E. Unamuno et al., "An Interoperable EMS for the Provision of Grid Services with Hybrid Energy Storage Systems," IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, 2022, pp. 1-7.

DOI: https://doi.org/10.1109/IECON49645.2022.9968746

An Interoperable EMS for the Provision of Grid Services with Hybrid Energy Storage Systems

E. Unamuno[1*], H. Polat[2,3], D. Cabezuelo[1], J. Galarza[1], A. Anta[4], E. Toutain[5], T. Geury[2,3] and O. Hegazy[2,3]
[1] Electronics and Computing Department, Mondragon Unibertsitatea, Arrasate-Mondragon, Spain
[2] Vrije Universiteit Brussel (VUB), ETEC Dept., & MOBI-EPOWERS research group, Pleinlaan 2, 1050 Brussels, Belgium
[3] Flanders Make, 3001 Heverlee, Belgium
[4] Austrian Institute of Technology GmbH (AIT), Vienna, Austria
[5] EDF, Lab Les Renardières, 77250 Moret-sur-Loing, France
*E-mail: eunamuno@mondragon.edu

***Abstract*—This paper proposes an interoperable energy management system (EMS) for grid-connected HESSs, enabling the provision of ancillary services to the grid. Power systems are evolving towards a more renewable and decentralised structure, where energy storage systems (ESS) have emerged as a key energy asset to ensure the power balance and the system stability. In this context, hybrid ESSs (HESS) are an interesting solution because they take advantage of the dynamic properties of different ESS technologies. The proposed EMS structure ensures an adequate internal power allocation between the different ESS packs even when operating at power or state of charge limits. The proposed structure can be easily adapted and combined with specific control functions to provide a wide variety of grid services. Moreover, a power dispatch algorithm is included to allocate the power between the parallel power converters to maximise the system efficiency. The results from two representative use cases demonstrate the effectiveness of the proposed EMS to determine the operating setpoints of a modular HESS and to provide different grid-oriented services.**

***Index Terms*—Energy Management Systems, Grid Services, Hybrid Energy Storage Systems, Modular Power Electronic Converters, EV Charging Stations, Frequency Regulation**

I. Introduction

Converter-interfaced energy storage systems (ESSs) have become a key asset to improve the dynamic performance of modern power systems. They can act as an energy buffer to instantaneously balance the requested power (consumption) and the power generated by the inherently variable and distributed renewable energy sources (RESs), and they can provide a wide range of grid services to improve the reliability, power quality and stability of the system with a proper control strategy [1], [2].

In this context, the hybridisation of two or more ESS technologies is generating interest because their different dynamic properties can be combined to extend the overall system lifetime while facilitating the provision of a wider range of grid services [3], [4]. The main idea is to design a solution capable of providing services requesting a fast response as well as a relatively high energy reserve. Some examples of these services are frequency or voltage regulation, maximum power and ramp-rate limitation, harmonic or reactive power compensation, etc. Therefore, hybrid energy storage systems (HESSs) are usually a combination of high energy (HE) and high power (HP) technologies (electrochemical batteries, supercapacitors, flywheels, etc.). In addition to permitting the operation in a wider spectrum of applications, in some cases the HESS can be sized more optimally (reducing the overall system cost), and the accelerated degradation of the HE-type ESS might be decreased by providing the most demanding sudden powers peaks with the HP systems [3], [5].

For the grid connection, HESSs can be also combined with modular power electronic (PE) topologies, significantly improving the reliability of the system and increasing the flexibility and the control degrees of freedom [6]. Fig. 1 illustrates the typical structure of a HESS with a modular PE topology.

One of the main challenges with grid-connected HESS is the internal management of the power and the energy to exploit the advantages offered by the different ESS technologies. Several energy management systems (EMS) have been proposed in the literature to optimise the allocation of power requested by certain grid services. Some of the most relevant control proposals have been recently reviewed in [4], [7]. Such controllers can be grouped into Intelligent and Classical control methods [7]. Classical control methods include rule-, droop- and filter-based algorithms, among others. They consist of relatively simple control structures and can be easily adapted for different applications, operation profiles or HESS structures. In [8], for instance, a filter-based technique is proposed for a hybrid battery/supercapacitor ESS to provide a frequency droop response towards the grid. In [9], a coordination strategy is designed for distributed ESSs in combination with generators to carry

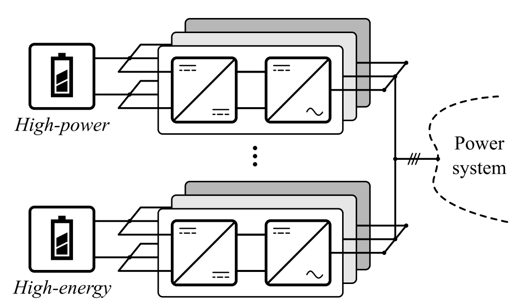

Fig. 1: Conceptual diagram of a HESS with a modular PE topology.

out the frequency support while regulating the state of charge (SoC) to a desired value. In [10], on the other hand, a rule-based EMS is proposed to provide services such as current harmonic mitigation or reactive power transfer. Intelligent control methods, on the other hand, incorporate different types of machine-learning or optimisation algorithms. Usually they are trained with data obtained from the real application or from accurate simulations, so they can provide a better performance. However, they come at the cost of a more complex and demanding control structure and a worse scalability because data-driven algorithms are less tractable and intuitive. In [11], as an example, a deep reinforcement learning controller is designed to provide an enhanced frequency response (EFR) service with multiple parallel ESSs while regulating their SoC level. In [12], on the other hand, a particle swarm optimisation technique is employed to tune the hybrid ESS controller, which is based on a fuzzy logic algorithm.

In most cases, the EMSs proposed in the literature are designed for a specific application and their performance is evaluated under ideal operation conditions—i.e., not at SoC or maximum power boundaries. Moreover, the control structure proposed to split the power setpoint between HP and HE modules is kept at a high level and the combination with lower-level power allocation techniques to take advantage of the modularity of the PE converter is not considered.

The purpose of this paper is to present an interoperable EMS (iEMS) to take advantage of the full capabilities of grid-connected HESSs with modular PE converter topologies. One of the main contributions is that the proposed strategy includes dynamic power and SoC constraint management functions that recalculate the power setpoints when any operation boundary is reached. Besides, an internal SoC balancing algorithm is developed to increase the system's accessible energy. The proposed structure is a combination of classical control functionalities including rule-, filter- and PI-based controllers. The benefits of this approach are that the controller behaviour does not depend on previous data from the system being controlled (as in data-driven algorithms), it does not require an exact mathematical model of the system (as in model-predictive controllers), is computationally efficient (unlike optimisation-based algorithms), and can be easily adapted to systems with other dynamic properties or to provide grid services with different transient response requirements—hence the name interoperable. In combination with the power allocation between HP and HE packs, a control block is included to allocate the power setpoints between the parallel PE converters to maximise the overall system efficiency.

The rest of the paper is structured as follows: Section II provides a detailed description of the proposed iEMS functions, which are then applied to two use cases in Section III. Section IV shows the dynamic performance of the proposed algorithm with time-domain simulations. Section V provides the most relevant findings of the study.

II. Description of the Proposed EMS Algorithm

Most HESS EMS structures proposed in the literature are designed for a particular application, and adapting them for other use cases is either not considered, or cannot be easily carried out because the employed algorithms are specifically designed for a particular ESS or PE converter topology.

The proposed EMS structure is designed to carry out the internal energy and power management of a modular HESS similar to the one shown in Fig. 1. The core control blocks of the proposed EMS are illustrated in Fig. 2, and consist of a power setpoint manager, a SoC constraint manager and a converter power allocation algorithm. The input of the iEMS is an overall power setpoint (p^*) determined by specific control function to provide the requested grid service (discussed in Section III). The outputs are the power setpoints for the PE converters interfacing the ESS packs ($p^*_{i_1}$–$p^*_{i_n}$).

The main characteristics of the iEMS functionalities are described in the following subsections, and even if the explanations are provided for a HESS comprised by a single HP and a single HE battery pack, the implementation could be extended for a HESS with i ESS packs in parallel.

A. Power setpoint management

This control block receives the general power setpoint (p^*) required to provide a certain grid service, and dynamically calculates the power to be provided by each ESS ($p^*_{m_1}$ corresponds to the HP pack and $p^*_{m_2}$ to the HE one). The block is comprised by a power splitting algorithm, an internal SoC balancing regulator and a maximum power constraint manager as illustrated in Fig. 3.

1) Power splitting algorithm: This control function is responsible for dynamically dispatching the power setpoints for the HE and HP battery packs. The algorithm consists of

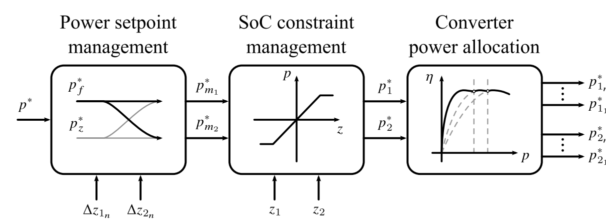

Fig. 2: Proposed interoperable EMS functionalities for HESS and modular PE converter topologies.

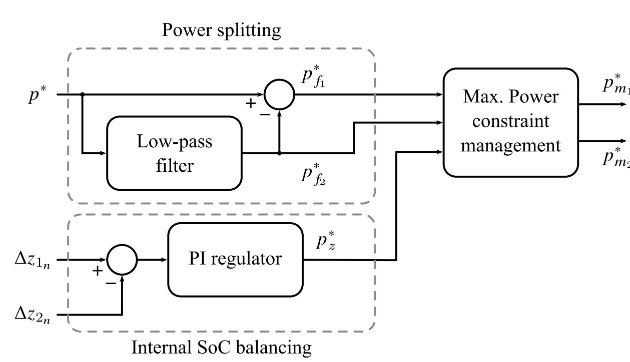

Fig. 3: Control structure of the proposed power setpoint manager.

filtering the overall setpoint with a low-pass filter (LPF) to extract the fast and slow dynamics of the profile. Depending on the dynamic properties of the ESSs, the time constant and gain of the filter can be adjusted to determine the transient and steady-state response of the power setpoints.

If the LPF gain is kept at one, the output $p^*_{f_1}$ will contain the fast transients of the original power setpoint, but its steady-state response will tend towards zero. On the other hand, $p^*_{f_2}$ will contain the slowly-varying response of the original power setpoint. Since the degradation of HE-ESS is, among other factors, closely related to the temperature, current-rate and the fast transients of the exchanged current, the purpose of this algorithm is to take advantage of the faster capabilities of HP packs to avoid over-stressing the HE packs [3].

The design of the LPF will highly depend on the service to be provided. For instance, for frequency-regulation services, the type of grid where the HESS is connected will have a significant influence in the required response time, since the frequency dynamics under power perturbations will be directly related to the inertial strength of the grid [13].

2) Internal SoC balancing: The aim of this function is to increase the accessible energy of the HESS—i.e. to take advantage of all the stored energy—to provide the requested grid service. Similarly to what happens inside a battery module, if the SoC of the ESS pack is not balanced, when one of them reaches an SoC limit the HESS will have to stop providing the service. By dynamically balancing the SoC, ideally all ESSs will reach the SoC boundaries at the same time, meaning that one pack will not limit the operation of the rest. In this paper, a PI-based approach is proposed to calculate the internal SoC balancing power (p^*_z). The diagram can be observed in Fig. 3, and consists of minimising the difference between SoC deviations by a PI regulator.

It is worth noting that the n subscript in Fig. 3 represents that SoC deviations are normalised. This normalisation makes it possible to set different SoC setpoints for the HE and the HP packs, which might be interesting for certain grid services. For a HESS with two parallel battery packs, the SoC normalisation is carried out as follows:

$$\Delta z_{1_n} = \frac{1}{2}\left[\frac{\Delta z_1}{\Delta z_{1_{\max}}} + 1\right] \quad \Delta z_{2_n} = \frac{1}{2}\left[\frac{\Delta z_2}{\Delta z_{2_{\max}}} + 1\right] \tag{1}$$

where $\Delta z_i = z^*_i - z_i$ and $\Delta z_{i_{\max}}$ are the instantaneous and maximum SoC deviation of the i-th battery pack, respectively. From (1), the following normalised values are obtained at specific SoC deviations:

$$\Delta z_{i_n} = \begin{cases} 0, & \Delta z_i = -\Delta z_{i_{\max}} \\ 0.5, & \Delta z_i = 0 \\ 1, & \Delta z_i = \Delta z_{i_{\max}} \end{cases} \tag{2}$$

The normalised SoC deviations are in the $[0, 1]$ range. This normalisation makes it possible to balance the SoC with different setpoint values with a PI-based controller. At this stage it is important to mention that the overall SoC of the HESS is not regulated, since it will directly depend on the power margin left by the type of grid service. As will be detailed in Section III, a frequency-regulation service leaves a very small margin to regulate the overall SoC of the system; however, an HESS connected to an electric vehicle (EV) charging station will have less constraints to regulate the system's SoC to a predefined level.

3) Maximum power constraint management: The last function in the power setpoint manager (shown at the right-hand side of Fig. 3) is aimed at limiting the power setpoints based on the maximum power of each ESS pack. When one of the setpoints exceeds the power limit, this manager checks whether the service-provision setpoints ($p^*_{m_1}$ and $p^*_{m_2}$) and internal SoC balancing setpoint (p^*_z) can be readjusted to continue operating at the maximum power range.

This algorithm is implemented in the form of predefined rules. A simplified diagram of this control block for a single iteration is illustrated in Fig. 4, where $p_{\max_1}$ is the maximum power of the HP pack and $p_{z_{\max}}$ is the margin left to balance the SoC internally. The same rules are then applied for a discharging power (i.e. $p_{f_1} < 0$). The power reference for the HE pack is calculated with the same flow diagram, but with the maximum power being $p_{\max_2}$.

B. SoC constraint management

This control block limits the power setpoints of the battery packs if their SoC reach a predefined limit. The instantaneous SoC is monitored and compared to the predetermined boundaries. In a HESS comprised only by two ESS packs it is very unlikely that the system will be able to continue providing the requested service when one of the packs reaches a SoC boundary. Besides, since the SoC of both packs will be at a similar level thanks to the SoC balancing algorithm, this control block has been designed to bring the power setpoints to zero whenever a SoC boundary is reached or exceeded. The upscaling of this algorithm for an HESS with more than two ESS packs is left as a future research activity.

C. Converter power allocation

PE converters are usually designed to achieve very high efficiency levels when operating near their rated power value. In a modular converter topology (e.g. the one shown in Fig. 1), the conventional approach is to split equally the power setpoint calculated by the EMS between the parallel PE converters.

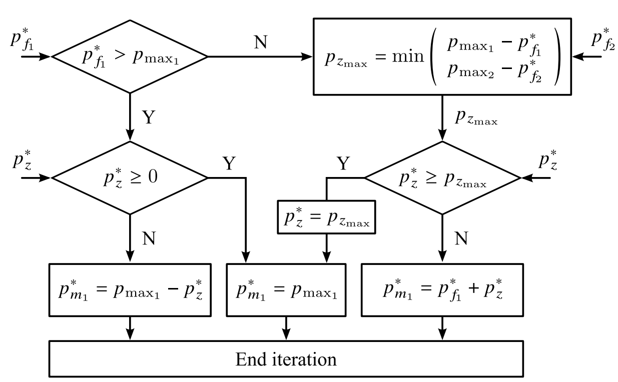

Fig. 4: Rule-based maximum power constraint manager.

As a consequence, the overall system efficiency is negatively affected when operating at low power levels because each converter is transferring only a small percentage of its rated power.

Thus, at low power levels, it makes sense to decrease as much as possible the number of active converters so that they operate closer to their rated power and hence at higher efficiency levels. In [6], Kolar *et al.* determine which power distribution should be established when two or more converters are active, and at which power level an additional converter should be activated. The solution provided in that study is adopted here in combination with the already proposed control blocks. It consists of switching from n to $n+1$ converters at the intersection of the efficiency curves of both configurations. The intersection where the two efficiency values are the same can be expressed as follows [6]:

$$\eta\left\{\frac{1}{n}p_{sw}\right\} = \eta\left\{\frac{1}{n+1}p_{sw}\right\} \quad (3)$$

where $\eta\{\}$ represents the value of the efficiency at a certain point, and p_{sw} is the total output power at the intersection of the efficiency curves, which is given by [6]:

$$p_{sw} = p_{\eta_{\max}}\sqrt{n(n+1)} \quad (4)$$

where $p_{\eta_{\max}}$ is the power level of a converter at the maximum efficiency point. As an example, the switching from $n=1$ to $n=2$ converters has to be performed at $p_{sw} = p_{\eta_{\max}}\sqrt{2}$.

III. Use Case Description and Specific EMS Functionalities

The HESS tested in this paper is based on the structure shown in Fig. 1, and is comprised by a HP and a HE battery pack connected to the grid by three and two parallel converters, respectively. The maximum power of the HP battery pack is defined as 75 kW (connected via 3 parallel converters of 25 kW each) and the one of the HE pack 33 kW (connected via 2 parallel converters of 16.5 kW each), while the capacity is 50 kWh in both cases.

In the following sections two relatively different use cases are described, which will be employed to demonstrate the validity of the proposed interoperable EMS and the facility with which it can be adapted to other applications. Since the purpose is to evaluate the performance of the proposed EMS over long periods of time, the HE and HP battery pack models are based on simplified cell models represented by a linearised open circuit voltage (OCV) curve and a constant series resistance. Their SoC is estimated with the well-known Coulomb counting method—i.e. integrating the current flowing trough the battery pack. The PE converters, on the other hand, are modelled via power/efficiency maps to be able to estimate the overall efficiency of the system depending on how the power is dynamically allocated. The inner control loops as well as the hardware dynamics are considered ideal.

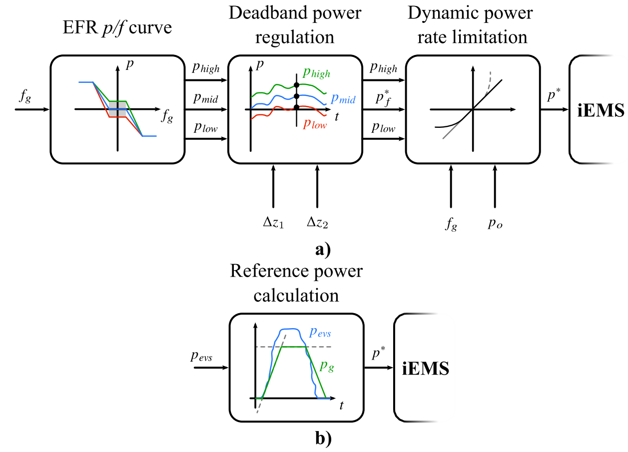

Fig. 5: Specific EMS control blocks for: a) the provision of the EFR service in Use case 1, and b) maximum power and rate limitation services in Use case 2.

A. Use case 1: Pan-European grid

The first use case (UC1) consists of a HESS connected to the Pan-European power system. The purpose in this case is to provide an enhanced frequency response (EFR) grid service. EFR is based on the UK market regulatory framework, and consists of a frequency regulation service oriented to facilitating the massive integration of RESs into the grid. Detailed information about the characteristics of this service can be found in [14], but in short it consists of exchanging power with the grid depending on the frequency at the point of interconnection.

The specific EMS control blocks to provide the EFR service are shown in Fig. 5a and include an EFR power/frequency (p/f) curve, a deadband power regulator and a dynamic power rate limiter, in order to generate the reference for the iEMS.

The p/f curve determines the power that is exchanged with the grid based on the instantaneous value of the grid-side frequency. The maximum power limits mentioned in [14] are calculated with the tendered power, which in this case is defined as 75 kW.

The deadband power regulator is a simple function that calculates the overall SoC status of the HESS when the frequency is close to its rated value, and determines whether the system has to absorb or provide power to approach a predefined SoC level.

Lastly, the dynamic power rate limiter curtails the power setpoint depending on the zone of operation and the rate of change of the power setpoint [14]. The purpose is to avoid abrupt changes in the power that might affect negatively the frequency of the power system.

B. Use case 2: EV charging station with PV generation

In Use case 2 (UC2) the HESS is connected to a substation in parallel with a high-power EV charging station. Distribution grids are facing challenges with the massive integration of such stations, and many parts of the infrastructure cannot sustain additional high-power consumers without oversizing transmission lines and transformers. For that matter, the purpose of the HESS in this application is twofold: on one hand, the maximum power absorbed by the EV charging station must be limited to a predefined value; on the other hand, the ramp of the absorbed power must be limited not to perturb the grid operation in excess. These constraints are applied using predefined rules in the block named 'Reference power calculation' in Fig. 5b.

IV. Dynamic Performance of the Proposed EMS

The two use cases are simulated in a Matlab/Simulink® environment, and the most relevant simulation parameters are gathered in Table I. The controller gain and time constants are determined by trial and error.

TABLE I: iEMS control parameters

Parameter	Symbol	Value	
		UC1	UC2
Power splitting LPF gain	k_{lpf}	1	
Power splitting LPF time constant	τ_{lpf}	1000 s	
SoC balancing PI proportional gain	k_p	10	
SoC balancing PI integral gain	k_i	500	2000

A. Use case 1: Pan-European grid

The input of the EMS is the frequency estimated at the point of connection of the HESS, which is illustrated in Fig. 6a. From this frequency, the EMS control blocks described in Section III-A calculate the power setpoint p^*. Fig. 6b shows this power setpoint and the real power exchanged by the HESS. Figs. 6c and d show the battery pack setpoints calculated by the power setpoint manager and the SoC constraint manager of the proposed iEMS, respectively. Lastly, Fig. 6e shows the SoC of the two battery packs.

As shown in the figure, the proposed iEMS successfully splits the power setpoint for the HP (1) and HE (2) battery packs. The setpoint of the HP pack provides the fast transients caused by sudden frequency variations, whereas the HE setpoint exhibits a much slower evolution.

The SoC curves also show that both battery packs remain at similar SoC levels during the entire simulation thanks to the implemented SoC balancing algorithm. This is an advantage because the HESS' available energy is maximised to provide the EFR for as long as possible. However, there is a very small margin to regulate the overall SoC level to a predefined level, so the batteries' SoC levels depict large excursions and reach the upper boundary set at 80%. One of the reasons for such a behaviour is that the frequency remains out of the deadband for most of the time, meaning that it is relatively challenging in terms of required restoring energy. Therefore, the HESS has to stop providing the EFR service until the frequency reverses its value. This can be seen in the zoomed portions of Figs. 6b, c and d, where the power provided by the HESS is zero during periods of time when power setpoints p_1^* and p_2^* are set to zero because of one of the two packs reaching the 80% SoC limit.

The effectiveness of the converter power allocation block described in Section II-C can be corroborated by the dynamic

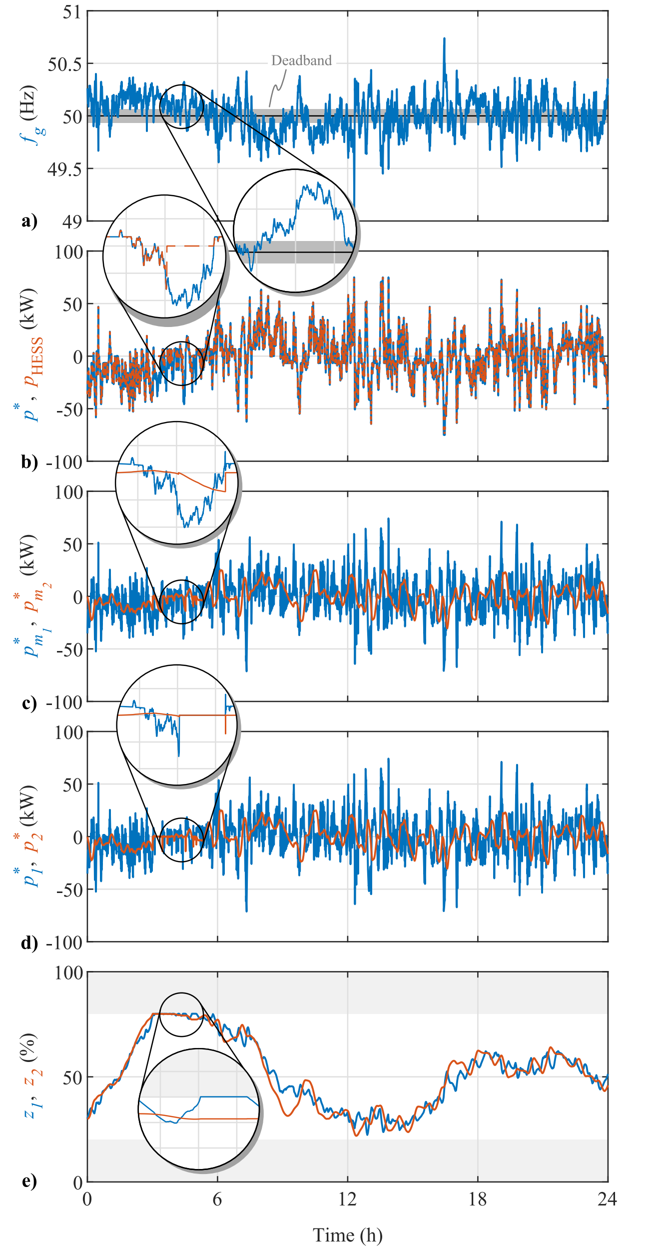

Fig. 6: Use case 1 simulation results with 75 kW/50 kWh HP (3 converter modules in parallel) and 33 kW/50 kWh HE batteries (2 converter modules in parallel): a) grid frequency (f_g), b) power reference to provide an EFR service (p^*) and delivered total power (p_{HESS}), c) power setpoints obtained with the power setpoint manager block, d) power setpoints after SoC constraints are applied, and e) SoC.

converter efficiencies illustrated in Fig. 7 for the 4.55–4.85h period. The dashed lines represent the conventional case where power setpoints p_1^* and p_2^* are split equally for the converters in parallel. On the other hand, solid lines represent the case where the activation of converters and their setpoints are controlled to maximise the system efficiency according to predefined efficiency curves. The results demonstrate that higher efficiency values can be achieved in the second case.

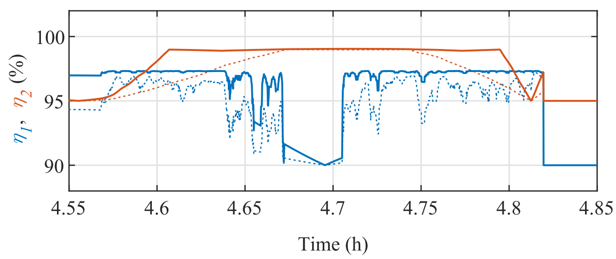

Fig. 7: Use case 1 efficiency, where dashed lines represent the conventional approach where the power setpoint is equally split between parallel converters, and solid lines represent the case where power is allocated to maximise the converter efficiency based on [6].

B. Use case 2: EV charging station with PV generation

The results of this simulation are illustrated in Fig. 8. The first plot shows the power required by the EV charging station in blue, and the power consumed from the grid in red. As it can be observed, the HESS is capable of effectively providing the required power to limit both the power consumed from the grid and the positive and negative power ramp-rate. Whenever the charging station demands power, the HESS provides a high power peak to limit the ramp-rate to its maximum ($r_{\max}$), and then it decreases to ensure that the power absorbed from the grid (p_g) not to exceed the maximum power limit ($p_{\max}$).

To provide this power, the proposed iEMS splits the power between the HP and the HE battery packs as shown in Fig. 8c. In this case, since the requirements of the application are more demanding in terms of power than in Use case 1, the integral gain of the PI to balance the SoC has been adapted to reduce the SoC deviations and the power oscillations between the HE and HP battery packs.

Finally, in some cases the power initially requested to the battery packs exceeds their limit. This can be observed for instance during the first two power peaks provided by the HESS, where p_1 first reaches the 75 kW value and subsequently p_2 reaches the 33 kW limit. Even though these power boundaries are reached, the proposed maximum power manager is capable of recalculating the power setpoints so that the requested total setpoint continues to be provided. In this case, the power that was being used to carry out the internal SoC balancing is curtailed, prioritising the provision of the application service.

Regarding the overall SoC of the HESS, no regulation has been included to bring it to a predefined setpoint. Even if the HESS could be charged during the periods when no service needs to be provided, an overall SoC controller has not been implemented because the purpose is to illustrate the effect of the proposed iEMS and the chosen HESS has sufficient energy to continuously provide the service during 12 h. In any case, this regulator could be easily implemented as another operation mode controlled by an overarching state-machine.

V. Conclusion

This work has presented an interoperable EMS to carry out the internal power and energy management of a grid-connected hybrid ESS. The aim has been to propose a flexible control structure that can be easily adapted to provide a wide range of ancillary services.

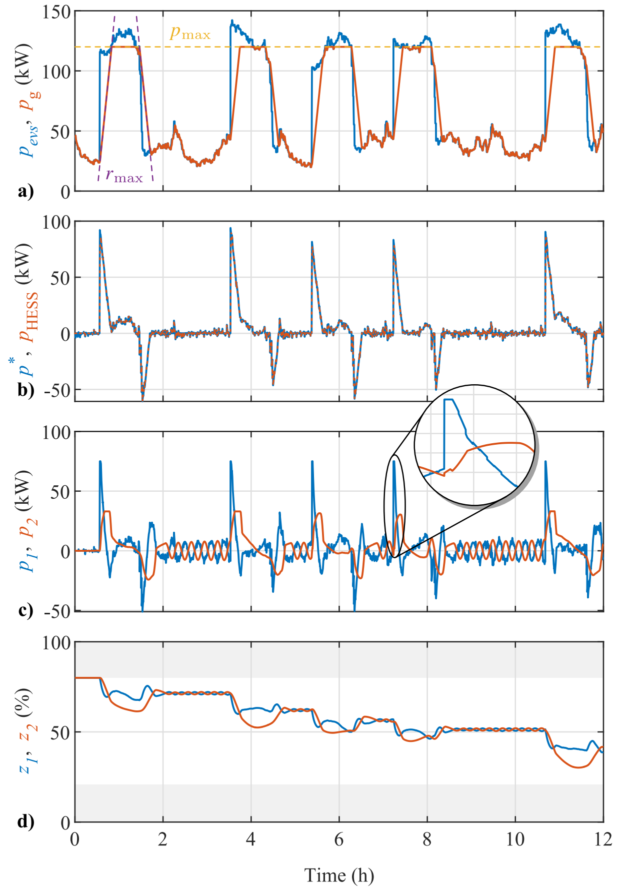

Fig. 8: Use case 2 simulation results with 75 kW/50 kWh HP (3 converter modules in parallel) and 25 kW/50 kWh HE batteries (2 converter modules in parallel): a) EV charging station power (p_{evs}) and power at the grid-connection point (p_g), b) HESS power reference to limit the maximum power and its change rate, c) power setpoints for the HP and HE battery packs, and d) SoC.

The core control blocks of the iEMS consist of a power setpoint manager, a SoC constraint manager and a converter power allocation algorithm. The validity of the proposed EMS structure has been demonstrated with two completely different use cases. In the first one the EMS has used to provide a frequency regulation service, and the results show that the SoC constraint manager is capable of curtailing the power references when exceeding the SoC boundaries. Moreover, the effectiveness of the internal SoC balancing algorithm is corroborated dynamically. In the second use case an EV charging station has been modelled, and the results demonstrate that the HESS can successfully limit the maximum value and ramp-rate of the power consumed from the grid. The internal power allocation shows that the proposed power constraint manager limits the maximum power of each ESS pack by prioritising the power required to provide the requested service.

Future Work

In this paper, the effect of the proposed iEMS and power sharing strategy on the lifetime of both batteries and PE modules was not assessed. Ageing data could be combined with machine-learning algorithms to enhance the proposed rule-based power sharing method with SoC balancing to increase the overall system lifetime.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 963527 (iSTORMY). Co-authors also acknowledge Flanders Make for the support to MOBI research group.

References

[1] I. Chernyakhovskiy *et al.*, "USAID Energy Storage Decision Guide for Policymakers," USAID, NREL, Tech. Rep., 2021.

[2] IRENA, "Innovation landscape brief: Utility-scale batteries," International Renewable Energy Agency, Abu Dhabi, Tech. Rep., 2019.

[3] J. I. Leon *et al.*, "Hybrid Energy Storage Systems: Concepts, Advantages, and Applications," *IEEE Ind. Electron. Mag.*, vol. 15, no. 1, pp. 74–88, mar 2021.

[4] X. Lin and R. Zamora, "Controls of hybrid energy storage systems in microgrids: Critical review, case study and future trends," *J. Energy Storage*, vol. 47, no. January, p. 103884, mar 2022.

[5] A. M. Gee, F. V. P. Robinson, and R. W. Dunn, "Analysis of Battery Lifetime Extension in a Small-Scale Wind-Energy System Using Supercapacitors," *IEEE Trans. Energy Convers.*, vol. 28, no. 1, pp. 24–33, mar 2013.

[6] J. W. Kolar *et al.*, "Extreme efficiency power electronics," in *Integr. Power Electron. Syst. (CIPS), 2012 7th Int. Conf.*, no. Cips, Nuremberg, 2012, pp. 1–22.

[7] S. Hajiaghasi, A. Salemnia, and M. Hamzeh, "Hybrid energy storage system for microgrids applications: A review," *J. Energy Storage*, vol. 21, no. December 2018, pp. 543–570, feb 2019.

[8] T.-A. Nguyen-Huu *et al.*, "Coordinated Control of a Hybrid Energy Storage System for Improving the Capability of Frequency Regulation and State-of-Charge Management," *Energies*, vol. 13, no. 23, p. 6304, nov 2020.

[9] J. W. Shim *et al.*, "Harmonious Integration of Faster-Acting Energy Storage Systems Into Frequency Control Reserves in Power Grid With High Renewable Generation," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6193–6205, nov 2018.

[10] N. R. Tummuru, M. K. Mishra, and S. Srinivas, "Dynamic Energy Management of Renewable Grid Integrated Hybrid Energy Storage System," *IEEE Trans. Ind. Electron.*, vol. 62, no. 12, pp. 7728–7737, 2015.

[11] F. Sanchez Gorostiza and F. M. Gonzalez-Longatt, "Deep Reinforcement Learning-Based Controller for SOC Management of Multi-Electrical Energy Storage System," *IEEE Trans. Smart Grid*, vol. 11, no. 6, pp. 5039–5050, nov 2020.

[12] H. Shayeghi *et al.*, "Assessing hybrid supercapacitor-battery energy storage for active power management in a wind-diesel system," *Int. J. Electr. Power Energy Syst.*, vol. 125, no. April 2020, p. 106391, feb 2021.

[13] F. Milano *et al.*, "Foundations and Challenges of Low-Inertia Systems," in *2018 Power Syst. Comput. Conf.* IEEE, jun 2018, pp. 1–25.

[14] National Grid, "Enhanced frequency response: Invitation to tender for pre-qualified parties," Tech. Rep., 2016.