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Agent based demand flexibility management for wind power forecasting error mitigation using the SG-BEMS framework

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***Abstract*—The integration process of renewable energy sources (RES) and distributed energy resources (DER) into the power system, is characterized by concerns that originate from their stochastic and uncontrollable nature. This means that system operators require reliable forecasting tools, in order to ensure efficient and reliable operation. Accordingly, this paper proposes the use of demand flexibility, to counteract the RES forecasting errors. For this purpose, distributed and decentralized intelligence is used, via the SG-BEMS framework, to invoke demand flexibility in a timely and effective fashion, while taking into account the negative effects on the building occupants comfort. Lastly, numerical results from a simulated case of study are presented, which confirm that demand flexibility can be used to mitigate the magnitude of forecast errors.**

Keywords*—Demand flexibility, wind integration, multi-agent systems, energy management.

I. INTRODUCTION

The electric power system has a dynamic structure, under constant change, and operated under uncertainty. Despite the recent economic crises, and the decline in oil prices, renewable energy sources (RES) have continued to grow to represent around 58% of the net additions to the global installed power capacity, comprising 28% of the world's power generation capacity by the end 2014 [1]. However, their integration into the power system poses a series of challenges, due to their stochastic, and uncontrollable nature. Compared to traditional power generation, the uncertainty in the generated power from RES technologies, such as wind turbines, translates into the need for more spinning reserves to prepare for the unforeseen power output changes, i.e., the forecast errors. Consequently, the accuracy of RES power generation forecasting is paramount in the integration process of these technologies. For instance, it has been stated that the costs of wind power prediction errors can reach as much as 10% of the total incomes from the generated energy [2]. To cope with forecast uncertainty and limited reserves, RES power output curtailment is taken as a measure to reduce the adverse effects of RES operation. Nevertheless, this results in a decreased generator efficiency, longer investment recovery times, and ultimately increased electricity prices. Furthermore, as the penetration of RES grows larger, the curtailment capacity is also increased. For example in China, where the wind power installed capacity has increased dramatically, the curtailed power quadrupled between 2010 and 2013; such quantity amounts to close to 10% of the total wind power installed capacity [3], [4].

Traditionally, electricity demand is considered uncontrollable, and power generation is dispatched such that it follows the power demand. However, the integration of computational intelligence and the advances in ICT, among other factors, are pushing for a change of the power systems operation. Through demand side management (DSM) and demand response (DR) programs, the role of demand side actions in the operation of the power system is highlighted. Being responsible for about one-third of the energy consumed in cities [5], non-residential buildings have the potential to significantly contribute to the efficient operation of the power system, accommodate a higher amount of RES, increase asset utilization, and reduce peak demand [6], [7]. Multiple studies have been carried out that demonstrate the viability of network support, and ancillary services by exploiting flexibility from buildings, such as voltage support, supply and demand matching, peak reduction, and congestion management [8]–[14]. This adaptable behavior of loads is commonly referred to as demand flexibility, and broadly defined as: '*the changes in consumption/injection of electrical power from/to the power system from their current/ normal patterns in response to certain signals, either voluntarily or mandatory*' [15]. However, the building and the power system are treated independently, and operated based on their own targets, simplifying their interoperation.

Therefore, to cope with the high complexity of the emerging power system, a shift is necessary from centralized energy management system, to a decentralized structure. In such structure, the global and local objectives must be achieved through the cooperation, and coordination of the different parts of the emerging power system. In contrast to traditional power systems, in the emerging structure, the flow of demand flexibility becomes an important commodity for efficient and reliable operation under increased uncertainty. Under the Smart Grid and Building Energy Management System (SG-BEMS) framework [16], the main objective is to fully invoke the flexibility from the built environment, to assist in achieving the

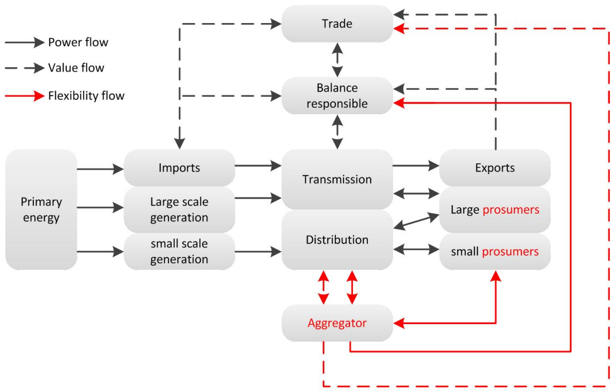

Fig. 1. The value chain of the emerging power system

energy efficiency and sustainable goals of the power system, with comfort as a necessary metric for this flexibility. Based on a multi-agent system (MAS) control structure, the SG-BEMS framework, reduces the control and communication burden through a mixture of decentralized and hierarchical control structures. Throughout the literature, MAS is being applied, not only in a wide range of applications in the power systems [17], [18], but also in the area of building automation, building energy management, and building control and operation [19]–[23].

Building on the previous works, i.e., [16], [24], this paper proposes the use of demand flexibility, under the SG-BEMS framework, to absorb the wind power forecasting error. Using a multi-agent system based platform, the integration and control of the flexible demand resources, i.e. non-residential buildings, is enabled, with the objective of compensating for the forecast uncertainty, while maintaining the building comfort. The rest of the paper is organized as follows: In section II, the SG-BEMS framework is presented in detail, and in section III the problem formulation is introduced. Subsequently, in sections IV and V, the agent based control and the methodology are discussed, respectively. In section VI, the results from the simulation based case study are presented and discussed. Finally, the paper is closed with some concluding remarks on the work.

II. THE SG-BEMS FRAMEWORK

The intertwined operation of the power system and the built environment is a complex task, in which different operation principles, strategies and goals have to be taken into account. Traditionally, the power system can be divided in four general domains: *a*) generation; *b*) transmission; *c*) distribution; and *d*) demand; while characterized by an unidirectional power and flexibility flow, from the generation to the demand domain. In such a system, the flexible behavior of traditional power generating units is used to adjust their outputs to unforseen changes in the demand and unit failures. However, under the SG-BEMS framework, the demand domain is extended into a prosumer domain, capable of acting as flexibility source, as illustrated in Fig. 1. This means that, under the SG-BEMS framework there is not only a bidirectional power flow, but also a bidirectional flexibility flow.

When looking at the energy use break down of non-residential commercial buildings, it is clear that the largest flexibility potential lies within comfort systems, as more than half of the energy consumed by the building, is used for comfort management, and space conditioning [25]. Therefore, demand flexibility could potentially have a negative impact on the building comfort. Moreover, demand flexibility requires aggregation to have a noticeably positive impact in operating the power system. Thus, cooperation, coordination and negotiation between the different flexible demand resources becomes central in the adopted control strategy. Next, the prosumer domain and the role of the aggregator will be described in detail.

A. The prosumer domain

In the present work we consider a building as a complex multi-zonal comfort system, governed by the energy and mass conservation principles. Furthermore, comfort is a complex and subjective human perception, defined mostly by the thermal, indoor air, visual and acoustic characteristics of the building. In general, building design and comfort management involve the use of both passive, such as windows, and active systems, like fans. Nevertheless, demand flexibility has a direct impact on the operation of the active comfort systems which include the space heating, air conditioning, and lighting systems. In previous work [**?**], we kept CO_2 concentration levels as a system constraint, and conceptualized comfort as a function of temperature and relative humidity, expressed as a combination of two Gaussian functions representing thermal and air quality comfort, as shown in the following equation:

$$C = \underbrace{\omega\ e^{\left[\frac{-(T-\mu_T)^2}{2\sigma_T^2}\right]}}_{\text{Thermal comfort}} + \underbrace{(1-\omega)e^{\left[\frac{-(R-\mu_R)^2}{2\sigma_R^2}\right]}}_{\text{Air quality comfort}} \tag{1}$$

where C is the building occupants' comfort satisfaction, ω is a weight factor, T is the building's temperature, μ_T is the mean temperature value, or the optimal temperature set point, σ_T is the thermal comfort standard deviation, which represents the discomfort tolerance, R is the relative humidity, μ_R is the mean humidity, or air quality optimal set point, and σ_R is the standard deviation for air quality comfort, which represents the discomfort tolerance.

The total power consumption, in kilowatts $[kW]$, of a building is the result of the operation of the different systems, i.e., comfort and non-comfort, present in the building. In this work, the air handling unit and the heater are the active comfort systems in charge of providing flexibility, namely:

$$P_{total} = \underbrace{P_{AHU} + P_{heater} +}_{\text{comfort}} \underbrace{\sum_{i=1}^{Z} P_i}_{\text{non-comfort}} \tag{2}$$

$$P_C = P_{AHU} + P_{heater} \tag{3}$$

where P_{AHU} represents the power demand of the Air Handling Unit (AHU) for air quality comfort, P_{heater} is the power consumed by the heating system for thermal comfort purposes, P_C represents the power demanded by the comfort systems, and P_i represents the power consumed by the zone's devices in the Z zones, e.g., lights, computers, etc. The comfort and energy dynamics are explained in detail in [24].

B. The aggregator role

In the context of the smart grid and smart cities, for flexibility from the built environment to have a noticeable and positive impact on the grid operation, the aggregation of individual flexibility resources is required. This process requires irrelevant information to be neglected, and the simplification of the models used. The task of the aggregator is to collect enough flexibility from the prosumers to meet a flexibility request, to solve network/system issues. This translates into the aggregator role of minimizing the difference between the demand and the flexibility offer.

III. PROBLEM FORMULATION

In this work, the problem is formulated as a two-levels optimization problem. At the first level, i.e., aggregator level, the problem is to make sure that enough flexibility is procured from the prosumers in order to mitigate the forecasting errors, defined as follows:

$$\textbf{Minimize} \quad \Delta\ F = F_d - \sum_{j=1}^{B} F_{s,j} \tag{4}$$

$$\textbf{Subject to} \quad C_j \geq\ C_{min,j}, \text{for } j \in \mathcal{B} \tag{5}$$

where $\mathcal{B} = \{1, \cdots, B\}$ is the set of buildings connected to the network, C_j is the comfort pertaining to the jth building as in (1), and $C_{min,j}$ is the minimum allowable comfort for the jth building. Furthermore, $F_{s,j}$ is the flexibility offer of the jth building, i.e., amount of power the customer can shift or shed; and F_d is the flexibility demand or request, e.g., amount of power to solve the wind power output forecasting error. The flexibility offer can be defined as follows:

$$F_{s,j} = P^n_{C,j} - P^f_{C,j} \tag{6}$$

where, $P^n_{C,j}$ is the nominal power demanded by the comfort systems in building j, (see eq. (3)), and $P^f_{C,j}$ is the amount of power that can be shifted, curtailed, or increased by the comfort systems in building j. Moreover, the flexibility request is described by:

$$F_d = P_{wind,f} - P_{wind,r} \tag{7}$$

where $P_{wind,f}$ is the forecasted wind power output, and $P_{wind,r}$ is the actual power generated.

Finally, at the second level, i.e., prosumer level, the problem is to maximize both comfort and energy use. This is done implicitly in the system model, as shown in [16].

IV. AGENT BASED CONTROL

The emerging power system, as described before, is highly complex, with an increasing number of subsystems that are involved in monitoring, control and operation tasks. By dividing the large control task into smaller sub-tasks, agent based systems aim to tackle complex problems, while relying on the cooperation, coordination and negotiation of individual agents. Throughout the literature, the agent concept has been given multiple definitions, having as a common basis the fact that an agent is an entity embedded in an environment, and capable of reacting autonomously to changes in that environment [26]. Therefore, an intelligent agent should exhibit: *a*) reactivity, that is, ability to react to changes in its environment in a timely fashion; *b*) proactiveness, i.e., goal-directed behavior; and *c*) the ability to interact with other intelligent agents, namely, coordinated or competitive behavior.

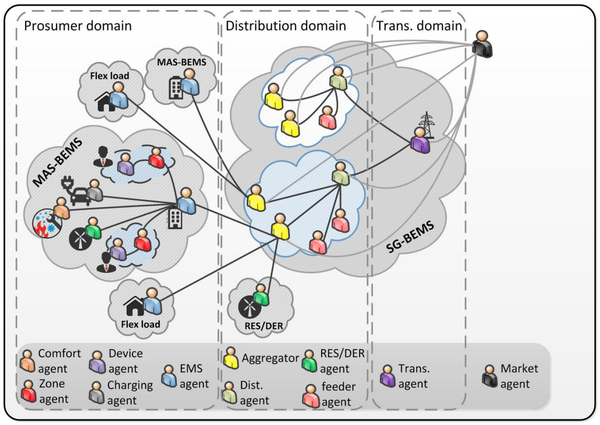

Fig. 2. SG-BEMS agent architecture, showing the SG-BEMS domains, control areas, and agents

The SG-BEMS agent architecture is shown in Fig. 2. Due to the characteristics of the prosumer and the SG domains, a hierarchical agent structure is preferred. In such a system, two main control areas are identified: *a*) the SG area, and *b*) the built environment area. Thus, multiple control levels can be realized. Within the SG area, the transmission and distribution domains are separated. At the building area, different comfort zones levels can be established, corresponding to the structural division of a building, i.e., floors and rooms. Therefore, the SG-BEMS structure is a dual agent-based control system, that addresses the inter-operation of both the power grid and the buildings.

V. METHODOLOGY

As mentioned before, the central objective of this work is to use the flexible behavior of the prosumers to mitigate the wind power forecast errors. For this purpose, a MV network model, with a $9MW$ wind farm, 15 buildings, and 4 agent classes are developed. The network, prosumers, and wind generator models are done in Simulink/MATLAB, while the SG-BEMS agents are implemented in JADE/Java. A co-simulation is made between the agent platform in JADE/Java environment, and the power system model in Simulink/MATLAB. Through the exchange of information between the MATLAB environment and the agents, the control of the buildings models is achieved.

The single-line diagram of the distribution grid is shown in Fig. 3. It represents a three-phase balanced system formed by 15 commercial prosumers in three MV sub-ring, and a $9MW$ wind farm. There are three types of transformers, a HV/MV distribution transformer $(120kV/25kV)$, a MV/MV transformer $(25kV/10kV)$, and a MV/LV wind farm transformer $(25kV/0.575kV)$ in a wind farm transformer. The MV loads are connected through self-owned step down transformers, Table I shows the cable data used for the simulations.

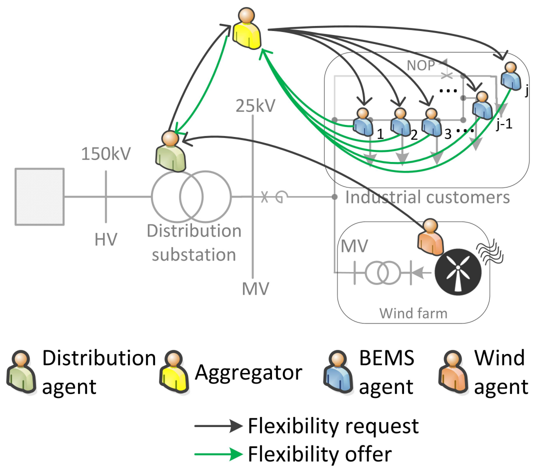

Fig. 3. Network model, showing the schematic of the system used for simulation

TABLE I. CABLE INFORMATION

No. Sections	Length $[m]$	R $[\Omega/km]$	L $[mH/km]$	Description
1	20e3	0.1153	0.105	25KV bus cable
1	1140	0.07	0.246	10KV bus cable
5	287 [avg]	0.532	0.311	MV sub-ring cable

Envelope models are used to describe the building energy and comfort behavior, while using different areas and construction material as shown in tables II and III[1]. Finally, we make use of the Wind model based on the Van der Hoven spectrum from [27]. This model considers a wind spectrum divided in two parts, namely, a turbulent wind contributing to the fast components and a mean wind accounting for the slower components. The purpose of the wind model is to provide the input wind to the wind agent, i.e., the wind speed that will ultimately determine the power output of the wind agent, as well as the wind power forecast signal.

A hierarchical agent structure is used to evoke demand flexibility and minimize the difference between the flexibility demand and offer, as described in eq. (4). It is assumed that agents have incomplete information and insufficient capabilities to solve the task autonomously. A TCP/IP communication is established between the two software platforms, with Simulink/MATLAB as the server client. The system response is simulated in seconds using Simulink/MATLAB, whereas the MAS based SG-BEMS interaction, i.e., observation, is done in 15 minutes intervals for the BEMS and distribution agents, while in a minute interval for the wind agent. Finally, the feedback, namely the control actions, are implement as event driven communication. Subsequently, the different agent instances are described in detail.

a) ***Distribution grid agent:*** The distribution agent is in charge of monitoring and controlling the distribution network operation. It is responsible for establishing the flexibility request, F_d, based on the local information and the information received from the wind agent.

TABLE II. BUILDING CHARACTERISTIC INFORMATION

Building	Floor Area $[m^2]$	No. Floors	Floor height [m]
A	$554, 25$	3	3.048
B	1005	12	3.048
C	4535	9	3.048
D	5233.58	6	3.048
E	9034	5	3.048

TABLE III. CONSTRUCTION DATA

	U value $[W/m^2/^\circ K]$	
Wall	Roof	Window
0.62	0.31	3.35
0.77	0.37	3.23
0.48	0.22	4.43
2.71	0.40	5.84
3.68	0.38	5.84
0.78	0.22	13.83

b) ***The aggregator agent:*** The role of the aggregator is to procure flexibility from the prosumer, in an economic and efficient way to meet the flexibility demand of its portfolio. It collects information from the portfolio of prosumers, and the distribution agent. Based on the information gathered, it establishes the $F_{s,j}\ \forall\ j\ \in\ \mathcal{B}$.

c) ***The building energy management system (BEMS) agent:*** Located at the highest level in the BEMS structure, and takes charge the building operation, while being the link to the distribution network. This agent is able to accept and prioritize requests made by agents and operators outside the building premises, i.e., the aggregator agent. Based on the information received, it optimizes the building operation, this is explained in detail in [24].

d) ***Wind farm agent:*** The wind agent is responsible for the operation of the wind generation units connected to the distribution network; based on the difference between the forecasted and actual power output it creates a flexibility request that is send to the distribution agent, $F_d = P_{wind,f} - P_{wind,r}$.

A. Control strategies and agent coordination

In order to solve the optimization problem described in eq. (4)-(5), two agent coordination strategies are implemented, as shown in Fig. 4. The first coordination strategy, "agent control 1", involves unidirectional communication from the aggregator to the BEMS agents. Once a request for flexibility, (F_d), is received by the aggregator, it establishes the type of action each BEMS argent should take. This is followed by an action request to each BEMS agent in the aggregator's portfolio. In turn, the BEMS agent takes the information received from the aggregator, and based on the occupancy and comfort state of the building, the BEMS agent decides on the action to take. This is repeated once a new flexibility request is received by the aggregator.

The second coordination strategy, "agent control 2" uses bidirectional communication between the aggregator and each BEMS agent. In a first step, the aggregator sends a request to each BEMS agent, that contains the type of flexibility required. In a second step, each BEMS agent replies to the aggregator with an flexibility offer vector. Finally, after receiving the offers of all the BEMS agents in its portfolio, the aggregator creates a dispatch order that matches the flexibility request, using a simple search algorithm. The result is sent to each

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[1] Each building size (Table II) is modeled three times using different construction information (Table III).

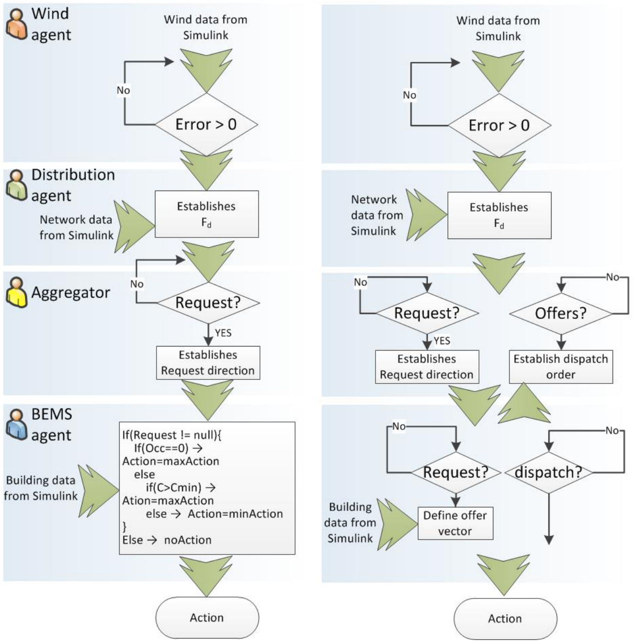

Fig. 4. Agent coordination, showing on the left the agent control 1 strategy and on the right the ageny control 2 strategy; the green arrows describe a TCP/IP communication step

BEMS agent, who takes the appropriate action. This is repeated once a new flexibility request is received by the aggregator.

VI. RESULTS AND ANALYSIS

Simulations are ran for a single winter day in the Netherlands. Fig. 5 shows the forecasted, and actual wind power production of the wind farm, as well as the resulting forecast error signal. For comparisons purposes, a business as usual (BAU) scenario is simulated, to assess the building action contribution under each agent coordination strategy. Fig. 6 shows the aggregated power demand and averaged comfort of the total number of prosumers. Under the BAU scenario, the buildings are operated to maximize comfort based on the occupancy information. This is shown in Fig. 6, where it can be observed that comfort starts increasing as the day starts and attaining its maximum during the day time (working hours). In order to mitigate the wind output forecast error, each building modifies its operation behavior, as it is shown in the aforementioned figure. In turn, this affects the comfort in each buildings. However, when only the required flexibility is dispatched, i.e., agent control 2, the loss of comfort is reduced. This is due to the fact that under the first coordination strategy, each building is asked to provide its maximum flexibility, which, at the aggregated level, could be more than needed.

In addition, Fig. 7 depicts the resulting wind forecast deviation, where it can be appreciated that, both coordination strategies help mitigate the forecast error by acting in the right direction and in the right times. In general, the wind forecast error is reduced 13%, i.e., agent control 1. Although enough energy is shifted by the buildings to mitigate most of the forecasting error, that is about 80% of the error energy, due to the communication and control delays, there is a delay in the response and the request of about a minute, which translates into an unnecessary contribution from the prosumers. This is shown in the zoomed box in Fig. 7. Lastly, by enabling a bidirectional communication, the aggregator can create an improved dispatch order for its resources, reducing the amount of over/under flexibility offer. This translates into a error reduction improvement of 12% by the second coordination

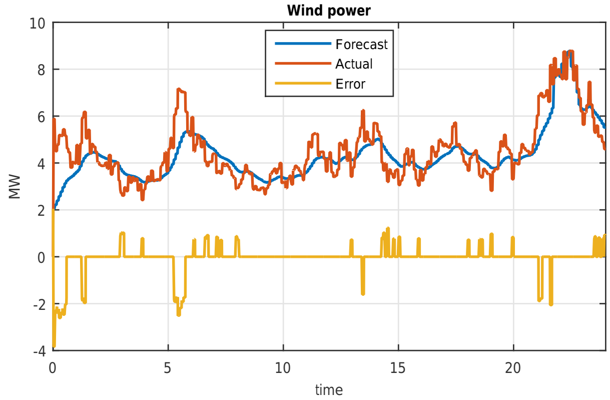

Fig. 5. Wind power output, showing the expected and the actual power output

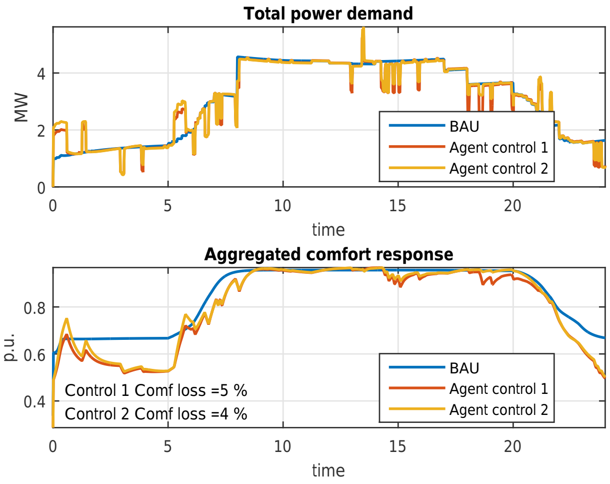

Fig. 6. Top figure: aggregated building power demand, showing the total BAU demand vs the agent controlled demand. Bottom figure: average comfort variation

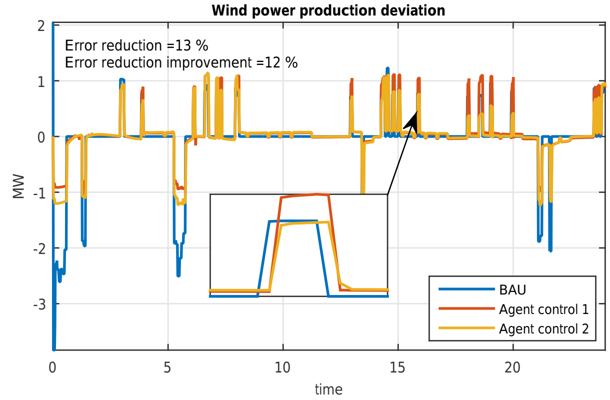

Fig. 7. Deviation from the wind power forecast and the actual power production, showing the difference between the deviation with BAU demand vs the error with agent controlled demand

strategy.

VII. CONCLUSIONS

In this paper the usage of demand flexibility, under the SG-BEMS framework, was investigated to mitigate the wind power generation forecast errors. From the presented results, it is clear that an inter-operation framework that enables the smart behavior of prosumers in benefit of not only local goals but also the grid operation, requires an adequate flexibility dispatch and an appropriate agent decision making strategy. Nevertheless, it is clear that the SG-BEMS platform and the SG-BEMS framework have the potential to invoke the demand flexibility of the built environment and assist the integration process of RES technologies into the power system. Moreover, it is shown that through an aggregator, large buildings can offer enough flexility to facilitate the integration process of RES into the power system. However, such flexility has an impact on the comfort of the buildings, i.e. about 5% comfort loss. One could argue that the comfort loss is not steep, but it can be reduced by the smart dispatch of the flexible resources and the use of the structural energy storage of the buildings.

Finally, despite being able to shift enough energy to significantly reduce the forecast error, a major issue is the synchronization of the flexible resources. Time delays could potentially result in energy being shifted in times in which is not required. Therefore, this type of application requires fast response systems, and reliable communication. It is clear that demand flexibility can contribute to the efficient and reliable operation of the power system.

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