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***Abstract*—The growing share of Variable Renewable Energy Sources (VRES) in power systems presents challenges for regulators, grid operators and energy producers, due to their limited flexibility in operation. To address these challenges, decision-makers must consider multiple objectives, including revenue, power system services and mechanical load on wind turbines. Coordinated operation of power plants and different wind farm control strategies are examples of measures that can benefit these objectives. This article presents a Multi-Objective Linear Programming (MOLP) model to optimize wind and hydropower projects with limited transmission capacity. It incorporates wind farm control dynamics to estimate power output and damage. A case study in Norway demonstrates the impact of wind-hydro coordination and wind farm management on cumulative turbine damages and total revenue. The study also investigates the benefits of variable-speed pumps in hydropower plants. Results show that optimizing multiple objectives improves the performance, with Pump Hydro Storage (PHS) allowing for better revenue and reduced wind power curtailment. However, no substantial difference is observed comparing a variable-speed pump to a fixed-speed pump.**

***Index Terms*—Grid utilisation, Optimisation, Scheduling, Wind-Hydro Coordination, Wind farm control**

NOMENCLATURE

Sets

T	All the time steps, t, of the simulations
R	All the power references of the simulations

Parameters

t_{max}	Total number of hours for the simulation [-]
$P_{w,r,t}$	Power output wind farm for power reference, r, at time step t [MW]
$D_{r,t}$	Damage accumulated for power reference, r, at time step t [-]
γ_t	Spot price in the day-ahead market at time step t [EUR/MWh]
$E_{inflow,t}$	Inflow to the hydro reservoir at time step t [MW]
Cap_{res}	Maximum capacity of the hydro reservoir [MWh]
Cap_{ht}	Production capacity of the hydro turbine [MW]
Cap_{pump}	Production capacity of the hydro pup [MW]
η_{ht}	Efficiency of the hydro turbine [%]
η_{pump}	Efficiency of the hydro pump [%]
$E_{res,init}$	Initial reservoir level [MWh]
Cap_{flood}	Maximum flood of the reservoir [MW]
Cap_{line}	Maximum power flow of the transmission line [MW]

Variables

$P_{w,prod,t}$	Produced power from the wind farm at time step t [MW]
$P_{w,exp,t}$	Exported wind power at time step t [MW]
$P_{w,curt,t}$	Wind power being curtailed at time step t [MW]
$P_{w,toPump,t}$	Wind power exported to the hydro pump at time step t [MW]
$P_{h,exp,t}$	Exported hydropower at time step t [MW]
$P_{pump,t}$	Power of the hydro pump at time step t [MW]
$P_{h,loss,t}$	Hydropower bypassed due to spillage at time step t [MW]
$P_{tot,exp,t}$	Total exported power from the hybrid system at time step t [MW]
$E_{res,t}$	Reservoir level at time step t [MWh]

Binary variables

$\alpha_{exp,t}$	Stating if power is exported to the grid at time step t
$\alpha_{imp,t}$	Stating if power is imported to the grid at time step t
β_t	Stating if the power pump is active or inactive at time step t
δ_r, t	Stating if power reference, r, is active at time step t

ABBREVIATIONS

VRES	Variable Renewable Energy Sources
MOLP	Multi-Objective Linear Programming
TSO	Transmission System Operator
PHS	Pumped Hydro Storage
WPP	Wind Power Plants
DLC	Design Load Case
AUGMECON	Augmented epsilon-constraint method

I. INTRODUCTION

In Norway, hydropower is the primary source of electricity, with a total installed capacity of 33.4 GW going into 2022 [1]. The International Energy Agency (IEA) identifies hydropower as the currently best option to provide emission-free flexibility to the power system [2]. However, a significant portion of the newly installed power capacity in Norway comes from wind farms, reaching a capacity of 5083 MW by August 2022 [3]. Moreover, the Norwegian Energy Agency (NVE) has recently launched a report identifying potential areas for 30 GW of offshore wind along the Norwegian coastline [4]. Wind farms are not able to provide the same flexible operation as hydropower. Thereby, the need for coordination between wind and hydro plants is increasing. Technical solutions for wind farm control and reservoir hydro systems with or without pumping capability may contribute to increased flexibility and optimal operation of the power plants in grid-constrained areas.

Overall, utilizing hydropower coordination together with wind farm control may benefit various different aspects such as minimizing curtailments and flooding, grid utilization, power balancing, ancillary services and revenue for the power plants. Another important aspect for the power producers is the damage accumulation to the wind turbines during operation, as this may lead to the need for additional maintenance investments. In order to increase the life span and reduce the maintenance costs on the turbine, control options to reduce the wear and tear on the turbines may be desired.

Previous studies investigating wind-hydro power coordination in congested areas show the benefits of grid utilization and wind energy curtailment [5]–[7].

Although several approaches have been proposed for providing power tracking services, most consider operating the turbines at off maximum power points [8], [9]. This employs a de-rating strategy, in which the turbine's maximum output power is capped at a specified level lower than the one following the power curve from the available wind power. However, when a single turbine is de-rated, this means that the wind speed deficit behind the turbine will change, affecting subsequent turbines and eventually the total WPP output. Besides the power output, such flow coupling will also affect the drive-train damage accumulated in each turbine due to different thrust levels, meaning that some turbines may be damaged at higher rates than others, leading to uneven degradation.

In this study, the different aspects of modelling and optimization regarding wind-hydro coordination and wind farm control dynamics will be investigated with the main contributions being:

- Developing a hybrid co-simulation model of the wind-PHS system by considering multiple objectives of total revenue and wind turbine damage.
- Comparative analysis of using a variable speed pump to the case of a fixed speed pump or no pump installed.
- Integration of wind farm control dynamics for improved wind-hydro coordination, considering accumulated turbines damage.

II. Background

A. Wind turbine damage and control

Wind turbines are exposed to harsh environmental conditions, in addition to a wide range of wind conditions. During the wind turbine certification stage, the manufacturer is required to prove their design is capable to sustain these conditions for the wind turbine's 20-year life expectancy. The design load cases (DLC) from the IEC 61400 standard are used to assess the response of the turbine to fatigue and extreme load cases [10]. Even though there has been a thorough review of the turbine's performance, it is not always the case that the asset won't suffer any damage. The combination of harsh conditions, and highly dynamic loading, has a contributing effect on the components' fatigue [11] and damage-induced failure is an option that operators consider under their operations and maintenance strategy. Special attention is given to the drivetrain given that is the most expensive sub-system to repair due to its required downtime, and mechanical complexity. In response, it is possible to control the turbine operation to reduce the loading in the components, but it can come at a cost in power performance. In a wind farm context, the wind farm controller can compute the right setpoints for each individual turbine based on the feedback of power and estimated damage. In this work, a damage-aware wind farm controller is employed, which is capable of redistributing the de-rating commands among turbines to enforce an uniform (and controlled) damage while satisfying the active power tracking requirement.

B. Multi-Objective Optimization

Multi-Objective Optimization (MOO) concerns problems with more than one objective to be optimized simultaneously. The decision maker may face various conflicting objectives when dealing with various optimization issues in the power system. Identifying a single solution that fulfils the preferences given by a decision maker, quantifying the trade-offs of the different objectives, or finding a representative set of Pareto optimal solutions are all possible objectives of the MOO. [12]

The augmented ϵ-constraint (AUGMECON) algorithm is a novel version of the ϵ-constraint method, developed for effective implementation of the standard ϵ-constraint method in MOLP problems. A table, referred to as the payoff table, is used to divide the ranges of the different objectives. These ranges are obtained using Lexicographic optimization, aiming to define a range that only covers Pareto optimal solutions. The lexicographic method obtains a set of solutions by only considering one objective at a time, while the other objective functions act as constraints to define the feasible region in the search space [12].

The AUGMECON version of the ϵ-constraint method to efficiently obtain Pareto optimal solutions are presented in the following equation system. [13]

$$\max \quad f_1(x) + eps \cdot (s_2 + s_3 + ... + s_p)) \tag{1a}$$
$$\text{subject to:} \quad f_2(x) - s_2 = e_2 \tag{1b}$$
$$f_3(x) - s_3 = e_3 \tag{1c}$$
$$... \tag{1d}$$
$$f_p(x) - s_p = e_p \tag{1e}$$
$$x \epsilon S \; and \; s_i \epsilon R^+ \tag{1f}$$

The different objective functions are represented by $f_p(x)$. A slack variable, s, represents the amount by which the constraint is relaxed or violated. By including the slack, each constraint is converted into equality constraints. A parameter, eps, is set to a low number, usually between 10^{-3} and 10^{-6}, in order to add slack variables to the objective function that are secondary to the objective function. As a result, each constraint is binding and weakly efficient solutions are avoided in the obtained Pareto front.

As the solutions obtained in the Pareto front are all considered equally good from a neutral point of view, a decision maker would be required to find the most preferred solution from the Pareto front. A common approach involves utilizing a fuzzy decision maker (FDM), which leverages a membership function to handle the imprecision and uncertainty present in various parameters, including the decision maker's desired level of achievement for the objectives. [14]

Rezvani et al. [15] utilize a linear membership function, where a utility value, μ_i^r, is defined for each objective, based on its range obtained in the pay-off table. From this, a total utility value, μ^r can be calculated for each Pareto optimal solution, by multiplying the resulting utility value, μ_i^r, of every objective with its corresponding weight, w_i.

$$\mu^r = \frac{\sum_{i=1}^{p} w_i \cdot \mu_i^r}{\sum_{i=1}^{p} w_i} \tag{2}$$

III. Methodology

Figure 1 presents an overview of the proposed methodology for the co-simulation framework, including different input data and constraints of the optimization program. The block-diagram differentiates between the baseline single-objective using the potential wind power directly and the multi-objective co-simulation framework including wind farm control dynamics.

The previous work of Stave [6] and Jamessen [7], which is represented by black boxes in the figure, served as the foundation for the framework proposed in this study. An extension with wind farm control is conducted in the present work, providing a more realistic power generation from the wind farm. This control framework also aims to consider the mechanical operation of the wind farm in more detail, adding a new objective of wind turbine damage to the original optimization problem. The different elements of the framework will be described further in the following sections.

A. Reference case study

The reference case builds on the study conducted by Stave [6], consisting of a single hydro plant with a capacity of 72 MW and a 96.6 MW wind farm. This is based on a location in Northern Norway sharing a single transmission line connecting to the grid with limited capacity, set to 140 MW for the purpose of this study. As with the case study conducted by Jamessen [7], a hydraulic pump is added to the hydro plant, resulting in a PHS system. Further, this case study differentiates by investigating a new wind farm consisting of

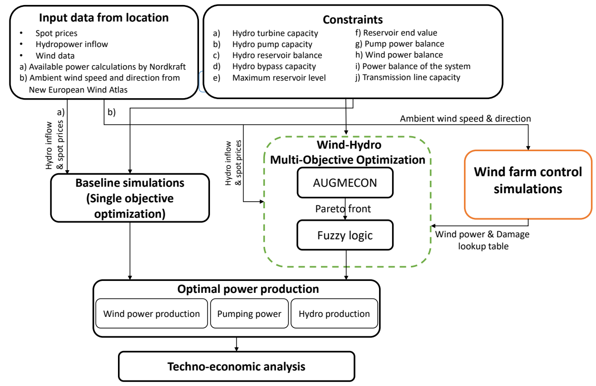

Fig. 1. Block-diagram of the co-simulation framework

20 DTU 10 MW wind turbines [16], as a result, the total wind power capacity is increased to 200 MW. Moreover, the two power plants act as a hybrid coordinated system. A schematic figure of the power flows of the system is presented in Figure. 2.

B. Wind farm control

The implemented damage-aware wind farm controller is based on the principles described in Section II-A. Figure 3 presents a flowchart illustrating the process of the wind farm control simulations, resulting in a lookup table for power output and its respective damage accumulation at each time step for different power references.

Synthetic turbulence is generated using a turbulence method as in [17]. This generates an output of a higher resolution turbulent wind speed time series per turbine, represented by $\phi_{Ws,TI}$ in the flowchart. The resulting lookup table is used as an input for the multi-objective optimization for wind-hydro coordination, as illustrated in Figure 1.

C. Multi-objective optimization model

The multi-objective framework designed by Jamessen [7] is further developed and extended in this study in order to include all the objectives of the different entities accounted for in the case study. A flowchart of the existing process of solving the model using AUGMECON, lexicographic optimization and fuzzy logic is presented in Figure 4.

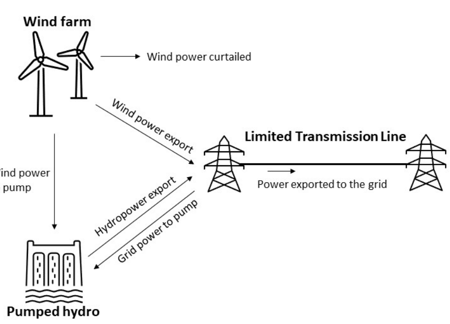

Fig. 2. Reference case system design

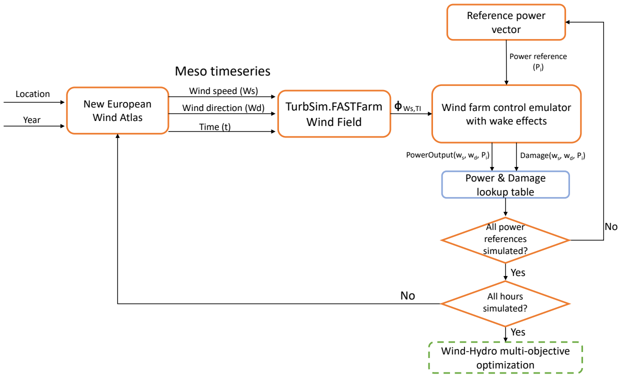

Fig. 3. Flowchart of the wind farm control simulations

The method is further improved by adding a tailored software extension by Bles and Paterakis [18], pyAUGMECON, using a Python and Pyomo-based implementation of AUGMECON and lexicographic optimization to obtain an approximation of the exact Pareto front.

Five different weights are used to present different trade-offs between the two objectives in fuzzy decision-making. These are presented in Table I, where the ratio of 1/9 means that the revenue objective is granted a much higher priority than damage for the decision maker. Correspondingly, a ratio of 9/1 grants greater priority to the damage objective.

D. Multi-Objective Linear Programming Model

The different objectives of the MOLP to maximize the total revenue of the hybrid plant and minimize the accumulated damage to the wind turbines are given by Eq. 3a and 3b.

The optimization constraints are formulated in equations from 3c to 3q, which are represented in the constraint-box in Figure 1. These equations include operating conditions for the PHS system, including hydro production capacity (3c, maximum reservoir level (3d), maximum bypass water (3e) and reservoir balance (Eq. 3f). The pump may be set to either

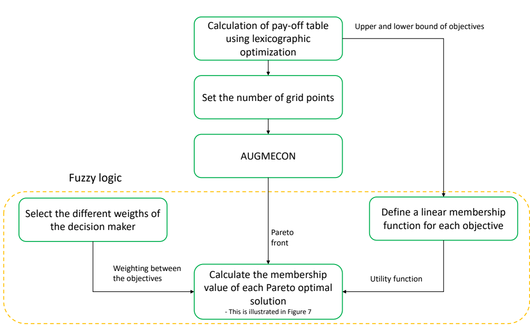

Fig. 4. Flowchart of the multi-objective optimization process

TABLE I
DIFFERENT WEIGHTS OF THE DECISION MAKER

	Weight 1	Weight 2	Weight 3	Weight 4	Weight 5
w_d/w_r	1/9	1/4	1/1	4/1	9/1

fixed speed or variable speed (3g). The power may come directly from the wind farm or be imported from the grid 3h. Then it must be ensured that no power is exported to and imported from the grid simultaneously 3i.

Further, the wind production is selected at each hour from the lookup table obtained from wind farm simulations (3j), where the potential wind power being curtailed is defined by Eq. 3k. The wind power may either be exported to the grid or directly to the hydro pump (Eq. 3l). Eq. 3m is included in order to ensure that only one power reference is used at each time step. The wind farm can export its power to grid and directly to the pump.

The total exported power from the hybrid system can not exceed the transmission capacity, this is ensured in Eq. 3n, where total exported power is the sum of power exported from the hydro plant and the wind farm (Eq. 3o). Finally, the power balance of the whole system is defined in 3p.

These constraints apply to every hour of the simulation throughout the year, except for Eq. 3q, which ensures that the reservoir level remains unchanged from the initial level at the end of the simulation.

$$\max \quad \sum_{t\epsilon T}(P_{w,exp,t} + P_{h,exp,t} \cdot \eta_{ht} - P_{imp,t}) \cdot \gamma_t \tag{3a}$$

$$\min \quad \sum_{t\epsilon T}(\sum_{r\epsilon R} D_{r,t} \cdot \delta_{r,t}) \tag{3b}$$

subject to

$$P_{h,exp,t} \leq Cap_{ht} \tag{3c}$$

$$E_{res,t} \leq Cap_{res} \tag{3d}$$

$$P_{h,loss,t} \leq Cap_{flood} \tag{3e}$$

$$E_{res,t} = E_{res,t-1} + E_{inflow,t} + P_{pump,t} \cdot \eta_{pump} \cdot \Delta t - P_{h,exp,t} \cdot \Delta t - P_{h,loss,t} \cdot \Delta t \tag{3f}$$

$$P_{pump,t} \leq Cap_{pump}$$

$$P_{pump,t} = Cap_{pump} \cdot \beta_t \tag{3g}$$

$$P_{pump,t} = P_{w,ToPump,t} + P_{imp,t} \cdot \alpha_{imp,t} \tag{3h}$$

$$\alpha_{exp,t} + \alpha_{imp_t} \leq 1 \tag{3i}$$

$$P_{w,prod,t} = \sum_{r\epsilon R} P_{r,t} \cdot \delta_{r,t} \tag{3j}$$

$$P_{w,curt,t} = P_{w,r,t,max} - P_{w,prod,t} \tag{3k}$$

$$P_{w,prod,t} = P_{exp,t} + P_{w,ToPump,t} \tag{3l}$$

$$\sum_{r\epsilon R} \delta_{r,t} \leq 1 \tag{3m}$$

$$P_{h,exp,t} \cdot \eta_{ht} + P_{w,exp,t} \leq Cap_{line} \tag{3n}$$

$$P_{tot,exp,t} = P_{h,exp,t} \cdot \eta_{ht} + P_{w,exp,t} \tag{3o}$$

$$P_{tot,exp,t} \cdot \alpha_{exp,t} - P_{imp,t} \cdot \alpha_{imp,t} = (P_{w,exp,t} + P_{h,exp,t}) - (P_{pump,t} - P_{w,ToPump,t}) \tag{3p}$$

$$E_{res,t_{max}} = E_{res,init} \tag{3q}$$

E. Shortcomings and assumptions

The current modeling has certain shortcomings and assumptions that are worth noting. The optimization assumes perfect information on input parameters (spot price, wind data, and hydro inflow), but in reality, input data is subject to stochastic environments. Nevertheless, the optimization can still illustrate the potential benefits of wind-hydro coordination and wind farm control. Computational limitations restrict the input data to be represented by every 9th hour throughout the year of simulation, thus not fully representing the short-term variations and the full range of ambient conditions throughout the year.

IV. Results

A. System simulations

The model provides output data of optimal hourly power production throughout the year. An illustration of this is presented in Figure 5, where the wind power being curtailed and the reservoir level at each hour is also visualized. The horizontal black line represents the capacity of the transmission line.

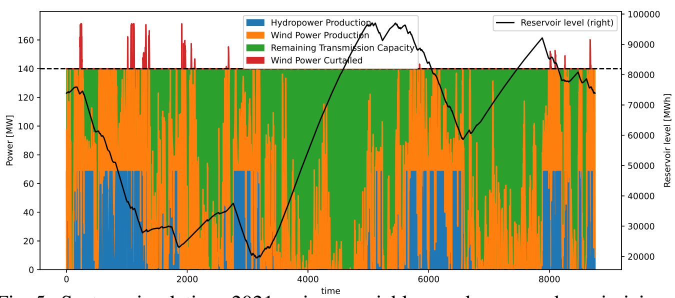

Fig. 5. System simulations 2021, using a variable speed pump and maximizing the revenue of the hybrid system.

B. Impact of using a pumped hydro storage

Simulations to compare the outcome from using a variable speed pump, a fixed speed pump and no pumped hydro storage have been conducted in this study. The resulting revenue, pumping power, wind curtailment and grid utilization for the different cases is presented in Table II. These results are obtained from baseline simulations conducted on the reference case study, where only the revenue objective for the hybrid power plant is considered in the optimization. Additionally, the wind farm control simulations are excluded, using the potential wind power directly, as presented in Figure 1.

TABLE II
Comparison of results for fixed vs variable speed pump using power prices from 2021.

	No PHS	Fixed Speed Pump	Variable Speed Pump
Grid utilization [%]	40,644	40.911	40.927
Wind power curtailed [MWh]	10 214	3 730	3705
Total pumping power [MWh]	-	89 240	88 370
Revenue hydro plant [MEUR]	7,167	8,093	8,096
Revenue wind farm [MEUR]	14,532	14,811	14,813
Combined revenue [MEUR]	21,699	22,904	22,910

C. Multi-Objective Simulations

The resulting pay-off table in the case study resulted in a range of $9.03 - 35.19$ MEUR for the total revenue, and $0 - 4045.66$ for the damage.

The obtained Pareto front from the multi-objective is presented in Figure 6, showing the Pareto optimal solutions.

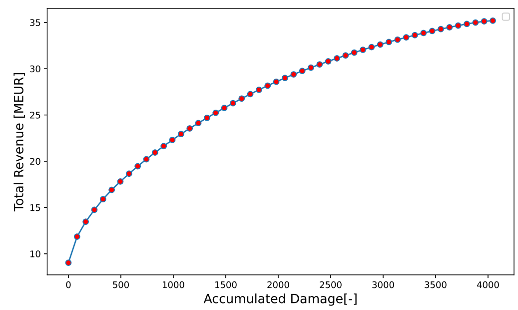

Fig. 6. Pareto front for 50 grid points

Further, Figure 7 presents the utility value for every Pareto optimal solution given in Figure 6 using the different weights from Table I. The utility values are obtained using the multi-objective framework presented in Section III-C

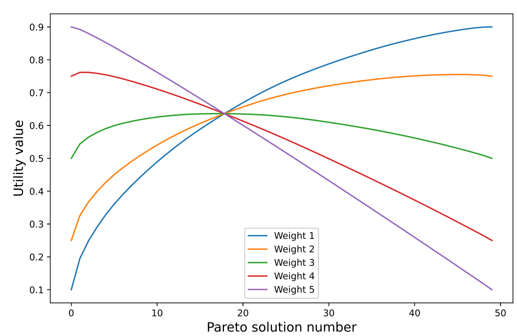

Fig. 7. Utility value for the different weights, using fuzzy logic.

V. Discussion

The utilization of pumped hydro storage in the hybrid power plant system has been found to offer significant advantages, including a reduction in wind curtailment and an increase in revenue. However, the benefits related to grid utilization are somewhat limited. A major contributing factor to this limitation is the dissipation of energy that takes place during the pumping stage. Despite this drawback, there are still clear benefits to be gained from integrating pumped hydro storage into the grid, as it enables the production of power to be shifted towards periods of high demand. The results presented in Table II show no significant benefits of using a variable speed pump compared to a fixed speed pump. One reason is that the fixed-speed pump is sufficient to utilize seasonal price differences. However, the benefits of increasing the hydro pump's efficiency by adjusting the speed toward its optimal operating point are not considered in the simulations. The variable speed pump may also be of great value to the system operator because it offers more flexibility and improves ancillary services. The multi-objective optimization analysis demonstrates that the minimization of wind turbine damage, causing no power production from the wind farm, would result in a substantial reduction in income. However, this is not a realistic scenario, as investors generally seek to realize a swift return on their investments. A coordinated approach that leverages the flexible operation of hydropower and selectively produces energy during periods of elevated electricity prices can potentially achieve acceptable levels for both objectives. This strategy has the potential to obtain satisfactory revenue while simultaneously mitigating damage to the wind farm. Overall, these findings suggest that a careful balance of different energy sources and production strategies can lead to improved performance and greater financial returns for stakeholders.

VI. Conclusion and further work

Overall, the study highlights the importance of coordinated operation and control strategies for maximizing the benefits of the power system. The results underline this with achieved improvements in revenue and curtailed energy by utilizing a PHS system. Moreover, by implementing the co-simulation multi-objective framework, the overall potential benefit attained for conflicting objectives is demonstrated. The coordinated operation of wind and hydropower optimization strategies, supported up by appropriate control strategies, is projected to deliver significant techno-economic advantages to Norwegian power market stakeholders such as the transmission system operator and wind and hydropower plant operators. The framework may be extended to include other significant aspects important for the modelling, resulting in a more realistic case study. This includes stochastic programming of uncertain parameters, realistic power flow studies and the inclusion of environmental constraints for the hydro plant. Further, the wind farm control may also consider adding an objective of ancillary services and minimization of power fluctuations. As mentioned in Section III-E, the output from the wind farm control simulations is only based on restricted input data due to computation limitations. In further studies, simulations using complete real ambient wind conditions throughout the year may provide more realistic results. The computational efforts required may be reduced by implementing multiprocessing parallelization.

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