Electrical Power and Energy Systems 80 (2016) 26–36

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Smart grid energy storage controller for frequency regulation and peak shaving, using a vanadium redox flow battery

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ARTICLE INFO

Article history:
Received 15 June 2015
Received in revised form 7 January 2016
Accepted 12 January 2016

Keywords:
Vanadium
Grid storage systems
Frequency regulation
Peak shaving
Smart grid
Flow batteries

ABSTRACT

Grid connected energy storage systems are regarded as promising solutions for providing ancillary services to electricity networks and to play an important role in the development of smart grids. Thus far, the more mature battery technologies have been installed in pilot projects and studies have indicated their main advantages and shortcomings. The main concerns for wide adoption are the overall cost, the limited number of charging cycles (or lifetime), the depth of discharge, the low energy density and the sustainability of materials used. Vanadium Redox Flow Batteries (VRFB) are a promising option to mitigate many of these shortcomings, and demonstration projects using this technology are being implemented both in Europe and in the USA. This study presents a model using MATLAB/Simulink, to demonstrate how a VRFB based storage device can provide multi-ancillary services, focusing on frequency regulation and peak-shaving functions. The study presents a storage system at a medium voltage substation and considers a small grid load profile, originating from a residential neighbourhood and fast charging stations demand. The model also includes an inverter controller that provides a net power output from the battery system, in order to offer both services simultaneously. Simulation results show that the VRFB storage device can regulate frequency effectively due to its fast response time, while still performing peak-shaving services. VRFB potential in grid connected systems is discussed to increase awareness of decision makers, while identifying the main challenges for wider implementation of storage systems, particularly related to market structure and standardisation requirements.

Introduction

EU imports 53% of its energy at a cost of around EUR 400 billion, which makes it the largest energy importer in the world [1]. Six Member States depend on a single external supplier for their entire gas import and therefore remain too vulnerable to supply shocks. The targets set by the Energy Union Package [1] and the continuous implementation of Renewable Energy Sources (RES), pose new types of challenges to the electricity grid in its path to become "smarter". Unlike traditional centralised generation plants, RES may be located everywhere along the grid, perhaps closer to the load centres they serve, dispersed across the network, even in remote offshore locations or in isolated environments. Such fundamental changes in the architecture and controllability of the grid call for smart and efficient power transmission and distribution networks. Maintaining the balance between generation and consumption in different time frames (from a few seconds for grid stability to several hours for servicing the varying demand) is fundamental for ensuring power system security. Increasing the use of traditional backup fossil-fuelled facilities on the grid (either for providing spinning reserve or for meeting peak demand), would reduce the environmental benefits that RES are intended to bring. Energy storage is hence becoming a key component of smart grids overcoming many of these challenges. Nevertheless, grid connected energy storage installed capacity is still approximately 140–150 GW world-wide [2], of which 99% are pumped hydro systems (PHS) [2].

When referring to RES, where supply does not follow the demand, energy storage systems (ESS) have been used to shift such

Abbreviations: AC, alternate current; CAES, compressed air energy storage; DC, direct current; DESS, distributed energy storage systems; DSO, distribution system operator; EDLC, dbl-layer capacitors; ESS, energy storage systems; EV, electric vehicle; FCP, frequency containment process; FCR, frequency containment reserves; Freq, Frequency; FRP, frequency restoration process; FW, flywheels; HV, high voltage; L/A, lead–acid; Li-ion, lithium-ion; LV, low voltage; MV, medium voltage; Na–S, sodium–sulphur; Ni–Cd, nickel–cadmium; Ni–MH, nickel–metal hydride; PCC, point of common coupling; PHS, pumped hydro storage; PI, proportional integral; PLL, phase lock loop; RES, renewable energy sources; SOC, state of charge; TDD, total demand distortion; THD_i, total harmonic distortion (current); TSO, transmission system operator; VRFB, vanadium redox flow batteries; VR, vanadium redox; Zn–Br, zinc–bromine.

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http://dx.doi.org/10.1016/j.ijepes.2016.01.025
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supply. However, in terms of grid control stabilisation, its use is not so extensive. Solar or wind power variability are generally not of concern when the penetration level is less than 10% of the total load [3]. In such scenarios, the present methods of balancing generation and load are sufficient to compensate for RES power variability. However, when the penetration level increases to a significant portion of the total load (>20%), the regulation capacity of a controlled area will reduce. This happens because RES do not offer such services (unless operating curtailed). Thus, the more RES in the system, the more strained are the conventional plants that offer automatic frequency regulation. For load generation RES variability is a problem, because it requires additional spinning reserves in the time frame of several minutes, and may require a thermal fleet with adequate ramp up/down rates for the time frame of hours [3].

Storage systems have been seen as a great potential to provide ancillary services, potentially replacing spinning reserves, or regulation services for voltage and frequency. Thus far, many technologies have been studied for different purposes, and these can be divided in five categories: Chemical (Hydrogen and Synthetic Natural Gas), Electrical (Capacitors and Super Conducting Magnetics) Electrochemical (lead–acid, Na–S, Ni–Cd, Li-ion, and flow batteries Vanadium, Za–Br), Mechanical (Flywheels, compressed air, Pumped hydro) and Thermal (ex: Heat, Molten salt) [4]. In the group of ancillary services provided in the open market management of the grid, the frequency regulation service has been identified as the highest priority [4,5]. Traditionally frequency regulation is mainly provided by ramping (up and/or down) of generation assets. Electricity storage has the capability of providing this service by acting in milliseconds.

In recent years, high-performance electrochemical energy storage technologies such as sodium–sulphur, lithium-ion, and Redox Flow Batteries (RFBs) have been developed to support grid applications. Electrochemical storage technologies offer a possibility to mitigate the drawbacks caused by RES and load variability with a number of applications, such as power quality improvement, peak load management or voltage and frequency control. Despite advances in electrochemical energy storage technology, batteries have only been sparingly implemented for grid services purpose. This fact can be attributed to the high cost of existing battery systems and uncertainty of their long-term reliability. Additionally, there is uncertainty about the precise economic value of battery energy storage in grid-level applications. There are primarily two reasons for this uncertainty. The first reason has to do with the technical characteristics of each system as there is no technology to fit all needs. Some are less expensive but not scalable, other have high energy density but are more expensive, some others have low energy density and are lower in cost but have limited lifetime. The second reason has to do with the high initial cost of most technologies and their long payback expected period. A multi-function of such systems is defended as desirable [6–8] in order to mitigate system's high cost and reducing the risk of the project. However, for many batteries, their more intensive use may decrease their lifetime depending on the technology. Recently, among many storage technologies, the Vanadium Redox Flow Battery (VRFB) has drawn much attention. Its use is being demonstrated in a number of projects in various locations, proving that the VRFB technology can be successfully exploited. Applications vary in sizes from several kilowatts to some megawatts [9] and commercial solutions are already available.

Nevertheless, there are only limited studies addressing the technical performance of a VRFB, especially in providing ancillary services. Furthermore, even if Vanadium may present itself as a promising solution for energy storage, it must also be studied regarding its compliance with applicable standards and main implementation barriers must be understood. This study provides such an assessment, presenting a grid energy storage model, using a modelled VRFB storage device to perform frequency regulation and peak shaving functions. The study presents the development of a controller to provide a net power output, enabling the system to continuously perform both functions. Section 'Background' provides an overview of the present main storage technologies, characterising them regarding rated power and discharge time capabilities. These are two main technical factors to understand their grid applicability. It then focuses on Vanadium technology explaining its main principles and differentiation. Section 'Method ology' presents the base structure of the studied grid model and associated residential and EV loads, showing the resulting total load and frequency variation. This is followed by Section 'Test design' where the controller for frequency regulation and peak shaving functions is developed and the VRFB is modelled. Results are presented in Section 'Results', showing frequency variation and peak power reductions as well as power supply during lower power demand periods. In Section 'Discussion' the study focuses on the main barriers still needed to be overcome to enable the wider implementation of grid connected storage systems in Europe and a final section with conclusions.

Background

Grid connected energy storage

Today, the grid operator has a set of options and instruments to keep the grid stable during different, daily load profiles and network disturbances. Primary Frequency Response or Frequency Containment Process (FCP) under the terminology of the new ENTSO-E network codes are provided automatically. The TSO contracts specific units to provide this service usually for 1 year. These units are mostly, if not completely, thermal plants, but not necessarily peak ones. The new network codes anticipate to the provision of Frequency Containment Reserves (FCR) by devices in the distribution network, but the market mechanism by which this is to be implemented is quite vague. Secondary Frequency Response (or Frequency Restoration Process (FRP)) is now made by real-time balancing markets in most cases, which are pool markets. A command by the market operator (which is usually the TSO) must be sent to the accepted bidder's units. There are hence two frequency response types: (i) frequency response (indicating FCP) and (ii) generation-demand balance (indicating FRP). In the present study, the storage system could provide FCP and peak-shaving which is not as such a generation-demand balance service. The storage device could offer FRP if it bided on the balancing market. Peak-shaving has a meaning only if combined with load and could have two possible implementations:

(i) Keep the actual net load limited to the contracted one in the day ahead market volume, at each specific settling period in order to nullify imbalance charges. In fact such an application would most probably be more adequate for a negative load (variable generation).
(ii) Shift the load/generation into settling periods of low/high electricity prices.

Yet, in order for such a scheme to have an economic sense for loads, time-of-use or dynamic pricing should be implemented. The best options (active bidding in balancing market, nullification of imbalance charges or load/generation shifting) depend on the specific application and market structure. Modern battery technology can provide a better way to match electricity supply with demand in real time, either with centralised or decentralised units. As batteries can alternately charge and discharge without realising emissions or suffer from major efficiency losses, using them for grid balancing could save energy, improve air quality and reduce greenhouse gas emissions. Additionally, since batteries use fast electrochemical reactions to store energy, they can keep electric supply and demand in balance even with large amounts of variable renewable energy on the grid. Further they can mitigate unwanted frequency or voltage variations or even smooth peak loads. The role of this new agent can thus boost the penetration of further RES, while maintaining power quality. Its flexibility and managing potentials makes it a key element of smart grids, and it is likely to continue to attract the attention of industry, academia and policy makers over the next years.

Several studies have performed reviews on the available technologies, identifying main technical characteristics and most appropriate applications [7–16]. Their optimised uses depend mostly on storage capacity, response time, energy density, lifetime, roundtrip efficiency and cost. Some studies focus on techno-economic feasibility of several storage system technologies [10,12,17–19]. Authors in [17] defend that RES in collaboration with certain storage technologies bring economic advantages, apart from the clear environmental benefits. Na–S batteries may be thought as suitable for very small island cases, while PHS comprises the optimum solution for big installations. The use of lead acid batteries, which is a mature technology, may also be considered as an option for big scale implementation; however, they are only suitable for moderate capacities. Concerning CAESs, they are largely dependent on the fuel cost factor, whereas fuel cells and flow batteries are suggested to be promising future solutions in terms of price. Authors in [20] develop a coordinated control for large-scale EV charging facilities and energy storage devices. The study shows that the storage system can effectively suppress power system frequency fluctuations and quicken the response rate. It will provide a fast response when the introduced disturbance is large and has a short duration. However, due to the limited storage capacity and limited charging cycles of the used lithium-ion batteries, they are not proper for small disturbances and for disturbances with a longer duration. In the latter scenario, only traditional thermal units would continuously participate in the response. In [10], authors highlight the prohibitive kW h cost tendency of Li-ion batteries, super capacitors, flywheels and SMES, even though they present very high efficiencies, which can reach 90%. Na–S and PHS are reported to show the lowest cost per kW h, however their potential is limited due to safety issues and geographical constrains, respectively. VRFB cost/kW h is positioned between Na–S and Lithium-ion systems, while having high cycling tolerance, higher depth of discharge but lower energy density.

Some studies have tended to focus on VRFB systems alone, as they have been regarded as a very good solution to mitigate various shortcomings of more mature battery technologies. Studies have focused on cell modelling, efficiency improvements and performance features [21–28]. VRFB devices can reach 80% efficiency and have response times of 2–3 ms [29]. A study [30] presents a model describing the dynamic behaviour of a VRFB system's voltage and state of charge, based on the instantaneous charging or discharging power required from the battery. A case study where the battery system participates in an organised electricity market is presented. The authors develop an optimisation problem to show the potential value of a VRFB used for frequency regulation service in Texas. Even though the study does not address multi-function services, they find that VRFB systems used for frequency regulation may be financially viable. The authors highlight that to perform frequency regulation technologies must have a low response time. Fig. 1 presents a comparison between technologies showing discharge time, rated power ranges as well as suitable applications.

Applications may differ on the size of the system and their location in the grid. Decentralised energy storage systems may go up to 1 MW of rated power, suitable for uninterrupted power supply and some grid support functions, whereas bulk storage systems may provide both grid support and large scale energy management. At distribution level, the main functions can be characterised as follows [2]:

- Capacity support: a storage unit is used to shift load from peak to base load periods to reduce maximum currents flowing though constrained grid assets.
- Dynamic, local voltage control: Distributed Energy Storage Systems (DESS) may help to maintain the voltage profile within admissible contractual/regulatory limits. In distribution grids, voltage support can rely both on reactive power (made possible for DESS by power electronics) and active power modulations. The main benefit derives from the deferral of distribution upgrades that would otherwise be necessary to meet the voltage level requirements.
- Frequency regulation: storage systems may compensate fast and effectively variations in frequency caused by load fluctuation, thus helping to maintain values within admissible contractual/regulatory limits.
- Contingency grid support: performing capacity/voltage support to reduce the impacts of the loss of a major grid component. They might as well be useful in emergency situation, for example after loss of a major component of the distribution grid.
- Intentional islanding: it consists in using DESS to energise a non-loopable feeder during an outage where DESS is used as a voltage source. Technically it's an option, even though generally prohibited, especially in Europe.
- Distribution power quality: with storage, the Distribution System Operator (DSO) can maintain the voltage profile within acceptable limits, which increases the quality of supply (less probability of black out or interruptions).
- Limitation of upstream disturbances: DSOs have a network access contract with one or more TSOs, and must therefore limit the disturbances they cause in upstream HV grids to contractual values. If these limits are exceeded, some types of advanced storage systems can help to comply with these commitments by performing active filtering.
- End-user peak shaving: energy storage can be used by customers such as industrial users for peak shaving in order to minimise the part of their invoice that varies according to their highest power demand. Such a service might be profitable if the peaks are sufficiently predictable and of relatively short duration.
- Continuity of energy supply: a storage device is able to substitute the network in case of interruption; this service is important for critical services and used today at small localised level.
- Limitation of upstream disturbances: the customer's contract with a given DSO may account for the limitation of disturbances; the storage can help them to comply with their commitments.
- Compensation of the reactive power: a DESS, via the power electronics converter, is able to locally compensate for the reactive power.

Vanadium batteries occupy a privileged position since they can be used for grid size connection, as they can reach several megawatt capacities, while still maintaining a relatively high discharging time of several hours. Such characteristics make these systems ideal for daily intervention as normally required for frequency regulation and peak smoothing. The limit of charging

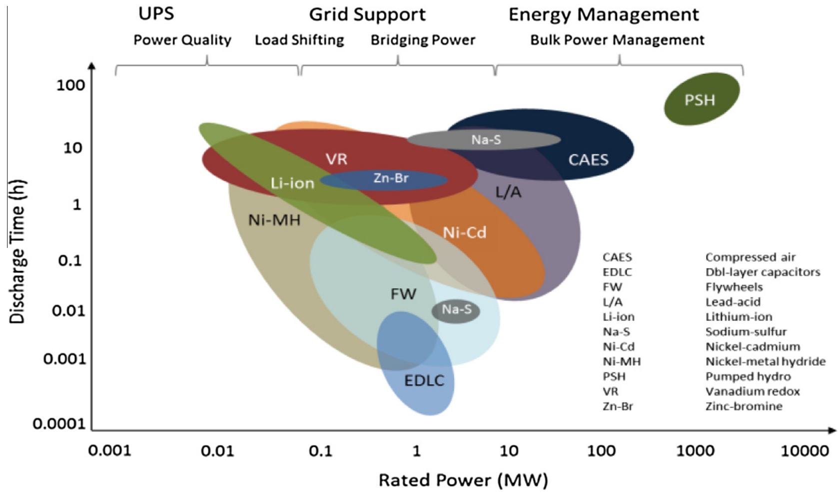

Fig. 1. Energy storage technology comparison considering rated power, discharge time and suitable applications [4,8].

cycles are not a concern such as in lithium-ion batteries and they are not geographically constrained as PSH.

Vanadium batteries

The use of flow batteries and most of its development was carried out by NASA for long-term space flight projects, which initially considered iron and chromium as solutions [31]. Later on, other elements for the electrolytes were also considered, but a problem seemed to persist on the membrane separating the two elements. As the membrane separating the positive and negative solutions is not perfect, the two will contaminate one another, eventually completely reducing the chemical energy potential of the battery.

The VRFB exploits the ability of Vanadium to exist in solution in four different oxidation states, and uses this property to make a battery that has just one electroactive element instead of two. In principle this means that even if the membrane is not perfect and the solutions migrate from one side to the other, the elements will maintain their properties, i.e. there is no cross-contamination of different elements allowing the same element to be used limitless. Even though Vanadium is an abundant element on earth, currently mostly used as a steel additive or ferrovanadium, its main drawback is its relatively low energy density (approximately 25 W h/L) [31]. The higher solubility of vanadium–bromine results in higher energy densities (35–70 W h/L) compared to the VRFB systems (25–35 W h/L). However, the potential concern of vanadium/bromine redox systems is the toxic bromine-vapour emissions during operation [22]. This requires other agents to be used in order to decrease or eliminate vapour emissions, which are expected to increase the cost of the overall system.

The VRFB system also requires connection to storage tanks and pumps, so that very large volumes of the electrolytes can be circulated through the cell, as can be seen in Fig. 2. For these main reasons, the systems are currently thought to be limited to stationary applications, even though rare transportation applications have been tested.

The battery stores energy by employing vanadium redox couples (V^{2+}/V^{3+} in the negative and V^{4+}/V^{5+} in the positive half-cells). These active chemical species are fully dissolved at all times in sulphuric acid electrolyte solutions. During the discharge cycle, V^{2+} is oxidised to V^{3+} in the negative half-cell and an electron is released to do work in the external circuit (either DC or, for AC systems, through an AC/DC converter).

In the positive half-cell, V^{5+} in the form of VO^{2+} accepts an electron from the external circuit and is reduced to V^{4+} in the form of

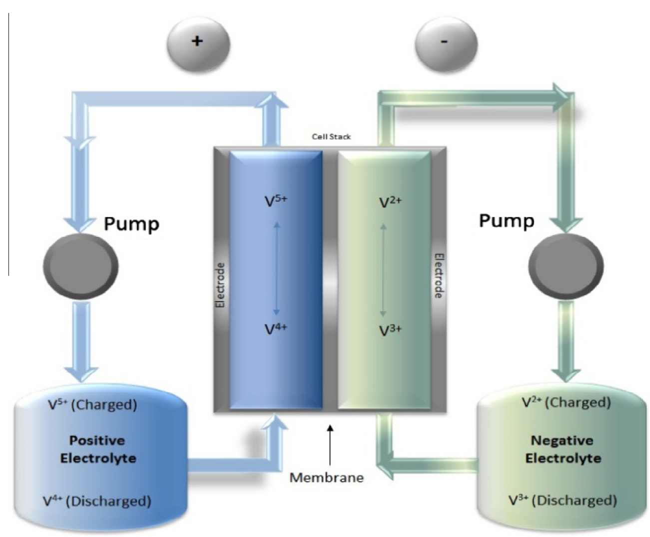

Fig. 2. Generic diagram of vanadium flow battery system.

VO^{2+}. Hydrogen (H^+) ions are exchanged between the two half-cells to maintain charge neutrality. The hydrogen ions diffuse through the anion or cation-ion permeable polymer membrane that separates the half cells. Charged vanadium species and water can also diffuse across the membrane. The cross-diffusion results in direct energy loss for that cycle.

However, when vanadium is the only element present on both sides of the cell, this cross diffusion mechanism does not result in permanent capacity loss, as long as the total vanadium in the system remains constant (i.e., there is no loss due to precipitation). In a V^- only system there is no need to maintain balance between positive and negative sides of the system. In the positive half-cell, the vanadium is present in solution as oxy-cations. These oxy-cations are vulnerable to irreversible precipitation as V_2O_5 if the electrolyte temperature exceeds 50–60 °C. Moreover, when precipitation occurs, it typically does so in the form of benign compounds, not V_2O_5 [32].

The normal operating temperature of a VRFB is approximately between 10 and 40 °C. In the case of ambient temperatures exceeding 40–45 °C active cooling sub-systems are normally installed. The capacity to cool the system actively is an advantage, since the system can remain operating without risking any damage to it. By contrast, if integrated cell architectures overheat, the best option is to stop using them until they cool down. The cell voltage is typically 1.4–1.6 V and cell power densities have an order of magnitude of 100 mW/cm^2.

Due to their large size, these systems can only be installed inside a High Voltage (HV) or Medium Voltage (MV) power substation. At HV/MV stations there is often room to install additional assets of some 100 m^2. In case DSOs own the station and its site, they can offer the possibility to install the device with a minimum of expenditure. Technically this location is both near the HV grid and the distributed generation in the MV grid. This implies that it offers the best conditions for all ancillary services supply. Currently some demonstration projects of battery storage systems in the range of several MW are installed at various sites and with various applications, but mostly coupled with solar or wind generation for power output smoothing [33]. Alternatively at MV/LV stations there is also often space to install additional assets, even though of smaller scale. The capacity of those stations limits the power of the storage device to some 10–100 kW h. As owners of the station and its site, DSOs could install storage devices with a minimum of expenditure. Storage technologies which can be placed in containers and which are independent of harsh weather conditions may be especially suitable for those locations.

As explained vanadium flow batteries store their energy in tanks, one with a positively charged electrolyte and another with a negatively charged electrolyte. The fluid that transfers charges inside the battery, flows from one tank through the system and back to the same tank. The tanks can be increased depending of the application and space available. For this reason it becomes easy to adapt flow batteries to industrial-scale applications without high initial costs, since increasing capacity of the system only requires that the tanks are expanded. With the expansion of the systems, economies of scale are achieved. The more capacity the battery has the lower the price per kilowatt hour becomes.

In terms of lifetime of the systems, vanadium-based flow energy storage systems can operate for decades. The active ingredient is a low-cost, rechargeable electrolyte, which never wears out due to the type of chemical reaction involved. The electronics and software to manage the system can be easily upgraded like any computer. The plastic tanks used for holding the electrolytes are expected to last at least 20 years. They are not affected by rapid charging and discharging variations and depth of discharge does not affect the lifetime of the system. Vanadium-based systems are made for industrial-size applications from a few kilowatts to several megawatts and there is no danger of thermal reactions. The production process is also simple, and ecologically safe. The electrolyte and other active components are combined as one process step. The enclosure made of pipes, tanks and electronics is assembled as a second process step, and they are then assembled into battery packs.

Methodology

The first step in this study was to build a model in MATLAB/Simulink where the frequency variation could be perceived and the problem identified. For this reason a model of a micro distribution grid was developed, which can be seen in Fig. 3. The power system at the 11 kV terminals of the step-down transformer is modelled as a Synchronous Generator with isochronous governor. The Synchronous Generator also regulates the voltage at its terminals at 1 pu. The micro distribution grid has a group of loads at 400 V, representing commercial activity, a residential neighbourhood and three charging station. The model is built in such a way that other loads or profiles can be introduced in Excel files or directly in MATLAB so that they can be analysed. Furthermore, also different storage technologies can be used to compare the differences in providing the same service and test performances.

The EV loads were considered to have 24 kW h battery capacities and capable of being charged according to the load profile in Fig. 4. The profiles were adjusted accordingly to the time frame used. The charging times were foreseen to occur during peak times.

Fast charging is assumed to be performed from low (below 10%) SOC (State of Charge) until 100% SOC. Assuming a real time step, the charging has a typical duration of 35 min at a maximum power of 50 kW and maximum current of 67.5 A. The other fast charging profiles used follow similar behaviour, under the assumption that the same type of vehicle is used.

A representation of a daily load profile was considered, but in a reduced time frame for the sake of simulation processing. The total load, which can be seen in Fig. 5(a), is measured at the substation level as well as the frequency variation presented in Fig. 5(b). The figure shows typical valley hours which occur during the night, followed by a first increase in demand and a stabilising period right in the middle of the profile.

The higher demand phase can be considered as the peak hours of a day, which normally happen in the afternoon followed by a decrease of demand when the end of the day approaches. The frequency progression during the input profile is regulated by the generator governor to stabilise its value to 50 Hz. The example perfectly shows the amplitude of the frequency variation when changes in load occur during time, making the problem easy to identify. Whenever a sudden increase in the load demand occurs, the frequency decreases. On the other hand if the demand drops the frequency will increase. The load profile used caused the system's frequency to have a maximum variation of 1.6%. From this first approach it can be observed that the traditional method of frequency compensation is working.

In the next stage a VRFB was modelled in Simulink and a storage system controller was developed to enable the multi-function (frequency and load shaving) simultaneously. The analysis then focused on short time steps and the system with and without the storage system was studied. A specific load was considered to enhance all stages of the battery going in and out of service, with one or two services being provided. After the simulations were completed the results of the frequency regulation with and without the storage system were overlapped. Regarding the power supply function results show the load power demand, grid power supply and battery power. The study then discusses the main barriers to multi-function storage system implementation in terms of market design and technical implications, giving examples of power quality standards that are difficult to be applied in the current versions.

Test design

Since the system is intended to perform two functions (frequency regulation and load shaving), it must be expected, that the two may be requested at the same time. Otherwise, if the storage system was required to charge at a certain power to compensate for frequency increase but, immediately after, received a contradictory order to supply power during peak hours, the system would only perform one function. For such reason, the two functions should not be controlled independently, but instead provide a net power output resultant from the frequency and power supply response.

The Voltage Source Inverter (VSI) of the storage system is controlled according to a classical decoupled d–q axis control scheme, where the q-axis current regulates the voltage at the point of connection of the storage system (400 V terminal of the step-down transformer), and the d-axis current regulates the power transfer

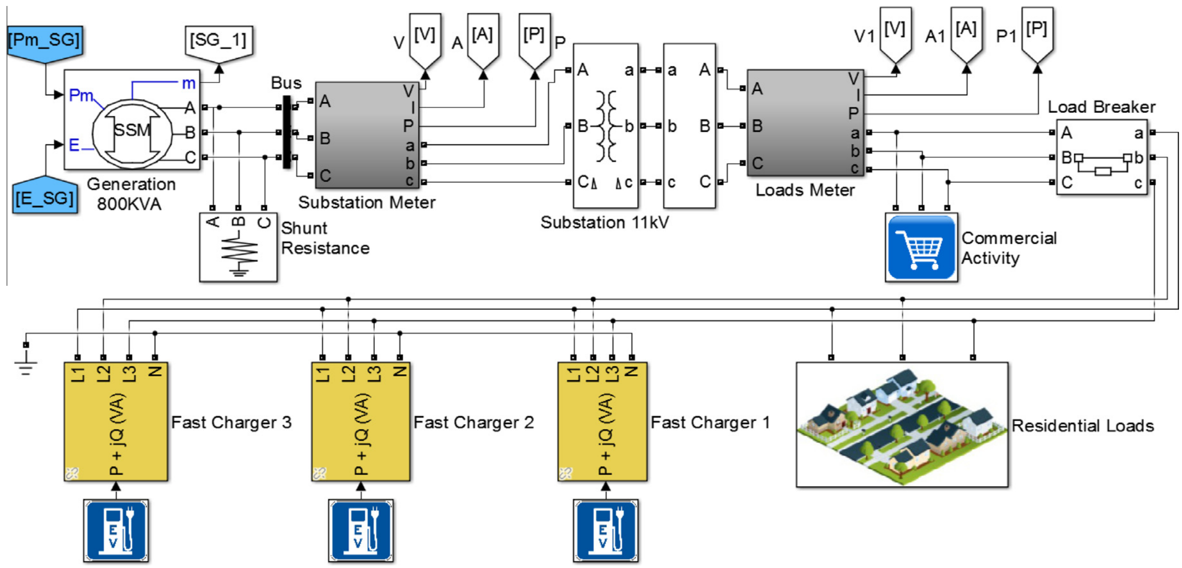

Fig. 3. Distribution grid model input to MATLAB.

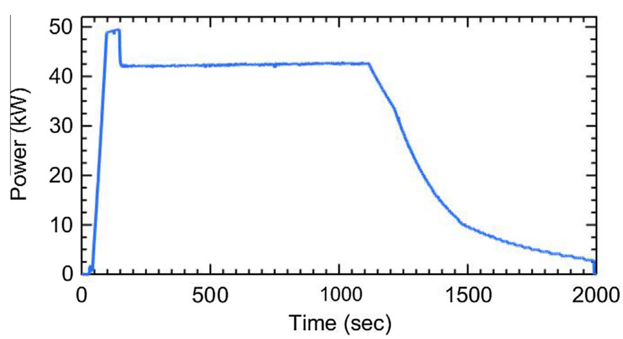

Fig. 4. Example of a load diagram for EV fast charging.

between the battery and the grid [34]. Of particular interest is the control logic for the latter, which is shown in Fig. 6. The controller of the d-axis current performs two functions simultaneously. These are frequency regulation and net load regulation. Frequency regulation is implemented according to classical droop control (where $\Delta f = f_0 - f$, being f_0 the nominal frequency of the power system). The scope of the net load regulation is to contain the net load of the micro distribution grid between 100 kW and 400 kW. Take note that the net load comprises both the overall load and the real power injection/absorption of the storage device (20 kW).

The storage system was programmed with two main commands: a first to charge during low demand hours, where it can establish its initial SOC and store energy to supply it back to the system when most demanding hours occur (peak hours). These limits established are set to 5 pu or 100 kW (charge below this value) and 20 pu or 400 kW (discharge above this value). Prioritisation is given to frequency regulation by setting the output limits to ±2 pu, while the respective output limits of the net load control loop are set to ±1 pu. Hence, even when the two outputs are contradicting, the full injection/absorption capability of the VSI can still be employed for frequency regulation. The final d-axis current, and thus real power, command of the storage device is also determined by the state of charge of the battery. When the SOC is below 10%, only commands that lead to absorption of power are accepted (negative d-axis current reference). The opposite is true when the SOC is above 90%. In this way, detrimental to the power system charging and discharging of the battery under very low/high SOC conditions respectively, are avoided.

Complementing the micro distribution grid shown in the base case, Fig. 7 presents the storage system and its control logic, containing the power regulator subsystem and current loops subsystem. The VRFB is connected to an average-model type of voltage source converter to represent the power-electronic switches. The complete system can be seen in Fig. 7. Since the simulations using the complete system were very time consuming a load profile was submitted where the stages of intervention of the storage system can be seen according to the programming pre-sets and results can be enhanced.

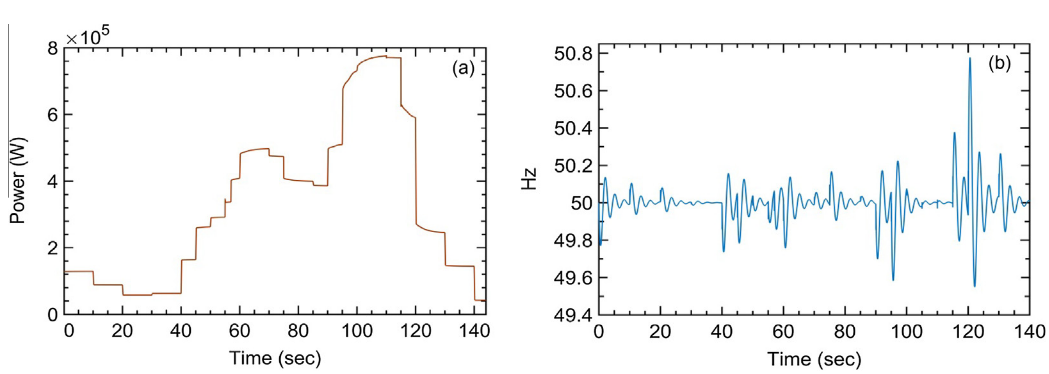

Fig. 5. (a) Load profile applied to the grid model and (b) corresponding frequency variation.

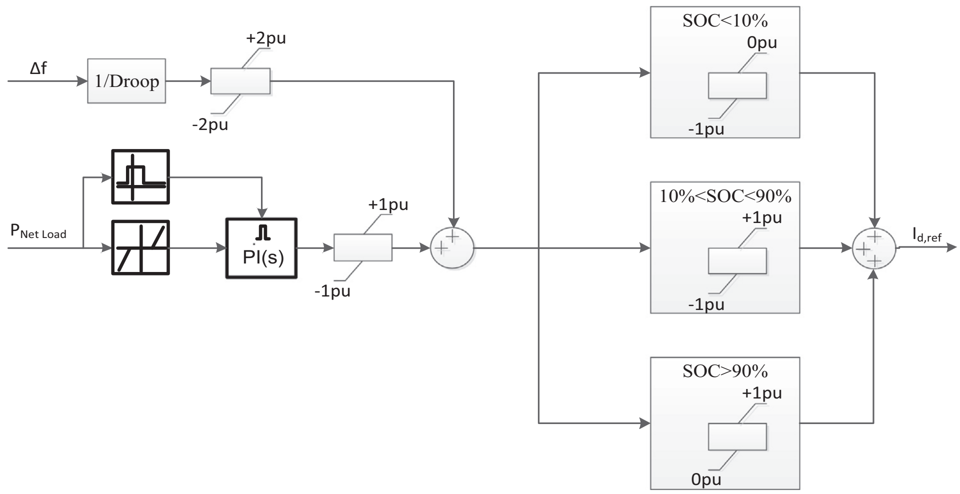

Fig. 6. *d*-axis reference current control loop.

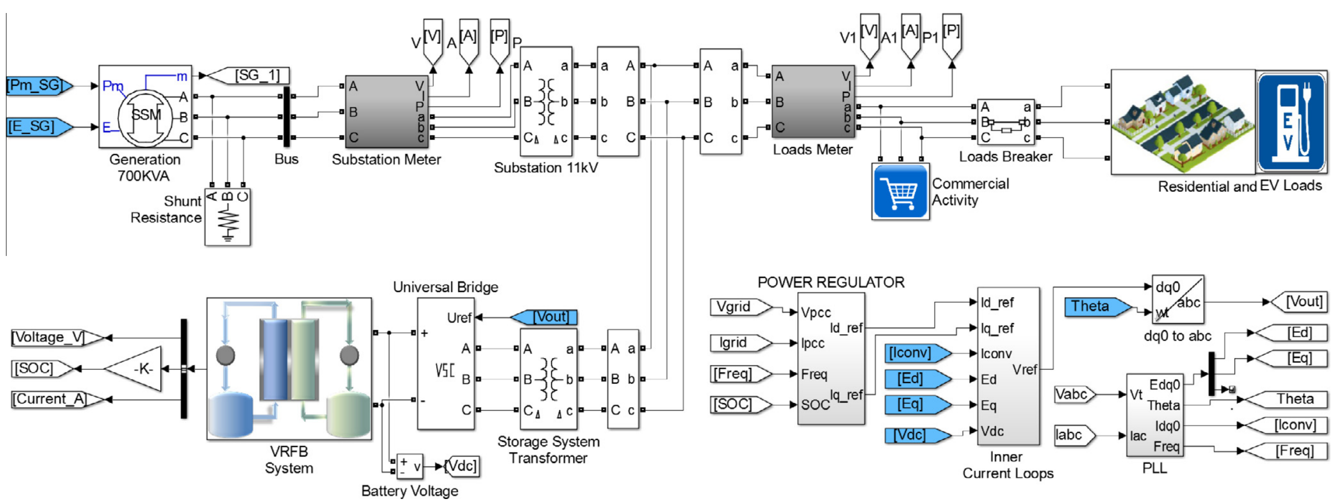

Fig. 7. Distribution grid model with grid VRFB system implemented.

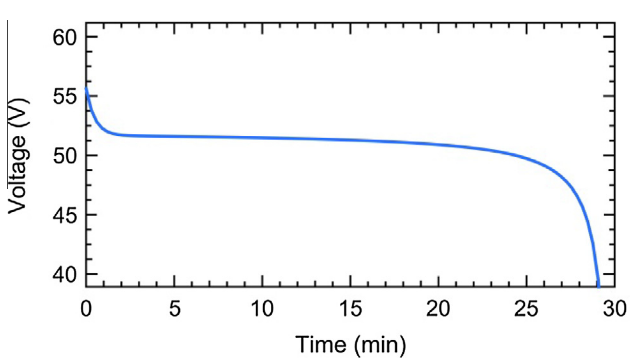

Fig. 8. VRFB discharging curve at 2C.

The battery is set to an initial SOC of 50%. It will charge or discharge during valley and peak hours to regain its initial state. The system chosen is a commercial available solution and it consists of a battery with nominal charge and discharge power of 20 kW, 48 VDC to 400 VAC (3-phase) [29]. The internal resistance considered was 0.00861 Ω [35] and the discharge curve profile [25] can be seen in Fig. 8. The system considers a 2C (1432 A) rate for the discharge current and a battery response time of 2 ms. The system used considers modelling work based on real life equipment [21].

One of the main features of the VRFB is its time to respond when asked. The requested power is available almost instantaneously, being mostly limited by the electrical equipment. The discharging curve has three different stages. The initial part of the discharging curve has an exponential zone which lasts a few seconds, followed by a second stage which is almost constant in voltage and lasts the great majority of the cycle. When the discharging is at the end the voltage rapidly drops until it reaches zero volts. For this reason the range of 10–90% of SOC was used as limits of operation.

Results

After having simulated the system in Fig. 7 with and without the storage system, results for frequency and power supply services were compiled. The VRFB successfully provided both services when required. Results for frequency regulation can be observed in Fig. 9(a). It is observable that even with such a small storage system, which represents just over 4% of the maximum load, the frequency is regulated faster, resulting in lower variations. Fig. 9(b) shows the power behaviour during simulation. The load was modelled to begin at a level of power demand below the bottom limit set for the dead zone block, which was 100 kW.

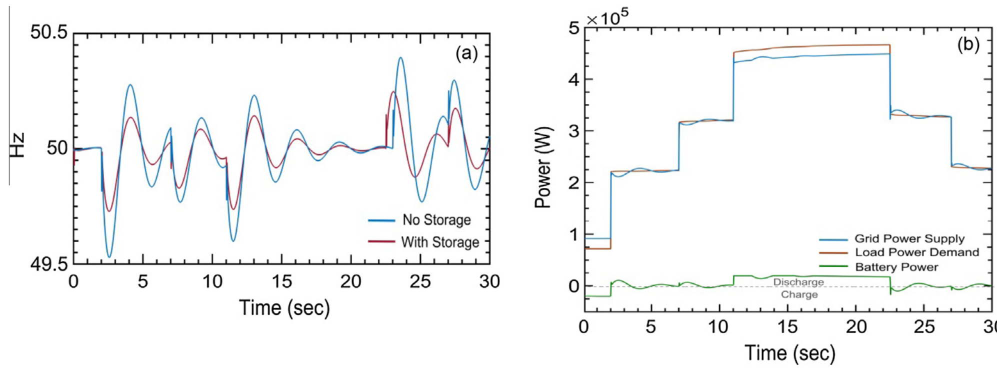

Fig. 9. (a) Frequency variation with and without storage system and (b) load power demand, grid power supply and storage unit power.

At this stage it can be observed that the battery is charging as expected, which corresponds to a negative value in the Battery Power curve. Correspondingly, the grid power supply curve is the sum of the load power plus the battery power demand. This initial stage changes at 2 s, when there is a load increase and the load power demand reaches a value of 220 kW. At this point one can observe that the frequency decreases. As a response, the battery supplies power back to the grid in order to compensate for the grid's instantaneous lack of power supply capacity. The frequency after this first response from the battery, suffers from a series of transitions in a tendency to stabilise. This is followed by the battery charging and discharging when required. It must be pointed out that in the same way when the battery is charging is considered as an extra load to be supplied by the grid; the contrary is also true. This means that when the battery is discharging, less power is required from the grid. At 12 s the load power demand reaches a value which is higher than the upper limit set for the dead zone (400 kW). This means that the battery system is required to discharge its power to support high demand hours. At this point the grid power supply becomes lower than the load power demand. It can be verified that the VRFB still performs the frequency regulation function seen at the 13th second, as the frequency increases making the storage system to charge. This however still results in a positive net power output, i.e. it decreases the discharge rate. The storage system continues the discharging cycle throughout the peak demand.

Fig. 10(b) shows the battery charging behaviour in accordance with the load power demand in pu given in Fig. 10(a). The power supply or demand of the battery in this case barely changes the SOC, due to the limited time of the simulation (30 s). However, regarding the power output two main trends can be verified. The first trend lasts until 12 s of the simulation where the battery receives the order to charge. A second trend occurs after 12 s, where the battery supplies energy to the system resulting in less power output from the grid, thus performing the peak shaving activity.

DESS is an effective solution for demand shifting and peak reduction where energy demand can be shifted in order to match it with supply and to assist in the integration of variable supply resources. Moreover VRFB modularity characteristics and high capacity potential may enable even seasonal storage. With low self-discharge, it is able to store energy for days, weeks, or months to compensate for a longer-term supply disruption or seasonal variability on the supply and demand sides of the energy system.

Discussion

Vanadium reserves

When it comes to deciding about technological paths and wide adoption, main concerns are price and environmental impact, which is greatly influenced by the materials used. Materials such as platinum or palladium for fuel cells, silicon for solar panels, germanium or even dysprosium in wind generators are often reluctantly considered due to their foreseen demand, high cost or scarcity. Vanadium is widely dispersed in nature, but not found in its metallic form. Instead it occurs in approximately 152 different minerals and fossil fuel deposits, like crude oil, coal, or tar sands. Vanadium accounts for about 0.02% of the Earth's resources [36], making it one of the most abundant elements in the Earth's soil. These estimations suggest that vanadium is more abundant than copper, zinc, nickel and chromium [37].

Although vanadium occurs in a number of elements, it is largely produced as a co-product of other metals with the vast majority of commercially mined vanadium coming from the processing of various iron ores or uranium. Vanadium occurs in deposits of titaniferous magnetite, phosphate rock, and uraniferous sandstone and

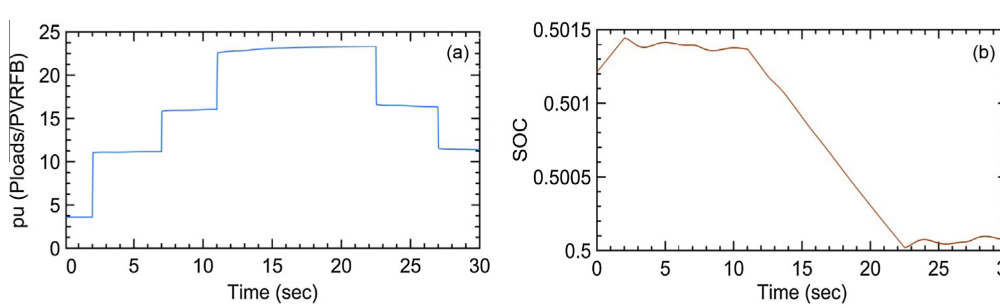

Fig. 10. (a) System power in pu (power demanded in loads/nominal power from the storage system) and (b) storage system discharge and charge behaviour during simulation.

siltstone [36]. Only three countries however, China, Russia and South Africa represent 95% of the vanadium resources that are currently in production [37]. There are nevertheless other vanadium deposits in Australia, Peru and the USA, with commercial viability. Sandstone and siltstone uranium deposits also contain between 0.1% and 2% of vanadium. Large deposits on these formations can be found in the USA, Kazakhstan, Uzbekistan, Gabon, and South Africa. With roughly 92% of all vanadium used in steel production, China accounted for 34% of the world vanadium demand in 2012, while Europe accounted for 14% of the demand, matching the USA demand [37]. Unlike many other commodities, vanadium is not traded on the open market, instead buyers and sellers negotiate privately. Prices are then published by independent market consultants. The European Union (EU) accounts for approximately 2.6% [38] of vanadium production, mostly from Czech Republic, Germany, Italy, the Netherlands, and Spain [38,39].

Barriers on grid storage implementation

The majority of the studies discussed tend to focus on a single storage service for a specific application. Such approach undermines the financial assessments, since it does not consider the full potential of such technologies. The model presented in this study shows a successful application of providing two services (simultaneously) which currently belong to differently organised markets. Evidently, the supply of several services from the same asset poses new challenges and technical, market and regulatory barriers still do not seem to mitigate them.

With vertically integrated electricity sectors, the same typically public utility is in charge of all the grid's functions. Hence, any investments required, benefits provided or responsibilities taken, are all covered by the same organisation and are more straightforward to be performed. In Europe, with the European Directive 2003/54/EG, the unbundling of the electricity sector made generation, transmission, distribution and end-user power supply activities controlled by many different entities. Being able to track and allocate costs and benefits to specific functions, which were former control mechanisms and today are called grid services, is a regulatory and market structure challenge.

If assets are distinguished between transmission and generation and their corresponding functions are separated, the full value of a storage resource cannot be achieved. This can only be solved if storage assets can be compensated for all of the services that they can offer (potentially simultaneously), rather than being assigned to provide a single service or to operate in a single market. The markets in a liberalised electricity system are futures, spot (day ahead and intra-day), balancing, ancillary services, and retail [40].

The direction given in Directive2009/28/EC, clearly states that storage systems should be included in the renewables targets for 2020. However current market differentiation does not facilitate flexible and mixed participation of transversal capable storage technologies.

CEN-CENELEC-ETSI Smart Grid Coordination Group [41] makes the distinction between two concepts regarding the ownership of the storage asset. The first, called Energy Storage refers to an electrical energy storage which is installed within the distribution grid or DER site and operated either by a utility or a market participant. The second, Local Storage, refers to an electrical energy storage which is installed behind the meter point and operated by the energy consumer or producer and not by the utility.

The requirements for legal unbundling based on EU Directive 2009/72/EC, prevent transmission and distribution network operators from controlling power generation and supply, to avoid anti-competitive behaviours in the electricity market. This prevents the network operators from investing in ESS as a network asset. From a market design perspective the following limitations should be tackled if further storage systems are to be incentivised [7,8]:

- At the moment there is a lack of a common European electricity market and balancing market, which will affect the use of ESS across EU countries due to different market rules, preventing the beneficial interaction between markets [42].
- Capacity mechanisms are considered in most EU member states for peaking power plants and not for other flexible forms of generation like ESS [43].
- The Directive2009/72/EC determines that priority is to be given to renewable generators regardless of their effect on the grid and electricity market. Hence compensation has to be provided to RES owners for curtailing renewables to reduce bottlenecks on the network and the need for network upgrade or reinforcement.
- RES providers are paid using generation based price driven incentives (such as Feed in Tariffs). These factors provide no incentive for RES providers to invest in ESS to provide dispatchable energy.

With the targets set for 2030, foreseeing an increase of RES penetration in the electricity mix, current regulatory and market arrangements will be challenged and will need to be updated. The increase in RES will affect conventional operation and performance of Transmission and Distribution Networks and will create the need for alternative solutions such as ESS. Unbundling of the power sector was conceived to drive down consumer costs by increasing competition and ensuring a secure and reliable power supply in an economical manner. An EU report [42] infers that the benefits of ESS in providing competitive services are better realised in an unbundled power sector. This however requires in many cases, the application of for example a cost benefit analysis methodology to realise those benefits and determine for example co-investments. Such methodologies comprehend subjective evaluation of benefits or positive externalities causing possible disputes among stakeholders.

Currently, most ESS technologies are expensive when compared to conventional solutions. Without the right policy, regulatory and electricity market changes, investment in them will lead to higher costs for consumers. This goes contrary to one of the goals of unbundling, which is to drive down consumer costs. Overall, there is limited operational experience of ESS, apart from PHS on the grid.

As discussed in [8], there is no agreed method to evaluate the regulated (grid support) services ESS can provide, due to the limited transparency of pricing mechanisms and lack of data for the different services. This causes difficulties in calculating the value for different applications ESS provides, thus affecting use in a regulated business model.

Standards

VRFB as well as other storage systems are relatively new and developing technologies with minimal deployments (except PHS). This has resulted in a lack of necessary standards and practices to carry out thorough economic assessments, system design and deployment evaluations. The same barriers regarding definitions and classification of assets can be seen in an analogous way in existing standards as well.

A set of procedures is still missing to measure and remunerate different services within the same unit. In the case presented in the current study, it can be verified that even though there is a net power output, this power flow is a combination of frequency regulation, which may have defined benefits, and peak shaving, which may have others.

Standards are required so that producers, utilities and prosumers follow the same rules. Current standards are often thought to be applied to a certain type of equipment or system, which can draw up to a certain amount of current or follow a certain set of characteristics. However, when storage systems are considered, it should be foreseen that charging and discharging curves may have different behaviours and rated values may differ on the application (since multi-function is foreseen).

An example of this is the IEC 61000 standard series, which makes a distinction between various current levels, i.e. systems below 16 A, up to 75 A and greater than 75 A. Examples of these standards are:

- IEC 61000-3-11 – Electromagnetic compatibility (EMC) – Part 3-11: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems – Equipment with rated current >75 A and subject to conditional connection [44].
- IEC 61000-3-12 Electromagnetic compatibility (EMC) – Part 3-12: Limits – Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and ⩽75 A per phase [45].
- IEC 61000-4-14 – Electromagnetic compatibility (EMC) – Part 4-14: Testing and measurement techniques – Voltage fluctuation immunity test for equipment with input current not exceeding 16 A per phase [46].
- IEC 61000-4-27 – Electromagnetic compatibility (EMC) – Part 4-27: Testing and measurement techniques – Unbalance, immunity test for equipment with input current not exceeding 16 A per phase [47].
- IEC 61000-4-28 – Electromagnetic compatibility (EMC) – Part 4-28: Testing and measurement techniques – Variation of power frequency, immunity test for equipment with input current not exceeding 16 A per phase [48].
- IEC 61000-4-34 – Electromagnetic compatibility (EMC) – Part 4-34: Testing and measurement techniques – Voltage dips, short interruptions and voltage variations immunity tests for equipment with mains current more than 16 A per phase [49].

These standards clearly state that they should be applied to equipment or systems drawing current and do not refer to bi-power flow. In the case under study it may happen that the system uses current above 16 A for discharging and below 16 A for charging, or may well be above and below in both cycles but during uncertain times.

If as an example the IEC 61000-3-12 standard [45] is used to verify the compliance of harmonic distortion, should it be considered only for the demand/charging function and should the supply/discharging function be evaluated as a generation unit? In such case, where different standards are to be used for the same system, possible contradictions could occur. Definitions of Point of Common Coupling (used as the measuring point on the standard) should be verified depending on the nature of the asset as well.

Furthermore, in the case of IEC 61000-3-12 [45], the standard refers to the use of the maximum current for the THD_i estimation. When the storage system is operating, as the current may vary, this may result in misleading high values of THD_i. Instead, as defended in [50], the TDD as explained in IEEE-519 [51], should be used, considering the fundamental current. Harmonic Distortion standards are just examples of opportunities to update and rethink the application of these technologies.

As the experience from demonstration projects increases, this will enable a standardisation of methods for evaluation, connection, operation, maintenance, and disposal of ESS technologies used on the grid. This will help in reducing the risks and uncertainties of investing in ESS. Based on the standards of assessment, it is recommended that all beneficiaries of the ESS operation contribute towards the cost of the ESS investment, i.e. based on the benefits the stakeholders get. This should help in determining the contribution of ESS and the amount of support or remuneration they should realise from such an investment. With the current market and regulatory structure in Europe, where utilities cannot provide ancillary services, but only buy them, it will be most probably up to private stakeholders to deploy ESS.

Conclusions

ESS implementation should be considered for multiple functions, both regulatory and competitive, to enable maximum benefits for investors. It is apparent that radical changes need to be made to current regulatory and electricity market arrangements by independent regulatory authorities and regulators to promote the integration of such systems. Given the foreseen contribution of RES in the near future and an increasing horizontal grid, ESS are expected to play a major role in supplying services to the grid and making it *smarter*.

This study presents the development of a storage system model in a distribution grid, which can provide frequency regulation and power supply services at the same time. The model considers a VRFB, which due to its response time and intrinsic characteristics can provide multiple services in an effective way. Both functions were demonstrated to work simultaneously proving the developed control logic to work. Environmental friendliness and material abundance makes VRFB a promising technology to perform these types of services both in a centralised and distributed way. Increasing awareness of this technology may push forward its deployment. However lack of demonstration projects and gaps in standardisation, and unclear market opportunities under current arrangements are still a problem. How multi DESS in the same grid interact with the DSO while providing their services, interoperability with the DSO and with each other or check for standardisation conflicts, are some of the areas for future research.

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