Flexibility provision from battery storage and PV inverters using IoT platform: Real-life demonstrations at Chalmers campus

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***Abstract*— In this paper the real-life demonstrations for grid control and flexibility intervention based on advanced controllability of flexible resources that were performed at Chalmers University of Technology campus are presented. The demonstration activities were facilitated by the implementation of an IoT platform, which was also used for the visualization and assessment of the results. Through the demonstrations, the successful integration of the required tools to the IoT platform, as well as the efficient employment of the platform for real-life applications have been validated. The evaluation of the results against the defined key performance indicators (KPIs) shows that the coordinated voltage control by solar PVs through model predictive control (MPC) efficiently keeps voltage within the desired limits, while the optimization algorithm for battery energy storage systems (BESs) dispatch for flexibility service (FS) provision, provides financial benefits to the energy cluster that includes the BES, minimizing its energy cost.**

***Index Terms*— Battery storage, Flexibility provision, IoT platform, Real-life demonstrations, Voltage control**

I. Introduction

The need for energy transition increases the challenges in future distribution networks [1]-[4]. In addition, the use of demand side flexibility further increases distribution network complexity, while raising its controllability challenges. Moreover, the increasing installation of distributed energy resources (DERs), especially solar photovoltaics (PVs), in distribution grids, along with the increasing number of electric vehicles (EVs), lead to deteriorated power quality and local grid congestion issues. Thus, the need for enhanced flexibility and controllability of distribution networks increases [5]-[7].

To address these challenges, the FlexiGrid project [8] developed advanced tools and algorithms for flexibility and controllability enhancement in distribution networks. An IoT platform was designed to integrate the developed tools and algorithms as well as to interface with the control platforms and local assets (i.e., distributed energy resources-DERs) in different distribution networks. To this extent, Chalmers University of Technology campus network has been used to demonstrate in real-life conditions the impact of the developed tools on the advanced controllability of local resources used for grid control and support, as well as for the provision of flexibility services [9]. However, the obtained conclusions can be extended to any environment with smart energy systems.

For the demonstration activities, FlexiGrid IoT platform was interfaced to Chalmers campus network through the monitoring and control platform Webport, already existed on campus [10]. Several test cases were defined to showcase the ability of the developed tools complemented by FlexiGrid IoT platform to support distribution network and increase its flexibility. This paper focusses on: i) the employment of a coordinated voltage control strategy based on an MPC model that controls campus PVs; and ii) the employment of an optimization algorithm for the control of BESs for flexibility exploitation and FS provision from the BESs to the distribution network [11]. The demonstration results were evaluated against the defined KPIs. The assessment of the demonstration activities validates the satisfactory performance of the developed tools and the agility of FlexiGrid IoT platform.

The main contributions of this work are: i) integration of BES optimization and MPC-based coordinated voltage control tools in FlexiGrid IoT platform and real-life demonstration of their efficiency; ii) increased grid flexibility through FS derived by BESs; iii) increased power quality through MPC-based voltage control based on PVs' reactive power control; iv) visualization of the results through the IoT platform; and v) evaluation of the results against KPIs.

II. Demonstration site preparation and IoT platform integration

For the demonstration activities, Chalmers campus network, owned by Akademiska Hus (AH), was used. FlexiGrid IoT platform, developed by SIMAVI, was integrated

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in the existing infrastructure and Chalmers campus Webport platform.

A. *Chalmers Campus demonstration site and used resources*

Chalmers campus consists of several office buildings, lecture halls and research lab facilities. The campus includes different assets i.e., heat pumps, PVs, BESs, and a combined heat and power unit. The one-line diagram of Chalmers campus MV and the used resources are shown in Fig. 1.

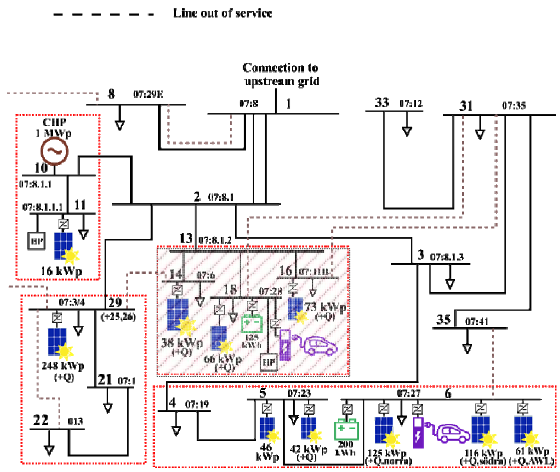

Fig. 1. One-line diagram of Chalmers campus indicating flexibility resources.

For the demonstrations regarding the control of PVs for coordinated voltage control, the PV panels connected at nodes O7:17, O7:27, and O7:24 were used. For the demonstrations regarding the flexibility exploitation for service provision, the BESs connected at nodes O7:27 and O7:28 were used.

B. *IoT Platform features and integration*

A schematic figure of the software gateway developed for Chalmers demonstration site is presented in Fig. 2 [12].

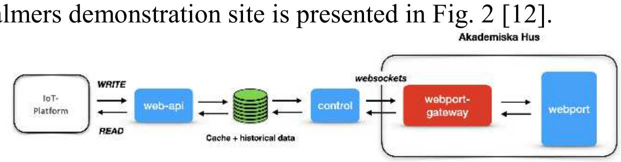

Fig. 2. Overview of the "Webport gateway" that enables external parties to communicate with Akademiska Hus.

The software gateway is installed within AH network and initializes the communication with the existing Webport system, as well as a WebSocket server that enables the communication with a control module running on a Chalmers server. To collect and store the data within Chalmers campus, a time series database was set up using the FIWARE architecture. For this, a middleware layer was created for reading and reformatting data and pushing them into the database using the Orion Context Broker and Quantumleap. The database can then be accessed by other users within the network and the data can be visualized using e.g., Grafana. The control module consists of a WebSocket client that communicates with the gateway and pushes data into a mongoDB database used as a cache for data. A webAPI, based on RestAPI, was designed to enable communication with external systems, such as FlexiGrid IoT platform. The API uses basic HTTP authentication and only allows access to users within Chalmers campus network or to specific IP addresses that have been granted access [12].

In parallel to the already existing Chalmers platform, FlexiGrid IoT platform was integrated on campus to facilitate the demonstration activities through the integration and execution of the developed tools, as well as the visualization and evaluation of the demonstration results. For the integration of FlexiGrid IoT platform, Chalmers platform is used as a local distributed platform (subordinate/edge) capable of getting data, running models, and sending commands. Chalmers platform is linked to FlexiGrid IoT platform and exchanges raw data with it. The raw data represent values from the resources sent by the local platform to the central IoT platform, as well as commands sent by FlexiGrid IoT platform to Chalmers platform for the control of the resources. The developed tools (i.e., MPC-based coordinated voltage control and optimization algorithm for BESs control for FS provision) are also adapted and run on FlexiGrid IoT platform, hence, raw data are transmitted by Chalmers platform to FlexiGrid IoT platform where they are processed, and commands are sent back from FlexiGrid IoT platform to Chalmers platform. The data was read through the webport gateway shorn in Fig 2, using standard restAPI queriesFig. 3 presents an overview of the data sources from which data are collected for the demonstration activities described in this paper [12]. To simplify the procedure, the MPC and the BESs optimisation algorithms were directly run on Chalmers server, and the algorithms automatically sent the set points to the APIs to establish communication with FlexiGrid IoT platform.

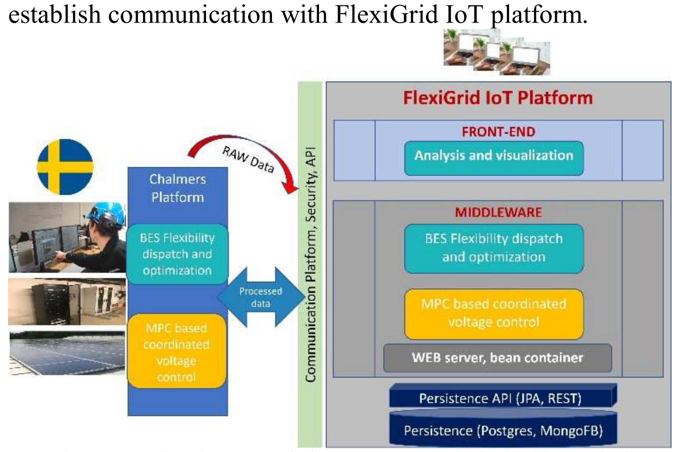

Fig. 3. Data flow between Chalmers campus and FlexiGrid IoT platform.

III. DEMONSTRATION RESULTS AND EVALUATION

Two demonstrated test cases are studied: i) Control of PVs for coordinated voltage based on an MPC model; and ii) Flexibility exploitation for service provision through the optimal dispatch of BESs.

A. *Test cases*

1) *Control of solar PVs inverters for voltage control*

To provide voltage support to distribution grids with increased renewable penetration, a coordinated voltage control scheme based on the MPC technique was implemented on three controllable PVs on Chalmers campus. Voltage control is feasible through the control of PVs' reactive power output Q by controlling the reactive power set-point Q* sent to PV inverters. Thus, when the PVs are used for voltage control, they do not operate at a unity power factor [12]. The developed model illustrates how the voltage $V(k+1)$ at time $k+1$ is intended with the variations in $\Delta u(k)$ while the reactive power output from the converter at time k is conditional on the sensitivity gain ∂V/∂u. The sensitivity gain is formulated using on-site step-response tests or by a static power flow solution. The state space model is presented in (1) [13],[14].

$$V(k+1) = V(k) + \frac{\partial V}{\partial u}\Delta u(k) \quad (1)$$

The various states for the model are the remote bus voltage measurements as well as the inputs to the model to change the reactive power output from inverter. In the MPC controller information is accumulated regarding the control buses of Chalmers demonstration site, its measurement buses, the capacities of the converters controlling the controllable PVs, and voltage limits as input. The controller creates new reactive power set-points (Q*) of the PVs which are controlled at the control nodes. The new reactive power setpoints are input to the PQ controller which provides the required injected active and reactive power to the system at the point of connection of the inverters. For the specific inverters used, the reactive power set-point should be a percentage of PV active power output.

2) Flexibility exploitation for service provision

To provide FSs to the distribution grid, the dispatchable BESs of Chalmers campus were controlled according to an optimization algorithm that considers spot market price. The details of the BES energy scheduling problem solved for the provision of FSs to the upstream network from a part of Chalmers campus that acts as an energy cluster can be found in [11],[12], [15], and [16]. The objective of the optimization problem is to minimize the total cost of energy cluster, and it is calculated by (2), where c_e^t is the total cost of the cluster, c_e^{imp} is the cost of the total imported energy and c_e^{FS} is the total revenue from FS provisions.

$$c_e^t = c_e^{imp} - c_e^{FS} \quad (2)$$

With this control applied on the BES converter, the battery should try to discharge, hence, sell energy to the distribution grid, when the spot market price is high and charge, hence, import energy when the spot market price is low.

B. Demonstration results

1) Control of solar PVs for voltage control

The demonstrations activities were performed from June 12th to June 27th 2023. The voltage at nodes O7:17, O7:27, and O7:24, where the three dispatchable PVs are connected was measured and controlled with a resolution of one minute. The data were read through the webport gateway (Fig 2), using standard restAPI queries.

The voltage profile at node O7:17 and the MPC controller for the PV connected at this node are shown in Fig. 4, through FlexiGrid IoT platform.

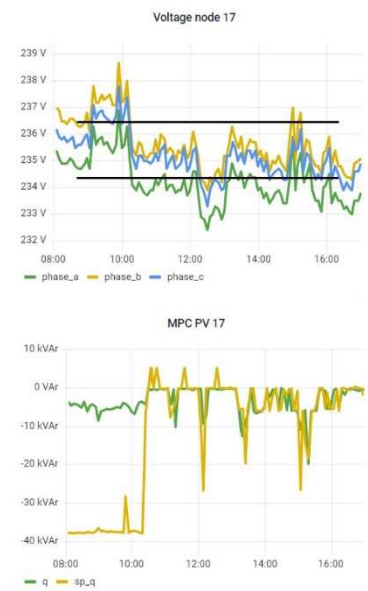

Fig. 4. a) Phase voltages at node O7:17 on June 25th 2023 between 08:00-17:00, b) Reactive power set-point and reactive power measurement on June 25th 2023 between 08:00-17:00.

Since the network was strong a narrow voltage band was selected to activate the voltage control ($[V_{min}, V_{max}]$= [1.01, 1.02] pu). Similarly, the resulting change in voltage was also limited, making it difficult to evaluate the results. With weaker grids a more substantial impact could be achieved.

The MPC controller responds when the voltage limits are violated by setting a new reactive power set-point to the PQ controller of PV's converter (i.e., sp_q in Fig. 4b). It is not guaranteed that the PV can provide the necessary reactive power to keep voltage within limits, as the MPC algorithm evaluates the voltage deviation at all nodes to estimate the need for reactive power and not just node O7:17. Moreover, the reactive power output of the PV depends on its active power production. Thus, when there is limited sunshine, the PV cannot satisfy the command of the controller even though its PQ controller receives a command for a high Q set-point.

Inverter reactive power was limited by active power production. Without any PV production the reactive power output was limited, resulting in a large deviation between the requested setpoint and the delivered reactive power. Moreover, from a practical standpoint the set-up of the communication interface was challenging. By having a close collaboration with the facility owner, it was possible to set up a secure system where the data and measurements could be shared.

2) Flexibility exploitation for service provision

The demonstration results regarding FS provision for the BES connected at node O7:27 are presented in Fig. 5. The active power output of the BES (green line) follows with adequate precision the set-point that is transmitted to the BES converter by the output of the optimization algorithm. The limits (here 20%-80%) of the BES state of charge (blue line) are not violated as they are considered as constraints of the optimization problem.

Fig. 5. Results of the optimization algorithm for flexibility provision by the BES connected to node O7:27.

C. *Evaluation of the demonstation results*

1) *Control of solar PVs for voltage control*

The demonstration results are evaluated against the following KPIs:

a) *Time to set a reactive power set-point*

The demonstration results validate that it is possible to limit PVs' active power output to provide voltage control through reactive power injection. To effectively control reactive power, measurements are collected and fed back to the controller which produces new reactive power set-points for the PV converter. This procedure is iterative. Fig. 6 shows the per phase voltages and power factor changes that are brought by a modification in the reactive power set-point, so that the required reactive power is provided.

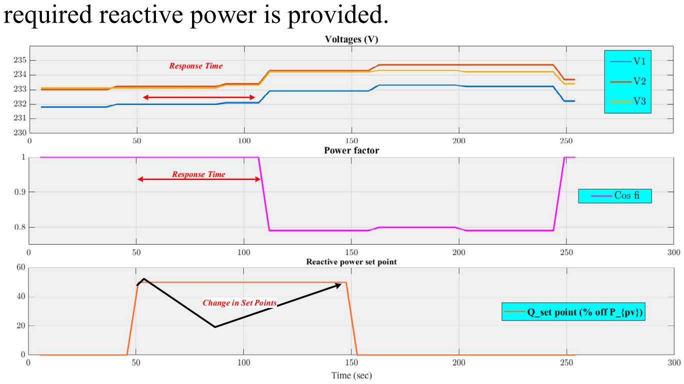

Fig. 6. Variation in the power factor and voltages per phase with the change in Q set-point of PV inverter connected to node O7:24.

With a change in reactive power set-point from 0 to 50% of active power output, the change at voltages and power factor is reflected after 60 seconds, due to the sampling rate of the data collection system/API, which is acceptable for real-life applications.

b) *Reactive power set-point accuracy*

To assess the set-point accuracy, (3) was defined.

$$SPE = \frac{1}{N}\sum_{n=1}^{N}\sum_{i=1}^{T} a_{i,n}, a_{i,n} = \begin{cases} \left|\frac{Q_m - Q_{sp}}{Q_m}\right|, if Q_{sp} < P_m \\ \left|\frac{P_m * Sign_{Qsp} - Q_m}{Q_m}\right|, if Q_{sp} > P_m \end{cases} \quad (3)$$

The reactive power set-point produced by the MPC model does not consider the limitations of the PV at each moment, i.e., its active power generation. In addition, PV reactive output is a predefined percentage of the active power output, which is also not considered by the MPC model. P_m is the measurement of the active power output of PV n at time interval i which is defined as the actual limitation of the reactive power output of PV n at time i, Q_m is the measurement of the reactive power output of PV n at time interval i, Q_{sp} is the desired reactive power set-point produced by the MPC controller, and $Sign_{Qsp}$ is the sign of the reactive power set-point produced by the MPC controller. Set-point error (SPE) represents the difference between Q_{sp} and Q_m. Large SPE values represent situations where PVs' available reactive power is not sufficient to keep the voltage within desired limits. In such cases, more PV capacity might be required, or the weather conditions might not allow for PV-based voltage control. Thus, the presented method should be combined with other voltage control methods.

To evaluate the set-point accuracy of the MPC control, SPE was calculated for the three dispatchable PVs, hence, in each case $N = 1$. The average set-point error for each PV ($\overline{SPE}$) was also calculated to give a better understanding of the set-point accuracy. Finally, the daily average of the set-point accuracy $\overline{SPE}_{day}$ was calculated to separately evaluate accuracy of the tool for each day, given that PVs are heavily affected by weather conditions.

Fig. 7 shows $\overline{SPE}_{day}$ for the PV connected at node O7:17. For most of the days SPE is less than 1, which means that there is a satisfying accuracy of the tool. However, there are some days (i.e., June 12th and June 18th) that create large errors, hence increasing $\overline{SPE}$. For the whole duration of the demonstration activities, $\overline{SPE}$ was found 2.718. Therefore, SPE is on average 2.718 times larger than the reactive power measurement of the PV in absolute value, primarily due to the inability to generate reactive power without active power.

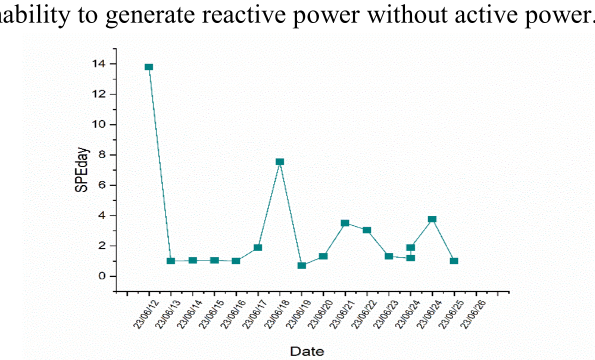

Fig. 7. Daily set-point error of the PV connected at node O7:17.

2) *Flexibility exploitation for service provision*

The results are assessed based on the following KPI:

a) *Profit from BES optimization algorithm employment*

The revenue of the FS provision through the used BES optimization algorithm is calculated as the difference between the cost with and without the BES optimization algorithm employment as per (4), where c_r is the reduced cost, $c_{wo,bes}$ is the energy cost without the operation of the BES optimization algorithm, and $c_{w,bes}$ is the energy cost with the operation of the BES optimization algorithm:

$$c_r = c_{wo,bes} - c_{w,bes} \quad (4)$$

Equation (4) can be concluded as the benefit of operating the BES according to the optimization algorithm. Therefore, the reduced cost can be calculated as per (5):

$$BES_{sav} = \sum_t P_{t,BES} \rho_t^s \, \Delta t \quad (5)$$

P_{BES} is the active power provided by the BES, ρ_t^s is the energy spot market price and t denotes time. The total BES energy for the demonstration activities ($P_{BES} * \Delta t$) indicates the difference between BES charging and discharging. Hence, (5) should calculate the net profit or loss from the use of BES.

To evaluate BES dispatch, we use the demonstration results of the employment of BES optimization algorithm for two different periods (i.e., May 4th-May 5th 2022 and May 11th-May 12th 2022) to the BES connected at node O7:27. The results are summarized in Table I. Negative energy indicates BES discharging, hence, money profit, while positive energy indicates BES charging, hence, money loss. The algorithm promoted BES charging in low prices (i.e., May 4th and 12th) and BES discharged in high prices (i.e., May 5th and 11th).

TABLE I. RESULTS OF BES OPTIMISATION ALGORITHM

Date	***Energy production/consumption (kWh)***	***Total profit/loss (€)***
04/05/2022	4.757	1.053
05/05/2022	-41.93	- 8.92
11/05/2022	- 149.29	- 29.81
12/05/2022	14.83	1.69

The BES optimization algorithm performs satisfactorily, as, in both demonstration periods, results in profit. The total profit for the studied days was almost 35€, while the BES at the end of the demonstrations is charged with almost 170 kWh more compared to the beginning. The resulted savings represent direct monetary savings, and the aging cost has not been included when calculating the aging. However, since the aging cost is part of the objective function the potential profit would be higher than the aging cost. Thus, there is financial profit by FS from the BES optimization algorithm.

IV. CONCLUSIONS

The demonstration activities for enhanced grid control and flexibility intervention were successfully performed at Chalmers campus through the efficient integration of FlexiGrid IoT platform to the existing campus infrastructure. The demonstration results have been visualized through FlexiGrid IoT platform, while they have been evaluated against the defined KPIs. It was validated that the coordinated voltage control based on the MPC method through the control of PVs' reactive power output and the FS provision through the optimization algorithm for the dispatch of BES can be efficiently applied in real-life conditions. Specifically, the MPC-based coordinated voltage control for PVs manages to keep voltage within the desired limits by efficiently controlling the reactive power output of the PV. In addition, the FS provision through an optimization algorithm for the dispatch of BESs provides financial benefits to BES owners, minimizing their energy cost. Hence, the IoT platform implementation along with the employment of intelligent control methods (i.e., MPC-based voltage control, FS provision from batteries) can lead to increased energy system flexibility as well as financial benefits for flexibility providers.

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