RePlan
Ancillary services from Renewable Power Plants

A Review on Optimal Dispatch Methods for ReGen plants

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Preface

This report is a deliverable in WP1 in the project "Ancillary services from renewable power plants" (RePlan). RePlan is funded as POS project 2015 no. 12347 by the Danish PSO-programme ForskEL, which is administered by Energinet.DK. RePlan is carried out in collaboration between DTU Wind Energy, DTU Elektro, Aalborg University Energy Technology, Aalborg University Wireless Communication Networks and Vestas Wind System A/S. DTU Wind Energy is manager of the project.

1 Scope of document

The scope of this document is to present optimal dispatch methods used in the coordination of ReGen plants to provide ancillary services, such as active power control and voltage/reactive power control. The report describes the state-of-the-art of dispatch algorithms, including relevant mathematical methods as well as the exchanged information between participating power plants (i.e., between WP plants, or between WP and PV plants) at the different levels of the hierarchy, ensuring robust operation. The report also addresses some of the uncertainty and variability features of the power production of ReGen plants, which have to be handled by the dispatch methods. The design requirements for dispatch methods and the validation of dispatch methods are described based on literature study. In addition, the most appropriate dispatch method in the context of RePlan project is proposed. In the end of this report, a description of a validation scenario of ancillary services in SYSLAB with assumptions and limitations, as well as the examples of services which can be validated in SYSLAB is provided.

2 Control objective and constraints

The objective of the optimal dispatch is to maximize the utilization of ReGen plants, e.g. minimize the overall activated capacity while guarantee the adequate certainty on providing the service. The economical perspective is not considered as part of the control objective in RePlan project. The optimal dispatch problem is formulated as an optimization problem given the objective function and hard constraints it has to satisfy. The mathematical formulation of an optimal dispatch problem (e.g., whether there are nonlinear terms in the formulation) determines which programming model to be used.

The constraints of the optimization problem are composed by the technical limitations of ReGen physical units (e.g., the ramping rate and the rated power production of the plants), the service specified constraints (e.g., the ramping rate of the aggregated power curve, and the size of down regulation), and the grid related constraints (e.g., the rated capacity of a transformer, the maximal thermal capacity of a cable, and the maximal voltage angle in the network).

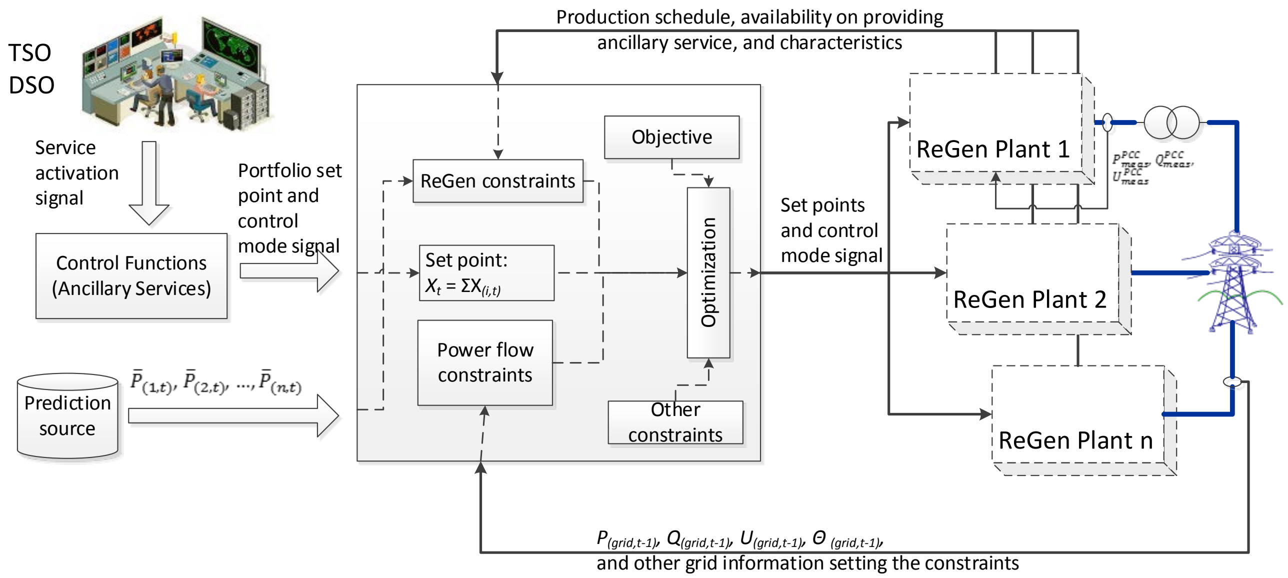

Figure 1. Input and output signals of dispatch process

Figure 1 illustrates the input and output signals of the dispatch process. The ancillary services and the specifications of the ReGen plan model, as well as its control structures are described in [1] and [2]. The input signals to the dispatch algorithm include the portfolio set-point (e.g., total active power to be activated) and the control mode derived from the Ancillary Service Control Function block [1] that a portfolio of ReGen units should match, the production schedule, availability on providing a given service, technical constraints from individual ReGen plant controllers, and the predicted operating conditions of ReGen plants. The output signals of the dispatch algorithm are set-points for ReGen plants to plant controllers.

3 Background introduction

RePlan project aims at developing the control and coordination methods to enable provision of ancillary services by coordinating the support from ReGen plants in different levels of the power system. The replacement of conventional generation plants by WP and PV plants has significant impacts on system behaviors [3, 4], which also lead to impacts on system operation.

3.1 High penetration of ReGen units and their capabilities

The control capabilities and aggregated models of ReGen plants are specified in RePlan report D1.1 [1]. It is assumed in the report that a ReGen plant controller is able to control aggregated WP or aggregated PV units to let the aggregated active / reactive power injection reach the set-point given by the entity higher in the control hierarchy within its operating limit. The control diagram of the ReGen plan level is illustrated in Figure 2. For instance, the set-points ($X^{ReGen}_{setpoint}$) of a ReGen plant (i.e., WPP or PV plant controllers) is calculated by the ReGen aggregator with the goals on providing ancillary services. The mismatch between $X^{ReGen}_{setpoint}$ and X^{PCC}_{meas} is captured by the plant controller, and is tuned in a closed loop. The power output and the amount of power that can be used for providing ancillary services from a ReGen plant are derived by an aggregated WPP model. The optimal dispatch method will be implemented between the ReGen aggregator and several plant controllers on providing $X^{ReGen}_{setpoint}$ to these plants.

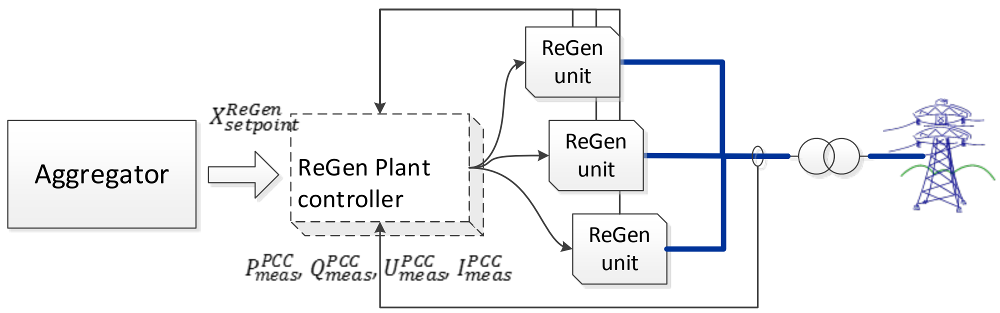

Figure 2. Plant level control diagram

3.2 Variability and uncertainty of wind and solar PV generation

In the existing power system control paradigm, wind and solar resources are regarded as non-dispatchable resources, because of the uncertainty and intermittency of their production. The production of ReGen plants is associated with the availability of wind and solar irradiation, therefore is not constant along the time. In addition, the prediction of ReGen plant production has uncertainties. Such features have to be captured and handled by the optimal dispatch method.

3.3 Ancillary services using optimal dispatch method

By performing an optimal power flow calculation, a best combination of set-points from reserves of generation units can be proposed. Traditionally, this is done by activating a few large scale generation reserved capacity. However, this can be replaced by activating the reserved capacity from a number of ReGen plants. By aggregating the ReGen plants, larger reserved capacity and better quality on service delivery may be obtained than that of individuals. In RePlan project, we aim at aggregating multiple ReGen plants to provide ancillary services. Optimal dispatch is used to allocate the required service to ReGen plants within the portfolio.

Optimal dispatch provides an optimal solution for the ReGen portfolio, but requires the knowledge of all the available resources to be dispatched. The whole process requires time to exchange information, computing the dispatch results, and execute the set-points at plant level. Therefore, we limit our scope to activate the following ancillary services using optimal dispatch method.

- Frequency restoration reserve / secondary frequency control
- Voltage control / reactive power regulation / loss minimization

For the rotor angle stability support, the relevant optimal dispatch method might be used to tune the controller parameters (i.e. power oscillation damping controller) in the ReGen plants. The requirements and the specification s for these ancillary services have been described in RePlan deliverables D1.1 and D1.2 report [1] and [2].

4 Problem formulation and hypotheses

4.1 Handling of uncertainty

The main challenge in using ReGen plants for ancillary services provision is due to the inability of fully (or perfectly) forecasting their output. Wind power forecasting tools have been developed for many years. The smaller deployment of photovoltaic (PV) units with respect to wind generation, along with the fact that most of PV installations have a small capacity and are usually connected to the distribution transmission network (DSO) explain the lower degree of attention drawn by solar forecasting with respect to wind forecasting.

There is a clear correlation between variability and predictability. In [5] a comprehensive study of the correlation between the variability (wind power fluctuations) and predictability (forecast quality) for a single wind farm and for clusters of wind farms (Figure 5). The results show that in both cases, the correlation between the Mean Absolute Gradients (MAG) of the measured 1h-power time series, defined as the absolute difference between the power in each time step, and the Root Mean Square Error (RMSE), normalized with the installed capacity, is very good.

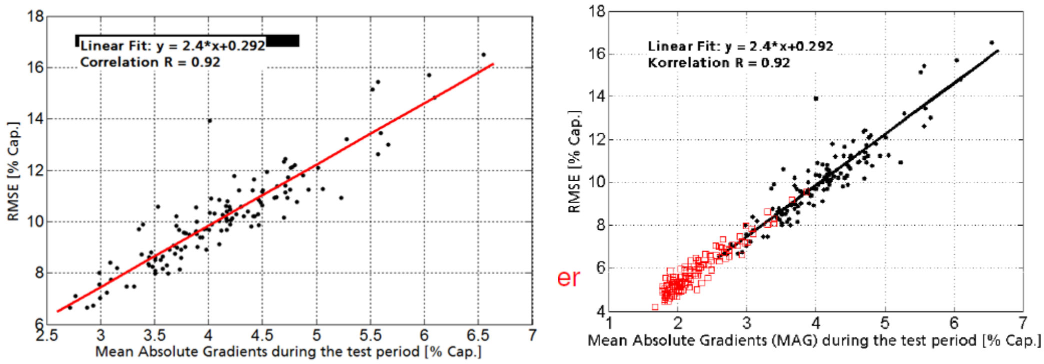

Figure 3: Correlation between RSME and MAG for a single wind power plant (left) and clusters of wind power plants (right) [5].

Therefore, minimizing the wind power variability will result in better predictability. The analysis showed that wind power fluctuations are influencing the quality of the power forecast more than the numeric weather prediction (NWP) grid resolution.

Spatio-temporal correlation of ReGen plants power forecast errors is very important. Based on empirical data, wind and solar forecast error tend to be cross-correlated between different locations. As shown in Figure 6, the correlation tends to decrease exponentially as a function of the distance.

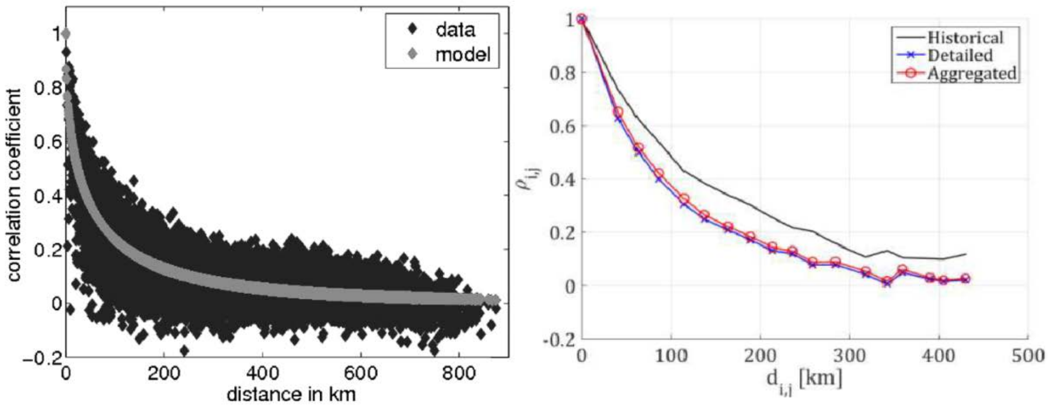

Figure 4: Correlation coefficient of forecast errors between two stations as a function of distance: solar forecast errors in Germany (left), [6] and wind forecast errors in Denmark (right), [7]

The uncertainty introduced by ReGen plants' generation depends a lot on the considered horizon. Typical examples of ReGen plant forecasting performances are given in Figure 7 for wind and Figure 8 for solar PV.

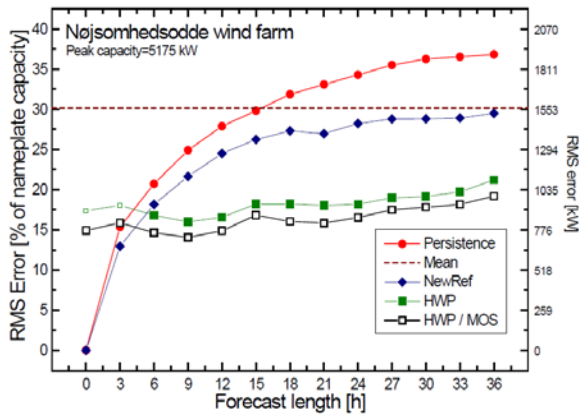

Figure 5: Performance of wind power prediction systems [8]

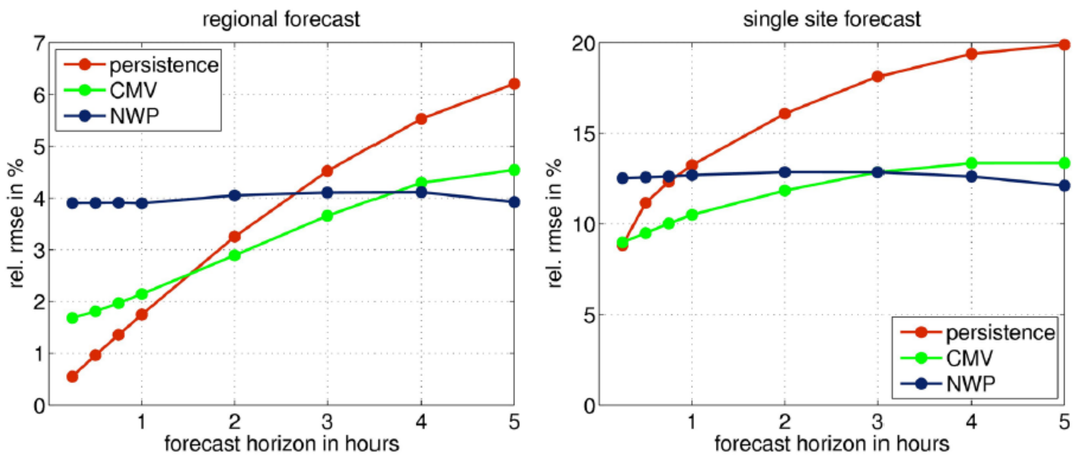

Figure 6: Performance of solar-PV prediction systems German average (left) and single site (right) [9]

PV generation forecasting accuracy is mainly influenced by the variability in meteorological conditions and to a minor extent to the uncertainties related to the different modelling steps needed to predict power generation from meteorological forecasts [10] Solar generation presents a high sensitivity to changes in solar irradiation, making the variability (probability of ramp events or sudden changes in production) an additional component of a comprehensive solar forecast [11].

4.2 Control structure

The control structure, presented in Figure 7, depicts the interaction between the TSO/DSO, the aggregator and the ReGen plants both at the transmission and distribution system level. The following actors are involved in the optimal dispatch process:

- **TSO/DSO**: monitors the system, identifies operational issues, and asks for ancillary service from ReGen aggregator based on a contract
- **Aggregator**: includes an optimal dispatch algorithm, receives the request from TSO/DSO, and provides set-points to ReGen plants, such that ReGen plants can be coordinated to obtain better control performance.
- **Plant controller**: provides the information about the availability of capacity for service provision of the corresponding ReGen plant to the aggregator, and implements the ReGen plant set-point.

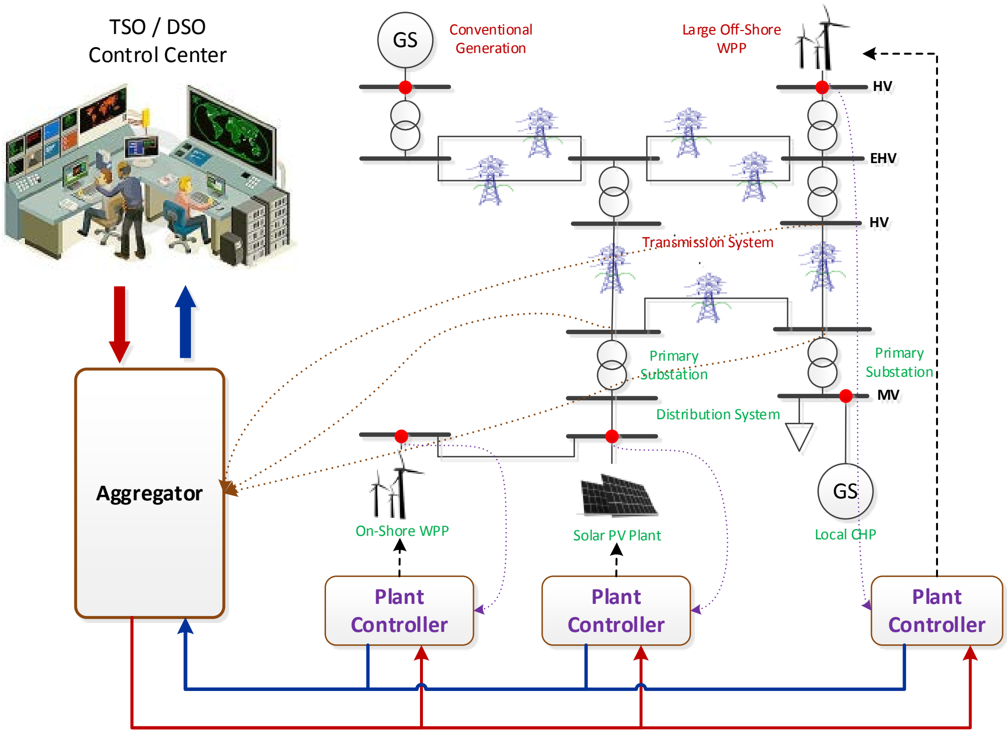

Figure 7: Sketch map of the aggregator control architecture.

5 Literature review on optimal dispatch method

Traditionally, an optimal dispatch problem is formulated in a deterministic form, given the operating constraints (e.g., the start-up cost, operating cost, ramping rate, minimal-on time, and rated power of a certain power plant). The problem is optimized by minimizing the overall cost on using the reserved capacity from multiple plants [12].

A lot of literature proposes optimal dispatch methods on handling the intermittency of ReGen plants with a combination of multiple energy sources as a Virtual Power Plant (VPP) [13,14,18—20]. In these applications, ReGen plants are regarded as non-dispatchable sources. However, in the context of RePlan project, the problems can be handled in a similar approach by activating the dispatch capability of ReGen units. Article [13] presented a multi-agent-based coordinated control method for large-scale wind-photovoltaic-storage units. In the set-up, the wind and PV may cancel each-other's fluctuation. In the case when the fluctuations are not cancelled, the battery reacts to the fluctuation based on its State-of-Charge (SOC). In [14], an adaptive dispatch strategy for a virtual power plant (VPP) was proposed. In the proposed method, the stochastic nature of wind and photovoltaic units are treated in an adaptive neural network, and further handled by the dispatchable units in the VPP portfolio. The key factor in such applications is to capture the fluctuating features so that the dispatchable units can schedule their efforts accordingly.

Some applications, e.g., [15, 16] use distributed control structure. The optimal dispatch problem is decomposed into multiple sub-problems solved in different locations. Article [15] proposed a peer-to-peer method that individual ReGen units communicate with their neighbors according to the N - 1 criterion using graph theory with redundant communications, so that the optimal dispatch still works if one control element fails. The control objective is to dispatch active power from power plants on providing secondary frequency reserve. Article [16] proposes a distributed method with a common database for coordinating the efforts shared by individual wind turbines on providing active power. The turbine controllers coordinate with others to make sure that the total active power matches the set-point from the TSO.

The uncertainty of ReGen is handled stochastic approach (for real-time operation) [17-11] in some literature. Article [17] provides a mathematical method that integrate stochastic producers in the traditional economical dispatch, so that the forecast errors are also part of the decision making process. A two-level dynamic stochastic optimal flow method is proposed in [18]. In this method, adaptive critic design technique is used to train the dynamic of the network. Dual heuristic dynamic programming technique is used for online training and control. The lower-level area distribution system optimal power flow controllers control their own area power network. The top-level global controller coordinates the area controllers by adjusting the inter-area tie-line flows. In [19], a two-stage stochastic programming strategy is proposed to handle the uncertainty of ReGen plants. In the proposed set-up, a risk measure is introduced to describe the probability that the profit of a VPP is less than a pre-determined value. The risk measure is formulated as part of the optimization function so that the risk is handled by the optimization function. The first stage or “hear and now” decision is made prior to the realization of the stochastic process, and the second stage or “wait and see” decision is made after knowing the actual realization of the uncertainties. This two-stage problem could also be used for providing ancillary service.

In [20-22], the reactive power capability from ReGen plants is exploited. Article [20] presented a hierarchical multi-mode optimal dispatch method for wind turbines on performing the voltage control within a wind farm. The voltages at PCC and at individual nodes are taken care of. Different security constraints and objectives are formulated for different voltage situation. In this way, the contribution of reactive power from different points in the farm can be coordinated to avoid cascading problem. A multi-mode method can help the control system adapt to operating scenarios in a wide variety. It can also be applied to ReGen plant coordination, such that individual ReGen plant can respect both local and global needs. A risk adverse multi-period reactive power generation dispatch application from ReGens and demand responses was presented in [21]. Information Gap Decision Theory is used to address the variability and uncertainty of ReGen plants. Critical limits are introduced to guarantee the robustness of the control strategy when the realized value is worse than the forecasted one. By doing so, the problem is formulated in a deterministic way, such that the computing speed is fast enough for applying it in large-scale cases

DC power flow model is commonly used for optimal dispatch considering the grid model, which is a simplified linear system model. Recently, convex computational skills are developed to enable nonlinear AC optimal power flow calculation [22, 23]. Article [22] provided mathematical derivations of convex forms of optimal power flow models based on convex relaxation techniques. The sufficient and necessary conditions are discussed. Compared with the results calculated from DC flow model and linearized flow model, the results calculated from convex AC flow model is closer to the actual optimum.

6 Requirements for the optimal dispatch method in RePlan

A lot of techniques presented in the previous section are applied in formulating the solving optimal dispatch methods. However, in regard to optimal dispatch of ReGen plants, there are not many literatures available. Therefore, based on the literature review, an appropriate optimal dispatch method for ReGen plants in RePlan project should be able to handle the following design requirements:

- ***Variability***. Based on the prediction of the future production, a proper schedule of ReGen plants should be able to handle some predicted fluctuation features, so that the resources are allocated efficiently. Some methods in the literature are extending the decision making horizon using Model Predictive Control (MPC) method, using restrictive constraints to improve the robustness of the control system, and using adaptive methods to update control parameters and system models.
- ***Uncertainty***. The production uncertainty should be reflected in the problem formulation, so that the control strategy is able to overcome some issues brought by the uncertainty on providing the service. The uncertainty is either treated in a stochastic optimization problem or transformed into deterministic quantity.
- ***Efficiency***. To be applied in large scale system, the control strategy should be able to compute feasible solution within the given time, and should be able to efficiently exchange the information with ReGen plant controllers.
  - The multi-agent system (MAS) has a lot of advantages on providing flexible modularized structure that is beneficial for a large scale system. It could be potentially used for ReGen optimal dispatch application.
  - System modelling using convexification / linearization techniques can be used for reducing the complexity of the mathematical model.
  - Optimization decomposition methods can be used to decompose the optimization problem, so that the problem can be solved in parallel or in distributed fashion, which may improve the computational speed.

7 Experiment initiatives in SYSLAB

The experiments in SYSLAB will focus on having a better understanding of the control performance and risks related to real implementation in practice. The scope of the experiments is to identify and confirm the implementation factors that affect the control performance, e.g., delays in the computation, communication, and actuation, in other words, how the hardware and its features have impacts on the design of coordination strategy and the control performance. The ancillary service to be implemented and validated in SYSLAB is secondary frequency control.

Due to the limitations on the size of SYSLAB, and the controllability of physical components, the experiments cannot involve real wind turbines in SYSLAB. Instead, a battery will be used to simulate a wind power plant by outputting a programmed power curve. The experiments will involve physical power sources (e.g., PV panels, and batteries), and power cables that form a downscaled transmission network. On top of the power system units, the ICT infrastructure is available for data collection, on-line monitoring, and real-time communication. The aggregator level controller will be implemented in a SYSLAB node to perform explicit control actions. The designed dispatch method will be implemented in the system to enable the control process, and the control performance will be evaluated under certain ICT scenarios. The physical layout of SYSLAB experiment is shown in Figure 8. Correspondingly, the control architecture of the SYSLAB dispatch experiment setup is illustrated in Figure 9.

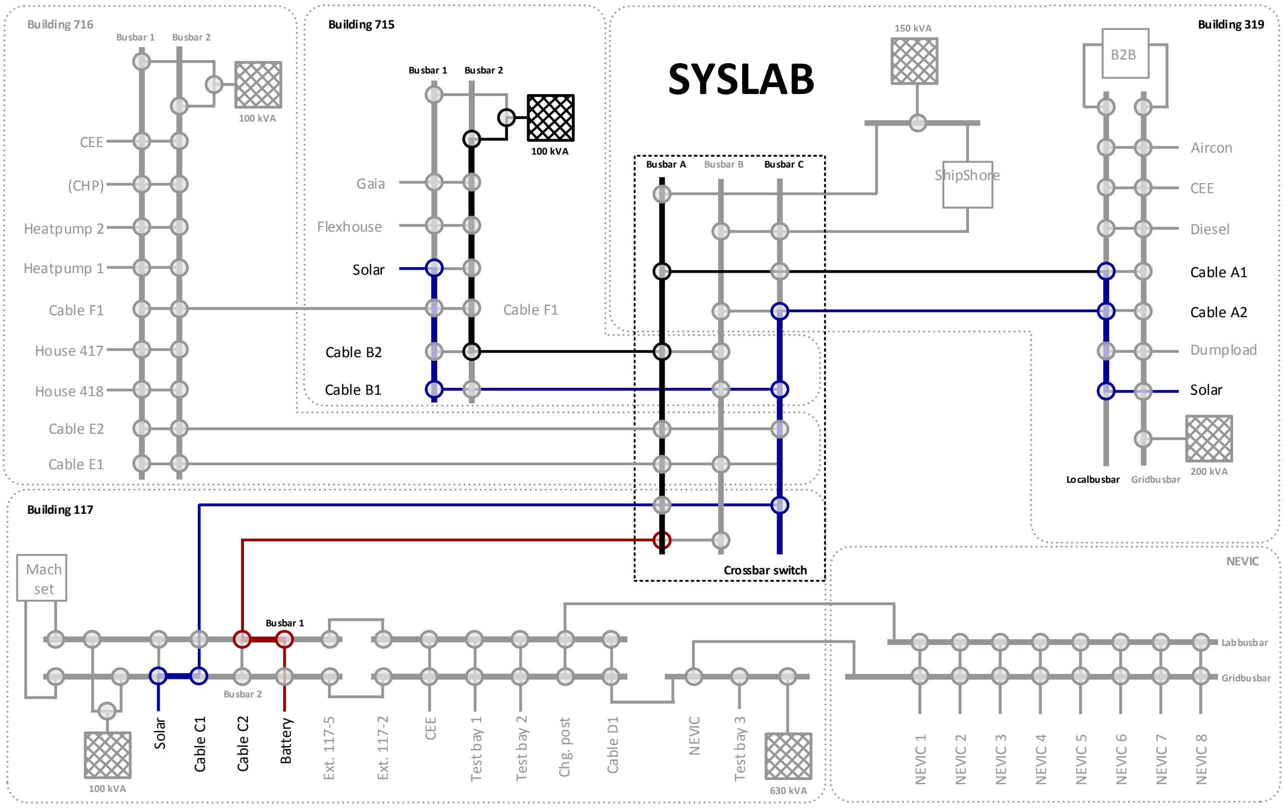

Figure 8. Physical layout of SYSLAB experiment

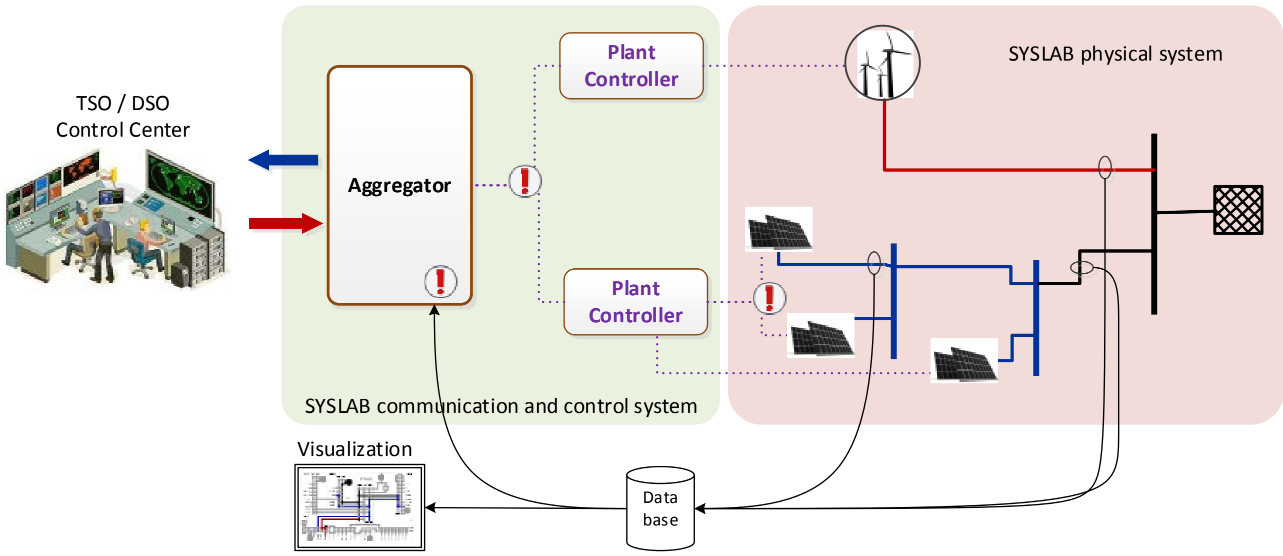

Figure 9. Control architecture of SYSLAB experiment

In relation to service validation, the validation scenarios with expected outputs from the experiments are listed as follows. They are marked in Figure 9 with “!”s.

1. In SYSLAB experiment, a PVP controller will control three real PV panels from different locations in SYSLAB remotely through SYSLAB ICT network. How PV inverters react to the control signals from

the PVP controller will be characterized and validated in SYSLAB experiments under different operating and weather conditions.

2. The communication delays and other features between aggregator and plant controllers will be analyzed during the experiments when the dispatch method is deployed. The control performance impacted by the communication conditions will be modelled.
3. Similarly, the computation of dispatch program may also affect the control performance. Therefore, its impact will also be identified as one scope of SYSLAB experiment.

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