Performance Analysis of Building Integrated Microgrid with Electric Vehicle Integration using Typhoon HIL

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Abstract—Building integrated microgrids (BIMs) present a promising step towards a more efficient, decentralized and sustainable power system. Many buildings already have various renewable energy sources (RES) integrated, but the next step is adding energy storage (ES) systems, or proactive loads such as electric vehicles (EVs) to an already established system. However, ensuring the resilience of the system to accept these new elements presents a challenge in terms of stability, efficiency, and operational capability. This paper focuses on size optimized BIM simulated on Typhoon Hardware-in-the-Loop (HIL) platform using real measured load and PV production data. A rule-based energy management system (EMS) is proposed and its effective-ness is analyzed through testing resilience of the system under consideration. Performance analysis is conducted by adding an EV and assessing system response in several scenarios of load and EV use profiles. Through Typhoon HIL simulations the power profiles of system elements are analyzed, leading to conclusions on BIM performance.

Index Terms—building integrated microgrid, energy storage system, electric vehicle integration, hardware in the loop simulation, smart cities

I. INTRODUCTION

Recent years have been turbulent regarding upgrading of the power system. New RES were integrated into urban infrastructure in the transition towards more sustainable energy systems [1]. The building integrated small renewable power sources, have high potential to push the energy community towards greener power system [2]. The most common option for energy saving so far, in the building integrated power systems was introducing photovoltaic (PV) systems, which could, with the possibility of control, be considered as microgrids or BIMs [3], [4]. BIMs offer decentralized energy generation, low transmission losses and local management and control all practically seamlessly integrated within urban environment with relatively small investments. BIMs have the potential to enhance energy resilience, reduce dependency on centralized power grids, and mitigate environmental impacts associated with traditional energy generation.

While the introduction of renewable energy technologies in buildings is not new, and has seen considerable progress, the next step lies in fluent integration of additional distributed energy resources (DER) into existing BIM setup [5]–[7]. Those DER include increasing the capacity of existing sources or adding new RES, integrating ES like batteries, or EVs [8]–[11]. For a microgrid designed and implemented for existing load profile adding new elements present an opportunity as well as a challenge. The addition of ES systems can enhance energy storage capacity, thereby improving system flexibility and reliability. Similarly, integrating EVs into BIMs, taking into account the possibility of using them as dynamic energy storage, can provide opportunities for demand response, vehicle-to-grid (V2G) services, and enhanced energy utilization. However, ensuring the resilience and optimal operation of BIMs in the face of these new elements poses a challenge.

Modelling of a complex system with many interconnected elements, operating with several time constants, such as microgrid is not an easy task. If power electronic elements are included it becomes even more difficult. Testing such systems under realistic conditions can be very difficult and expensive. HIL technology enables designing and testing a virtual model of the system which is able to replace a physical prototype of the system. Typhoon HIL is recognized as a platform which enables design, testing, verifying and validation of power electronics, microgrids, e-Mobility and distribution control and protection systems [12]–[14].

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System under study is an grid-connected BIM, with real measured data based load profile, PV production profile and estimated battery ES. The sizing of system elements could be determined with arbitrary methods, and here was determined using particle swarm optimization method following some previous research on the same system. This paper addresses the need to evaluate the resilience and performance of such BIMs with integrated DER, particularly focusing on the integration of EVs, all under a zero energy export (ZEE) grid policy [15], [16]. Using the Typhoon HIL platform, system is modelled, and a rule-based EMS is developed to accommodate the dynamic interactions between renewable energy generation, building loads, and EV charging demands. Through resilience testing and performance analysis, we aim to assess the effectiveness of the proposed EMS in maintaining system stability, efficiency, and operational capability.

This paper is organized as follows. The structure and EMS of a standard BIM are presented in chapter II. A performance analysis for several microgrid operational scenarios based on real input data set and performed on Typhoon HIL platform is presented in chapter III. Final IV chapter summarizes the main conclusions and offers some future steps.

II. STRUCTURE AND ENERGY MANAGEMENT SYSTEM FOR BUILDING INTEGRATED MICROGRID

A. *Standard Structure of BIM*

The typical structure of a BIM is shown in Fig. 1, and it consists of a grid connected PV system, ES system and EV charging system. A smart meter with closed-loop controller enables regulation of the power and performs energy management, defined in the next subsection.

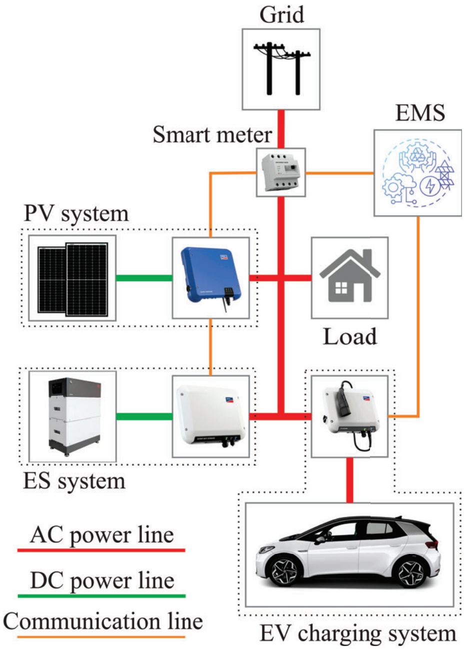

Fig. 1: Structure of a BIM

The BIM incorporates rooftop installed PV system to generate electricity from sunlight. The energy production profile of a solar PV system depends on the solar irradiance, the azimuth and tilt angle of the PV modules, the efficiency of the PV modules, the number and power of the PV modules, etc. The daily production profile for the solar PV system is usually S-shaped. For the oversized solar PV system, the profile is truncated S-shape. Typically, the production profile of a PV system depends on the size of the PV inverter. In situations where there are restrictions such as ZEE limitations, smart PV inverters are used, which can limit the power that is generated and supplied to the microgrid.

ES system is intended to store excess PV generated energy during sunny periods and discharge it when needed. There are several types of ES elements used in microgrids, but the lithium-ion battery based systems currently outperform the other types. Their advantages include low mass, high energy density, and low loss of charge, but significant drawbacks are the relatively high price and risk of bursting. For ES systems, it is important to take into consideration their state of charge (SoC) which represents a relative measure of the amount of energy stored in the storage element and it is defined as the ratio between the amount of charge extractable from the batteries at a specific point of time and the total capacity. The batteries are connected to a microgrid through a battery power converter equipped with smart functionality. This inverter must operate within a dynamic regime that follows the tasks set by the EMS.

The BIM can also provide EV charging infrastructure. EV owners can connect their vehicles to charging stations within the microgrid to recharge their batteries. Here, it should be emphasized that smart charging technology is very important. EV charger should prioritize charging when solar production is high, minimize charging during peak grid demand periods, and adjust charging rates based on grid conditions and electricity prices. Sometimes, the bi-directional charging concept is implemented in microgrid, allowing EVs to not only charge from the microgrid but also discharge stored energy back into the grid when needed. This is known as V2G concept and can help balance supply and demand within the microgrid. V2G concept can improve the microgrid performance due to larger storage capacity and reduce energy storage installation costs. Operation mode of EV charger depends on instructions of EMS.

In the microgrid structure shown in Fig. 1, a smart meter is an advanced metering device that enables real-time monitoring and management of energy consumption and generation within the microgrid. Together with EMS, smart meter optimizes energy usage, minimizes energy losses, and maintains grid stability, all while adhering to ZEE limitation.

B. *Energy Management System of BIM*

EMS plays a crucial role in balancing supply and demand, optimizing energy usage, maintaining grid stability, and ensuring efficient operation.

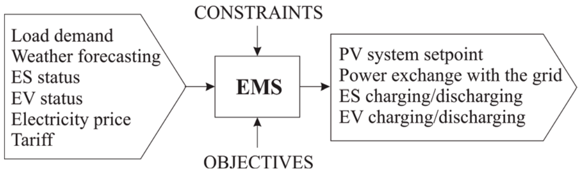

Fig. 2: Energy management system inputs and outputs in microgrids

The important information about EMS, shown in Fig. 2 are its inputs and outputs as well as constraints that are imposed by the distribution system operator, equipment and user. EMS inputs are load and weather data, with possibility to use measured or forecast data, and market data including electricity prices and tariff rules. For the considered algorithm the real measured load profile and PV production profile were used. If the BIM under consideration has elements with ES then their SoC status must be considered in order to maximize efficiency and mitigate buying the power from the grid during peak hours when prices are high. Both the ES and EV batteries are never discharged below 10% and charged above 90%. One important aspect is also the time of use (TOU) tariff. For the analysed case of Bosnia and Herzegovina, the high TOU tariff rate is applied during working days from 6 am to 10 pm and low TOU tariff rate is applied during the rest of the working days and during the weekend. Reducing the uncertainty of the inputs for EMS allows achieving better results, leading to savings for the customers. The outputs of the EMS are commands controlling the: operation of DER elements including PV system set points, operation of ES and EV with the charger, power exchange with the main grid, operation of smart meter and working mode of controllable loads if present. The objectives of EMS are defined depending on customer needs. The main goals of using the ES system and the EV battery in V2G mode are:

1) better utilization of the PV generation because part of the PV generated energy can be stored and therefore the energy that needs to be dumped due to ZEE restriction can be minimized.
2) reducing the electricity bill by charging batteries during low TOU tariff rate and discharging during high TOU tariff rate.
3) trim down the electricity bill by reducing the energy taken from the grid during peak demand (peak shaving).

The constraints depend on the grid policy regarding power export from the BIM, battery and EV charging/discharging constraints and any special requests made by the customer. In the considered case this is related to ZEE policy restrictions.

For proper operation of microgrid shown in Fig. 1, it is necessary to develop the concept of EMS, and based on that to define the rules by which the EMS operates. Taking into account the elements of the microgrid presented in the previous section and ZEE policy imposed by distribution system operator, the following rules are defined regarding the operation of EMS:

Rule 1: If the PV production is higher than or equal to the load demand and ES is not fully charged, there is no need to take energy from the grid and the surplus of PV production can be stored in ES. It is important to note that the load demand can also include EV charging.

Rule 2: If the PV production is higher than or equal to the load demand and ES is fully charged, there is no need to take energy from the grid and the surplus of PV production will be dumped except in the case when the EV battery is connected to the system and charging. After the EV battery is fully charged, the surplus of PV production will be dumped.

Rule 3: The ES and EV battery can be charged from the grid only during low TOU tariff rate on working days.

Rule 4: The ES and EV battery are discharged in order to peak shave the grid supplied energy. The priority for discharging is the EV battery down to 50% SoC, then the ES and after that the EV battery again. The reason for limiting the EV SoC at 50% is to preserve the EV for possible driving until the end of working day. At the end of working day, both ES and EV battery are discharged.

Rule 5: During weekends, both ES and EV battery are charged only if there is surplus of PV production and discharged immediately when the load demand exceeds the PV production.

Rule 6: During collective vacation, both ES and EV battery are discharged during high TOU tariff rate, prioritizing the discharging of the ES.

III. PERFORMANCE ANALYSIS AND DISCUSSION

The analysis was performed using Typhoon HIL solutions. The real-time simulation testbed for BIM structure shown on Fig. 1 is developed on Typhoon HIL 402 unit. Analyzing simulation results helps to assess the efficiency, reliability, and resilience of the microgrid in terms of component sizing, control algorithms, and operational strategies.

Performance analysis of BIM is performed for a University building's PV system with 60 kWp of installed PV modules with a limited power production of 40 kW due to inverter limits, lithium-ion battery ES with total capacity of 40 kWh and a battery inverter of 16 kW. Furthermore, the system contains a 22 kW EV charging system, allowing a maximum charging power of 22 kW as well as 10 kW discharging power if V2G concept is used. For analysis purposes, it is assumed that the University has its own EV, with battery capacity of 75 kWh. Since the car will be used only for business purposes, it will be connected to the charging system during the night and a significant part of the day. Also, during collective summer vacation, the car will stay connected to the charging system and can be used as a battery storage for better utilization of the surplus PV generation due to ZEE limitations.

During the night, both ES and EV battery are charged from the grid. Since the only goal is to fully charge the batteries before the start of next working day and before the high TOU rate, the batteries are charged at a lower power than the maximum one. The building ES is charged at 4 kW, while the EV battery is charged at 6.5 kW.

TABLE I: Daily use of the EV

Day	**Week 1**		**Week 18**		**Week 42**	
	from	**to**	**from**	**to**	**from**	**to**
Monday					09:00 14:00	09:30 16:00
Tuesday			08:30	09:30		
Wednesday			14:30	15:00	14:00	14:30
Thursday	08:30 13:30	10:00 14:30			13:00	14:00
Friday	13:00	13:30	13:00	14:00		

The maximum power taken from the grid is charged for the maximum value measured over one month and during the high TOU tariff rate. Therefore, it is important to have a good estimate for the upcoming month and to adjust the targeted maximum grid power value for each month. During the winter season the consumption of the University building is higher than during the rest of the season. Furthermore, the expected PV generation is lowest during the winter. Therefore, the target maximum power that is allowed to be taken from the grid is chosen at $50\ kW$ for the winter and $35\ kW$ for the rest of the year. It is important to notice that the EV battery is not at disposal at some times during the day when the EV is in use and therefore not connected to the charging system.

Table I shows time intervals when the car was not connected to the charging system in the simulation case. This excludes 33^{rd} week since it is the time of vacation and during that time the car is expected to stay connected to the charging station and it is used in V2G mode. The simulation results obtained for four specific weeks of the year (1^{st}, 18^{th}, 33^{rd} and 42^{nd}) are shown in Fig. 3, Fig. 4, Fig. 5 and Fig. 6.

Week no. 1 starts with two non-working days due to New Year holiday. Such holidays are not treated separately by the EMS and therefore will be managed as regular working days. Both ES and EV are charged during the night at low TOU tariff rate. Since the consumption during non-working days is rather small, there is no need to discharge the batteries for peak shaving. The PV production will lead to reduction of grid supplied power in accordance with the load profile. After the end of working day at $5\ pm$ the batteries start to discharge, first the ES and after that the EV as V2G. At $10\ pm$ the low TOU tariff rate starts and therefore, both ES and EV are getting charged again. The same process repeats on Tuesday as well.

Wednesday is the first working day and is characterized by significant consumption peak of $74\ kW$. Both batteries are used for peak shaving, resulting in successful limitation of grid supplied power to the predefined value of $50\ kW$. The PV production is also helping to reduce the grid supplied power and to slow down the battery discharging. The remaining part of battery energy is used after the end of working day. Similar behaviour is noticed on Thursday and Friday. The only difference is the lower maximum consumption on Friday and no PV production due to snowfall. During the weekend there was no PV production, so the grid supplied power was equal to the load demand.

Weeks no. 18 and 42 have very similar load profiles with a maximum load demand of about $65\ kW$ and $60\ kW$, respectively, on Mondays. Significant PV production, especially during week no. 18 helps to reduce the grid supplied power.

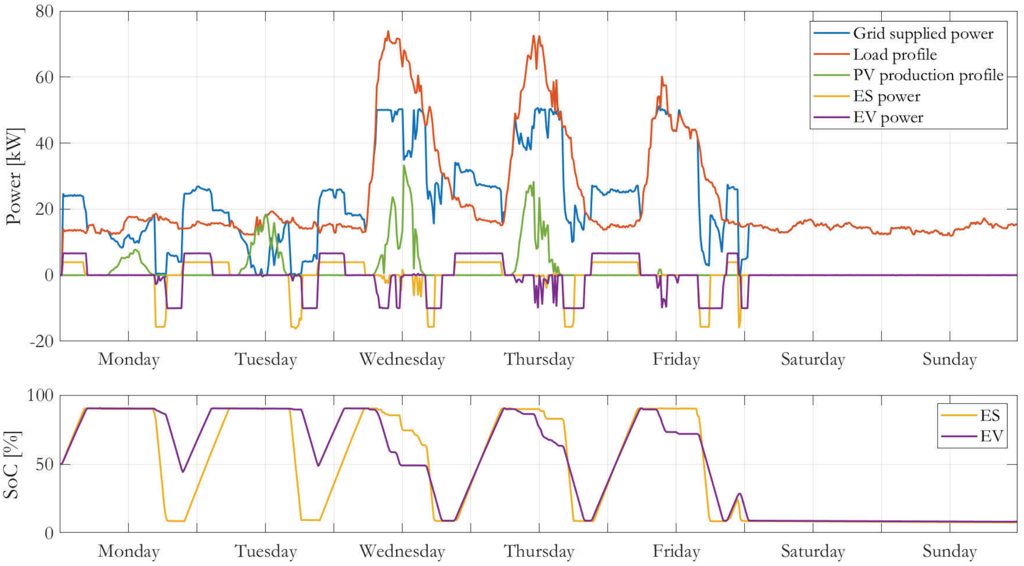

Fig. 3: Power and SoC diagrams for 1^{st} week

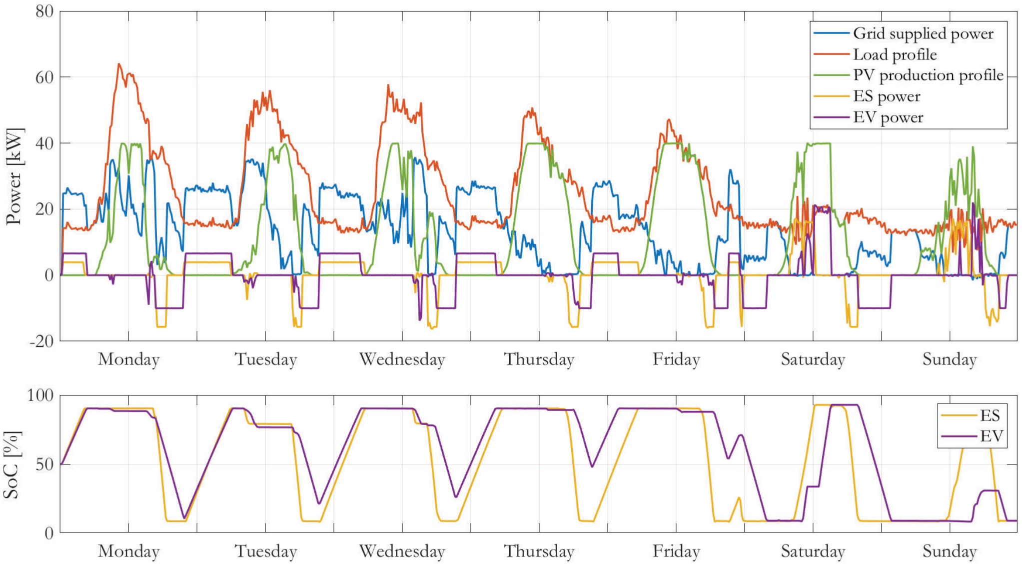

Fig. 4: Power and SoC diagrams for 18^{th} week

However, the batteries still play a crucial role in limiting the maximum grid demand to the predefined value of 35 kW. Unlike week no. 1, with no PV production during the weekend, the PV production during weekends in weeks no. 18 and 42 reduces the grid supplied power and furthermore charges the batteries, which are later used to cover the load demand. In this way the total grid supplied power is significantly reduced during the weekend.

Since the collective vacation for University is during the summer when high PV production is expected, the EMS has to be adjusted for this period to incorporate V2G mode of car use. Since the consumption is very low during this period, the surplus of PV production is used for charging both ES and EV battery. In order to prepare the batteries for the next day charging, the batteries are discharged as soon as the consumption exceeds the PV production. This behaviour is observed for week no. 33.

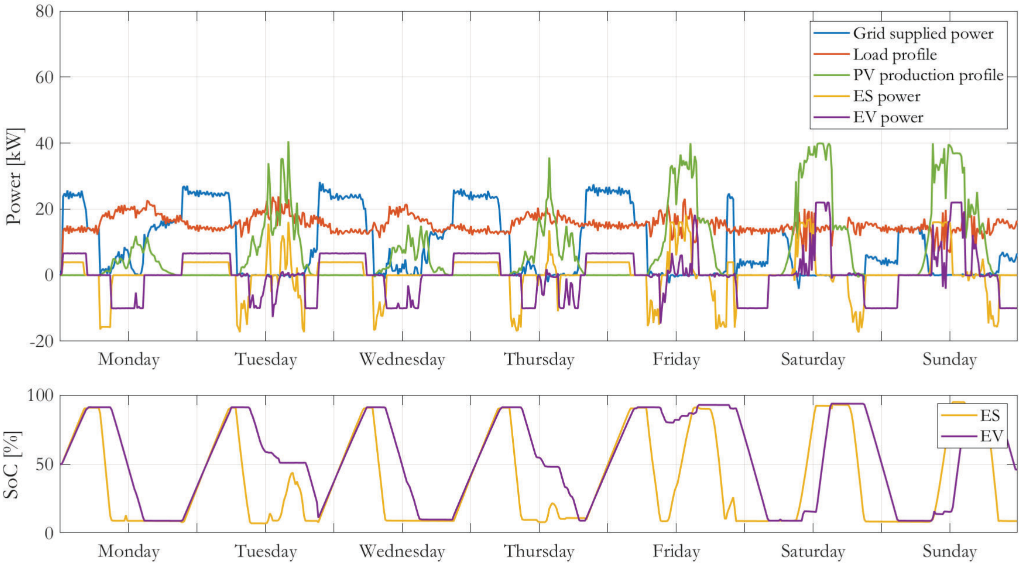

Fig. 5: Power and SoC diagrams for 33^{rd} week

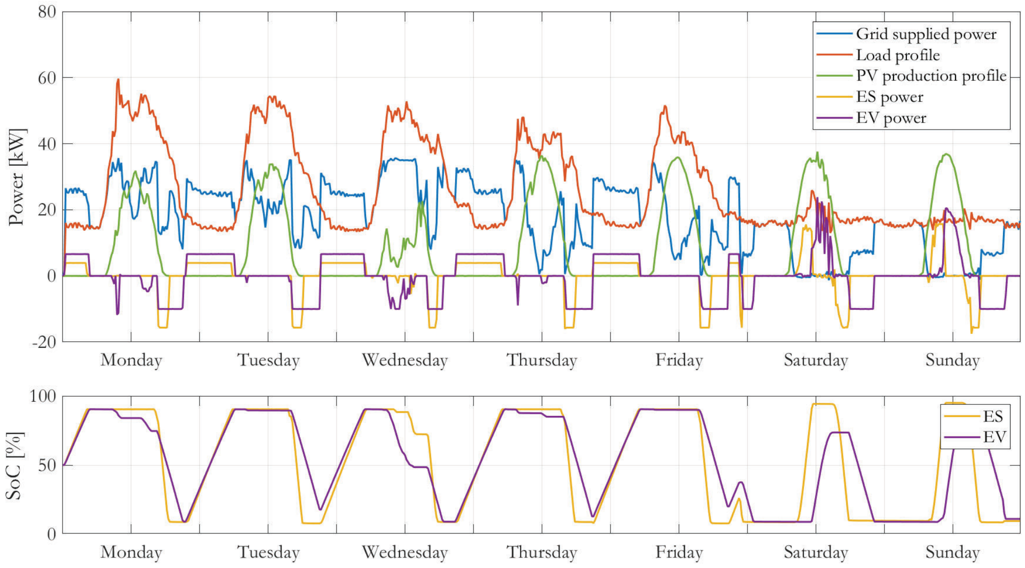

Fig. 6: Power and SoC diagrams for 42^{nd} week

IV. CONCLUSION

In this paper, a BIM with PV system, ES and EV, operating under ZEE policy, is tested using Typhoon HILL platform. The proposed system is implemented to demonstrate performance of resilient rule-based EMS under various scenarios. The system can operate under V2G mode if necessary. Presented experimental study has demonstrated the interactions between batteries, solar system, the grid, and customer loads in several scenarios. Operational results obtained have confirmed the validity of the proposed EMS. The developed algorithm presents one example of EMS for considered BIM and can be easily adapted to achieve different requirements.

The research from this study can help in making informed decisions and developing strategies for the design, deployment, and optimization of BIMs, ultimately contributing to the realization of sustainable and efficient power systems for future smart cities. Future research can be done in the direction of incorporating new rules for the EMS to be applicable to other object types or more complex microgrid systems. Including dynamic load management techniques could also be incorporated into EMS and improve system performance.

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