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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: Henni Ouerdane

I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Signature:** **Date: 20-12-2019**

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

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

The doctoral thesis *Optimal siting, sizing and technology selection of energy storage systems for power system applications*, submitted by Mr. Timur Sayfutdinov, focuses on the mathematical formulation and numerical solutions of a complex and highly topical optimization problem in the context of power systems modernization. The thesis is structured over 5 chapters, including the introduction and the conclusion that summarizes the main findings, followed by the list of references used throughout the manuscript, and a series of 3 appendices offering additional useful data. The doctoral thesis has a well-balanced content where the concepts used by the author, the methodology he developed and his ideas are well explained, so that

the added value of the research results appears clearly upon reading. Mr Timur Sayfutdinov made efforts to properly communicate on the highly technical content and put forth the main messages of his research work.

- **Relevance of the topic of dissertation work to its actual content**

Energy storage system (ESS) play a growing and strategic role as components of modern energy systems, which are being modernized to reduce fossil consumption. With the increasing penetration of the so-called renewable energy sources, grid management to ensure balance between the supply and demand becomes increasingly complex due the intermittent nature of these sources like solar and wind. Widespread energy storage would facilitate the matching of the electrical energy supply that acquires a stochastic character and the demand that fluctuate over different time scales but these are subjected to various constraints including, e.g., lifecycle; cost; fast response; reliability; efficiency, etc. More precisely, in the case of batteries, the ESS technology studied in the present thesis, these constraints include the effects of the depth of discharge and the state of charge on the battery degradation. Therefore, though energy storage solutions can be varied, their implementation must account for the constraints and ideally be optimal considering siting, sizing, and technology selection (SST). There exist different models and approaches that are formulated in such a way that the optimization problem is kept convex. In his thesis, Mr Timur Sayftutdinov, explains that as battery degradation can be seen as a cumulative and irreversible process, there is a need to extend the scope of the previous models and frameworks, which he does by reformulating the optimization problem as a mixed integer convex programming problem, considering Li-ion battery storage. The obtained results compare favorably against those obtained with other approaches.

- **Relevance of the methods used in the dissertation**

The mixed integer convex programming approach of Timur Sayfutdinov permits the integration of a battery degradation model in the optimization problem, but at the "cost" of becoming nonconvex. This naturally implies that one cannot guarantee that solutions computed with standard solvers correspond to the global optimum. To circumvent this fundamental obstacle, Mr Timur Sayfutdinov proposed to reformulate the nonconvex problem into an effective convex one, by constraining the continuous variables that cause nonconvexity to assume integer values, thus making it a mixed integer convex programming problem whose guaranteed globally-optimal solution is found with the Branch-and-Bound algorithm using convex programming. The issue of scalability, i.e. tractability with the increase of the system size is successfully addressed by employing the so-called augmented Lagrangian relaxation and barrier function relaxation to decompose the original problem per bus and per ESS unit relaxing the power balance constraints. The optimization problem is then reformulated in a set of "decoupled" sub-problems with decreased search-space size, and solvable in parallel, which in fine, requires less computational power.

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

The work and results presented in the doctoral thesis of Mr. Timur Sayfutdinov certainly are on par with the current state of the art in the field, and even extend it as recognized in particular by the publication in one of the top journals: IEEE Transactions on Sustainable Energy. Two oral presentations at two different international conferences confirm the interest of the power systems community for this research work.

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

Since the optimal siting, sizing and technology selection of energy storage systems, concerns a range of different stakeholders in the power systems industry, like system operators, investors, engineers, I believe that the research work of Mr. Timur Sayfutdinov, will attract attention beyond academia and serve useful practical purposes. One other useful aspect of the framework developed by Mr. Timur Sayfutdinov is that it permits the analysis of second-life energy storage solutions, since the focus can also be on the actual characteristics of the storage device.

- **Quality of publications**

As of yet, Mr. Timur Sayfutdinov is co-author of 3 published articles: 2 proceedings at leading international conferences, of which one as first author; and one, as the leading author of a high-level journal article published in IEEE Transactions on Sustainable Energy (Scopus Q1 journal, CiteScore: 10.32). The level of the international conferences and the high impact of the above IEEE journal warrant the quality of the publications authored by Mr. Timur Sayfutdinov. This clearly satisfies the publication requirements of the Skoltech Engineering Systems doctoral program. Interestingly, he also is the first author of an article written with two other PhD students only, i.e. *without* senior authors like faculty or experienced postdocs; the paper submitted to Electric Power Systems research (Scopus Q1 journal, CiteScore: 4.02) is currently under review.

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

The doctoral thesis is well-written and offers a quite transparent development of the methodology on the one hand, and a discussion of the results on the other hand. There is no particular issue to address before the defense, from my viewpoint, and I leave some particular questions for the thesis defense, as it is also important that Mr Timur Sayfutdinov shows actual mastery of his work without being told questions in advance.

That said, I believe that in his manuscript he demonstrates that he has a sound knowledge of his scientific field, and that he made a significant scientific contribution to the field of power systems in the frame of his doctoral work. I am pleased to state that his PhD thesis is worthy of consideration for the formal defense leading to the award of the PhD degree.

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*