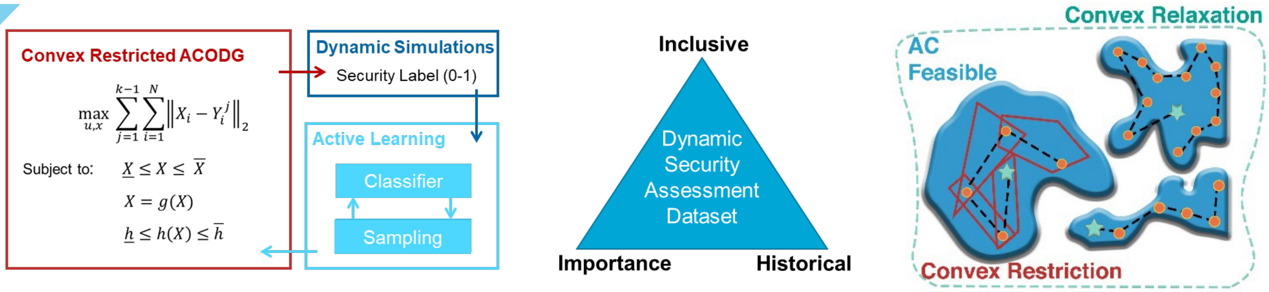
AC Optimal Data Generation (ACODG) for Power System Security



Scope: This thesis project will focus on developing a novel data generation method for machine learning (ML) models for the dynamic security assessment problem (DSA). Convex restriction of the AC optimum power flow (AC OPF) optimization enables the generation of feasible possible operating conditions based on historical observations. Active learning framework further improves the quality of the dataset.

Problem definition: ML based dynamic security assessment (DSA) requires a rich dataset for successive prediction. Generation of synthetic training data from simulations is challenging due to the complexity of power system operation and vast possible operating conditions. Training data must cover past observations, possible future operations, and samples around the security boundary. Sampling strategies from historical data cannot anticipate unseen possible conditions. Greedy search algorithms suffer from the nonconvex feasibility space of the power flow. ML labels require costly dynamic simulations for predefined contingency cases. Label generation costs can be reduced extensively with an efficient, effective, and automatic data generator.

Methodology: You will develop a sequential optimization problem called AC optimal data generation (ACODG) that explores nonconvex AC optimal feasible space with convex constrained envelopes around the historical feasible operating points. The objective function maximizes the dissimilarity between discovered points and control variables. You will conduct dynamic simulations with generated feasible conditions to calculate security labels against the disturbance. The database is used to train support vector classifier (SVC) and artificial neural network (ANN) models to measure the performance. Furthermore, ML can identify misclassified samples. These samples can be used as new initial samples for the ACODG. The overall process constructs an enriched database and associated DSA classifier.

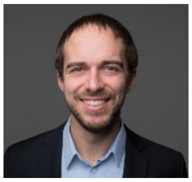
Research objectives:

- Literature review on AC OPF, quadratic optimization, supervised learning algorithms, sampling methods, and power system dynamic security assessment.
- Development of the modified convex restricted AC OPF to obtain a rich operating condition dataset.
- Conducting dynamic root mean square (RMS) simulations on the test network to generate security labels.
- Development of the ML pipeline: Preprocessing, feature selection, model construction, training, and tuning.

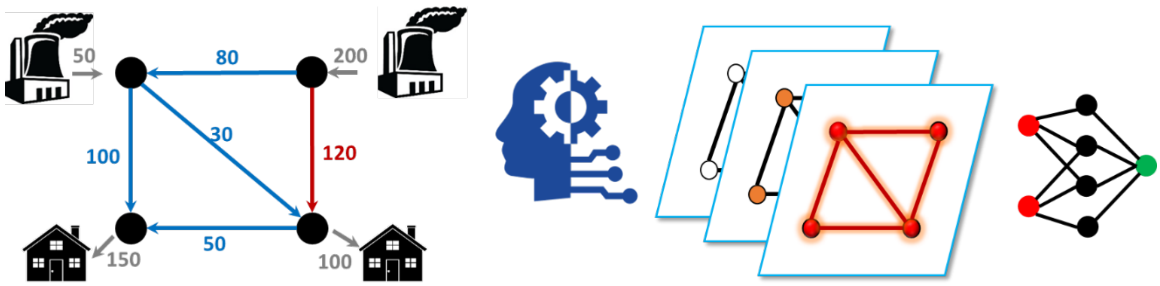
Industry relevance/partner: Security of the operation is an essential and challenging task for transmission system operators like RTE (France), National Grid (UK), or Tennet (NL, DE) in Europe. This thesis combines optimization, power system analysis, ML, and dynamics which are highly valuable in both academia and system operation.

Contact details:

- PhD supervisor: Mert Karacelebi (m.karacelebi@tudelft.nl)
- Supervisor: Dr. Jochen Cremer (J.L.Cremer@tudelft.nl)



Graph Neural Networks for Security Constrained Optimal Power Flow



Scope: This thesis project will focus on developing a machine learning method based on graph neural networks to accelerate the solving process of security constrained optimal power flow (SC-OPF) optimization.

Problem definition: The security-constrained optimal power flow (SC-OPF) optimization problem is an essential and widely sued tool for system operators to achieve system security with respect to a set of possible (mainly N-1) contingencies. In general, the SC-OPF determines the optimal settings of control means (e.g., generators' active power) to ensure static security (i.e., line congestion and voltage magnitude) under normal and contingency states. With growing integration of uncertain renewable sources into power grids, system operators are interested to solve the SC-OPF problem faster and more frequently, which is problematic for large scale systems.

Methodology: Taking into account that the SC-OPF problem with a similar formulation and structure but slightly different input data for different instances is frequently solved, machine learning (ML) methods appear as a natural and promising answer to take advantage of the structure of such recurring problems and accelerate the solving process. Recent research works have showed promising results in using standard neural networks for SC-OPF problem; however they are not scalable to large power systems. Recently, graph neural networks (GNN) were found useful for problems that can be represented on graphs, which is the case for power networks. In this project, you will develop a GNN-based method that exploits the graph structure of the power systems and accelerate the solving process of the SC-OPF problem.

Research objectives

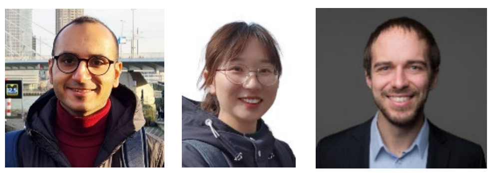
- Literature review on SC-OPF optimization formulation, graph neural networks, and ML methods for optimization problems.
- Investigate SC-OPF optimization problem characteristics in Python on a test system.
- Develop a ML-based method to accelerate the solving process of SC-OPF optimization problem.
- Develop a scalable graph neural network training approach for SC-OPF optimization problem.
- Test the developed approach with state-of-the-art optimization methods and ML-based approaches.

Industry relevance/partner:

The SC-OPF optimization problem is one the most widely used tools by system operators like TenneT .You will learn technical skills on operation of transmission systems, optimization problems, and state-of-the-art deep learning methods.

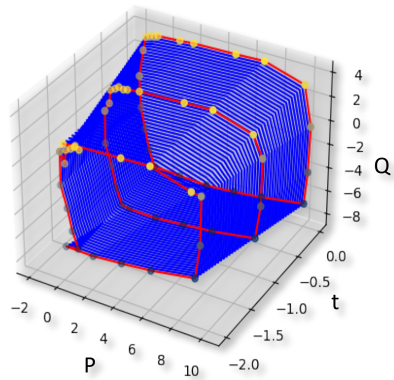
Contact detail:

- PhD supervisor: Ali Rajaei (a.rajaei@tudelft.nl)
- PhD supervisor: Haiwei Xie (H.Xie-2@tudelft.nl)
- Supervisor: Dr. Jochen Cremer (j.l.cremer@tudelft.nl)



Estimating the Flexibility Evolution in Active Distribution Grids

Scope: This thesis project develops an AI-based algorithm to estimate the time evolution of flexibility in distribution networks.



Problem definition: The massive increase of distributed renewable energy leads to higher variability and unpredictability. As a result, transmission system operator and distribution system operator need to cooperate. This cooperation requires accurate estimation of the flexibility of the distribution network given an operating state. The flexibility can be illustrated as a 'region' around the operating state. The system state could be quickly shifted if needed within this 'region'. In estimating such a region, some issues are:

1. the time dependency of a flexibility area is neglected,
2. the time characteristics of flexibility sources such as ramping rates are neglected,
3. the computational complexity for an accurate flexibility estimation can be high given the system constraints.

In light of the recent improvements of AI-based algorithms, they may be used to predict this flexibility. Your own developed algorithm will have to address the first two abovementioned issues, i.e. anticipating the changing flexibility 'region' over time and the evolution of the available primary control dynamic performance.

Methodology: Recent advancements in pattern recognitions illustrate the capabilities that recurrent convolutional neural networks and other machine learning based algorithms have to infer the underlying evolution dynamics captured in images. You will initially critically study the flexibility estimation issue and their time evolution and define performance requirements for a desired pattern estimation method . Then, you will study recent ML-based methods for modelling evolving patterns. Later, you will develop and apply a modified version from one or more of these methods to the flexibility estimation problem. Finally, you will report (i.e. scientific publication(s) and thesis report) the findings on flexibility evolution dynamics and the capabilities and boundaries of the developed algorithm.

Research objectives:

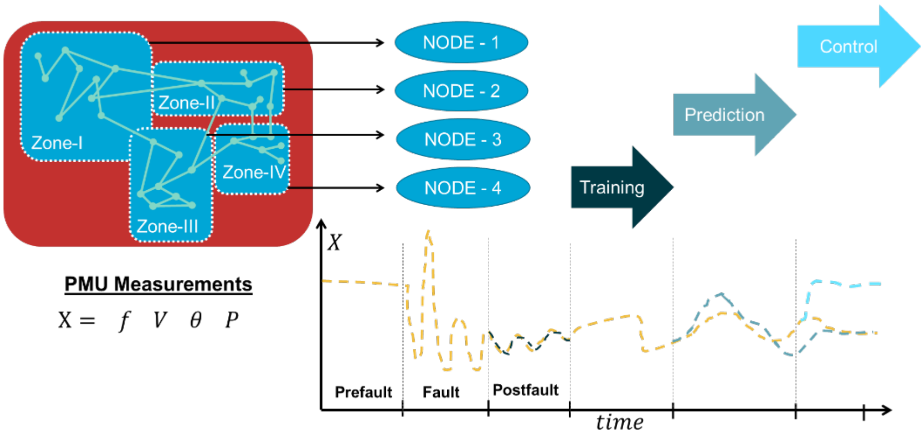
- Software based modelling of distribution network flexibility estimation,
- Develop and apply ML-based algorithms inspired from patterns or image analysis,
- Test (against the best method from literature) and improve the algorithm for predicting the time evolution of flexibility,
- Write and publish scientific manuscript(s) with the developed algorithms and the findings of its application, e.g. peer-reviewed conference/journal paper in the fields of energy systems and AI applications

Industry relevance/partner: This research is part of the MEGAMIND project (https://megamind.energy/) .

Contact details

- Demetris Chrysostomou (D.Chrysostomou@tudelft.nl),
- Dr. Jochen Cremer (J.L.Cremer@tudelft.nl),
- Dr. Jose Rueda Torres (J.L.RuedaTorres@tudelft.nl)

Neural Ordinary Differential Equations for Power System Dynamics



Scope: This thesis project will focus on using machine learning (ML) to predict power system dynamic trajectories after system disturbances. You will use the ML method of Neural Ordinary Differential Equations (NODE) to train efficiently known power system dynamics.

Problem definition: The structure and operation of the power systems are evolving while our society must move toward a sustainable and carbon free future. Power grids become more vulnerable to large disturbances that can cause power outages. Dynamic simulations reveal the system performance for a specific disturbance scenario but simulation of real operation is highly challenging due to the unpredictable nature of the blackouts and the large number of scenarios to consider. Alternatively, ML models can be trained in near real time by using high-resolution post fault measurements. NODE models are promising to mimic dynamical systems efficiently and accurately.

Methodology: You will develop a NODE algorithm for the prediction of power system dynamics. You will review the literature about dynamical systems, numerical integration, neural networks, and time-series models, and NODEs. Then, you will conduct dynamic simulations of a test system in a simulation environment (e.g., DIgSILENT PowerFactory). You will generate data by simulating a disturbance, analyze the data. Subsequently, you will investigate efficient training methods using your own neural network architecture that utilizes NODEs. Finally, you will analyses the NODE performance in terms of accurately approximating dynamics and training time requirements.

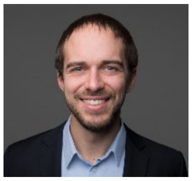
Research objectives:

- Literature review on dynamical systems, numerical integration, neural networks, time-series models, NODEs
- Conducting dynamical simulations of a power system to investigate blackout events.
- NODE modeling, training, and prediction of simulated power system events.
- Performance testing of NODEs with unseen dynamics using real time training approaches.

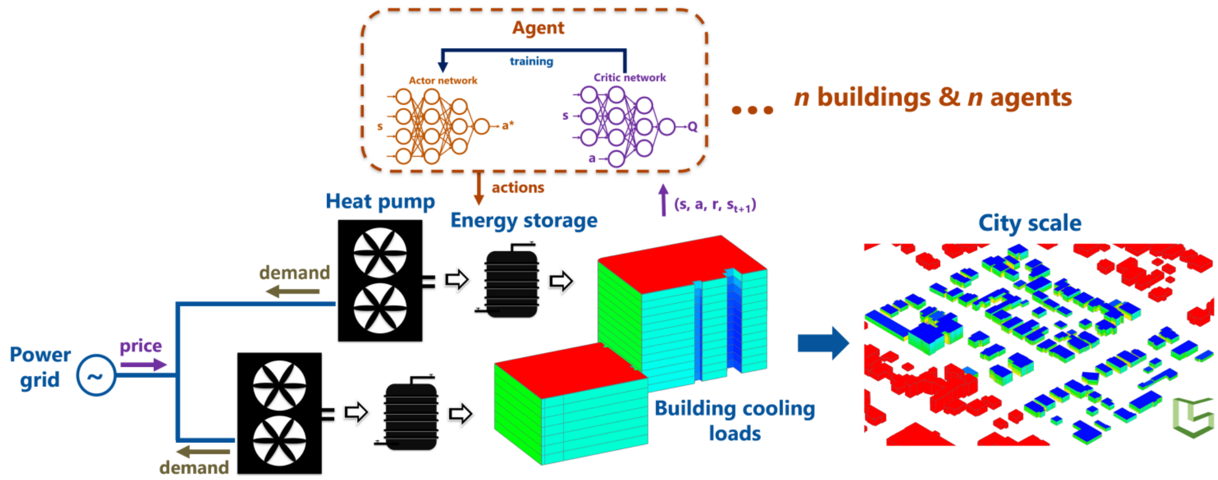
Industry relevance/partner: The security of the operation is one of the most important and challenging tasks of a transmission system operator. This thesis combines the ML and power system dynamics which is highly valuable in both academia and system operation.

Contact details:

- PhD supervisor: Mert Karacelebi (m.karacelebi@tudelft.nl)
- Supervisor: Dr. Jochen Cremer (J.L.Cremer@tudelft.nl)



Reinforcement Learning for Coordinating Energy communities



Scope: This thesis project will focus on the coordination of energy communities with reinforcement learning

Problem definition: Energy communities aim at balancing their own energy demand and generation to reduce congestion of the grid. Community participants have individual constraints and objectives, and little information are known about the other participants. However, the community balancing objective is known to the participants and minimal information can be exchanged between participants while preserving their privacy. The problem is that when each participant aims for the same objective symmetric responses can be expected resulting, if no coordination is present, in mismatches in the balance (e.g. rebounce effect). Hence, you will develop novel decentralised control methods where individual agents coordinate and focus on individual objectives at the same time.

Methodology: Multi-agent reinforcement learning (MARL)'s outstanding methodological advantage is learning from a dynamic environment with the objective of maximizing a local reward. You will investigate novel MARL techniques that aim at balancing cooperation and competition to the application of coordinating energy communities.

Research objectives:

- Learn about Deep Reinforcement Learning, Actor-Critic, cooperative Deep Reinforcement Learning, and other AI methods for coordination
- Develop a testing model environment for coordinating energy communities (e.g., based on Pecan street)
- Develop a novel cooperative Reinforcement Learning approach to coordinate energy communities (e.g., through incentive based demand response)
- Investigate the developed approach on specific use cases, e.g., sustainability impact, carbon reductions or reducing network congestions
- Communicate findings to scientific community

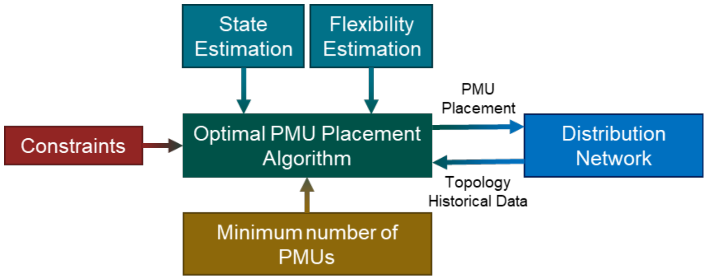
Industry relevance/partner: You will learn highly relevant technical skills on AI, neural networks, and sustainable energy systems. The developed methods can be used for distribution system operators (DSOs) and energy community managers, municipalities, and behavior analytics.

Contact details:

- Dr. Jochen Cremer (J.L.Cremer@tudelft.nl), Dr. Luciano Cavalcante Siebert (L.CavalcanteSiebert@tudelft.nl)

DAI ENERGY

Optimal PMU Placement for Flexibility and State Estimation



Scope: This thesis project focuses on identifying the optimal phasor measurement unit placement to improve the distribution network flexibility estimation and state estimation.

Problem definition: The massive increase of renewables and distributed generation in power systems led to higher variability and unpredictability. As a result, the need for flexibility from the distribution networks is high to ensure a reliable grid operation. An accurate assessment of the distribution network's operating state is needed to estimate this flexibility. Real-time measurements in distribution and transmission networks can be obtained through measuring devices such as phasor measurement units (PMUs). PMUs estimate the magnitude, phase, frequency and rate of change of frequency of the voltage and current waveforms. However, distribution networks have limited PMUs placed, which limits their observability. This observability limitation can be crucial to the state's performance and flexibility estimation. Therefore, identifying the optimal PMU placement for an accurate flexibility estimation can be significant.

Although the effect of PMU placement on the state estimation problem can be highly correlated to the effect of the flexibility estimation problem, the latter has been overlooked in existing research. Nevertheless, modifications of the OPP problem have been applied to simultaneously improve the state estimation and fault observability [1], to include component reliability for observability improvement under contingency [2], and to find attack-resilient OPP [3]. Similarly, adapting the algorithms to also focus on flexible components is promising. Accordingly, OPP can be expressed as a problem of simultaneously optimizing the placement for flexibility and state estimation while minimizing the number of measurement units.

Methodology: Recent PMU placement approaches for state estimation include greedy algorithms [1], linear programming branch and bound algorithm [2], and reinforcement learning guided tree search [3]. You will initially study the state and flexibility estimation algorithm process, inputs and sensitivity to these inputs. Then, you will study recent OPP techniques and identify which algorithms/modifications align with the flexibility and state estimation focussed OPP problem. Finally, you will implement the proposed algorithm and showcase its performance in a study case.

Research objectives:

- Learn about distribution network flexibility estimation,
- Learn about distribution network state estimation,
- Learn about OPP algorithms and their trends,
- Develop an OPP algorithm improving the state and flexibility estimation,
- Communicate findings to energy system modelers and AI experts

Possible industrial partner: Alliander, Innovation Center for AI: AI for Energy Grids Lab

Contact details: Demetris Chrysostomou (D.Chrysostomou@tudelft.nl), Lucas Narbondo (lucasnarbondo@gmail.com) Dr. Jochen Cremer (J.L.Cremer@tudelft.nl)

[1] Y. Peng, Z. Wu, C. Fang, S. Zheng and J. Zhao, "Optimal PMU Placement in Distribution Networks for Improving State Estimation Accuracy and Fault Observability," *2021 IEEE Sustainable Power and Energy Conference (iSPEC)*, 2021, pp. 1413-1418, doi: 10.1109/iSPEC53008.2021.9735708.
[2] S. Kumar, B. Tyagi, V. Kumar and S. Chohan, "Optimization of Phasor Measurement Units Placement Under Contingency Using Reliability of Network Components," in *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 12, pp. 9893-9906, Dec. 2020, doi: 10.1109/TIM.2020.3004680.
[3] M. Zhang, Z. Wu, J. Yan, R. Lu and X. Guan, "Attack-Resilient Optimal PMU Placement via Reinforcement Learning Guided Tree Search in Smart Grids,"

Intelligent Electrical Power Grids

Non-intrusive Load Monitoring of the Electricity Consumption

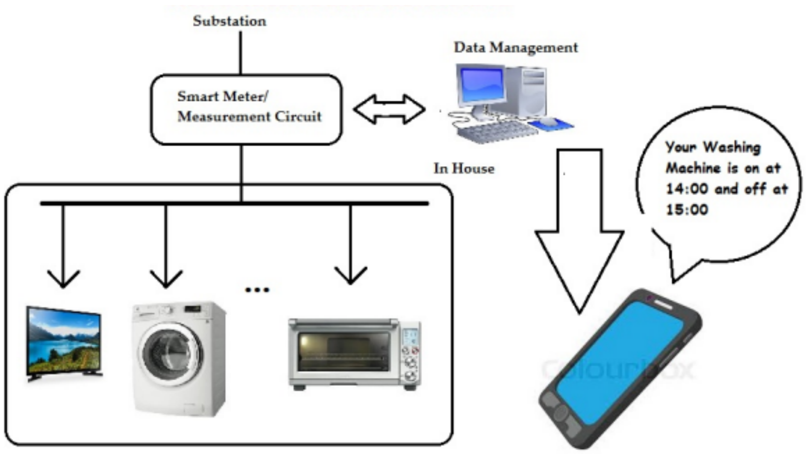


Image taken from: Linh, Viet Nguyen. "Deep Recurrent Neural Network to Disaggregate Household Energy Consumption." PhD diss., Universidad de Oviedo, 2017.

Scope: This thesis project will investigate Physics-Informed Deep Learning to non-intrusive load monitoring.

Problem definition: Often, electricity data can be observed from smart meters. Smart meters typically measure the electricity consumption over time of a household, several households or businesses. From the recorded data it is of high interest to analyse which appliance was active at what times. However, such a non-intrusive way of monitoring directly the appliances is not always feasible from the recorded smart-meter data. The data may be noisy, the system of appliances may not be known, and the appliance characteristics vary.

Methodology: Deep Learning is promising for the NLM-task, and recently substantial improvements were made on Physics-informed DL. We will investigate a novel hybrid-approach based on control theory of appliances. Subsequently, we will investigate combining such theory with AI-based approaches for the NLM-task. We will investigate a deep learning approach using latest SynD data published in Nature, 2020.

Research objectives:

- Literature analysis for NLM, Physics-Informed DL
- Investigating Physics-Informed combining control theory with Physics-informed DL.
- Utilize DL and applied control to maximize the learning outcomes.
- Test the approach against state-of-the-art NLM approaches.

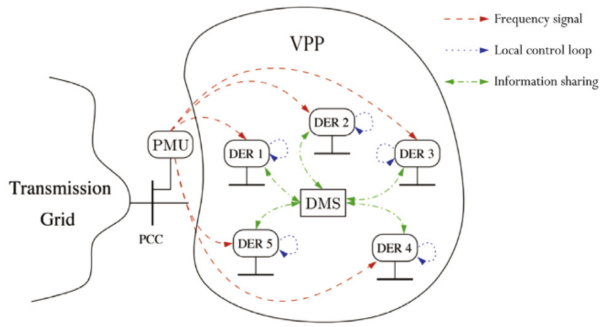
Business relevance: Identifying appliances "behind the meter" opens up start-ups the chance for smart home energy management**. There, we will share our findings with a Dutch startup seeking combining NLM with PV data.** You will develop skills in data analytics, artificial intelligence and apply these directly to a very relevant energy application of NLM.

Contact detail:

- Dr. Jochen Cremer (j.l.cremer@tudelft.nl)
- Dr. Peyman Mohajerin Esfahani (P.MohajerinEsfahani@tudelft.nl)

DAI ENERGY

Coordinated Control of Virtual Power Plants for Frequency Stability



Scope: This thesis project will focus on developing control techniques coordinating heterogeneous sources in virtual power plants, such that the virtual power plants can provide desired dynamics and participate into power system frequency regulation in a modern low-inertia system scenario.

Problem definition: Dynamic Virtual Power Plants (DVPPs) [1]-[3], coordinating groups of small-scale prosumers, is a proposed solution to allow small players with more variable production to offer dynamics ancillary services and thus enter the ancillary market. In order to form the desired dynamics required from transmission system operators, the owner/operator of DVPPs need to design coordinated control methods for each participators which usually have very diverse dynamics due to heterogeneous sources.

Methodology: You will first study the control and dynamics of diverse production units in VPPs, including wind turbines, PVs, batteries, hydro power plants, etc. You will model these dynamical components in MATLAB Simulink. In second stage, you need to connect the VPP including multiple sources to a transmission network and simulate its frequency dynamics under disturbances. Thirdly, you will investigate and design different coordination control methods, and test their performance on the system above. You will study in detail the impact of decentralization, communication on the frequency regulation of the whole system.

Research objectives:

- Literature review for modelling of renewable energy sources, coordinated control for VPPs.
- Build up the model in MATLAB Simulink.
- Study, develop and implement one coordinated control method for the defined VPP.
- Investigate how the control methods influence the frequency dynamics of the VPP and thus the system.

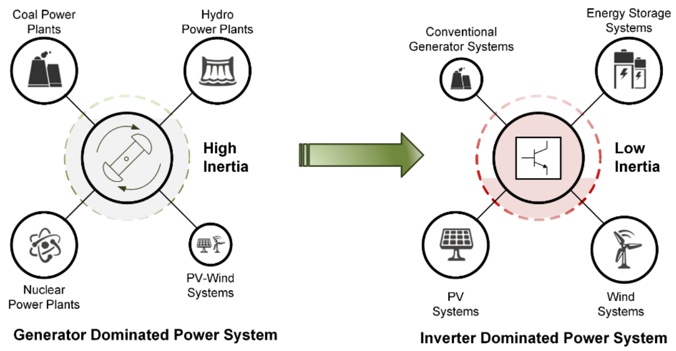
Reference:

[1] J. Björk, K. H. Johansson, and F. Dörfler, "Dynamic Virtual Power Plant Design for Fast Frequency Reserves: Coordinating Hydro and Wind," arXiv:2107.03087, Jul. 2021.
[2] B. Marinescu, O. Gomis-Bellmunt, F. Dörfler, H. Schulte, and L. Sigrist, "Dynamic Virtual Power Plant: A New Concept for Grid Integration of Renewable Energy Sources," Jul. 2021.
[3] V. Haberle, M. W. Fisher, E. Prieto Araujo, and F. Dorfler, "Control Design of Dynamic Virtual Power Plants: An Adaptive Divide-and-Conquer Approach," IEEE Transactions on Power Systems, pp. 1–1, 2021.

Contact details:

- PhD student: Haiwei Xie <H.Xie-2@tudelft.nl>
- Supervisor: Jochen Cremer <J.L.Cremer@tudelft.nl>

Market Mechanism Design for Virtual Inertia



Scope: In future power electronics-based power systems, the converters should be responsible for ensuring frequency stability, as conventional generating units previously did. This can be achieved by 1) emulating virtual inertia with power electronics control techniques and 2) strategically locating these virtual inertia devices. In this context, a suitable market is needed to encourage more virtual inertia providers to participate in the system regulation. The inertia response provided by the heterogeneous renewables to the system will be considered a valuable tradeable commodity, and the generating units can demand financial compensation via a payment rule.

Problem definition: This thesis project will focus on investigating and designing market mechanisms for virtual inertia, to answer the question: how the system operators would procure and pay for these devices for their provided virtual inertia response. The bids are invited from agents providing virtual inertia, who in turn are compensated via a payment rule. The designed mechanism should ensure incentive compatibility and to be the dominant bidding strategy.

Methodology: The mechanisms from game theory and the design of the methodology are the key of this project and mainly what you should learn. In addition, you will first study the impact of virtual inertia to power quality and system stability, based on certain criteria such as maximum allowable ROCOFs and/or frequency deviation. Then, you will further explore how the virtual inertia can be deployed as a service or product. A thorough literature review of the current existing markets for ancillary service is needed and you should connect and compare them with the one you designed for virtual inertia.

Learning objectives:

- Literature review on the current existing markets for ancillary service, including for virtual inertia.
- Study methodology for market mechanism design.
- Design a market mechanism for virtual inertia.

Reference:

[1] B. K. Poolla, S. Bolognani, N. Li and F. Dörfler, "A Market Mechanism for Virtual Inertia," in IEEE Transactions on Smart Grid, vol. 11, no. 4, pp. 3570-3579, July 2020.
[2] U. Tamrakar, D. Shrestha, M. Maharjan, B. Bhattarai, T. Hansen, and R. Tonkoski, "Virtual Inertia: Current Trends and Future Directions," Applied Sciences, vol. 7, no. 7, p. 654, Jun. 2017.

Contact details:

- PhD student: Haiwei Xie <H.Xie-2@tudelft.nl>
- PhD student: Viktor Zobernig <Viktor.Zobernig@ait.ac.at>
- Supervisor: Jochen Cremer <J.L.Cremer@tudelft.nl>

Offering Strategies of Virtual Power Plants in Ancillary Service Markets Based on Stochastic Programming

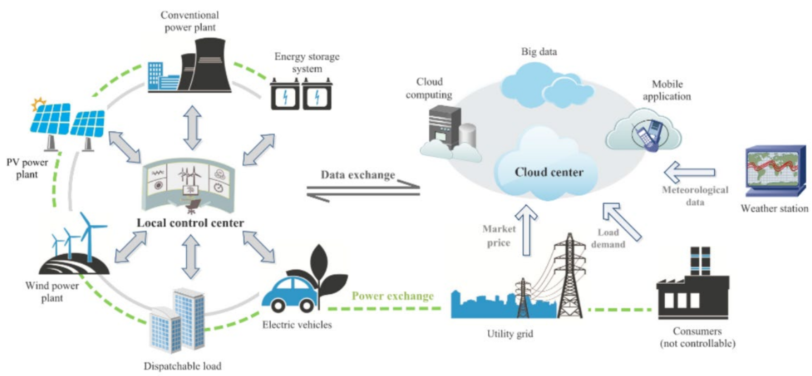


Fig.1 Structure of a VPP

Scope: This thesis project will focus on developing the optimal bidding strategy of a Commercial Virtual Power Plant (CDVPP), which comprises of distributed energy resources (DERs), battery storage systems (BSS), and electricity consumers, and participates in the ancillary service market.

Problem definition: Commercial Virtual Power Plants (CVPPs) [1], aggregating groups of small-scale prosumers, is a proposed solution to allow small players with more variable production to offer ancillary services and thus enter the ancillary market. It is essential that the VPP owner is able to determine the optimal bidding strategy of the VPP portfolio so as to maximize their profit, while at the meantime, take into considerations the uncertainty in the program.

Methodology: You will need to mathematically formulate the optimal bidding strategy problem of a CVPP based on stochastic programming [2]. To do so, firstly you should figure out where the uncertainty lies in the problem comes from. Secondly you need model market mechanisms of Europe ancillary service market and embed the CVPP into the market. Thirdly, you will use stochastic programming techniques or related optimization techniques to solve the model and investigate in detail the economic influence of your algorithm. A further step in this project is to consider how the VPP can offer their real-time ancillary service (working as a Dynamic VPP) to the market.

Research objectives:

- Literature review for ancillary service, ancillary service market and VPPs participating into the market.
- Mathematically formulate the problem considering uncertainty.
- Study, develop, implement, and investigate stochastic programming methods for the defined problem.
- (Optional) Investigate ancillary service market mechanism for dynamics and consider DVPP's real-time ancillary service offering.

Reference:

[1] H. Saboori, M. Mohammadi, and R. Taghe, "Virtual Power Plant (VPP), Definition, Concept, Components and Types," in 2011 Asia-Pacific Power and Energy Engineering Conference, Mar. 2011, pp. 1–4.
[2] E. G. Kardakos, C. K. Simoglou, and A. G. Bakirtzis, "Optimal Offering Strategy of a Virtual Power Plant: A Stochastic Bi-Level Approach," IEEE Transactions on Smart Grid, vol. 7, no. 2, pp. 794–806, Mar. 2016.

Contact details:

- PhD student: Haiwei Xie <H.Xie-2@tudelft.nl>
- Supervisor: Jochen Cremer <J.L.Cremer@tudelft.nl>