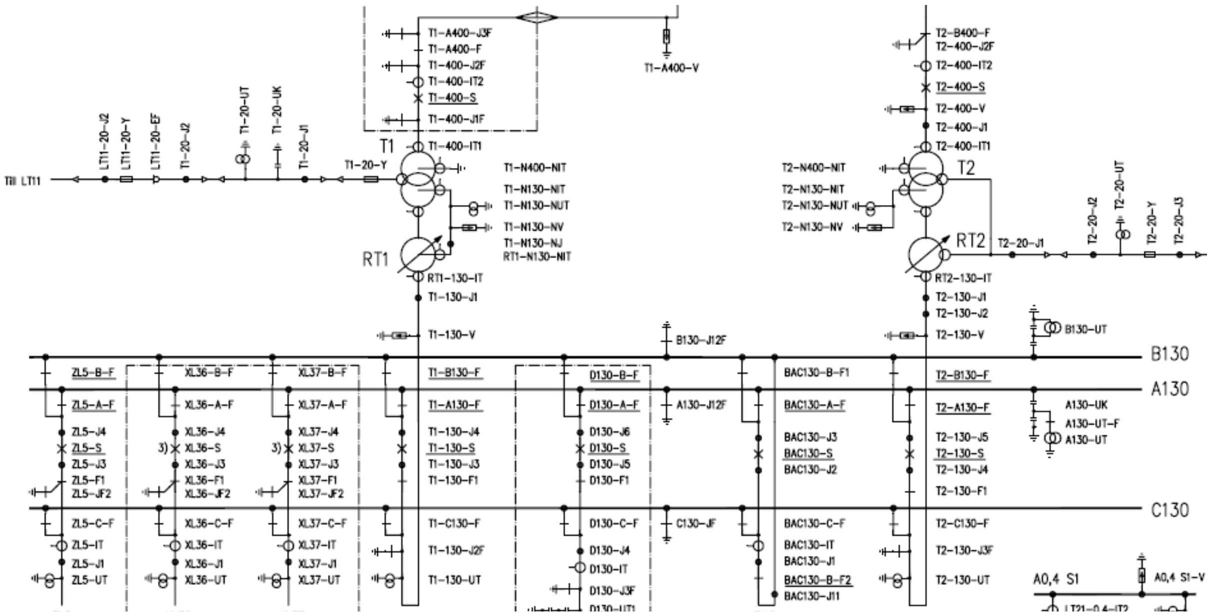

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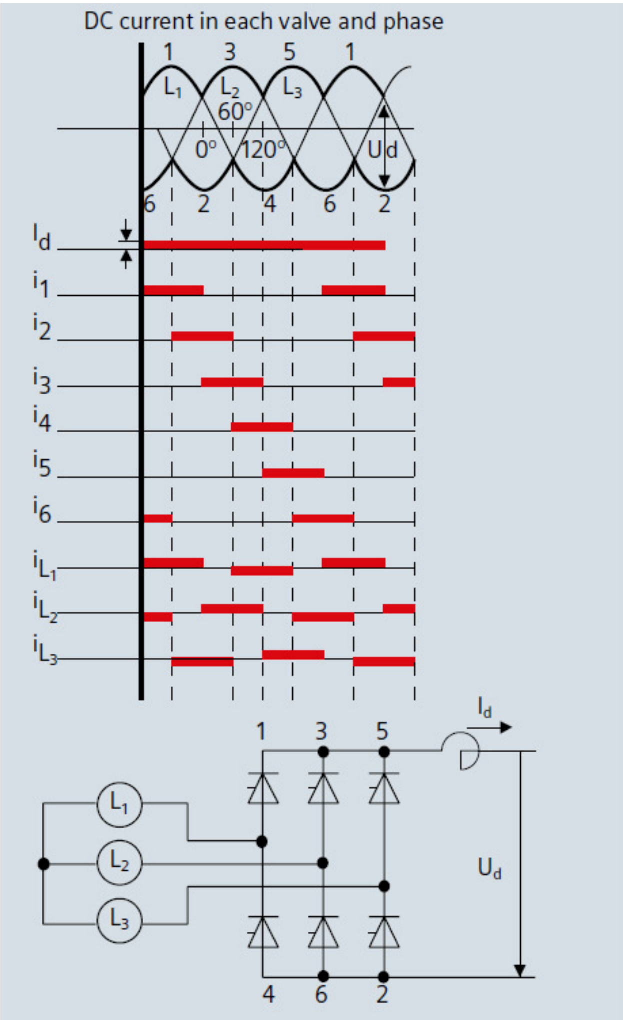

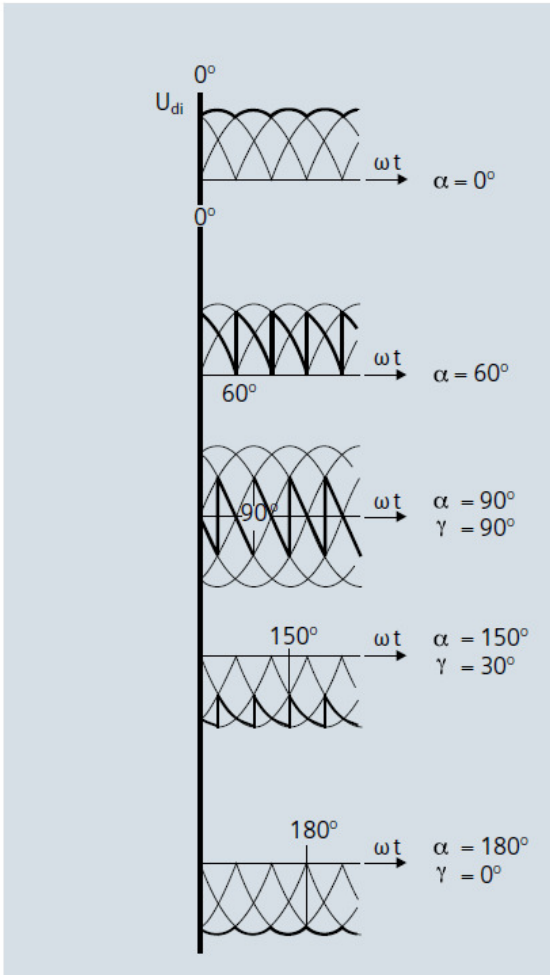

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