Predictricity project - Final content report

Executive summary

The Predictricity project investigated machine learning (ML) applications for Virtual Power Plants (VPPs) as well as software architectures for VPPs that are beneficial for effectively exploiting the ML capabilities. The key results have been published in several scientific journal articles. All of these articles have an acknowledgement to the Business Finland Predictricity project funding grant number 7439/31/2018. This report is structured around these articles. Below, we give the details of the articles, the Finnish Publication Forum JUFO rank, and a description of the key results. Finally, we discuss the impact of the overall contributions of these works in a summary section.

A vision of artificial intelligence to industrial automation, with a case example from power grid frequency reserves

De Silva D, Sierla S, Alahakoon D, Osipov E, Yu X, Vyatkin V (2020) "Toward Intelligent Industrial Informatics: A Review of Current Developments and Future Directions of Artificial Intelligence in Industrial Applications", IEEE Industrial Electronics Magazine, vol. 14, no. 2, pp. 57-72, https://doi.org/10.1109/MIE.2019.2952165

JUFO rank 2 (leading)

This was our first article written at the very beginning of the project with our international research partners are La Trobe University Melbourne. In it, we assessed the recent hype on artificial intelligence (AI) with a review of the scientific literature, especially focusing on development relevant to industrial automation applications. Based on the review, an architectural vision for industrial AI was developed and illustrated with power grid frequency reserves. This included AI solutions for 1) forecasting several markets, 2) for forecasting asset availability on such markets and 3) for making market participation decisions relying on the forecasts that are available at the time when market participation decisions must be made. The architecture and solutions 1-3 correspond to the main goals of the Predictricity project and specific results related to these have been published in scientific journals articles, discussed below in more detail.

An extensive scientific literature review of machine learning applications to virtual power plants

Sierla S, Pourakbari-Kasmaei M, Vyatkin V (2022) "A taxonomy of machine learning applications for virtual power plants and home/building energy management systems". Automation in Construction, volume 136, April 2022, 104174, https://doi.org/10.1016/j.autcon.2022.104174

JUFO rank 2 (leading)

A Virtual power plant is defined as an information and communications technology system with the following primary functionalities: enhancing renewable power generation, aggregating distributed energy resources and monetizing them considering the relevant energy contracts or markets. A virtual power plant also includes secondary functionalities such as forecasting load, market prices and renewable generation, as well as asset management related to the distributed energy resources. Machine learning has recently been applied to realize various functionalities of these systems. Indeed, an explosive growth of such publications has been observed over the last 3 years. This article presents a 3-tier taxonomy of such functionalities. The top tier categories are optimization, forecasting and classification. An infographics-based approach has been used to visualize trends and thus identify the current and foreseeable focus of the research, as well as to identify topics in which a combination of several machine learning techniques has been used.

A software architecture for virtual power plants, with special attention to interfacing novel machine learning based analytics capabilities, and forecasts in particular

Subramanya R, Yli-Ojanperä M, Sierla S, Hölttä T, Valtakari J, Vyatkin V (2021) "A Virtual Power Plant Solution for Aggregating Photovoltaic Systems and Other Distributed Energy Resources for Northern European Primary Frequency Reserves", Energies 2021, 14(5), 1242, https://doi.org/10.3390/en14051242

JUFO rank 1 (basic)

Primary frequency reserves in Northern Europe have traditionally been provided with hydro plants and fossil fuel-burning spinning reserves. Recently, smart distributed energy resources have been equipped with functionality needed to participate on frequency reserves. Key categories of such resources include photovoltaic systems, batteries, and smart loads. Most of these resources are small and cannot provide the minimum controllable power required to participate on frequency reserves. Thus, virtual power plants have been used to aggregate the resources and trade them on the frequency reserves markets. The information technology aspects of virtual power plants are proprietary and many of the details have not been made public. The first contribution of this article is to propose a generic data model and application programming interface for a virtual power plant with the above-mentioned capabilities. The second contribution is to use the application programming interface to interface our third-party machine learning application that forecasts day ahead the frequency reserve capacity that the photovoltaic systems and other distributed energy resources can provide to the frequency reserves markets in the upcoming bidding period. Such a forecast is source information for the bidding module of the virtual power plant, and thus an industrial grade virtual power plant has a place in its information model where it can receive such a forecast. The contributions are demonstrated with an operational virtual power plant installation at a Northern European shopping center, aggregating photovoltaic Primary Frequency Reserves resources.

A short-term photovoltaic generation forecast based on time series data and sky imaging, integrating two kinds of machine learning models to handle these two diverse data sources

Haputhanthri D, De Silva D, Sierla S, Alahakoon D, Nawaratne R, Jennings A, Vyatkin V (2021) "Solar Irradiance Nowcasting for Virtual Power Plants Using Multimodal Long Short-Term Memory Networks", Frontiers in Energy Research, 9: 469-482. https://doi.org/10.3389/fenrg.2021.722212

JUFO rank 1 (basic)

This work was mainly done by our collaborators at La Trobe University Melbourne. The Predictricity project leader Seppo Sierla supported this research in an advisory role and as a co-author of parts of the paper. The motivation for this paper is that short-term photovoltaic forecasts can be useful for a virtual power plant if it participates on real-time electricity markets or if it needs to allocate assets from a pool of available assets to meet previously made market commitments. For photovoltaic forecasting, a sequence of sky images can be a useful input stream that can help a machine learning model to predict the cloud cover at the virtual power plant site on a timescale of minutes. An image detection machine learning model was constructed for this purpose. Additionally, a conventional time-series forecasting model was developed. These two machine leaning models were both based on neural networks with different kinds of layers, so they were combined to a single ‘multi-modal’ neural network by an integrating layer, that outputs the solar irradiance forecast. The complete approach was empirically evaluated on a real-world solar irradiance case study across the four seasons of the northern hemisphere, resulting in a mean improvement of 39% for multimodality.

A multi-market forecasting and bidding intelligence solution

Kempitiya T, Sierla S, De Silva D, Yli-Ojanperä M, Alahakoon D, Vyatkin V (2020) "An artificial intelligence framework for bidding optimization with uncertainty in multiple frequency reserve markets", Applied Energy, vol. 280, no. 115918, https://doi.org/10.1016/j.apenergy.2020.115918

JUFO rank 3 (top)

The global ambitions of a carbon-neutral society necessitate a stable and robust smart grid that capitalizes on frequency reserves of renewable energy. Frequency reserves are resources that adjust power production or consumption in real time to react to a power grid frequency deviation. Revenue generation motivates the availability of these resources for managing such deviations. However, limited research has been conducted on data-driven decisions and optimal bidding strategies for trading such capacities in multiple frequency reserves markets. We address this limitation by making the following research contributions. Firstly, a generalized model is designed based on an extensive study of critical characteristics of global frequency reserves markets. Secondly, three bidding strategies are proposed, based on this market model, to capitalize on price peaks in multi-stage markets. Two strategies are proposed for non-reschedulable loads, in which case the bidding strategy aims to select the market with the highest anticipated price, and the third bidding strategy focuses on rescheduling loads to hours on which highest reserve market prices are anticipated. The third research contribution is an Artificial Intelligence (AI) based bidding optimization framework that implements these three strategies, with novel uncertainty metrics that supplement data-driven price prediction. Finally, the framework is evaluated empirically using a case study of multiple frequency reserves markets in Finland. The results from this evaluation confirm the effectiveness of the proposed bidding strategies and the AI-based bidding optimization framework in terms of cumulative revenue generation, leading to an increased availability of frequency reserves.

A market participation artificial intelligence solution for battery resources

Aaltonen H, Subramanya R, Sierla S, Vyatkin V (2021) "A Simulation Environment for Training a Reinforcement Learning Agent Trading a Battery Storage", Energies 2021, 14(17), 5587. https://doi.org/10.3390/en14175587

JUFO rank 1 (basic)

Battery storages are an essential element of the emerging smart grid. Compared to other distributed intelligent energy resources, batteries have the advantage of being able to rapidly react to events such as renewable generation fluctuations or grid disturbances. There is a lack of research on ways to profitably exploit this ability. Any solution needs to consider rapid electrical phenomena as well as the much slower dynamics of relevant electricity markets. Reinforcement learning is a branch of artificial intelligence that has shown promise in optimizing complex problems involving uncertainty. This article applies reinforcement learning to the problem of trading batteries. The problem involves two timescales, both of which are important for profitability. Firstly, trading the battery capacity must occur on the timescale of the chosen electricity markets. Secondly, the real-time operation of the battery must ensure that no financial penalties are incurred from failing to meet the technical specification. The trading-related decisions must be done under uncertainties, such as unknown future market prices and unpredictable power grid disturbances. The market forecasting solutions presented in above mentioned articles are used as state information for the reinforcement learning agent. In this article, a simulation model of a battery system is proposed as the environment to train a reinforcement learning agent to make such decisions. The system is demonstrated with an application of the battery to Finnish primary frequency reserve markets.

Summary

The key contributions of the project discussed above cover the 4 main research goals of the Predictricity project: market forecasting, asset forecasting, decision making for profitable market participation with the available energy assets, and software architecture for virtual power plant systems for integrating the advanced machine learning solutions for forecasting and decision making. The publication record in well regarded journals is a quality assurance of the scientific and technical soundness of the work. The machine learning research contributions jointly form an advanced market intelligence solution for distributed energy resources. The software architecture research that applies these contributions to the virtual power plant context ensures a pathway to real-world exploitation and contributes to the emergence of standard software architectures that can underpin open industrial ecosystems in this area.