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Skolkovo Institute of Science and Technology

Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Stanislav Bogdanov

PhD Program: Engineering Systems

Title of Thesis: Modeling and operation optimization of vanadium redox flow batteries

Supervisor: Dr. Mikhail Pugach, Skoltech

Co-supervisors: Associate Professor Federico Martin Ibanez, Skoltech
Dr. Sergei Parsegov, Skoltech

Name of the Reviewer: Aldo Bischi

I confirm the absence of any conflict of interest	**Date: 07-10-2024**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense.

If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.

Reviewer's Report

Overall, the dissertation topic is relevant, considering the electric energy storage being one of the more important fields of research in the energy community, as well as vanadium redox flow batteries (VRFB) being a very promising solution alternative to Li-Ion. Furthermore, the VRFB model development is crucial for a thorough understanding and improvement of the technology as well and paving the way to future digitalization of control, health monitoring, so improving the battery management systems, and it could also be used to improve the battery design in term of sizing and in terms of assessing new components.

The thesis is well structured, with clear logic and it is up to the state of the art of current methodologies, combining modeling and experimental validations, this is confirmed by three high impact journal publications.

Summary of issues to be addressed before/during the thesis defense:

In the thesis the flow Batteries are often mentioned as important for large scale applications, but in my opinion they are also important for long duration applications not only daily charge-discharge cycles (so Energy/Power ratio above 8-10h), thanks to their modularity, having power and energy decoupled vs Li-Ion where to increase the energy/power ratio you have to oversize them and use it with power lower than the nominal. So it would be interesting to discuss also the long duration and have it considered in the motivation. Sometimes, is mentioned "long-scale" in chapter 2.1, I would improve the clarity. When is discussed in Chapter 3 large and small tank volume, how many h of storage it corresponds?

What is meant for industrial application, we are around 5-10kW of power, so it not a matter of size. I would clarify what is meant.

On the objectives and novelty, please elaborate better the last point, I understood it only after reading the Chapter 5, because the optimal operation strategy is often intended as an optimal charge discharge policy of the battery via optimization problems often mixed-integer non-linear, which will tell accordingly to load, renewables production and costs the optimal policy of charge-discharge. The same at point 4 page 39, there are optimization models that take into account the loss of capacity and degradation and accordingly suggest optimal scheduling also of the rebalancing and servicing, see K. Rodby and M. Jafari from MIT (USA) and D. Cremoncini University of Pisa (Italy). While in this work, you decide the scheduling a priori assuming a daily charge discharge cycle, and accordingly the battery is sized and operated optimally to reduce the losses.

Page 79 non isothermal effects are labelled as negligible, please reference it. Then why they should be object of future studies, please elaborate more.

Among the battery's configuration, all the innovative chemistries such organic and the hybrid (with Hydrogen) flow batteries are not considered, is it because we look only at the commercially mature? This also then for Table 2.1, where to the best of my knowledge the roundtrip efficiency for redox flow batteries above 70% would be then too high, I have seen also at page 25 even 90% is claimed, this is if you look at the cell and not at the whole system. Same other claims of 80-87% not clear if roundtrip or only charge or discharge. Also for the statement about pumps and shunt currents, being negligible, actually they could easily be shunt of several % points and Pumps/hydraulic losses as well, in the charge and then in the discharge affecting in the roundtrip estimation (e.g. Trovò from Padova University: https://doi.org/10.1016/j.jpowsour.2019.227144). These losses may also be an issue with respect to the scalability, e.g. small pumps and electric motors much less efficient than large ones.

In addition, I would encourage to define roundtrip efficiency, state of charge and state of health accurately to avoid misunderstandings.

At chapter 5, what would happen if also renewables are considered in addition to the demand profile, an option is filling the battery depending on when renewable are available when electricity is not needed, so that you refill it almost for free because injecting in the grid is not much paid. Actually, here the battery is filled after the sunset (Fig. 5.3), thus not clear why the battery is charged during the load peak when electricity is needed by the user (to reduce the idle time, but is there a concrete need to shift load from 8pm to midnight?). About the economic figures please remember to specify the exchange rate adopted, and I was wondering whether you thought at its impact in countries where the cost of electricity is higher, furthermore with 0.05$/kWh one can hardly pay back the cost of the battery itself.

Finally, I would try to stress more on the importance of the model, seeing what are the savings obtained with the charging strategy developed with the model and what one can do without it, to show the economic impact that such detailed model can bring.

Lot of emphasis is on the crossover and consequent rebalancing, what about the servicing? See K.Rodby https://doi.org/10.1016/j.jpowsour.2020.227958 Overall what about the usage of the model for organic RFB?

Some minor details:

Pages 34, in "all the above models" not clear to which is referred and which are the "ranges of applicability" mentioned.

The paragraph 2.3.4 Parameters identification, could you guide a bit more the reader introducing to it.

Often used lumped references, I would in general reduce its usage detailing which information each of them brings.

Sometimes more technical-quantitative terms could be used, e.g. page 30 "complicated models".

Sometimes less emphasis, e.g. page 116, "VRFBs emerge as the most promising", it is not a conclusion of this work and I would keep it among the most promising.

Some typos, e.g. page 22 "which ensures which ensures".

Provisional Recommendation

☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*

☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*

☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*