24th International Conference on Renewable Energies and Power Quality (ICREPQ'26)
Santander (Spain), 10th to 12th June 2026
ISBN-13: 978-84-09-82044-3

Battery energy storage capacity for self-consumption according to the required autonomy in transformer substations

K. Deželak[1]

[1] Environment and Energy Statistics Section
Statistical Office of the Republic of Slovenia (SURS)
Litostrojska cesta 54, 1000 Ljubljana (Slovenia)
Phone/Fax number: +386 1 234 0825, e-mail: klemen.dezelak@gov.si

Abstract. Batteries and DC power supply in the transformer substation are of essential importance for the timely and correct operation of electrical power systems and for ensuring the safe and reliable operation of devices in the substations. Due to their characteristics and long charging cycles, existing stationary lead-acid batteries (Pb) are currently extremely oversized compared to the expected 12-hour autonomy. With the use of modern protection and control devices, the consumption of DC self-consumption has been greatly reduced in practice. However, the battery capacity should still remain the same, mainly due to the need for a large current load, which may occur with the possible simultaneous operation of a large number of circuit breaker trip coils in the event of a fault in the substation. In addition, the possibility of using Li-ion battery packs is proposed, as this technology has several advantages, such as smaller dimensions and more efficient use of space for installing batteries, the possibility of fast charging, and less sensitivity to temperature and microclimate changes. The article thus presents the selection of some characteristics for Pb and Li-ion batteries under continuous loads for small and large substations. Aforementioned, were performed using battery models in the Matlab software package, with the model previously validated with measurements.

Key words. Battery energy storage, self-consumption, transformer substation.

1. Introduction

The procedure for selecting a battery energy storage capacity for the typical transformer substation is briefly presented. The following shows the general capacity calculation for small and large substation. The battery autonomy lasts 12 hours with continuous and short-term load included, as well.

For the transformer substation [1], we have chosen the same configuration and capacity of lead-acid batteries as are normally in operation [2]-[3]. The average capacity values for small substations have been chosen as 200 Ah and for large substations as 600 Ah. In the same way, we also selected Li-ion batteries, taking into account the specific characteristics stated by the manufacturers [3]-[7]. When choosing a specific technical solution, it is also necessary to take into account that Li-ion batteries do not require air-conditioned rooms, while the connections between Li-ion modules are screwed and there are fewer of them, and that maintenance is not required. Basically, these are Li-ion batteries with a titanium oxide anode [8], [9], which can be used as batteries for storing larger amounts of energy (self-consumption in transformer substation or energy storage systems in combination with renewable energy sources, etc.). Lead-acid batteries have many connections between cells, which need to be maintained and the resistance measured regularly due to heating. The mass of lead-acid batteries is also significantly greater than when using Li-ion modules [2], [4]. In case of battery switching system the battery charging is separated from the load. Towards the end of the charging process, the battery charging voltage could be approximately 2,7 V/cell. When the full state is reached, the process should be stopped or switched to maintenance charging. Within a battery operation the load is powered only from the battery. In this case, the battery voltage towards the end of the charging is the same. When the appropriate charge is reached, the charging process is interrupted. The battery can be connected to the desired load.

The rectifier unit plays an important role within those cycles. It has a cascade regulator that regulates the output voltage and current, consisting of an external voltage loop (charging level of the battery), and an internal current loop (limiting the output current and limiting the charging current). The internal loop is faster and ensures current stabilization, while the superior and slower external voltage loop ensures output voltage stabilization. The regulator enables automatic switching of the output characteristic to the charging level.

2. Model validation

The measurements were performed with the maximal sampling frequency equal to 1 MHz, where inputs allow for the measurement of voltages up to 1 kV and are basically intended for direct voltage measurement. The other inputs measure voltages only up to 10 V. To measure other quantities as current, pressure or temperature, measuring transducers are needed to convert the measured quantity into electrical voltage. These inputs could be used for measuring direct and alternating currents. Additionally, in most cases the measurement is more accurate if the current is measured through a resistor.

Firstly is shown, how the Li-ion battery system works during discharge (Figures 1-4). It is known that the voltage of the batteries changes during discharge, which also changes the current. Based on both quantities, the power and, by integrating the power, the energy could be defined. The measured variables (Figures 1 and 3) changed during the battery system discharge. If the load is larger, the voltage drops more at the beginning and reaches the limit value of voltage of sooner with less energy delivered.

After each discharge, the battery system should be recharged (Figures 5-8). The charging current is regulated by the voltage level, and the maximum voltage at the battery terminals is defined (Figures 5 and 7). When the converter reaches this voltage, it no longer increases it, and the current therefore begins to decrease. Additionally, charging with high currents reduces the life of the batteries.

For calculating batteries characteristics (Figures 2, 4, 6 and 8) the Matlab software tool was applied [10]-[12]. We started from the so-called equivalent circuit, in which the shape of the discharge curve is taken into account in the battery model, as well. In this way, the calculations capture the battery current, battery capacity, exponential voltage and the dynamics of the exponential region, polarization resistance and battery state (charging or discharging). The equivalent circuit parameters can be changed, representing a different type of battery, depending on its discharge characteristics. For example, the rated capacity and the internal resistance 2 mΩ could be obtained from the specification tables. The other detailed parameters are derived from the typical discharge characteristics plot (fully charged voltage 1,39 V, nominal discharge current 1,3 A, exponential voltage 1,28 V and exponential capacity 1,3 Ah, respectively).

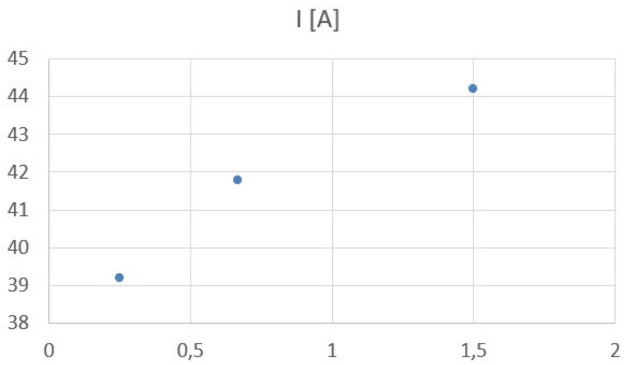

Fig.1. Measured current of batteries when discharging (x-axis: time [h])

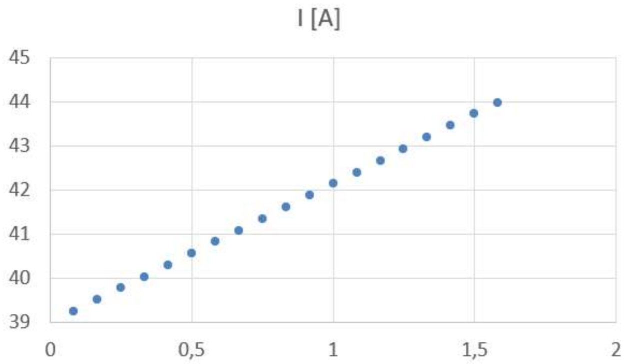

Fig.2. Calculated current of batteries when discharging (x-axis: time [h])

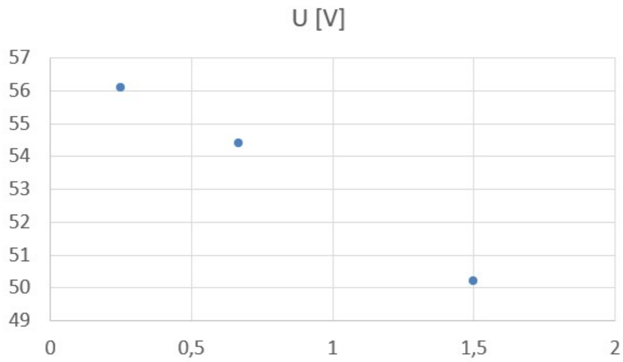

Fig.3. Measured voltage of batteries when discharging (x-axis: time [h])

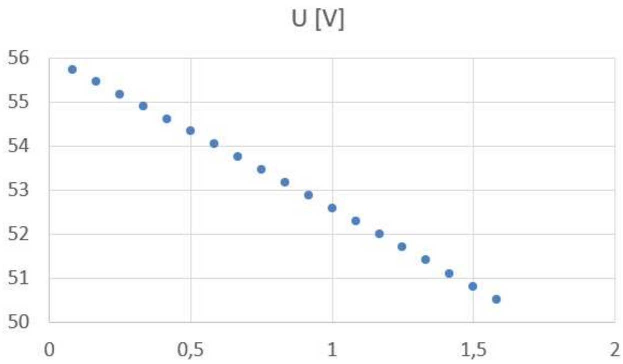

Fig.4. Calculated voltage of batteries when discharging (x-axis: time [h])

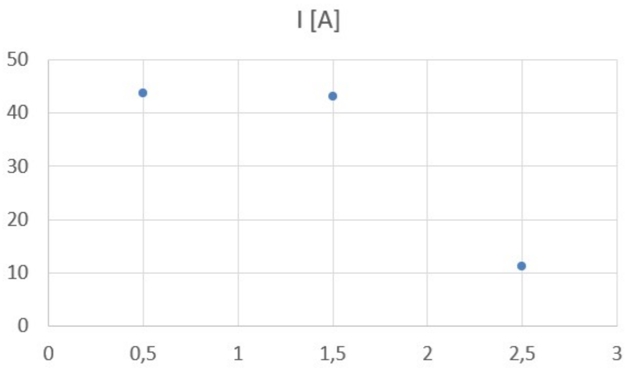

Fig.5. Measured current of batteries when charging (x-axis: time [h])

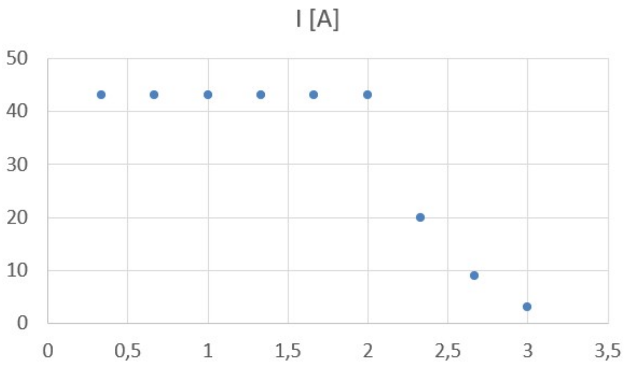

Fig.6. Calculated current of batteries when charging (x-axis: time [h])

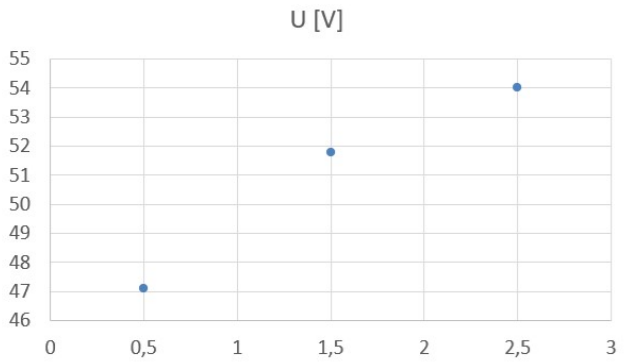

Fig.7. Measured voltage of batteries when charging (x-axis: time [h])

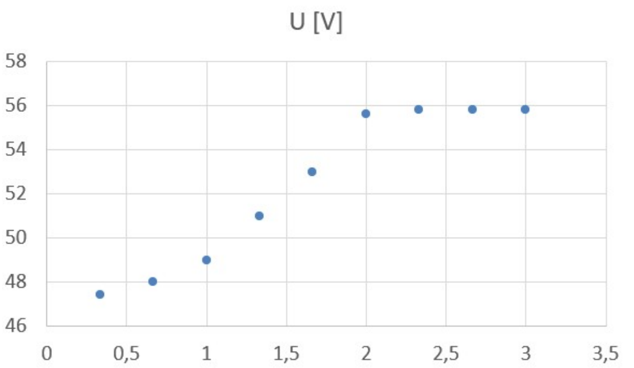

Fig.8. Calculated voltage of batteries when charging (x-axis: time [h])

3. Selection of battery energy storage characteristics

A typical discharge characteristic is constructed in the manner presented in Figure 9 (x represents time, while y represents voltage), where A is the area under the exponential curve and B is the nominal area. The C area is related to the limited operation area.

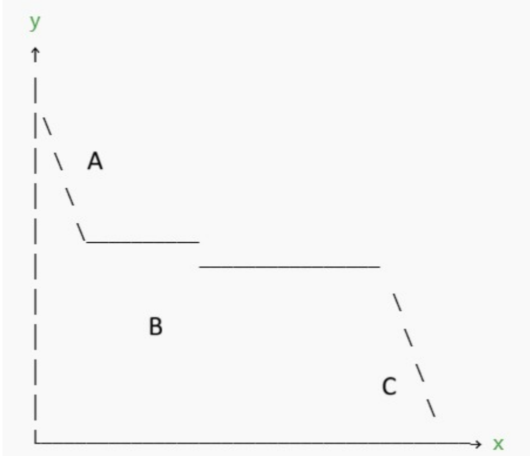

Fig.9. Typical discharge characteristic within a battery model

The parameters of the equivalent battery circuit to Pb or Li-ion batteries were adapted. In that manner the capacity of Pb and Li-ion batteries were varied. We were interested in the capacity at which the battery voltage reaches the minimum permissible value within 12 hours of autonomy. For small transformer substations, the continuous load on the battery is minimal. The voltage during battery discharge as a function of time is shown in Figure 10 (Pb = blue curve and Li-ion = red curve). As Figure 10 shows, 12 hours of autonomy cannot be achieved with a Pb and Li-ion battery with a prescribed capacity. Therefore, within 12 hours of autonomy, we reduced the voltage to the minimum permissible 190 V depending on the battery capacity (Figure 11, Pb = blue curve and Li-ion = red curve, as well).

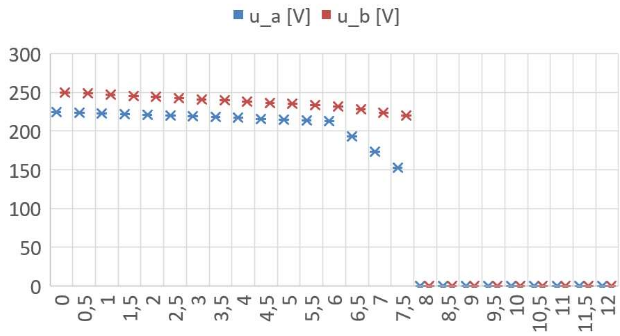

Fig.10. Voltage of Pb (blue curve) and Li-ion (red curve) batteries when discharging with continuous load (x-axis: time [h])

Figure 11 shows that for 12 hours of autonomy of a lead-acid battery, a capacity of approximately 70 Ah is required, and for a Li-ion battery, 60 Ah. At lower capacities, the autonomy of the batteries is shorter. Both values are related to an emergency self-consumption devices with AC power supply at 0,4 kV for continuous (steady-state) and average load demand.

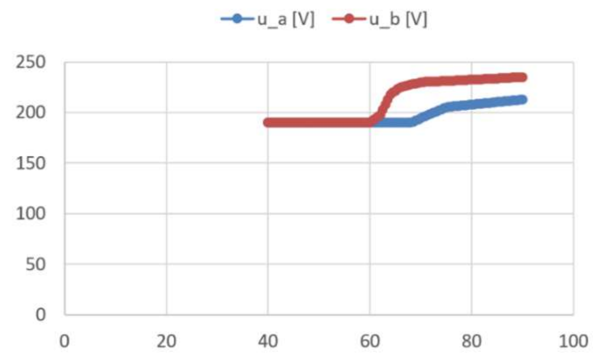

Fig.11. Minimum voltage of Pb (blue curve) and Li-ion (red curve) batteries depending on capacity *C* (x-axis: *C* [Ah])

For large transformer substations, the continuous load on the battery is significantly higher than for small substations, both for Pb and Li-ion batteries. The battery discharge voltage as a function of time is shown in Figure 12 (Pb = red curve and Li-ion = green curve, as well).

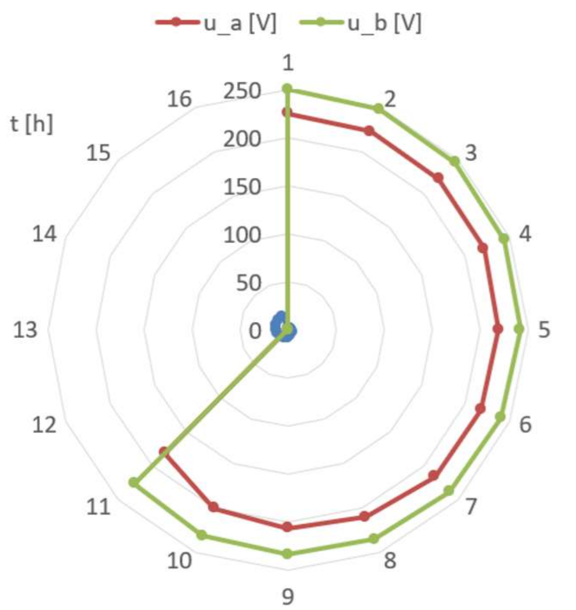

Fig.12. Voltage of Pb (red curve) and Li-ion (green curve) batteries when discharging in large transformer substation

4. Conclusion

Related to the to the minimal value of permissible voltage depending on the battery capacity can be seen that, with increasing continuous load on the batteries, the difference between the required capacity of Pb and Li-ion batteries increases. It is clear that such a value of capacity is not enough for 12 hours of autonomy under continuous load for both Pb and Li-ion batteries, while Pb battery reaches a value almost two hours worse.

It should be added that the advantages of using Li-ion compared to Pb batteries become easily recognized when simultaneously considering the processes of discharging and charging of batteries. Looking at the battery from the discharge point of view brings differences in the capacity limit up to 20-40 Ah between Pb and Li-ion technology, while the difference in the capacity of the aforementioned batteries increases significantly when considering simultaneous discharging and charging. Even for a relatively simple load cycle, the difference can be as much as 100 Ah and more.

The capacity sizing approach appears to account only for continuous or average load demand, while within practical substation environments, batteries are not primarily designed for steady-state energy supply, but rather to ensure reliable operation under transient, high-power conditions, particularly during fault events, as well. For that very reason short-term peak loads, such as those required for circuit breaker operation, are critical within a general substation applications.

References

[1] W. Dołęga, Advanced substations and electrical equipment, Wrocław University of Technology, Wrocław (2011).

[2] D. Pavlov, Lead-Acid Batteries Science and Technology, A Handbook of Lead Acid Battery Technology and its Influence on the Product, Elsevier, UK, Oxford (2011).

[3] Y. Ryutaka, D. Khatiwada and F. Sanchez, “A comparative life cycle assessment of lithium-ion and lead-acid batteries for grid energy storage”, Journal of Cleaner Production (2022).

[4] Y. Wu, X. Yuan, S. Zhao and T. van Ree, »Introduction«, v: Lithium-ion batteries Fundamentals and Applications, CRC Press Talyor & Francis Group (2015).

[5] M. Martí-Florences, A. Cecilia and R. Costa-Castelló, “Modelling and estimation in lithium-ion batteries: A literature review”, Energies (2023).

[6] O. Bruj and A. Calborean. “Electrochemical impedance spectroscopy investigation on the charge–discharge cycle life performance of lithium-ion batteries”, Energies (2025).

[7] Y. Pan, K. Xu, R. Wang, H. Wang, G. Chen, and K. Wang, “Lithium-ion battery condition monitoring: A frontier in acoustic sensing technology” Energies (2025).

[8] M. Soltani, S. B. Vilsen, A. I. Stroe, V. Knap and D. I. Stroe, “Degradation behaviour analysis and end-of-life prediction of lithium titanate oxide batteries”, Journal of Energy Storage (2023).

[9] E. Dalla Maria, M. Dallapiccola, D. Aloisio, G. Brunaccini, F. Sergi, D. Moser and G. Barchi, “A data-driven equivalent circuit model’s parameter estimation method applied to lithium-titanate battery” Journal of Energy Storage (2023).

[10] S. Bhagat, C. Archana, K. Khade, A. Budukh, A. Bhosale and V. K. Mathew, “Simulation of Li-ion battery using MATLAB-Simulink for charging and discharging”, E3S Web of Conferences (2022).

[11] M. Neubauer and C. Kerssen, C. “Evaluation of the simulation of lead-acid batteries in MATLAB Simulink and measurement-based optimization of model parameters”, (2025).

[12] A. T. Zau, M. J. Lencwe, S. D. Chowdhury and T. O. Olwal, “A battery management strategy in a lead-acid and lithium-ion hybrid battery energy storage system for conventional transport vehicles”, Energies (2022).