GLOBAL PST CONSORTIUM

Inaugural Teaching Agenda

March 2021

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How to Read this Document

This document summarizes the outputs from a consultation process led by the Global Power System Transformation (G-PST) Consortium’s Teaching Agenda Group (TAG). The aim of the consultation was to develop a ‘forward-looking’ teaching and training agenda that would prepare the university graduates and upskill the power engineering professionals to meet the challenges posed by very high penetration of variable renewable energy sources (VRE) and inverter-based resources (IBR) in power systems. As power systems are evolving rapidly, the current research priorities outlined in the G-PST’s Inaugural Research Agenda will need to be moved to adoption quickly and therefore become topics where teaching and training is needed. Therefore, the research questions set out in the Research Agenda is directly relevant to the Teaching Agenda. However, the scope of the Teaching Agenda is broader and covers subject areas such as active distribution networks, electricity markets for example, which are not the current priorities in the Research Agenda.

Note that we are committed to leverage any existing open-source material that are aligned with the teaching agenda presented here or could be used for prior learning and would welcome any pointers on that. We expect this teaching agenda to evolve as we collectively embark on the path towards developing the teaching and training material, hence the document title, Inaugural Teaching Agenda. The authors strongly welcome your feedback and further interaction on this document.

ARE YOU A SYSTEM OPERATOR?
Please reach out to provide us with your feedback, share your training needs on the topic areas presented in this document, and explore opportunities to collaborate.

ARE YOU A POWER ENGINEERING EDUCATOR?
Please provide your feedback, reach out to us if you think this teaching agenda could complement your current offering at the post-graduate level, and explore opportunities to collaborate.

ARE YOU A PROSPECTIVE FUNDER?
Please provide us with your feedback and inform us of your aligned funding for workforce development and opportunities for us to provide appropriate input to your activities.

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Executive Summary

The workforce development pillar of the Global Power System Transformation Consortium (G-PST) focuses on 1) upskilling of the existing workforce to address newly emerging technology and the operational changes that come with it and 2) revamping the post-graduate power education programs in universities that are preparing the next generation of the workforce.

The plan is to facilitate this by developing cutting-edge teaching and training material as a collection of bite-sized topics which could be incorporated selectively into an existing curriculum or training program based on the gaps and local priorities. Each topic would typically have 3 to 6 hours of lecture material supported by exercises/case studies. The Teaching Agenda Group of the G-PST comprising academics from six universities in Europe and North America identified about 100 such topics which are important for deep transformation of power systems globally. The focus has been on 'forward-looking' topics rather than 'traditional' but important topics that have been part of the education of power systems engineers for many years.

This document outlines these topics under 9 subject areas (e.g., planning, operation etc.) and contains a brief (1-2 page) description of some selected topics as exemplars. The topic descriptors include the context (why the topic is forward-looking and important in the context of G-PST), content summary, prior knowledge required, target audience, assessment method etc. These are meant to provide a flavor of the teaching/training material to be developed in due course.

The main purpose of this document is to initiate wider consultation and get feedback from various stakeholders. This includes the Founding System Operators of the G-PST, other system operators around the world, G-PST core partners, university partners in different countries/regions and individuals/organizations who have expressed interest in contributing to or benefitting from the workforce development pillar of G-PST.

Feedback in any form is welcome including highlighting omissions, existing aligned content and teaching programs, thoughts on collaboration, willingness to participate and contribute etc. We look forward to your responses.

Contributors

The members of the Teaching Agenda Group of G-PST, listed below, contributed to the preparation of the inaugural teaching agenda presented in this document.

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The guidance and support of the G-PST interim secretariat based at the National Renewable Energy Laboratory (NREL) in USA is gratefully acknowledged.

List of acronyms used in this document

AC	Alternating current	ML	Machine learning
ADMS	Active distribution management system	MTDC	Multi terminal direct current
AI	Artificial intelligence	MVDC	Medium voltage direct current
CIG	Converter interfaced generation	OPF	Optimal power flow
DC	Direct current	PES	Power and Energy Society
DCOPF	DC optimal power flow	PJM	Pennsylvania, New Jersey Maryland interconnection
DER	Distributed energy resource	PLL	Phase locked loop
DG	Distributed generation	PMU	Phasor measurement unit
DLL	Dynamic linked library	PSLF	Positive sequence load flow
DNO	Distribution network operator	PSS	Power system stabilizer
DSA	Dynamic security assessment	PST	Power system transformation
DSO	Distribution system operator	PTI	Power Technologies International
DSS	Distribution system simulator	PV	Photovoltaic
ESCR	Effective short circuit ratio	PWM	Pulse width modulation
EV	Electric vehicle	RUC	Reliability unit commitment
FSO	Founding system operator	SCED	Security constrained economic dispatch
FSR	Financial storage right	SCR	Short circuit ratio
FTR	Financial transmission right	SCUC	Security constrained unit commitment
G-PST	Global power system transformation consortium	SFT	Simultaneous feasibility test
HVDC	High voltage direct current	SG	Synchronous generator
IBR	Inverter based resource	SO	System operator
ICT	Information and communication technology	STATCOM	Static Synchronous Compensator
IEEE	Institute of Electrical and Electronic Engineers	TAG	Teaching agenda group
ISO	Independent system operator	TSO	Transmission system operator
LCC	Line commutated converter	VRE	Variable renewable energy source
LMP	Locational marginal pricing	VSC	Voltage source converter
MC	Monte Carlo	WECC	Western electricity coordinating council

Overview of G-PST and its Workforce Development Pillar

The Global Power System Transformation Consortium (G-PST) is an expert- and practitioner-driven initiative which engages key power system operators, research and educational institutions, governments, businesses, and stakeholders in all regions of the world to accelerate transitions to modern energy systems. The Consortium features eleven "Core Team" technical institutions[1] and a group of five Founding System Operators[2] (FSOs). The FSOs are a unique group that are on the absolute leading edge of power system transformation and variable renewable energy integration. The Consortium has two core objectives: (1) supporting cutting-edge research and development activities for the FSOs and other advanced power system operators; and (2) supporting developing and emerging economy system operators as they transform their power systems.

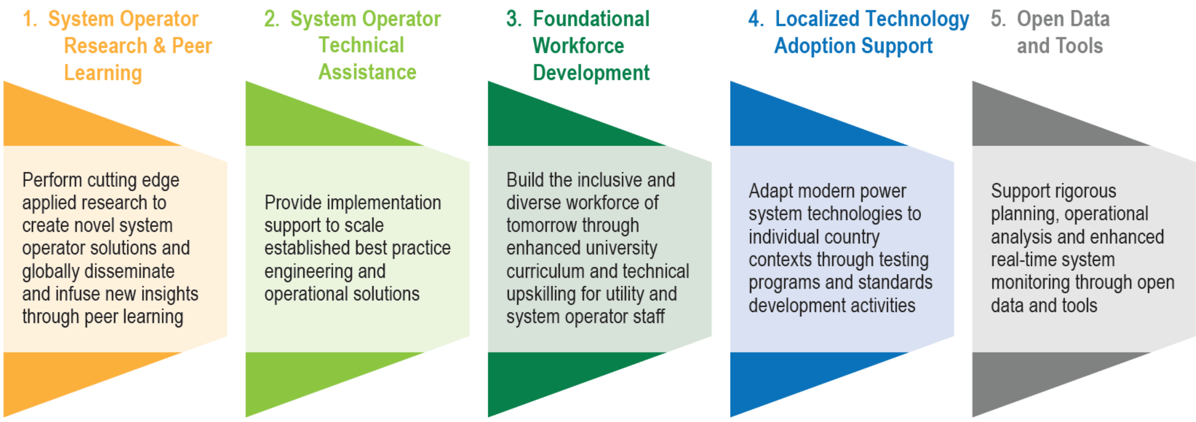

Figure 1 - Five Pillars of the Global Power System Transformation Consortium

The G-PST is organized into five key pillars of activities to support power system operators (Figure 1). 'Pillar 3 – Foundational Workforce Development' is focused on the second objective, supporting developing and emerging economy system operators as they transform their power systems. The Teaching Agenda Group (TAG) of Pillar 3 has identified a list of topics that will need to be addressed in workforce development in preparing for deep transformation of power systems globally. Workforce development concerns not only the upskilling of the existing workforce to address newly emerging technology and the operational changes that come with it but also the education programs in universities that are preparing the next generation of the workforce.

The focus is on 'forward-looking' topics of relevance to G-PST rather than 'traditional' but important topics that have been part of the education of power systems engineers for many years. It is envisaged that the core power system concepts delivered in a bachelor's degree will remain largely unchanged, but that master's degree programs will need to incorporate the new topics. Although methods of delivery may differ for upskilling and master's degree audiences, it is envisaged that the content will be very similar.

The topics are organized under 9 subject areas. The size of these topics is not strictly defined but is equivalent to roughly 3-6 hours of lecture material. A set of exemplar topic descriptors are included on page 14 onwards. For each topic, we have noted if the material is known to already

[1] Energy Systems Integration Group (ESIG), Imperial College London, Council of Scientific and Industrial Research (CSIR), Fraunhofer Cluster of Excellence for Integrated Energy Systems, National Renewable Energy Laboratory (NREL), Latin American Energy Organization (OLADE), Institute of Electrical and Electronic Engineers (IEEE), Electric Power Research Institute (EPRI), Commonwealth Scientific and Industrial Research Organization (CSIRO), the Technical University of Denmark (DTU), and ASEAN Centre for Energy, are actively developing the consortium and will be engaged in implementation of technical work as well as coordinating specific pillars.

[2] Australian Energy Market Operator (AEMO), California Independent System Operator (CAISO), EirGrid, Energinet, and National Grid Electricity System Operator (NG ESO).

exist at one or more of the universities or other platforms such as IEEE PES resource center, Consortium of Universities for Sustainable Power hosted by the University of Minnesota etc.

The G-PST Consortium is addressing the major challenges to the operation and planning of electricity grid with much higher penetrations of variable renewable generation than today and a set of resources that are much more diverse in technical characteristics and include large numbers of small-scale distributed resources alongside large-scale resources. Accompanying these changes in energy technologies are changes in supporting technologies in communications, data acquisition, data analysis and machine learning. Beyond technology are changes in behavior and uses of energy in transport and buildings and new threats to infrastructures from cyberattacks and extreme weather events.

The increase in variable renewable generation creates challenges not only from its variability but also from the fact that its two major technologies, solar and wind energy, are both interfaced through power electronic devices (and known variously as Inverter-Based Resources, IBR or Converter-Interfaced Generation, CIG) and are non-synchronous sources without directly connected spinning mass. As synchronous sources are stood down because their energy output is not required, the system also loses the services that they provide, and those services will have to be sought from these non-synchronous sources. The growth of non-synchronous generation is accompanied by other non-synchronous resources such as battery energy storage and other power electronic equipment such as converters of High Voltage Direct Current (HVDC) links and Static Synchronous Compensators (STATCOMs).

Much of the operation of a power system rests on having flexible resources that can be called upon at times of need such as when responding to a sudden change in demand or an unplanned outage of a transmission line or generator. As well as looking to create that flexibility in variable renewable / non-synchronous generation, it is also being sought from energy storage devices, demand-side response and increased interconnection. The optimization and control of a system using such a wide range of resources is itself a challenge.

The pace of the transformation of power systems is rapid. Topics which are currently in the research and development domain (e.g., Pillar 1 of the G-PST) will need to be moved to adoption quickly and therefore become topics where educational material is needed for both upskilling an existing workforce and for the education of the aspiring new entrants to that workforce. Therefore, the work of the Research Agenda Group of Pillar 1 in setting out research questions is directly relevant to the Teaching Advisory Group of Pillar 3.

Subject Areas

The discussion to date has identified over 100 topics organized into 9 subject areas. Arising from the very strong coupling within the power system many of the topics are strongly interrelated and overlapping. As a consequence, many topics could just have easily been assigned to another subject area some examples of which are indicated within parenthesis alongside the topic listed in subsequent sections. This strong coupling also drives the need for a holistic educational approach where to some extent "little is learnt until it is all learnt". These 9 subject areas (as illustrated in Figure 2) will be described in more detail in what follows. As well as the detailed technical material, there is a need for an introductory material that sets the overall context for power system transformation and that can be used to encourage participation and to motivate study of each subject area.

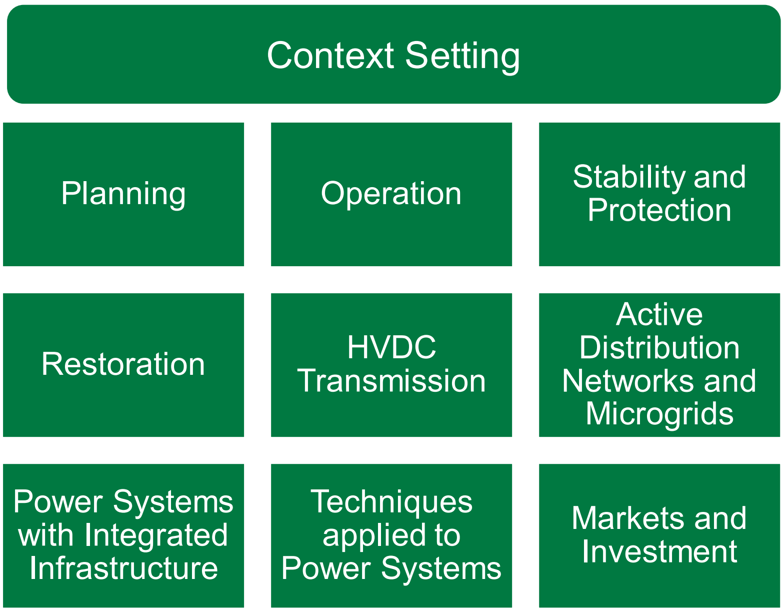

Figure 2 – Subject areas

Each subject area, if taken as a whole, should also have its own scene setting lecture by an industry expert who would highlight the most up to date pressing issues and recent developments in the area. Each subject area should be wrapped up by a seminar given by leading researchers outlining a few important research questions and results in that area.

Context Setting

This introductory context setting material should be localized and is meant to:

- Motivate undertaking a series of courses (as supplement to recruitment activities of universities or for recruitment within SO for upskilling).
- Provide examples of successful career paths with special emphasis on promoting equality and diversity in the workforce.
- Set the scene for the subject areas/topics that follow by describing the transformation foreseen.
- Describe key ideas that underpin items in several of the areas (and where covering them here would avoid duplication).
- Draw links between areas so that the system aspects can be tackled (either as a prelude to the subject areas/topics below or as a conclusion after them).

Topics to be covered could be:

- Summary of perspective on decarbonization and the position of energy within that via Intergovernmental Panel on Climate Change, Conference of the Parties and the Nationally Determined Contribution.
- Summary of energy access in low- and middle-income countries.
- Global and national trends in deployment of renewables and phase-out of coal, deployment of electric vehicles.
- Summary and trends in other key infrastructures including, information and communication technology, gas, transport and water networks.
- Overview of key challenges in variable generation and inverter-based resources.
- Overview of behavior change and its drivers.

1. Planning

As the primary energy resources change from fossil/nuclear fueled to more variable renewable resources and as more of these resources are distributed the planning paradigm needs to change to account for their different characteristics. As other technologies e.g., batteries, become more pervasive, they also impact on the need to change how we plan the power system. Electrification and integration of the other parts of the energy system (e.g., transport and heat) can dramatically alter the demand patterns which will also impact the planning paradigm. Furthermore, this integration of infrastructures more generally e.g., information and communications technologies broaden the planning canvas both in terms of resources and potential events that need to be accounted for. The events themselves, driven in part by climate change are also starting to become more extreme and highlight some common mode failures, which are also important to account for in the planning activities. As the consumer becomes more active on the power system possibly creating a more heterogenous demand side the whole concept of planning standards may need to be adapted to enable a more optimal system. Finally, the more dynamic a power system is with VRE, consumer participation etc. the more complex its operations become (see the Operations area next) and the more important it is to account for the operations in more detail within the planning process than heretofore. Therefore, the planning stage needs to ensure the correct resources are available for operating the power system.

The topics in this area are dominated by the need to perform forecasts, understand the uncertainty and make decisions/optimize around these and at all times account for how the power system will be operated with a similar set of objectives but over a much shorter time scale and with fewer decision variables. This leads to the following set of proposed topics.

1.1 VRE and load forecasting (linked to “Operation”)
1.2 Data-enabled weather-related outage prediction
1.3 Probabilistic planning
1.4 Decision making under uncertainty: long-term investment planning
1.5 Risk analysis and mitigation
1.6 Reserve deliverability analysis
1.7 Emerging essential services in a VRE dominated power system
1.8 Stochastic modelling of renewables and load
1.9 Generation contingency modelling and generator loss distribution factors
1.10 Demand side flexibility and effective demand response program design
1.11 Modelling and analysis of low probability high impact and cascading events
1.12 Modelling and analysis of remedial action schemes
1.13 Future network design standards

2. Operation

Similar to planning as the resource mix evolves, as new technologies are connected to the power system and as the power system becomes more integrated with other infrastructures and as consumers also become more active the operation paradigm must change to ensure a reliable and cost-effective power system. In contrast to the planning area here the time scales are shorter, and the decision variables do not include investment decisions but similar to planning must make decisions and optimize on forecasts that are uncertain and ensure the reliable and cost-effective operation of the power system. This requires scheduling the supply and part of the demand to meet supply demand balance and to be prepared for inevitable forecast errors and unexpected events. This is achieved by “ancillary services” and by controlling the key characteristics such as frequency and voltages in the power system. This leads to the following proposed topics.

Scheduling

2.1 Economic dispatch under uncertainty
2.2 Uncertainty modelling in unit commitment and economic dispatch models

2.3 Chance-constrained optimal power flow
2.4 Power system operational scheduling during extreme weather events
2.5 Security constrained economic dispatch and unit commitment
2.6 Role and value of flexibility – demand response, storage
2.7 Harnessing electricity demand flexibility

Ancillary services

2.8 Ancillary services scheduling from VRE
2.9 Ancillary services provision from aggregated DERs
2.10 Flexible ramping product requirements and deliverability assessment
2.11 Dynamic reserve requirements (linked to "Planning")

Inertia and frequency control

2.12 Declining system inertia – challenges and solutions
2.13 Radically different approach to grid frequency management

Control

2.14 Aggregated DER participation in transmission system operation
2.15 Preventive vs. corrective control
2.16 Multi-stage decision making
2.17 Decision making under uncertainty: operational planning (linked to "Planning")
2.18 Contingency analysis in power systems with high VRE
2.19 Real-time contingency analysis with corrective topology control

3. Stability and Protection

Increasing penetration of IBR shifts the focus of grid stability from slow "electromechanical" to faster "electromagnetic" time scale as IBRs have fundamentally different physical characteristics and electrical response compared to the synchronous generators. Lack of inherent inertial response from IBR, their limited short circuit current contribution and dynamics governed by control-loop choices change the nature of the grid stability problem. An IBR typically has fast inner current control loops together with slower outer loops plus a synchronization function using either a phase locked loop (PLL) or a governor-like frequency droop function. These control loops could interact with electromechanical dynamics of synchronous generators on the one hand and the electromagnetic transients of the network on the other, leading to instabilities over a wide frequency range (tens of Hz to kHz) and thereby, necessitating new approaches to modelling, stability analysis and mitigation. IBRs operating in grid-forming mode are less vulnerable to such instabilities but require a margin for power variation (through energy storage or de-loaded operation) and hence must be scheduled with a cost-benefit case for its service and its energy in mind (see "Operation").

Traditional network protection relies on the natural fault response of synchronous generators which typically deliver high fault currents including negative and zero-sequence components as appropriate. Fault response of IBR, on the other hand, is constrained by the limited short-term over-current capability of the converter (perhaps no more than 20% beyond the rated current) and the sequence composition is determined by converter control strategy. Fault current injected by IBRs is close to the rated current and may lack negative and zero sequence components (unless provisions are made in the converter control) which risks maloperation of traditional protection through either misdetection or longer detection time. New protection strategies are needed based for example on travelling waves, differential phase angle or dynamic state-estimation, that can avoid or reduce reliance on high fault current magnitude. This leads to the following proposed topics:

Stability

3.1 Impact of IBR on rotor angle stability
3.2 Converter-driven resonance
3.3 Grid-forming inverters

3.4 Modelling adequacy for IBR dominated power systems
3.5 Transient stability models for wind turbines and solar PV resources
3.6 Stability with 100% IBR
3.7 AI-enabled online transient stability assessment

Protection
3.8 Limits of traditional network protection under low short circuit levels
3.9 Alternative protection schemes (e.g., travelling waves and dynamic state estimation)
3.10 AI-enabled power system protection
3.11 Critical protective relay modelling in transient stability analysis

4. Restoration

Restoration of service to customers off-supply following an outage will need to evolve to account for the changing nature of the generation and the wide-spread use of distributed resources. In the extreme case, one needs to restart a system from complete shut-down – black-start – using generation resources that are both grid forming and able to run their auxiliary equipment without an external source. Wind and solar resources without storage can have very limited (or no) ability to perform cold-load pick-up so careful coordination of the restoration process is needed. The use of island operation of microgrids and gradual synchronization into larger grids also needs this coordination and deliberate islanding during a system collapse might be used to avoid black-out of all areas. Electricity is a vital service to other infrastructure, and, in turn, the electricity system relies on that infrastructure e.g., information and communications technologies (ICT). The co-dependencies and the resilience of these other infrastructures also need to be considered in a restoration strategy.

4.1 Black start capability of IBR
4.2 Resource (e.g., DER) coordination
4.3 Resilient ICT (Power Systems with Integrated Infrastructure)
4.4 DG management for enhanced resilience
4.5 Distribution system intentional islanding to enhance resilience
4.6 Power system resilience assessment (liked to “Planning”)
4.7 Optimal grid restoration procedures

5. HVDC Transmission

High voltage direct current (HVDC) transmission continues to grow in importance driven by the need for (i) very long distance overhead transmission from renewable energy resources (e.g. hydro, wind, solar) that are far away from load centers (as seen in China, Brazil and India), (ii) sub-sea interconnectors to exploit the geographical diversity in renewables (as in seen in the North Sea and Baltic Sea in Europe) and (iii) connections to offshore wind (as seen in Northern Europe but also in China and North America). Line commutated converter based HVDC (LCC-HVDC) continue to dominate the HVDC overhead lines (and cable) above 2 GW whereas voltage source converter based HVDC (VSC-HVDC) is the preferred option for windfarm connections and interconnection cables below 2 GW.

An LCC-HVDC link requires strong host AC system to operate satisfactorily. Weakening of the AC systems due to large penetration of IBR could lead to adverse interaction between LCC-HVDC links and the host AC systems and among multiple LCC-HVDC links in close electric proximity (a multi-infeed situation). Dynamic analysis of combined AC-DC systems with an appropriate model of the HVDC over a wide timescale (e.g., from sub-cycle commutation failure to tap-changer control) is needed. A VSC-HVDC link is less susceptible to adverse AC-side interactions but has limited ability to block or limit DC-side fault current without a design penalty on converter efficiency. So, while VSC-HVDC facilitates DC grids in terms of power flow, it has challenges in protection. New fault location and circuit breaker ideas have emerged specifically for DC grids and innovation continues here and in converters with fault controlling capability. This leads to the following proposed topics.

5.1 Challenges with LCC HVDC
5.2 Recent developments in VSC HVDC
5.3 Offshore networks
5.4 DC grid protection
5.5 AC-HVDC interaction

6. Active Distribution Networks and Microgrids

Distribution networks are changing radically with the growth in distributed energy resources (DER) including renewable sources that are effective at small-scale (such as roof-top solar), distributed battery storage and demand-side actions. There is both an opportunity to have more decentralized control and a challenge to make efficient use of assets and defer or avoid reinforcement when new flows occur in the network. New decentralized approaches to data analysis, state estimation, control and optimization that have been developed to deal with the very large number of data points and actions should be considered. As distribution systems become more active and use services from DER the transition from network operator (DNO) to system operator (DSO) occurs and beyond that leads also to exchange of services across the DSO/TSO boundary. The emergence of distributed resources underpins the concept of microgrids that can manage supply-demand balance within their boundaries, exchange services with a DSO and on occasion island to provide local resilience.

Power electronic devices are still less common in distribution than transmission, but changes are underway that will call for greater use of low and medium voltage DC links, soft-open points and STATCOMs in distribution. There are developments in power electronics circuits to address this need to tackle the power density and power efficiency challenges that need to be overcome to gain network acceptance.

6.1 Power electronics in distribution
6.2 Low and medium voltage DC distribution system
6.3 Distribution network design
6.4 Distribution systems with high penetration of DER
6.5 Distribution systems and DERs scheduling based on three phase unbalanced AC optimal power flow
6.6 Distribution system topology processor and state estimation
6.7 Advanced DER aggregation and uncertainty assessment
6.8 DER aggregation and disaggregation
6.9 Distributed and decentralized control
6.10 Impact of high PV penetration on distributions systems
6.11 Impact of EV charging
6.12 Microgrids – isolated and grid-connected
6.13 Network service across transmission-distribution boundary (linked to “Operation”)

7. Power Systems with Integrated Infrastructure

Deep decarbonization of society will almost certainly need electrification of other sectors in particular, transport and heat. This will have a profound impact on the electricity system itself in terms of scale, a further indication of the central role that power system transformation will play in the future energy system. With large scale variable renewable energy there will be times of over production and times of under production. Over production can be converted to heat or a fuel and stored for later use – this added storage dimension to electrification highlights the importance of sector coupling.

All parts of society are being impacted by the digital revolution which will continue as an important trend in parallel with decarbonization. It is important that they are supportive of one another. Power systems have always embraced advanced information and communications technologies (ICT) and this trend will continue. The ICT infrastructure is now so ubiquitous in power systems that in many instances for modelling and control the details of the ICT system need to be fully considered e.g., delays, congestion, drop-out etc. in order to understand power system behavior. These cyber physical systems however have opened up a potential weakness to bad actors who seek to harm society by attacking the power system.

7.1 Sector coupling – multi-vector energy systems
7.2 Electrification of society
7.3 Integrated electricity and ICT systems
7.4 Cyber-physical threat modelling
7.5 Cyber-physical threat detection
7.6 Preventive and corrective actions for cyber-physical attacks
7.7 Countermeasures to cyber-physical attacks

8. Techniques Applied to Power Systems

There may be advantages for power systems with very high penetration of VREs and IBR to adopt analysis techniques that are not used currently. For instance, large volatility in operating conditions necessitating high speed sampling and very large numbers of distributed resources lead to large amounts of data and the curse of dimensionality. Some existing analytical methods may not be able to process these large volumes of data quickly enough to be usable e.g., dynamic security assessment or active network management. Alternative methods rely on artificial intelligence, machine learning and big data techniques which should be explored and compared. Stochastic techniques may need to displace deterministic techniques in several applications such as in improving situational awareness under uncertainties enabling a paradigm shift from preventive to corrective control.

The dominance of electromagnetic (rather than electromechanical) transients and larger excursions in grid frequency with high penetration of IBR may render the phasor-based approach inadequate for stability analysis. The transient voltage, current, and power signals may need to be characterized by a continuous spectrum that is no longer concentrated around the fundamental component. Hence, the phasor approach based on the Fourier Transform which is meant for signals with discrete spectrum and energy concentrated at the fundamental frequency would be erroneous. The theory of analytic signals with a more generic transformation like the Hilbert transform may become necessary.

This area is devoted to showing applications of such new analysis techniques which have not been used in power systems traditionally but will be needed to operate power systems with very large penetration of VRE and IBR. The topics to be covered under this subject area are:

8.1 Artificial intelligence, machine learning, big data
8.2 Stochastic analysis
8.3 Advanced frequency domain techniques (e.g., Hilbert Transform)
8.4 Heuristic approaches
8.5 Stochastic optimization
8.6 Cyber physical and grey-box modelling

9. Markets and Investment

Physical power systems all work within a set of institutional frameworks that are defined by policy, regulation and market structures. These institutional structures can and do differ dramatically across the world and combined with the natural resources of a region are the biggest reasons for divergence in power system characteristics and hence the importance of certain topics compared to others. However, regardless of these differences there are also many commonalities in particular market design provided some basic economic and engineering principles are adhered to. Over operational time scales market design should reflect the operations of the physical operation of the power system and as it is changing so must the market designs. Over planning time frames the same principle applies although the longer-term investment in power systems has been a topic that has largely failed to reach a consensus. Many of the topics below are well represented in many traditional programs but will all be impacted by increased penetration of VRE, DER and other new technologies.

9.1 Ancillary services market
9.2 Framework for transmission operation and investment
9.3 Stochastic market design
9.4 Locational marginal pricing
9.5 Nonconvex markets
9.6 Financial transmission rights (FTRs) and financial storage rights (FSRs)
9.7 Pricing in a stochastic environment
9.8 Emerging resources (renewables, storage, DER) and their participation in markets
9.9 Market power analysis and mitigation
9.10 Trading of energy and reserve
9.11 Peer to peer trading
9.12 Trading across the DSO/TSO interface

A set of 20 exemplar topic descriptors are included here to give a flavor of the context, aims, content, intended learning outcomes etc. The list of these topic descriptors is provided below:

No.	Topic with topic no	Subject area	Author
TD1	1.1 VRE and load forecasting	Planning	Henrik Madsen, Peder Bacher
TD2	1.3 Probabilistic planning	Planning	Mark O'Malley
TD3	1.4 Decision making under uncertainty	Planning	Kory W. Hedman
TD4	1.7 Emerging essential services in a VRE dominated power system	Planning	Mark O'Malley
TD5	1.17 Future network design standards	Planning	Goran Strbac
TD6	2.5 Security constrained economic dispatch and unit commitment	Operation	Kory W. Hedman
TD7	2.7 Harnessing electricity demand flexibility	Operation	Mojdeh Khorsand Hedman
TD8	2.18 Contingency analysis in power systems with high VRE	Operation	Jochen Cremer
TD9	3.1 Impact of IBR on rotor angle stability	Stability and Protection	Balarko Chaudhuri
TD10	3.2 Converter-driven resonance	Stability and Protection	Tim Green
TD11	3.3 Grid-forming inverters	Stability and Protection	Qin Lei
TD12	3.5 Transient stability models for wind turbines and solar PV	Stability and Protection	Vijay Vittal
TD13	5.1 Challenges with LCC HVDC	HVDC Transmission	Balarko Chaudhuri
TD14	6.1 Power electronics in distribution	Active Distribution Networks and Microgrids	Tim Green
TD15	6.4 Distribution systems with high penetration of DERs	Active Distribution Networks and Microgrids	Raja Ayyanar
TD16	8.1 Artificial intelligence, machine learning, big data	Techniques Applied to Power Systems	Jochen Cremer
TD17	9.4 Locational marginal pricing	Markets and Investment	Kory W. Hedman
TD18	9.5 Nonconvex markets	Markets and Investment	Kory W. Hedman
TD19	9.6 Financial transmission rights and financial storage rights	Markets and Investment	Kory W. Hedman
TD20	9.10 Trading of energy and reserve	Markets and Investment	Goran Strbac

TD1 Topic descriptor #1

Topic	VRE and load forecasting	Topic no. 1.1
Area	Planning	
Author	Henrik Madsen and Peder Bacher	
Context and aims {100-200 words}	The purpose of this course is to look at forecasting for the future weather driven energy system. Efficient system integration and resilience are recognized to be of utmost importance for a secure and efficient path towards the future low carbon energy system. In less than 10 years the cost of offshore wind energy has decreased by a factor of 3, and the US's commitment has increased from 2 GW in 2016 to 30 GW in 2020. According to e.g., Tufts University, a 300 GW offshore capacity in 2050 in the US is realistic, but it requires careful transmission expansion planning covering both onshore and offshore grids. The share of renewables in Europe is currently about twice as large as in the US, and in Europe the high voltage grids have been expanded. However, for a secure and efficient operation of the future grids and weather driven energy systems there is a need for state-of-the-art methods for forecasting of wind, solar and load. In the future demand flexibility and demand response implies that also load forecasting will be more challenging. This module will introduce the basic methodologies for wind, solar, and load forecasting. The focus will be on forecasting for all levels of the power grid. It will be shown how appropriate methods from statistics and machine learning can be used to provide forecasts based on a combination of information from meteorological weather forecasts and measure output generation at wind and solar farms.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is: • Introduction to VRE and load forecasting • Understanding flexibility and demand response • Load forecasting • Wind and solar power forecasting • Point forecasting • Combination of meteorological forecasts and local data • Time series models • Machine learning and forecasting • State space models for forecasting • Probabilistic forecasting • Multi-horizon forecasting • Methods for evaluating and comparing the performance of forecasts Exercises will be given in applying forecasting techniques for grid operators.	
Recommended prior learning	Familiarity with basic statistics and methods for data handling in e.g., MATLAB, Python or R (recommended). A library for renewable forecasting in R will be provided.	

Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, it is expected that students will be able to • Understand methods for VRE and load forecasting • Understand how to combine data from several sources in order to obtain state-of-the-art forecasts • Use of model building for creating simple models for forecasting • Use software tools for creating probabilistic forecasts • Understand which type of forecasts (point, probabilistic, multivariate, scenario) to use in a given situation
Target audience	Grid operators, balance responsible parties, energy and power producers, wind and solar farm operators
Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 8 hours Private study – 8 hours Class/group exercises – 8 hours Consultancy with forecasting experts – 4 hours
Assessment {Note style of assessment if known at this stage}	Based upon a delivered report related to a practical forecasting exercise: pass/no-pass. A diploma will be offered.

TD2 Topic descriptor #2

Topic	**Probabilistic planning**	**Topic no. 1.3**
Area	Planning	
Author	Mark O'Malley	
Context and aims {100-200 words}	Planning of power systems is driven at its core by some forecast of the future. This future is driven by an enormous number of factors including expected increase/decrease in electricity demand, locational shifting of demand because of uneven population growth, electrification of other energy sectors, economic and/or policy driven competitiveness of certain types of generation and all the other potential new technologies. These forecasts will have errors and some sort of expected distribution of errors. Good planning should if possible be robust with respect to these errors and therefore the objective of planning should be to plan a system that is reliable and cost effective with respect to the distribution of futures. This is nontrivial problem and to make it more complex it should also strive to be optimal across and at different time horizons. In a competitive market environment, the market should decide what type of and where generation and demand locate –and the planning would only be associated with the network. This would require a forecast of the market outcomes in terms of investment which will be driven by many factors including market design and the risk appetite for the investment community. One important factor the investment community will consider is network infrastructure highlighting the integrated nature of planning regardless of market and regulatory structures.	
Summary of content {200-500 words. Bullet points might be appropriate}	• The material to be discussed includes: • Multi time horizon probabilistic forecasting of demand growth/decline, diurnal shape, yearly shape. • Probabilistic forecasting of generation builds over multiple time horizons. • Robust planning methods for network design that can maintain societal reliability needs and minimize expected cost over multiple time horizons.	
Recommended prior learning	Familiarity with the following: • with operation and planning of a power system. • with optimization and basic economics.	
Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, students will be able to • Understand the difference between deterministic and probabilistic planning methods • Appreciate the potential benefits of probabilistic planning but also its challenges in particular the need for extensive high quality data sets. • Understand the formulation of the objective in a probabilistic planning problem. • Understand how to formulate and solve a basic probabilistic planning problem. • Understand the	
Target audience		

Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 4 hours Private study exercises – X hours Class/group exercises – X hours Laboratory – X hours
Assessment {Note style of assessment if known at this stage}	A set of homework

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TD3 Topic descriptor #3

Topic	Decision making under uncertainty	Topic no. 1.4
Area	Operation	
Author	Kory W. Hedman	
Context and aims {100-200 words}	This module will provide an overview on classical formulations for SCED, SCUC, and other mathematical programs that form the basis within production cost modelling tools, day-ahead market management systems, intra-day scheduling, and real-time operational scheduling. The module will then show how to extend these models to incorporate various stochastic optimization modelling approaches. In particular, the module will present a two-stage scenario-based stochastic program formulation for SCED and SCUC where renewables are captured via horse-tail scenarios. The module will then cover how varying approaches to handle decision making under uncertainty provide different solutions, what those solutions can guarantee, and what they cannot guarantee to form an understanding to enable participants with the ability to choose what approach is needed when. The module will briefly mention algorithms that can be explored to solve these stochastic optimization problems but will not cover the details of those approaches.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is: • Deterministic SCED and SCUC • Two-stage stochastic SCED, SCUC, and RUC • Two-stage scenario-based stochastic programs • Renewable scenario modelling • Generator contingency modelling with optimal recourse • Transmission contingency modelling with optimal recourse • Generator contingency modelling with optimal recourse • Renewable scenario modelling with optimal recourse	
Recommended prior learning	The module on SCED and SCUC should be taken first, or the person should have a background in SCED, SCUC, production cost modelling, power system scheduling, steady-state power system economic operations and reliability, or mathematical programming.	
Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, it is expected that the participant will be able to • Understand deterministic mathematical program • Understand a two-stage (deterministic-equivalent) stochastic program • Understand difference between first-stage decision variables and second-stage, recourse decision variables • Understand non-anticipativity constraints and their purpose • Explain methods to capture the uncertainty of emerging grid resources (e.g., renewable resources) • Explain what various deterministic mathematical programs capture and do not capture versus stochastic optimization programs	

Target audience	• Graduate student in Electrical Engineering with specialization in power systems • Engineers using production cost modelling software tools • Dispatch operators • Market analysts • Operations engineers • Transmission and generation planners
Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 6 hours Private study exercises – 10 hours Class/group exercises – x hours
Assessment {Note style of assessment if known at this stage}	

TD4 Topic descriptor #4

Topic	Emerging essential services in a VRE dominated power system	Topic no. 1.7
Area	Planning	
Author	Mark O'Malley	
Context and aims {100-200 words}	Increasing penetration of variable renewable energy resources leads to a set of increasingly difficult challenges: they are weather dependent, inherently more distributed, and are accompanied by more energy storage and much more actively varied demand. At the heart of these challenges are "essential services" that need to evolve with the changing characteristics of the power system and are fundamental to its socio-technical objective of "reliably maintaining supply-demand balance, at all points in time, at all locations, at least cost, equitably, and with minimum impact on the environment". These essential services determine: the operation and planning of the electricity grid across all time scales; the required characteristics of the technologies connected to the power system; and, through commercial mechanisms, the incentives to innovate and invest and to do so equitably. Current state-of-the-art (e.g., capacity adequacy, ancillary services etc.) falls far short of future essential service requirements, and we are in danger of developing electricity grids that are costly, unreliable, inequitable and not resilient and will therefore not deliver the step-change needed for the energy transition. These services need to both adapt to the changing needs of the grid, society, and the changing capabilities of new technologies that are connected to the grid (e.g., increased digitalization) to obtain an optimal technology mix on both the supply and demand side.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is at a high level as the module is designed as a fundamental basis for other more specific modules targeted at future and evolving power system operations and markets. The content will include. • Defining physical characteristics of existing essential services across the entire range of time scales from milliseconds to seasons. • Illustrating how the demand for these essential services will change as more variable renewables are integrated, and the need for new essential services emerge. • Illustrate the system specific nature of these essential services • Illustrate how these services can be provided by generators, including the variable renewable generators, demand side and/or network assets. • The potential interactions and overlaps between these services • How to be forward-looking with respect to an electricity grid that has increasing levels of variable renewables. • How these essential services should be non-discriminatory towards various potential technical routes and hence both stimulate and be open to radical innovation. • A number of examples of some evolving essential services that have emerged recently in some regions due to increased variable generation penetrations.	

	• Characterizing the essential services in a mathematical model of a power system
Recommended prior learning	Familiarity with the following: • operation and planning of a power system. • optimization and basic economics.
Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, students will be able to • Understand the changes in the operation and planning of a power system that are needed as the penetration of variable renewables increases. • Understand the importance of defining essential services in the context of reliably maintaining supply-demand balance, at all points in time, at all locations, at least cost, equitably, and with minimum impact on the environment. • Understanding the most appropriate mechanism to acquire these essential services. i.e., grid codes, market products, interconnection standards • Understanding the system specific nature of the required services and quantities • Understanding the evolution of these services over the coming decades • Understanding the supply of these services • Understanding the approximate nature of these essential services with respect to what is needed and what is supplied. • Understanding how the supply of these essential services can be enabled through technology in particular digitalization
Target audience	
Resources {Identified in earlier survey. Note also software or laboratory}	It is intended that other modules (e.g., Energy and Reserves in Markets) will dig deeper into the existing essential services and will use software to facilitate exercises.
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 6 hours Private study exercises – X hours Class/group exercises – X hours Laboratory – X hours
Assessment {Note style of assessment if known at this stage}	Each student will be given a unique real existing power system (e.g., country/region etc.) and will be asked to prepare a detailed report on how the essential services will evolve in a high variable renewable resources scenario.

TD5 Topic descriptor #5

<table>
<tr><td>Topic</td><td>Future network design standards</td><td>Topic no. 1.17</td></tr>
<tr><td>Area</td><td colspan="2">Planning</td></tr>
<tr><td>Author</td><td colspan="2">Goran Strbac</td></tr>
<tr><td>Context and aims
{100-200 words}</td><td colspan="2">Delivering carbon targets cost effectively will require fundamental review of the historical philosophy of electricity network operation and design. Existing transmission and distribution networks, designed in accordance with the historic deterministic standards, have broadly delivered secure and reliable supplies to customers. However, the key issue regarding the future evolution of the standards is associated with the question of cost effectiveness of the use of existing assets and the role that advanced, non-network technologies and intelligence-based control could play in the future development and delivery of security of supply to consumers.

There is a significant potential for incorporating non-network solutions (such as flexible generation and demand, new storage technologies, dynamic line rating, automatic network monitoring, control based on new information and communication technologies etc.) in the operation and design of future electricity networks. It is not however clear to what extent the application of such solutions changes the security of supply delivered to the end consumers. In order to address these questions, this module will focus on the fundamental cost-benefit analysis for assessing the reliability and cost performance of various network design and operation strategies, taking into account a range of techniques or technologies recently developed, while applying appropriate modelling and that will inform the development of least-cost network design standards.</td></tr>
<tr><td>Summary of content
{200-500 words. Bullet points might be appropriate}</td><td colspan="2">The material to be discussed is:
• Assessment of the efficiency of the present network design standards though balancing the cost of network infrastructure with the security benefits delivered (focusing on the value for money to customers).
• Impact of key solution drivers, including network reliability characteristics, investment cost, cost of supply interruptions, alternative mitigation measures etc.
• Value of automation
• Contribution of distributed energy resources to network security, through establishing the level playing field between network and non-network solutions
• Smart management of network overloads through disconnection of non-essential loads
• Impact of enhancing network assets utilisation
• Impact of construction outages and asset replacement
• Long-term optimal design of transmission and distribution networks
• Robust network planning under uncertainty</td></tr>
<tr><td>Recommended prior learning</td><td colspan="2">Familiarity with the following:
• Present / historical network design standards
• Probabilistic characterization of uncertainties
• Fundamentals of electricity network / power system reliability</td></tr>
</table>

Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, it is expected that the participant will understand • Deterministic and probabilistic network design / security standards • Methodology for quantifying service quality delivered to end customers • Probabilistic cost-benefit analysis framework as a benchmark for assessing different options for the development of future network design standards • Ability of non-network solutions to displace network reinforcement • Key drivers / factors for development of network design standards • Difference between demand and generation driven network design • Difference between security and resilience of supply
Target audience	
Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 4 hours Private study exercises – X hours Class/group exercises – X hours Laboratory – X hours
Assessment {Note style of assessment if known at this stage}	

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TD6 Topic descriptor #6

Topic	**Security constrained economic dispatch and unit commitment**	**Topic no. 2.5**
Area	Operation	
Author	Kory W. Hedman	
Context and aims {100-200 words}	This module will provide an overview of the basic formulations for security-constrained economic dispatch (SCED) and security-constrained unit commitment (SCUC) problem formulations in practice today. These formulations will relate to the common practice of accounting for power flow through linearized formulations, economic system operations, congestion (both pre-contingency and post-contingency, i.e., transmission contingencies), reserve requirements, as well as inter-temporal constraints. The formulations will most closely reflect that of an independent system operator such as the Midcontinent ISO and PJM, in the USA. The module will then cover variations in formulations for these mathematical programs. The module will then extend into covering recent advancements to capture generator contingencies as is being developed by the California ISO along with other emerging trends, e.g., flexible ramp products to compensate for variability of renewable resource integration. The module will also then cover the abilities for these existing formulations to capture the true challenges of grids with emerging resources and changes in resource mix and characteristics.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is: • Power system scheduling • Power system economics • Power system reliability • Renewable resource modelling • Linearized optimal power flow • Power transfer distribution factors • Multi-period SCED and SCUC formulations • Linear optimization • Mixed-integer linear programming • Modelling of transmission contingencies (security criterion for transmission contingencies) • Line outage distribution factors • Modelling of generator contingencies (security criteria and their variations) • Generator loss distribution factors • Flexible ramp products	
Recommended prior learning	Familiarity with • basic power system operations, scheduling, and linearized optimal power flow. • optimization solvers and programming. • mathematical programming.	

Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, it is expected that the participant will be able to • Understand the objective and constraints associated with power system scheduling • Explain the standard structure for SCED and SCUC models • Explain day-ahead SCUC • Explain day-ahead and intra-day RUC • Explain real-time SCED • Model transmission contingencies • Model generator contingencies based on emerging security criteria approaches
Target audience	• Graduate student in Electrical Engineering with specialization in power systems • Engineers using production cost modelling software tools • Dispatch operators • Market analysts • Operations engineers • Transmission and generation planners
Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 6 hours Private study exercises – 10 hours Class/group exercises – x hours
Assessment {Note style of assessment if known at this stage}	

TD7 Topic descriptor #7

<table>
<tr><td>Topic</td><td>Harnessing electricity demand flexibility</td><td>Topic no. 2.7</td></tr>
<tr><td>Area</td><td colspan="2">Operation</td></tr>
<tr><td>Author</td><td colspan="2">Mojdeh Khorsand Hedman</td></tr>
<tr><td>Context and aims
{100-200 words}</td><td colspan="2">This module will first review importance of flexibility for operation of modern power system. A brief review of change of generation resource mix form conventional firm generators to variable and uncertain resources will be provided. Existing practices of power system operation for obtaining flexibility form generation and demand sides will be discussed. The importance of using a diverse set of flexible resources, from both generation and demand sides, for operation of power systems with high penetration level of renewable resources will be discussed. Practical examples such as California outages will be reviewed. Advantages and disadvantages of existing demand response programs, e.g., time of use plans, thermostatic load control, will be discussed. Next, human-in-the-loop feature of distributed energy resources (DERs) will be reviewed. The potential of smart appliances and electric vehicles as well as other forms of DERs to provide grid services will be introduced. Application of advanced measurement devices and data analytics to effectively design incentive-compatible demand response programs considering human-in-the-loop feature of DERs will be reviewed. Moreover, this module will familiarize the participants with application of machine learning for comfort-aware building energy management.</td></tr>
<tr><td>Summary of content
{200-500 words. Bullet points might be appropriate}</td><td colspan="2">The material to be discussed is:
• Intermittent bulk and distributed energy resources
• Flexibility procurement in modern power systems
• Demand side resources
• Human-in-the-loop feature of distributed energy resources
• Sensor-enabled data-driven approaches for designing demand response programs
• Application of machine learning for comfort-aware home energy management
• Procuring flexibility and grid services from demand side resources</td></tr>
<tr><td>Recommended prior learning</td><td colspan="2">Familiarity with basic power systems and power system operation</td></tr>
<tr><td>Intended learning outcomes
{5-10 learning items expressed with a sentence or bullet point each}</td><td colspan="2">At the end of the module, it is expected that the participant will be able to
• Understand the increased need for flexibility in modern power system operation and importance of pooling all available resources
• Know the existing practical methods of demand response
• Understand the human-in-the-loop complexity of distributed energy resources
• Learn about advanced approaches to manage distributed resources and demand side flexibility
• Understand the impact of these services in power system operation</td></tr>
</table>

Target audience	• Master's student in Electrical Engineering with specialization in power system • Planning and operation engineers from the system operators
Resources {Identified in earlier survey. Note also software or laboratory}	• A. J. Wood and B. F. Wollenberg, Power Generation, Operation, and Control, 2nd Ed. John Wiley & Sons, New York, NY, 1996. • W. H. Kersting, "Distribution System Modeling and Analysis," CRC Press. • Technical papers
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 5 hours Private study exercises – 5 hours Class/group exercises – 2 hours
Assessment {Note style of assessment if known at this stage}	

TD8 Topic descriptor #8

<table>
<tr><td>Topic</td><td>Contingency analysis in power systems with high VRE</td><td>Topic no. 2.18</td></tr>
<tr><td>Area</td><td colspan="2">Operation</td></tr>
<tr><td>Author</td><td colspan="2">Jochen Cremer</td></tr>
<tr><td>Context and aims
{100-200 words}</td><td colspan="2">This module will explore probabilistic methods for contingency analysis. Power systems with N equipment were designed to ensure secure operation also when a contingency occurs on a single piece of equipment (with N-1 equipment). This system design was based on equipment redundancy. However, since its design, the power system changes towards a larger system with high VRE, more weather dependency, and more frequent contingencies. With such high VRE, power flows are more volatile requiring high peak capacities. Therefore, operating with N-1 and equipment-redundancy becomes highly inefficient. More efficient is to operate flexibly the system with preventive and corrective control. However, for such a flexible control the situational awareness must be improved. Probabilistic methods can improve situational awareness and support operating the system in such a flexible way. Advanced sensors deliver data for outage probabilities, and the impact of contingencies is studied offline. By using such data and studies, probabilistic workflows promise to train assessment models for real-time contingency analysis including dynamic security. These supervised training workflows involve methods from statistical learning, including stochastic modelling, Monte-Carlo sampling, feature selection, (non-)linear regression, or classification for quantifying risks. The subsequent ranking of contingencies is the basis for situational awareness to act in a preventive or corrective way.</td></tr>
<tr><td>Summary of content
{200-500 words. Bullet points might be appropriate}</td><td colspan="2">The material to be discussed is:
• Summary of typical approaches for contingency analysis, including deterministic, N-1, probabilistic approaches
• Power system resilience, reliability, adequacy, security, and stability
• Methods for probabilistic contingency analysis with high VRE
• Use of statistical methods to create scenarios (extreme, rare, or likely) for contingency analysis including Monte-Carlo sampling
• Data-driven workflows for real-time, probabilistic security assessment</td></tr>
<tr><td>Recommended prior learning</td><td colspan="2">Familiarity with the following:
• Basics of statistical methods
• Power system reliability, e.g., stability, steady-state, transients, voltage stability
• Fundamentals of power system operations
• Python basics (essential) and scikit-learn (recommended)</td></tr>
<tr><td>Intended learning outcomes
{5-10 learning items expressed with a sentence</td><td colspan="2">At the end of the module, students will be able to
• Understand and describe the three different approaches to contingency analysis
• Use past-historical data to create new operating conditions for contingency analysis
• Use software tools on the contingency studies to learn ML models
• Use ML model for the prediction of probabilistic contingency analysis</td></tr>
</table>

or bullet point each}	• Use sensitivity analysis of ML models to compute confidence of predictions
Target audience	
Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 4 hours Private study exercises – X hours Class/group exercises – X hours Laboratory – X hours
Assessment {Note style of assessment if known at this stage}	

TD9 Topic descriptor #9

Topic	**Impact of IBR on rotor angle stability**	**Topic no. 3.1**
Area	Stability and Protection	
Author	Balarko Chaudhuri	
Context and aims {100-200 words}	This module will discuss the impact of increasing penetration of IBR on classical rotor angle stability. Although the fundamental nature of rotor angle stability would remain the same, its extent (e.g., damping and frequency of the inter-area modes) will be impacted by the reduction in system inertia due to replacement of synchronous generators (SGs) by IBR, change in resulting power flow patterns, removal of power system stabilizers associated with the displaced SGs, increase/decrease in damping torque contribution from SGs in electric vicinity of IBR. High penetration of IBR could impact small-signal and transient rotor angle stability positively or negatively depending on a number of factors such as: 1) capacity and location of IBR in the system with respect to the remaining SGs, 2) outer loop control strategy and fault-ride through characteristics of IBR, 3) system strength and loading level 4) topology of the system. Case studies on IEEE standard test systems will be discussed under a range of scenarios to capture these effects, explain the underlying reason behind the observed trends and back those up with frequency domain analysis in the small-signal case.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed includes: • Review of dynamic model of inter-connected power systems with a mix of IBR and SGs • Impact of various contributing factors (mentioned under 'Context and Aim') related to IBR on transient and small-signal stability • Case studies designed to capture the interplay between IBR and SGs and demonstrate both positive and negative impact on rotor angle stability • Underlying mechanism and root-cause analysis MATLAB Simulink based exercise on an example test system for the participants to vary the contributing factors and explain the observed trends in terms of improvement or deterioration in transient and small-signal stability.	
Recommended prior learning	Familiarity with the following: • Classical rotor angle stability problem (both transient and small-signal) and dynamic modelling of interconnected power systems with SGs and IBR to carry out time-domain simulation and frequency-domain analysis • Power systems modelling and simulation in MATLAB Simulink (essential) and modal analysis (recommended) in MATLAB	
Intended learning outcomes {5-10 learning items expressed with a sentence	At the end of the module, students will be able to • Analyze the impact of high penetration of IBR on transient and small-signal rotor angle stability • Understand the underlying mechanism behind the positive or negative impact and explain the observed trends	

or bullet point each}	• Devise appropriate mitigation strategies (e.g., supplementary control on IBR), as necessary
Target audience	• Master's student in Electrical Engineering with specialization in power system and/or power electronics • Planning and operation engineers from the system operators in countries/regions where SGs and IBR will coexist in comparable proportions in the foreseeable future
Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 4 hours Private study exercises – X hours Class/group exercises – X hours Laboratory – X hours
Assessment {Note style of assessment if known at this stage}	MATLAB/Simulink based case study as marked coursework assignment

TD10 Topic descriptor #10

Topic	Converter-driven resonance	Topic no. 3.2
Area	Stability and Protection	
Author	Tim Green	
Context and aims {100-200 words}	This module will explore the analytical methods for analyzing interactions between inverter-based resources (IBR) within a power grid. The rising prevalence of IBR in grids has already caused interactions between IBRs and between IBR and other grid components observed as lightly damped or unstable oscillations in voltage, current or power flow. Such oscillations have been observed with synchronous machines but decades of experience, well-stablished models and a range of analytical techniques have meant that problems very rarely manifest in real grids. IBR raise fresh challenges over the different and overlapping time horizons of their dynamics, the absence of standardized models, the reliance on impedance-spectrum models by equipment vendors. Although many forms of stability may be of interest the focus here will be on small-signal stability in sub- and super-synchronous regions. The emerging techniques to meet these challenges will be explained and examples of their use given.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is: • Summary of typical control-loop hierarchies in grid-forming and grid-following inverters and discussion of expected bandwidth of each level of hierarchy. • State-space representation of IBR • Methods of model-order reduction • Comparison of state-space and transfer-function approached to stability analysis • Use of participation factor analysis for root-cause analysis • Approaches to root-cause analysis in impedance spectrum methods Exercises will be given in applying the techniques present to example power grids (microgrids and relatively simple grids) with mixtures of synchronous machines and IBR.	
Recommended prior learning	Familiarity with the following: • classic linear control theory is required such as Nyquist stability criteria for transfer functions, state-space modelling, calculation of eigenvalues, tuning of control-loops. • structure of three-phase inverters, use of PWM and closed-loop current control. • MATLAB (essential) and Simulink (recommended)	
Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, students will be able to • Understand and describe the hierarchical structure of control in an IBR. • Use impedance spectrum model to determine the stability of a source-load pairing • Use model-order reduction to create a simplified state-space model of an inverter • Use software tools to build state-space and impedance-spectrum models of grids • Use software tools to identify unstable modes in grids form of IBR	

	• Use root-cause analysis to identify opportunities for re-tuning to stabilize modes
Target audience	
Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 5 hours Private study exercises – X hours Class/group exercises – X hours Laboratory – X hours
Assessment {Note style of assessment if known at this stage}	

TD11 Topic descriptor #11

Topic	Grid-forming inverters	Topic no. 3.3
Area	Stability and Protection	
Author	Qin Lei	
Context and aims {100-200 words}	This module will cover the requirements for grid-forming inverters from IEEE 1547 standard, and the control strategies of the converters to achieve these goals. In the high penetration network, the grid voltage and frequency will not be supported by the large synchronous generator anymore. It is required for the inverter interfaced renewables not only to provide the active power but also the grid-support, to prevent the fluctuation of the voltage and frequency. IEEE 1547 defines the five grid-supporting operation modes in normal condition: P-V, Q-V, P-Q, P-f, Q-f. The upper controller will decide which mode the inverter should work at according to the current status. Therefore, the inverter operation commands of P and Q can be generated. The local controller in the inverter will control the inverter output to follow the commands. The inverter usually adopts the P-Q control as the outer loop, the DC voltage control and the output current control as the inner loop. The current inner loop in the D-Q frame and the D-Q PLL is the frequently adopted control strategy. In abnormal conditions such as under/over voltage/frequency, the inverter is required to ride-through. This can be implemented by over-design the inverter in terms of voltage rating and current rating.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is: • IEEE 1547 grid-support function definition for inverters • PV and EV inverter modelling and basic control • Inverter control strategy to achieve the grid-support functions. • Inverter controller design • PLECS simulation of the grid-connected inverter • Communication between the inverter and the upper controller	
Recommended prior learning	Familiarity with • basic operation of power electronic converters, basic control theory. • PLECS software (recommended)	
Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, it is expected that the participant will be able to • Explain the P-Q, P-V, Q-V, P-f, and Q-f curves. • Draw the basic control block diagram corresponding to the five normal operation modes. • Explain the control strategy during ride-through in abnormal conditions. • Simulate the five grid-support modes of grid-connected inverters	
Target audience	• Master's student in Electrical Engineering with specialization in power system and/or power electronics • Distribution system planning and operation engineers	

Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 3 hours Private study exercises – 10 hours Class/group exercises – 3 hours
Assessment {Note style of assessment if known at this stage}	

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TD12 Topic descriptor #12

Topic	**Transient stability models for wind turbines and solar PV resources**	**Topic no. 3.5**
Area	Stability and Protection	
Author	Vijay Vittal	
Context and aims {100-200 words}	This module will review the operation and control of wind turbine generators and PV Solar resources. A brief introduction to wind turbine technology with an emphasis on modern Type3 and Type4 wind turbines will be followed with the development of a model to represent these wind turbines in positive sequence transient stability simulation studies. This will also include the representation of wind turbine generators in power flow studies which is a requirement to initiate the transient stability study. Steps in conducting simulations and examining results will also be described. The WECC models for Type3 and Type4 wind turbine generators available in the four most widely used commercial transient stability analysis packages in North America, GE-PSLF, Siemens-PTI – PSS/E, Powertech Labs DSA Tools, and PowerWorld will be used to demonstrate the simulation procedure on a standard test system. The module will also include the representation and modelling of bulk power system PV Solar resources. This will be based on the WECC models for solar PV power plants. The solar PV power plant models together with the associated controls will be described and detailed. These models are all available in the four software packages identified above. Software exercises using these models on a standard test system will be conducted to detail and describe the impact of various control features available in the models.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is: • Steady-state and dynamic models of Type 3 and Type 4 wind turbine generators • Control strategy for Type 3 and Type 4 wind turbine generators • Steady-state and dynamic models of bulk PV resources • Control strategy for bulk PV resources • Commercial software-based simulation exercises using the developed models	
Recommended prior learning	Familiarity with • operation of power electronic switches (diodes and thyristors), basic control theory and operation of AC transmission system. • commercial transient stability analysis and power flow analysis packages	
Intended learning outcomes {5-10 learning items expressed with a sentence	At the end of the module, it is expected that the participant will be able to • Understand the operation and control of wind turbine generators • Understand the operation and control of bulk PV Solar resources • Ability to represent these resources in large power system models and examine the impact of these resources on transient system behavior	

or bullet point each}	
Target audience	• Master's student in Electrical Engineering with specialization in power system and/or power electronics • Planning and operation engineers from the system operators
Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 6 hours Private study exercises – X hours Class/group exercises – X hours Laboratory – X hours
Assessment {Note style of assessment if known at this stage}	

TD13 Topic descriptor #13

Topic	Challenges with LCC HVDC	Topic no. 5.1
Area	HVDC Transmission	
Author	Balarko Chaudhuri	
Context and aims {100-200 words}	This module will review the operation and control of a line commutated converter (LCC) based HVDC link (LCC-HVDC), its interaction with the host AC system(s) and (electrically) nearby IBRs (e.g., other HVDC links). While voltage source converter (VSC) based HVDC has emerged as the preferred option primarily for cables with rated power capacity below 2 GW, LCC-HVDC continue to dominate the HVDC overhead line (and cable) landscape beyond 2 GW. The total installed capacity of LCC-HVDC links has proliferated over the last decade in Asia (China, India etc.) and Latin America, in particular, and the trend is set to continue. An LCC-HVDC link requires a strong host AC system to operate satisfactorily. Weakening of the AC systems due to replacement of synchronous generators by IBRs poses operational challenges for an LCC-HVDC link. Such adverse interaction between LCC-HVDC and host AC system will be explained and demonstrated through case studies. Potential runaway situations with weak AC systems will be discussed together with mitigation measures to avoid shut down (or de-loading) of an LCC-HVDC link. Role of LCC-HVDC in providing AC system support (e.g., transient stability enhancement) will be covered.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is: • Steady-state and dynamic model of an LCC-HVDC link • Control strategy at different layers (pole, converter, master etc.) • Characterization of AC system strength: SCR, ESCR and other variants • Interaction between LCC-HVDC and host AC system • Interaction with (electrically) nearby HVDC links: multi-infeed or dual-infeed situation • AC system support through LCC-HVDC MATLAB Simulink based exercises will be given to analyze interaction between LCC-HVDC and host AC system having different strengths.	
Recommended prior learning	Familiarity with the following: • operation of power electronic switches (diodes and thyristors), basic control theory and operation of AC transmission system. • MATLAB Simulink (recommended)	
Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, students will be able to • Understand the operation and control of an LCC-HVDC link • Use the steady-state and dynamic model of an LCC-HVDC to analyze its interaction with host AC systems and nearby (in electric proximity) IBRs (e.g., other HVDC links) • Appreciate the role of LCC-HVDC in providing AC system support (e.g., transient stability enhancement)	

Target audience	• Master's student in Electrical Engineering with specialization in power system and/or power electronics • Planning and operation engineers from the system operators
Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 5 hours Private study exercises – X hours Class/group exercises – X hours Laboratory – X hours
Assessment {Note style of assessment if known at this stage}	MATLAB/Simulink based case study as marked coursework assignment

TD14 Topic descriptor #14

Topic	Power Electronics in Distribution	Topic no. 6.1
Area	Active Distribution Networks and Microgrids	
Author	Tim Green	
Context and aims {100-200 words}	Power electronics is widely used in energy resources as interfaces for solar and wind generation and batteries. It is firmly established for certain functions in transmission such as long-distance DC links and as reactive power compensation devices. In distribution it is less common but yet use cases have been identified such as medium voltage DC links, soft-open points and electronic substation transformers. The difficulty is cost side of the cost-benefit analysis since several elements of the cost compare badly with standard equipment such as a tap-change transformer. This topic will explore what power electronics can offer to a distribution network operator, what power converter configurations are of interest, what specifications they need, what control should be used and what avenues exist for reducing all elements of cost. The topic will focus on power electronics for use in the 10 – 50 kV, 1 – 50 MVA range, described here as medium voltage power electronics.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed includes: • Use cases for STATCOM, Soft-open points, MVDC links and electronic transformers • Elements of cost in power electronics: capital, power losses, substation footprint, maintenance intervals, reliability • Relation between use case and ratings and power losses • Circuits topologies for trading-off loss, footprint, fault handing. This would include a review of modular multi-level converters from HVDC and the differences needed when applied at lower voltage and module numbers, hybrid structures that reduce power losses such as large & small modules, Si+SiC modules, treatment of redundancy in medium voltage cases. • Local and coordinated control of power electronics within active network management. This would include brief reviews of power converters and DC links in power flow and OPF, decentralized and agent-based control.	
Recommended prior learning	Familiarity with the following: • Power flow calculations on radial feeders • Basic (6-switch) inverters • Modular multi-level inverters • Control hierarchy for inverters (PWM, inner current control, outer voltage control)	
Intended learning outcomes {5-10 learning items expressed with a sentence	At the end of the module, students will be able to • Describe the benefits to a network operator of various power electronic controllers • Describe the operating principles of a variety of power converter topologies optimized for use at medium voltage. • Understand the tensions, trade-offs and material limits to key performance and cost features of various power converter types.	

or bullet point each}	• Perform calculation of key performance metrics of medium voltage converters such as power losses and component sizes. • Describe strategies for integrating power electronic controllers into network management
Target audience	This topic stretches across power electronics and active network management. It is intended to help those interested in network management appreciate what power electronics can and cannot offer.
Resources {Identified in earlier survey. Note also software or laboratory}	Some material on this taught at Imperial and elsewhere. Not yet in an on-line format. Two types of simulation would be valuable as coursework. One would address performance of medium voltage converters and would comprise Simscape simulation of a modular converter and its local control loops. Outcomes would be assessment of power losses, power quality and physical volume of principle components. The second simulation would explore impact on network in terms of voltage or power flow objectives and relation of these to both converter rating and integration into network management.
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 8 hours Private study exercises – 2 hours Class/group exercises – 0 hours Laboratory – 20 hours (taken to be use of simulation tools)
Assessment {Note style of assessment if known at this stage}	Assessed coursework. Coursework will include some summative items to build understanding followed by a final report or presentation on the coursework exercise as a whole.

TD15 Topic descriptor #15

Topic	**Distribution systems with high penetration of DERs**	**Topic no. 6.4**
Area	Active Distribution Networks and Microgrids	
Author	Raja Ayyanar	
Context and aims {100-200 words}	This module will cover the detailed modelling of distribution feeders and inverter interfaced PV generators and other distributed energy resources (DERs), the impact of high penetration of DERs on the design and operation of distribution systems, and control methods for integrated feeder voltage management and system protection. Dramatic growth in DERs, especially in roof-top and commercial PV systems has led PV penetration levels exceeding 100% and leading to significant reverse power flow into the substation in many feeders. This poses multiple challenges for the operation of distribution system, chief among them being overvoltage violations, miscoordination and reduced reach of protection devices, and potential unstable control interactions. Simultaneously, they also offer opportunities to mitigate many of the challenges and further improve performance of distribution through coordinated and high bandwidth control of four-quadrant inverters that interface PV, EV and storage to the grid. Recent standards such IEEE 1547-2018 have focused on addressing the impact of high penetration through several required control features in advanced inverters. A large number of utilities are also investing in obtaining DER situational awareness through large-scale edge devices and communication to Advanced Distribution Management System (ADMS) which can potentially enable real-time control of DER inverters and exploit their advanced capabilities. This module will describe integrated feeder voltage management techniques using volt-VAR and other DER control, design of protection system under high penetration scenarios and verification of the effectiveness of the control and optimization methods in distribution analysis tools such as OpenDSS.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is: • Feeder modelling in OpenDSS • PV and EV inverter modelling – DLL and dynamic models • High penetration impacts and hosting capacity analysis • Integrated voltage management – volt-VAR, volt-Watt and other mitigation measures • Protection design – reverse power flow, sympathetic tripping, reduced reach • 1547-2018 standard • DER situational awareness, edge devices, communication protocols OpenDSS for distribution system static and time-series analysis, and PLECS for power converter simulation studies will be used in lectures and student exercises/project.	
Recommended prior learning	Familiarity with • basic operation of power electronic converters, basic control theory and operation of distribution system.	

	• OpenDSS and PLECS or similar software (recommended)
Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, it is expected that the participant will be able to • Explain the specific challenges of distribution system operation under high DER penetration • Be able to create feeder models and run static and time-series power flow analysis • Be able to use PLECS for detailed modelling of advanced inverters and their control • Design basic volt-VAR control for feeder voltage management • Understand the impact of high penetration of DER on the protection device settings and reach
Target audience	• Master's student in Electrical Engineering with specialization in power system and/or power electronics • Distribution system planning and operation engineers
Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 6 hours Private study exercises – 10 hours Class/group exercises – 3 hours
Assessment {Note style of assessment if known at this stage}	

TD16 Topic descriptor #16

Topic	**Artificial intelligence, machine learning, big data**	**Topic no. 8.1**
Area	Techniques Applied to Power Systems	
Author	Jochen Cremer	
Context and aims	This module will explore data-driven methods for analyzing real-time operating data. The operation of modern power grids is surrounded by	

{100-200 words}	uncertainty from Distributed Energy Resources (DERs) and different types of loads connected to the grid. At the same time, more data is collected, for instance, from Phasor Measurement Units (PMUs), DERs power output, and load levels. Although the observed data has errors, is noisy, and has gaps, it can be used to learn models to forecast real-time operations. Aside from errors and noise, critically is the high dimensionality of the data levering the task for learning a model challenging. Spurious correlations may occur, and the curse of dimensionality renders the right design of ML workflows important. Such workflows require pre-processing of data, such as normalization, scaling, principal components analysis, selecting important features for model training. The subsequent ML trained model must be cross validated on several sets of data to avoid under-and overfitting. These ML workflows can be used for multiple purposes, such as creating critical scenarios for reliability studies with Monte-Carlo (MC) sampling, tracking the equipment 'health' and failures, the assessment of system security, prediction of future time-series data, clustering end-consumer loads on their energy demand behavior. This module will review established data-analytics and ML concepts along with their use for analyzing real-time energy data.

Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is:
	• Summary of supervised learning concepts including statistics basics, assessing data-driven models, bias-variance trade-off
	• Review state-of-the-art methods for learning models from data
	    ○ (non-)linear regression with example of wind power forecast
	    ○ classification with example of security assessment
	    ○ clustering approach for real-time monitoring
	• Probabilistic modelling and MC techniques to create artificial operating scenarios
	• Designing ML workflow including feature selection, feature engineering, cross-validation, model selection and regularization
	• An overview of other ML models and their energy applications

Recommended prior learning	Familiarity with the following: • Classic statistics such as mean, variance, Gaussian models • Probability theory such as random variables, probability density functions, law of large numbers, … • Python basics (essential) and scikit-learn (recommended)
Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, students will be able to • Understand the concept of supervised learning for energy data • Use data to learn models for linear regression, classification, and clustering • Use probabilistic modelling and MC sampling to create data • Use ML to conceptually design a workflow "from data to model" • Use software to implement a designed ML workflow, validate, test such a workflow, and perform troubleshooting
Target audience	
Resources {Identified in earlier survey.	

Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 5 hours Private study exercises – X hours Class/group exercises – X hours Laboratory – X hours
Assessment {Note style of assessment if known at this stage}	

TD17 Topic descriptor #17

Topic	**Locational marginal pricing**	**Topic no. 9.4**
Area	Markets and Investment	
Author	Kory W. Hedman	
Context and aims {100-200 words}	This module will start with the very basic formulation of the DC optimal power flow formulation, which forms the basis of many market management systems. Based on the simplified DCOPF formulation, the module will then demonstrate the calculation of the traditional locational marginal price based on the formulation of the susceptance-angle difference formulation versus a formulation based on power transfer distribution factors. Next, the module will cover the characteristics of LMPs by demonstrating how LMPs can be negative even if no agent is bidding negative and, similarly, how an LMP can exceed the bid cap. The module will then cover the existing practice by independent system operators to limit LMPs from exceeding bid caps. The next main exercise will then be to demonstrate that this linear program has a well-defined dual formulation in which it contains many other known price terms such as a susceptance marginal price and a flowgate marginal price. Furthermore, the module will cover the topics of congestion rent, generator rent, generator revenue, and load payment. Finally, the module will cover a multi-period DCOPF formulation to examine the influence on LMPs when there are inter-temporal constraints (e.g., ramping constraints).	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is: • Basics of DCOPF • Basics of locational marginal pricing • Demonstration of the components of LMPs • LMP properties • Congestion rent, generator rent, generator revenue, load payment • Social welfare, market surplus	
Recommended prior learning	Familiarity with • power flow and optimal power flow • linear optimization	
Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, it is expected that the participant will be able to • Understand the basics of the linearized optimal power flow, the DCOPF • Understand the basics and characteristics of LMPs • Understand the dual of a DCOPF and its properties • Understand inter-temporal constraints and their influence on LMPs • Understand market settlements for market participants	
Target audience	• Graduate student in Electrical Engineering with specialization in power systems • Engineers using production cost modelling software tools	

	• Dispatch operators • Market analysts • Operations engineers working in market environments • Transmission and generation planners working in market environments
Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 4 hours Private study exercises – 4 hours Class/group exercises – x hours
Assessment {Note style of assessment if known at this stage}	

TD18 Topic descriptor #18

Topic	Nonconvex markets	Topic no. 9.5
Area	Markets and Investment	
Author	Kory W. Hedman	
Context and aims {100-200 words}	This module will build on top of the introductory module focused on the basics of locational marginal pricing. This module will introduce the concept of convex markets and non-convex markets. Participants will learn how LMPs can achieve a market equilibrium for a convex market structure but that LMPs cannot provide this guarantee for a non-convex market structure. The concepts of lost opportunity cost and uplift payments will be covered, as a means to achieve a non-confiscatory market. The module will cover practices in place today to deal with non-convex markets. The topic of extended LMP / convex hull pricing will be introduced along with its properties.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is: • Convex market structures and their properties • Non-convex markets and their challenges • LMP characteristics • Ability for LMPs to settle a market • Non-confiscatory markets • Lost opportunity costs • Uplift payments • Extended LMPs / Convex-hull pricing	
Recommended prior learning	Familiarity with • power flow and optimal power flow • linear optimization Participants should have taken the module on markets and LMP basics	
Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, it is expected that the participant will be able to • Understand what market auction models include today that can cause a non-convex electric energy market • Understand lost opportunity costs • Understand make-whole payments / uplift payments • Understand when market imperfections cause the need for uplift payments • Understand the basics of the extended LMP / convex-hull pricing	
Target audience	• Graduate student in Electrical Engineering with specialization in power systems • Engineers using production cost modelling software tools • Dispatch operators • Market analysts • Operations engineers working in market environments • Transmission and generation planners working in market environments	

Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 3 hours Private study exercises – 3 hours Class/group exercises – x hours
Assessment {Note style of assessment if known at this stage}	

TD19 Topic descriptor #19

Topic	**Financial transmission rights and financial storage rights**	**Topic no. 9.6**
Area	Markets and Investment	
Author	Kory W. Hedman	
Context and aims {100-200 words}	This module will build on top of the introductory module focused on the basics of locational marginal pricing. This module will introduce the concept of financial transmission rights. Participants will learn the background regarding FTRs, why they were proposed, and their use today. The module will cover auction revenue rights, congestion revenue rights, financial transmission rights versus physical transmission rights, and the simultaneous feasibility test (SFT) for FTR auctions. The module will cover the auction structure and settlement scheme for FTRs. The module will cover revenue adequacy for FTRs. Then the module will switch from FTRs to financial storage rights. While FTRs are hedging products today, FSRs as a hedging mechanism tied to storage is still a proposed concept that has yet to be adopted. The module will cover the basics on how storage can participate in markets today along with a basic overview as to the concept of FSRs as proposed by various researchers today.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is: • Auction revenue rights • Congestion revenue rights • Financial transmission rights • Physical transmission rights • Flowgate rights • Revenue adequacy • Simultaneous feasibility test • Storage in existing market structures • Financial storage rights	
Recommended prior learning	Familiarity with • power flow and optimal power flow • linear optimization Participants should have taken the module on markets and LMP basics	
Intended learning outcomes {5-10 learning items expressed with a sentence or bullet point each}	At the end of the module, it is expected that the participant will be able to • Understand the role of financial transmission rights as a hedging mechanism in wholesale energy markets • Understand the role of storage today in existing energy markets (price arbitrage) • Understand the concept of financial storage rights	
Target audience	• Graduate student in Electrical Engineering with specialization in power systems • Engineers using production cost modelling software tools	

	• Dispatch operators • Market analysts • Operations engineers working in market environments • Transmission and generation planners working in market environments • Transmission owners in market environments • Storage owners in market environments
Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 4 hours Private study exercises – 4 hours Class/group exercises – x hours
Assessment {Note style of assessment if known at this stage}	

TD20 Topic descriptor #20

Topic	Trading of energy and reserve	Topic no. 9.10
Area	Markets and Investment	
Author	Goran Strbac	
Context and aims {100-200 words}	Energy and each type of reserve were traded in separate markets, which were cleared successively in a sequence determined by the speed of response of the resource. There is now a wide consensus that energy and reserve should be offered in joint markets and that these markets should be cleared simultaneously to minimize the overall cost of providing electrical energy and reserve. This co-optimization is necessary because of the strong interaction between the supply of energy and the provision of reserve. Furthermore, system operators must not only ensure that they have available a sufficient amount of reserve but also that this reserve capacity can be delivered across the network when the need arises. This issue is likely to become more important as the reserve requirements increase to cope with the larger uncertainty caused by renewable sources. The available transmission capacity therefore must be optimally allocated between actual energy transfers and capacity set aside for the delivery of reserve. This module will focus on using simple examples to discuss the market design that will optimize energy and reserve provision taking into account location, which is becoming very important with increased penetration of renewable generation.	
Summary of content {200-500 words. Bullet points might be appropriate}	The material to be discussed is: • Assessment of the impact on of reserve requirements of energy production costs • Optimization framework for co-optimization of provision of energy and reserve services • Evaluation of energy market prices with and without including provision of reserve • Evaluation of location specific energy market and reserve prices • Derivation of linear programming-based approach to solve this problem • Co-optimization of energy and reserve while ensuring that no generator is disadvantaged when being asked to provide reserve rather than produce electrical energy. • Evaluation of the income from the provision of energy and reserve services Exercise considering a small electricity market will be given in applying the optimization technique will be presented.	
Recommended prior learning	Familiarity with the following: • operation of basic electricity market • basic linear optimization	
Intended learning outcomes {5-10 learning items expressed	At the end of the module, students will be able to • Understand and operation of the electricity market with energy and reserve • Interactions between energy prices and reserve process • Impact of the coordinated energy and reserve markets on income to the providers	

with a sentence or bullet point each}	• Understand the impact of location specific energy market and reserve prices • Impact of penetration of large-scale renewable generation on the market operation
Target audience	
Resources {Identified in earlier survey. Note also software or laboratory}	
Duration {Provide tentative figures if not clear at this stage}	Video lecture material – 2 hours Private study exercises – X hours Class/group exercises – X hours Laboratory – X hours
Assessment {Note style of assessment if known at this stage}	