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Characteristics of the Parameters of Lithium Iron Phosphate Energy Storage in the Context of their Usefulness in the Management of Distribution Grid

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Abstract:

Purpose: *The article presents the results of research on lithium iron phosphate energy storage. The subject of the study was to gain knowledge about the potential benefits of using this type of storage for storing energy from distributed sources. The goal was achieved, among other things, by estimating the efficiency, calculating the capacity and investment /operating costs of the tested technology.*
Design/Methodology/Approach: *During the research, the following work was carried out: Comparative analysis of technical parameters, literature research, desk research.*
Findings: *The research results showed possible positive effects of the use of lithium iron phosphate energy storage in micro-source systems due to the low internal resistance. The authors also emphasize the twice longer service life of the tested solution about acid batteries, which is particularly important in high investment costs.*
Practical implications: *The dynamic development of distributed generation determines the growing interest in energy storage technologies. These solutions are tested in terms of the possibility of using them to stabilize the operation of power grids and the absorption of surplus energy. The storage technology described in this article is one of the few most promising for large-scale use. Distribution system operators can use the test results.*
Originality/Value: *The survey attempts to fill a gap in the literature on the subject. The study provides practical answers about the characteristics of the described solution and the costs of its use. The results may encourage the use of this technology by companies from the energy sector as one of the solutions supporting the energy transition.*

Keywords: *LiFePO4, energy storage, distributed generation, power engineering.*

JEL Classification: *L80, N74, O33, O44, P42, Q21, Q52, Q55, Q56.*

Paper Type: *Research paper.*

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1. Introduction

The electric power industry is a particular sector of the economy, and its products are crucial for the effective operation of other enterprises and economic development measured by GDP growth. The modern world needs energy, and its consumption has been growing globally. This growth stems mainly from the civilizational product, which requires more power to operate all economic sectors (Anwar *et al.,* 2017). Civilizational development also drives consumption which is inextricably linked to the growing use of energy throughout the production cycle. An additional risk is the concentration of global oil and gas resources in several countries, which may bring political criteria to the fore rather than economic considerations in investment decision-making (Bilan *et al.,* 2019; Chen *et al.,* 2018). The production and use of electric power involve greenhouse gas emissions and devastation of the environment, mainly driven by gas emissions from burning fossil fuels, particularly coal (Lavrinenko *et al.,* 2019; Brożyna *et al.,* 2017).

One of the most severe problems these days is excessive CO2 emissions causing a greenhouse effect. Therefore, reducing CO2 emissions and thus preventing climate change has become a critical goal that has become a challenge for the global energy sector (Tvaronavičienė *et al.,* 2017; Dudin *et al.,* 2019; Vlasov *et al.,* 2019). To reduce emissions, it is necessary to find and use highly efficient and cost-effective energy, including from renewable sources. However, the development of distributed energy sources has a negative impact on power grids, which were built according to the traditional energy model. It assumed transmission and energy distribution only in one direction, i.e., from large-scale generation through transmission and distribution grids to the end customer.

The dynamic increase in the number and capacity of RES connected to grids makes the energy flow in the case of distribution grids more and more bi-directional. This is of great importance for the functioning of Distribution System Operators, i.e., entities responsible for managing such grids, because it changes the way they operate, particularly in the field of traffic management and maintenance of quality parameters of the supplied energy (Drożdż, 2018). To enable the correct and failure-free operation of the grid in new conditions, it is necessary to develop and use new methods and tools supporting the system operation. In this respect, energy storage devices may play a vital role in this respect, which allows for the storage of surplus of produced energy and then its use for balancing and improving quality parameters depending on the system services provided. (Collins *et al.,* 2017; Savitz *et al.,* 2019).

This article presents the outcomes of testing under an R&D project, "Innovative services of an energy storage system to improve the quality and efficiency of use of electric power" (Innowacyjne usługi system magazynowania energy podnoszące jakość i efektywność wykorzystania energy elektrycznej) carried out by Enea Operator and co-financed by the National Centre for Research and Development through the

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2. Literature Review

Energy storage is a concept widely researched in several recent decades. It combines various technologies that can be linked to RES (e.g., solar power). Depending on the intended purpose, the energy thus produced can be stored for later use (The act of 10.04.1997; Announcement of November 29, 2018; The act of 20.02.2015).

For many years now, research has focused on studying the feasibility of energy storage technologies, mainly for RES energy storage (Abedin and Rosen, 2011). In this context, several research projects presented in peer-reviewed literature reviewed energy storage systems in terms of either re-electrification or supporting the power grid. However, none of these studies provides any tool to optimize the operation of energy storage systems in both applications, considering market prices for electric power and the investment potential of future investors (Wang *et al.*, 2002; Basu, 2010).

González *et al.* (2004) developed an algorithm to optimize and simulate a hybrid wind power/hydrogen system utilizing energy storage systems (Saxena *et al.*, 2009; Linden *et al.*, 2002). In the same context, Schenk *et al*. (2007) study the feasibility of energy storage systems to integrate wind power in The Netherlands better. The study found that connecting energy storage to the power grid supports it at times of large energy amounts fed by high winds, thus absorbing energy for hydrogen production (Daniel and Besenhard, 2011; Liu *et al.*, 2012).

To find solutions for energy security and reduce greenhouse gas (GHG) emissions, researchers have studied the implementations of energy storage systems on islands. Busuttil (2008) studied the prospects for high-RES integration in Malta, including a conversion system and the use of energy storage which might support the power grid (Chen *et al.*, 2009; Zakeri and Syri, 2015).

Salgi and Lund (2008) studied the perspectives of energy storage systems in western Denmark in grid support applications. The simulation model developed in that study demonstrated that even without energy storage constraints, energy demand projected for 2030 could be met at market price (Hadjipaschalis *et al.*, 2009).

Similarly, Carr *et al.* (2016) assessed the operation of energy storage fed from a wind turbine connected to the power grid in Rotherham, UK. Optimization of the system to maximize revenues (i.e., sales of electric power) accompanied by minimized operating costs (i.e., cost of electric power) showed that the prices and demand for electric power play a significant role in the economic life of the system (Zhao *et al.*, 2016; Miller and Winters, 2012; De Souza, 2011).

Colbertaldo *et al*. (2019) presented a simulation of the Californian power system with high-RES penetration that used energy storage. The study found that the complete transition of the Californian grid to renewables needed a massive increase in power output of solar/wind processors accompanied by a matching energy storage system (Carija *et al.*, 2012; Xia *et al.*, 2015). Weidner *et al.* (2018) also demonstrated the prospects of using energy storage systems as a business option in power-to-mobile and power-to-power systems in Germany, Belgium, and Iceland. The "power-to-power" scenario involves the production of hydrogen from excess RES using water electrolysis systems and re-feeding the grid with the stored energy using fuel cells (FC) at times of significant shortages of power. For large-scale systems, the authors found that the cost of electric power exceeds 500 EUR / MWh and is expected to fall to more than 300 EUR / MWh, which is a relatively high price compared to other technologies (Alami, 2015; Brown *et al.*, 2014).

Alshehri *et al.* (2019) documented energy storage as a support service for power grids. The study simulated four scenarios of the power grid in a northern region of The Netherlands, including a baseline scenario (the existing system) and a scenario with energy storage systems used for frequency control (Cabeza *et al.*, 2015). A simulated reduction of rotational inertia resulting in steeper frequency drops demonstrated that connecting topologies based on energy storage improved the frequency lowest point (i.e., frequency nadir) to more than 0.15 Hz.

3. Research Methodology

This study is focused on lithium iron phosphate (LiFePO4) energy storage systems with the specifications provided in Table 1 (accompanied by the specifications of the BMS management system). The combined capacity of the studied energy storage systems is 20 Ah.

Table 1. *Technical parameters of LiFePO4 energy storage*

Electrical specifications	**LiFePO4 (38120S battery)**
Nominal voltage	$3.2\ V_{DC}$
Critical voltage	$4.2\ V_{DC}$
Nominal capacity	10 Ah
Internal resistance	< 6 mΩ
Maximum charge voltage	3.65 ± 0.5 V
Minimum discharge voltage	2.5 – 2.0 V
Recommended charge current	1C (10A)
Max. charge current	2C (20A)
Max. impulse current	10C (100A)
Max. discharge current (continuable)	3C (30A)
Standard discharge current	1C (10A)
BMS	**HCX-D138**
Charge voltage	57.6 V
Max. charge/discharge current (continuable)	80 A

OVERCHARGE	
Overcharge cut-off voltage	3.90±0.025 V
Overcharge detection time	0.5~2.0 s
Overcharge cut-off “release”	3.80±0.05 V
DISCHARGING	
Cut-off discharge voltage	2.00±0.05 V
Discharge detection time	50~200 ms
Discharge cut-off “release”	2.30±0.1 V
BALANCING	
Voltage at which balancing is switched on (for a single cell)	3.60±0.025 V
Balancing current for a single cell	72± 10 mA

Source: *Study data.*

The specifications determined by the discharging/charging process of LiFePO4 energy storage were compared to the specifications provided by the manufacturer. On this basis, capacity determination errors δ_C i δ_D were estimated according to the equations. The results are shown in Table 2.

$$\delta_D = \frac{|E_N - E_D|}{E_N} \cdot 100\%$$
$$\delta_C = \frac{|E_N - E_C|}{E_N} \cdot 100\% \qquad (1)$$

where:
E_N – nominal energy provided by the manufacturer;
E_D – energy determined on discharging;
E_C – energy determined on charging;
δ_C – error of determination of capacity on charging;
δ_D – error of determination of capacity on discharging.

The efficiency of energy storage in the tested batteries was also estimated using a formula for a single case. The formula used energy values E_D and E_C for charging and discharging with 6A (other values were not available due to the maximum charge current which was restricted by the current output of chargers, i.e. 10A). The formula used the values of energy calculated based on the following formula:

$$\eta_C = \frac{E_D}{E_C} \cdot 100\% = \frac{1065{,}83}{1148{,}06} \cdot 100\% = 92{,}8\% \qquad (2)$$

Calculations for charging and discharging of the energy storage system with 6A show that efficiency is 92.83%.

Calculations in Table 2 use watt-hour rated capacity of energy storage (Wh). The ampere-hour capacity stated by the manufacturer is 20Ah (two parallel strings of 16 cells, each with rated capacity of 10 Ah and rated voltage 3.2 V). The watt-hour capacity can be, therefore, determined using the following relationship:

$$E_{Wh} = E_{Ah} \cdot U_{nom} = 20 \cdot 51{,}2 = 1024Wh \tag{3}$$

***Table** Σφάλμα! Δεν υπάρχει κείμενο καθορισμένου στυλ στο έγγραφο.**.** Calculation of the capacity of a LiFePO4 accumulator based on discharging specifications.*

DISCHARGING				
I [A]	t [s]	E_D [Wh] (sum of samples)	E_N [Wh]	δ_D [%] (formula 1a)
6	13,040	1,065.83	1,024	4.08
10	7230	1,053.09		2.84
15	4,849	1015.71		0.81
20	3,630	985.36		3.77
25	2,702	913.77		10.76

***Note:** E_N – nominal energy provided by the manufacturer;E_D – energy determined on discharging; δ_D – error of determination of capacity on discharging; I – discharge current; t – time of discharging, * energy E and error δ are calculated for Version 2: based on formula (2.1) and based on samples*
***Source:** Own elaboration based on discharging specifications.*

A major consideration for using energy accumulators for cost optimization of prosumer systems is the cost of energy storage. This cost should consider both the capital cost and useful life of the technology. Useful life of electrochemical accumulators such as LiFePO4 depends heavily on cyclical DOD (depth of discharge) level. In determining the cost of energy storage in LiFePO4 accumulators, DOD at 80% can be assumed. The cost of energy storage in the accumulator can be determined by this simplified relationship:

$$K_{ES} = \frac{K_I}{DOD \cdot N_{ES(DOD)} \cdot C_{N(kWh)}} \tag{4}$$

where:
K_{ES} – cost of energy storage [PLN/kWh];
K_I – investment cost;
$C_{N(kWh)}$ – rated capacity of accumulator [kWh];
$N_{ES(DOD)}$ – cycle life at average DOD;
DOD – average depth of cycle discharge [0 – 1];

For the LiFePO4 accumulators with the BMS system tested in this study, the cost of energy storage will be:

$$K_{ES} = \frac{K_I}{DOD \cdot N_{ES(DOD)} \cdot C_{N(kWh)}} = \frac{6600[PLN]}{0{,}8 \cdot 2 \cdot 10^3 \cdot 1{,}024[kWh]} = 4{,}03[PLN/kWh] \tag{5}$$

The calculations consider the capital cost of LiFePO4 accumulator with 1.024 kWh capacity.

This cost decreases with increasing capacity of the accumulator. For a 6.6 kWh accumulator equipped with BMS system it is:

$$K_{ES} = \frac{K_I}{DOD \cdot N_{ES(DOD)} \cdot C_{N(kWh)}} = \frac{24000[PLN]}{0{,}8 \cdot 2 \cdot 10^3 \cdot 6{,}6[kWh]} = 2{,}27[PLN/kWh] \tag{6}$$

Capital cost of a LiFePO4 accumulator with 1.024 kWh capacity compared to its rated capacity for the battery tested is:

$$K_{I(kWh)} = \frac{K_I}{DOD \cdot C_{N(kWh)}} = \frac{6600[PLN]}{0{,}8 \cdot 1{,}024[kWh]} \cong 8057[PLN/kWh] \tag{7}$$

Capital cost of a LiFePO4 accumulator with 6.6 kWh capacity compared to its rated capacity for the battery tested is:

$$K_{I(kWh)} = \frac{K_I}{DOD \cdot C_{N(kWh)}} = \frac{24000[PLN]}{0{,}8 \cdot 6{,}6[kWh]} \cong 4545[PLN/kWh] \tag{8}$$

4. Conclusions

Battery accumulators with LiFePO4 cells are characterized by low internal resistance, making them suitable for working in systems designed to reduce output power fluctuations resulting from RES micro sources.

The lithium iron phosphate technology ensures very high current efficiency, long service life (according to the manufacturer, approx. 2000 cycles), and, above all, high energy efficiency exceeding 92% for the tested energy storage. In many types of applications, energy efficiency is critical. These parameters can be achieved by using the required appropriate BMS protection system, which ensures the correct characteristics of the storage tank operation, among other things, by preventing overloading or unloading.

High capital cost (about 4545 PLN/kWh) is partially compensated by a very long cycle life of the accumulator and excellent performance; moreover, it has been proven that this cost decreases with the increasing capacity of the storage. The primary advantage of LiFePO4 accumulators over acid batteries is high DOD (80% in lithium iron phosphate versus 50% in acid batteries). In addition, these batteries have more than double cycle life, which makes them more cost-effective than batteries based on acid technology, despite the higher capital cost.

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