Skoltech
Skolkovo Institute of Science and Technology

Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Timur Saifutdinov

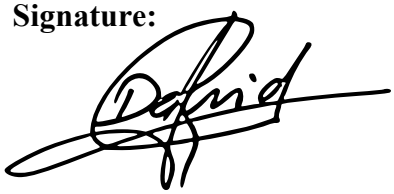
PhD Program: Engineering Systems

Title of Thesis: Optimal siting, sizing and technology selection of energy storage systems for power system applications

Supervisor: Prof. Janusz Bialek

Date of Thesis Defense: 20 January 2020

Name of the Reviewer: David Pozo

I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Signature:**  **Date: 21-12-2019**

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

Reviewers report should contain the following items:

- **Brief evaluation of the thesis quality and overall structure of the dissertation.**

The student addresses in his doctoral thesis the problem of optimal siting, sizing, and technology selection of energy storage, electrochemical-like storage, for power system applications by means of optimization. The thesis is composed of 5 chapters. A large part of the thesis is dedicated to building a model for electrochemical storage that can be embedded within power system applications. In this case, a planning model of electric grids is selected. The thesis demonstrates the applicability of modeling proposed in chapter 4. The last two chapters are dedicated to discussion and conclusion.

The overall thesis is well structured, and it has a coherent storyline. The contributions to the field are relevant. The quality of the thesis is adequate. The outcomes are extensively discussed, supporting this dissertation with merits for the aim and purpose of the present thesis manuscript.

There are some issues that should be clarified in the final version of the thesis manuscript. They are listed below.

- **The relevance of the topic of dissertation work to its actual content**

Power systems are constantly evolving. We are currently close to a tipping point where a new generation of power systems will be developed due to the maturity of new technologies that make them competitive. In the near future, power systems will have a totally different approach to operating and planning. For instance, increasing the level of renewable generation is reducing the overall inertia of the system by shifting conventional generators with new renewable generators. There are many challenges to keep supplying electricity with the reliability required. Energy storage is one of the most promising technology in the coming years for being installed on the power system legacy. This thesis focuses on developing a detailed model for Li-ion batteries of alike for being considered as new assets of the next generation of power systems. The modeling approach provides a set of analytical equations that can be embedded into more sophisticated models, e.g., for techno-economic analysis for power system planning.

- **The relevance of the methods used in the dissertation**

The mathematical battery models proposed by the student in his thesis has a non-linear representation. Embedding them into optimization problems for decision-making in power system applications would result in a non-linear and non-convex approach that inherits bad properties such as no guarantees of a global solution that can be proved using conventional methods for solving them. The thesis focuses on Reformulation-Linearization Techniques (RLT) for global optimization. Besides, the thesis presents a decomposition method based on Lagrangian relaxation and barrier functions to enhance tractability on the solution methodology. The proposed algorithms and techniques are solid and constitute an original contribution with regard to state of the art on developing battery models for being used in optimization models.

- **The scientific significance of the results obtained and their compliance with the international level and current state of the art**

This thesis focuses on the nonlinearity of battery behavior of degradation (idling and cycling). The thesis proposes a set of new approaches for first, characterizing the dependence with other states (e.g., SoC) or control variables (e.g., DoD) related to the battery behavior. The novel contribution is fitting and discretization by adding binary variables to construct a MIQP that guarantee global solutions. The scientific contributions are relevant with the current state-of-the art.

- **The relevance of the obtained results to applications (if applicable)**

The results obtained are relevant not only for academia but also for practitioners in power systems. A complete chapter is dedicated to the discussion of results endorsing the contributions collected within the scope of this thesis. The applicability has solid bases on mathematical programming theory, and the development of new formulations and models results in high applicability for other researchers.

- **The quality of publications**

The student has 3 published/accepted journal publications in top journals on the field (two of them as a first author). The student has a fourth journal publication under review in a top journal of the field. Apart of the journal publications, the student has presented his work in presented in one international conference and 3 local conferences/workshops.

- **The summary of issues to be addressed before/during the thesis defense**

Several issues should be addressed before the thesis defense. They are listed below.

a) About globality and uniqueness. The student referred in section 1.2., first paragraph, that "*convex programming and mixed-integer programming […] allows finding the globally optimal solution, which uniqueness is mathematically proven*." On page 28, it appears similar statement: "*a mixed-integer problem reformulation is proposed, where continuous variables that cause nonconvexity are replaced with integer ones with respect to which the rest of the problem remains convex*." It also appears in several parts of the text similar declaration.
Firstly, uniqueness only is proven if the problem is convex, and the objective is strictly convex. Second, a mixed-integer problem is not convex. However, there are algorithms, like B&B, that guarantee optimal global solution with enough time.

b) Equations (3.11) and (3.12) require knowing the initial and end time epoch of each cycle. IIn chapter 4, is described that it is approached by looking at the demand profile. However, this profile it could be very different with massive penetration of renewable generation, but most importantly at the local level, i.e., that at the very particular node that battery will be connected, the demand profile could be quite different of the demand aggregated system profile (see an example of ERCOT system). Please, elaborate more on the discussion section about the limitations of this approach.

c) In the abstract, it is said that "*The present thesis addresses the problem of optimal siting, sizing, and technology selection of energy storage systems for power system applications by applying the formal optimization methods*." It is confused in terms of optimization methods. This thesis does not develop optimization methods, but instead, it uses off-the-shelf solvers. The mathematical strength of this thesis is in the modeling and the problem reformulation in some of the existing canonical format of optimization problems. In addition, a decomposition method is applied.

d) Please, elaborate on the convergence of the ADMM developed in the thesis. Can be guarantee globality? Is feasibility always guarantee when reformulating the problem with barrier methods?

e) When referring to the size of the problem, it is common to use the number of binary variables for mixed-integer programming instead of all possible combinations. Please correct it along the thesis body, see one case on page 135.

f) Page 136. The student stated: "*Energy storage yields benefit from an energy arbitrage (buy low – sell high) and reduction of active power losses within a network.*" However, it is not true always, especially the last part. Please reformulate.

g) Please, elaborate on how can be estimated the price of active power losses (eq. 4.1).

h) Page 95. The student mentioned: "*Particularly, as was shown in the previous section, the degradation from idling might be represented as a convex hull."* There has not been mentioned or introduced what a convex hull is. This concept is neither used later in this dissertation.

i) In section 4.4.2., it is mentioned that the optimality gap was set to 0.1%. It represents 3452 pounds per diem on your problem. On page 120, it is said that the current approach "*adds up additional 856 £/day to average network operation cost" ... with regard to the existing state-of-the-art methodology.* The error from the optimality gap is more significant that the accuracy increase. Besides, according to the results obtained (page 120), degradation adds up an additional 6,661 £/day. Gap error could be more than half of the degradation cost. Please, review the results and extend the discussion on it.

j) Please consider presenting figures from 4.8. to 4.10 with additional axes that represent a percentage of a reference value.

k) Please, reconsider reformulating the assertion on page 123. "*As it can be seen from Figure 4.5, each of the considered cycles is limited within the proposed time frames, meaning that DoD limit constraints (3.31) and cycle temperature constraints (3.32) are properly formulated*." It has not been proved that they are "properly formulated," they worked well for your particular case study.

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*