Skolkovo Institute of Science and Technology

Thesis Changes Log

Name of Candidate: Alvaro José González Castellanos

Ph.D. Program: Engineering Systems

Title of Thesis: Flexibility Characterization in Power Systems

Supervisor: Prof. Aldo Bischi

Co-Supervisor: Prof. David Pozo

The thesis document includes the following changes in answer to the external review process.

I would like to thank both internal and external reviewers for their insightful comments and suggestions, which have contributed to enhancing the quality and readability of the thesis. I appreciate their time and effort spent on revising this work. I hope that this revision clearly responds the reviewers questions.

Below, I have grouped the sets of comments and have provided a detailed point-by-point reply. The reviewers are listed in alphabetical order by their last names (as they appear in the Skoltech system): **Janusz Bialek**, **Audun Botterud**, **Elena Gryazina**, **Line Roald**, **Vladimir Terzija**, and **Petr Vorobev**.

For better navigation, the information inside boxes in green corresponds to modifications that have been made to the revised thesis (RT). To improve readability, the equations belonging to the response text will be labeled as (R.#), and those of the manuscript will follow the convention (#).

I look forward to address this and more of your questions during the upcoming defense presentation.

Sincerely,
Alvaro González.

Response to Prof. **Janusz Bialek**

I thank Prof. **Janusz Bialek** for the very positive review of the thesis. There are no particular questions or modification requirements in the reviewer's report. I hope to address any remaining questions during the thesis defense.

Response to Prof. **Audun Botterud**

I thank **Prof. Audun Botterud** for his insights on the benefits' quantification of the proposed solutions. Below I address his comments.

Comment:
To make an impact on real-world industrial practice, however, the thesis would benefit from a more extensive discussion of how the proposed solutions compare to current industry practice and from larger-scale case studies with more realistic datasets, including out-of-sample simulations to more adequately measure the benefits of stochastic formulations.

Response:
As the reviewer has pointed out, the presented models are mostly tested on synthetic systems. Nevertheless, in this work we present numerical tests that allow to understand the fundamental benefits derived from the developed models and the base principles that were proposed in this thesis work, which would still be present in larger case studies:

- In the presented battery characterization model, its computational and reliability benefits have been corroborated against the ideal model predominant in the power systems literature and against the complete non-linear non-convex model.
- With respect to the proposed heat exchange market, there have been studies where the benefits of heat integration between diverse industrial processes could lead to up to 20% reduction in the total cost of the system operation [1]. Traditionally, the transfer of heat between locations is agreed bilaterally between the industrial agents with the pricing of the exchanged energy being fixed for the duration of the contract. The heat exchange market proposed in this work ensures that the resultant pricing is optimal for the market agents. Thus, the revenue of the participating agents is maximized and the inefficiencies of single-value pricing are removed.
- Regarding the stochastic energy and reserve market presented in Chapter 4, the developed asymmetric energy and reserve electricity market provides demand cost reductions when compared with the existing symmetric models. The proposed methodology allows us to consider the complete support set of random variables by employing a chance-constrained formulation in contrast to the use of scenario-based methods. Therefore, out-of-sample simulations cannot be performed, but only ex-post evaluations of the realization of the random variables, which only occurs in real-time operation of the systems.

As highlighted by the reviewer, the next step for this work is for its validation with real datasets for the accurate assessment of the benefits and further development of the proposed methodologies.

Response to Prof. **Elena Gryazina**

I thank **Prof. Elena Gryazina** for her comments on the computational aspects of the presented methodologies. Below I address the raised questions.

Comment - Modeling accuracy:
I have mainly one issue to be addressed before/during the thesis defense. The author emphasizes the convexity of the proposed routines. Most often convexity is needed to speed up the convergence and decrease the computational burden, but at the same time one may sacrifice accuracy.

Response:
This comment refers to the motivation behind the chosen modeling methodology. I thank Prof. Gryazina to point this out, allowing me to add the following explanatory text to the thesis:

Page 17, Section 1.4 Research gaps and thesis aim
The adopted modeling framework is that of convex optimization. The convex optimization framework provides the following benefits for our work:

1. Convex optimization is more computationally efficient that its non-convex counterpart.
2. Unlike non-convex optimization, convex optimization models guarantee the existence of a unique (global) optimal solution. Thus, the obtained results are reproducible on any device and optimization solver.
3. The uniqueness of the optimal solution makes convex models suitable for economic interpretation, since it guarantees the existence of a unique price when using a dual-pricing for market formulations.
4. Finally, convex optimization is the standard methodology employed in most of the electric power systems in the world.

Comment - Chapter 2:
When discussing the battery models (Chapter 2) the accuracy and computational time are addressed in Tables 2.1 and 2.2 with reported number of samples 14 and 20 used to construct the convex envelope. I'm curious on the robustness of the observed accuracy and computational time with respect to the number of samples. What if you use more/less samples? How would it affect the accuracy and computational time?

Response:
This is an interesting question that allows us to reflect on the benefits of the proposed model when compared to non-linear or mixed-integer approaches. Given that the proposed convex characterization method is a general one for energy storage units with fixed energy capacity and

performance independent from external conditions, the observed accuracy of the sampling approach depends highly on the shape of the characterization curve, i.e., how non-convex the approximated performance curve is. Additionally, the procedure for selecting the characterization points has an additional impact on the characterization accuracy, e.g., we would have a poor representation if our sampling points are accumulated in one corner of a highly non-convex surface. In the presented work I employed a naive sampling approach: the performance curves where sampled by a grid comprised of equidistant points along the three-dimensional space. For the discharging power, we used two sets of six equidistant points at the minimum and maximum state-of-charge levels, plus the two auxiliary ones. While for the charging power curve, we used three sets of six equidistant points at the minimum, SOC=0.13, and maximum state-of-charge levels, plus the two auxiliary ones. We used more points for the charging curve to better represent the existing "elbow" for low SOC levels. We observed that the characterization error, even for this naive sampling approach, for the discharging process has a maximum of 9.03% (mean= 1.21%), and a maximum of 1.12% (mean= 0.22%) for the charging process. Therefore, it is possible to have a high-fidelity representation of the storage performance, with a low number of points.

On the other hand, the computational time is affected by the choice of sampling points due to the introduction of additional variables for a better characterization. The number of additionally introduced variables can be calculated as: $n^{\text{PW-add}} = (|J| + |K| + 3) * |T| * |S| * |\Omega|$, where $|J|$ is the number of discharging sampling points, $|K|$ is the number of charging sampling points, $|T|$ is the number of time steps, $|S|$ is the number of storage units points, $|\Omega|$ is the number of states of the system (consider a security constrained scheduling or two-stage stochastic optimization one), and the number 3 corresponds to the addition of the p^{out}, p^{in}, and SOC variables. However, since the resulting model is a linear programming (LP) one the increased complexity is given in polynomial time, rather than exponential time, which would be the case if a mixed-integer approach was employed.

Comment - Chapter 3:
When presenting the convex heat market (Chapter 3) what are (non-convex) alternatives and their computational consequences?

Response:

There exists several non-convex modifications that can be performed on the presented heat market model, i.e., applied convexifications to the general model:

- Thermal flow between nodes: the heat transfer between areas is non-convex and dependent on the ambient temperature, nodal temperatures, and mass flow rate in the supply and return pipes. Therefore, the transfer efficiency is a non-constant parameter depending on both exogenous and endogenous variables of the optimization problem.
- Performance characterization of generation units: most energy generation technologies have non-constant first-principle thermodynamic efficiency that depends both on external weather conditions and the operating point. This non-convexity is reflected in the formulation of the cost functions for the equivalent area generation. A more detailed discussion of the non-convexity of cogeneration performance is given in the response to Prof. Roald's Comment

3.1. Additionally, the reviewer can find information on how to model the non-convexity of cogeneration units in our work [2].

- Network flows within areas: both electricity and heat energy flow within the microgrids, discarded in the presented market model, are non-convex in nature.
- Generation units scheduling: the scheduling of the generation units is in practice performed considering their start up and shut-down procedure, i.e., unit commitment. The unit commitment of the generation units introduces binary variables in the presented convex model. Thus, the resultant unit commitment model is non-convex and not directly applicable for dual pricing.

The above-mentioned non-convexities, if introduced, would increase the computational time required for the model solution. Additionally, the distributed optimization algorithms presented have no convergence guarantees on non-convex subproblems. Finally, the non-convexities would not guarantee the globality of the optimal solution, introducing unclear pricing references for the economic exchange between areas.

Comment - Chapter 4:
When describing stochastic power market (Chapter 4) how do you propose to derive the prices in OPF-N2N-AB model? Does it simply mean taking x^* equal $\hat{x}^*$ since it's always feasible?

Response:
This is exactly how the pricing-derivation works for the OPF-N2N-AB model. Once the optimal solution $\hat{x}^*$ is obtained within the established optimality threshold $100(C(\hat{x}^*)/\hat{C}(\hat{x}^*) - 1)$, then we obtain the prices as the corresponding dual variables of the obtained solution.

I thank **Prof. Line Roald** for her thorough revision of this thesis work. Below I address the given comments. I look forward to the discussion during the defense session.

Comment - On modeling depth:
I will note that while the breadth of the methods and results in the thesis is impressive, it does not seem to go very deep in either of the presented topics. For example, chapter 4 utilizes deterministic line flow constraints, which seems at odds with the idea of node-to-node balancing prices. Further, in chapter 3, the consideration of electricity seems to be more of an afterthought. A deeper analysis of interactions between heat exchange and electricity operation (i.e., how they complement and improve each other) would have been a natural inclusion. I will say that this impression might be due to the presentation of the work, where each topic is organized into a separate, somewhat disconnected chapter. As an example, in chapter 3, it might be useful to first present a centralized model (with analysis and numerical results) and the create another chapter which presents a more realistic model where each area optimizes its own operation (with a separate set of analysis and results). A similar comment could be made for chapter 2 and the decision of presenting stochastic unit commitment formulation in the appendix.

Response:

During the development of my doctoral work, we decided to investigate the broad topic of flexibility characterization in power systems. Given the diversity of topics and directions that make up the flexibility in power systems and that their holistic study could not be achieved, I decided to select the ones that will have a more immediate impact in future power systems, namely: electric energy storage modeling, the integration between the electricity and heating sector, and the development of stochastic power markets. For each of the three main topics selected, the emphasis was on providing new modeling perspectives rather that would advance the understanding of flexibility in power systems, rather than developing advanced mathematical tools that would increase the level of represented details. The modeling decisions and assumptions employed follow these principles, as does the structure of the thesis on which the material is presented in a way that emphasis is given to the introduced contributions, while the material already established in the literature is relegated to the appendices.

Comments on Chapter 1

Comment 1.1:

On page 9, I believe that the definition of FACTS (described in the section on dynamic line rating and FACTS devices) is not quite correct. In my understanding, FACTS devices is also used to control power flows.

Response:

I thank the reviewer for this clarification. I have expanded the definition of FACTS provided in the thesis as follows:

> **Page 9, Section 1.2.4 Flexibility from the electric network - Dynamic line rating and FACTS devices**
> FACTS devices provide reactive power balancing along the power lines, thus reducing the total apparent power transmitted and increasing the active power holding capacity of the lines. Additionally, FACTS devices increase the power controllability of the line flow and and improve the stability of the power networks [3].

Comment 1.2:
On page 10, it might be helpful to include a reference to European imbalance netting schemes.

Response:
Thank you for bringing up this relevant example to the use of cross-border balancing areas. I have added the following text to the thesis:

> **Page 10, Section 1.2.4 Flexibility from the electric network - Cross-border interconnection**
> An example of the use of cross-border interconnection for load balancing is the future European balancing market in which over 40 transmission system operators (TSOs) of 35 countries will be able to exchange balancing services in the intraday market for different types of products, i.e., provision of balancing power with an associated activation time frames [4].

Comments on Chapter 2

Comment 2.1:
The model assumes the solution would automatically enforce that the battery does not charge/discharge at the same time. This is not true in all circumstances and should be discussed appropriately.

Response:
The reviewer is correct in this remark, we have added the following explanatory text in Section 2.4:

> **Page 45, Section 2.4 Linear Reformulation Approach**
> Therefore, simultaneously charging and discharging would go against the economic objective of minimizing the cost of power system operations because energy would be lost during the imperfect (and simultaneous) charge and discharge processes. This behavior is ensured for a majority of power system applications where the power balance constraints can be satisfied

within the technical limits of the generators and demand, i.e., when the demand can be fulfilled without recurring load shedding or generation curtailment. An exception to this case is when there exist economic incentives for the use of a particular type of generation, e.g., renewable energy generation, or when the cost of simultaneous changing/discharging losses are too small in comparison to the total system costs. If simultaneous charging and discharging is possible in the storage application, the proposed method could be combined with the use of a binary variable to represent the state of the battery, i.e., charging or discharging.

Comment 2.2:
What does it mean that the difference between the NLP model and the proposed linear model is so large in Fig 2.6? Does this mean that the linear model is not accurate?

Response:
The obtained results for the NLP model are subject to the optimal solution found by the IPOpt solver that has no guarantee of finding the optimal solution. This, combined with the fact that the energy storage capacity is relatively small when compared to the total system demand, can contribute in obtaining a different scheduling for the local optimal solution found for the NLP model than that obtained for the other models. The difference of the obtained solutions can also be evidenced for the MILP model which is the second most accurate one.

Comment 2.3:

On page 44:

- How were the sample points identified when deriving the convex envelope?
- How did you identify the Max errors in the linear model?
- Would this improve with more sampling points?
- What are the trade-offs you face when choosing the number of and location of the sampling points?

Response:

How were the sample points identified when deriving the convex envelope?

In the presented work I employed a naive sampling approach: the performance curves where sampled by a grid comprised of equidistant points along the three-dimensional space. For the discharging power, we used two sets of six equidistant points at the minimum and maximum state-of-charge levels, plus the two auxiliary ones. While for the charging power curve, we used three sets of six equidistant points at the minimum, SOC=0.13, and maximum state-of-charge levels, plus the two auxiliary ones. We used more points for the charging curve to better represent the existing ”elbow” for low SOC levels. We observed that the characterization error, even for this naive sampling approach, for the discharging process has a maximum of 9.03% (mean= 1.21%), and a maximum of 1.12% (mean= 0.22%) for the charging process. Therefore, it is possible to have a high-fidelity representation of the storage performance, with a low number of points.

More advanced sampling algorithms can be employed to obtain the convex hull of the characterization surfaces.

How did you identify the Max errors in the linear model?

The sampling errors in the linear characterization model were calculated as the distance between the original performance surface and the convex combination of the sampling points. For this, I created a grid of 10 000 points for the characterization surfaces (100 points along the SOC-axis and 100 along the $p^{\text{dis/cha}}$-axis), then compared the value of our approximation for $p^{\text{out/in}}$ versus the real value obtained from the analytical model, i.e., the original characterization curve.

Would this improve with more sampling points?

Undoubtedly, the use of more optimally-located sampling points would increase the representation accuracy of the approximating grid-generated surface. However, if the sampling points are obtained via a convex hull approach, an increase in the number of points would not increase the representation accuracy.

What are the trade-offs you face when choosing the number of and location of the sampling points?

As discussed above, the chosen sampling points have an impact on the approximation accuracy. On the other hand, the computational time is affected by the choice of sampling points due to the introduction of additional variables for a better characterization. The number of additionally introduced variables can be calculated as: $n^{\text{PW-add}} = (|J| + |K| + 3) * |T| * |S| * |\Omega|$, where $|J|$ is the number of discharging sampling points, $|K|$ is the number of charging sampling points, $|T|$ is the number of time steps, $|S|$ is the number of storage units points, $|\Omega|$ is the number of states of the system (consider a security constrained scheduling or two-stage stochastic optimization one), and the number 3 corresponds to the addition of the p^{out}, p^{in}, and SOC variables. However, since the resulting model is a linear programming (LP) one the increased complexity is given in polynomial time, rather than exponential time, which would be the case if a mixed-integer approach was employed.

Comment 2.4:

How is the MILP model on page 48? Can you include a mathematical definition and/or a more careful comparison with your proposed model?

Response:

The mathematical description of the MILP model has been included in Appendix A. Mixed-integer linear programming (MILP) battery characterization.

Comment 2.5: Can you include a discussion of the results in Table 2.1?

Response:

Below I presented the added discussion for Table 2.1:

Page 48 Section 2.5. Test Case 1: Economic Dispatch
As seen in Table 2.1, the employed battery models result in comparable objective values. However, the selection of different modeling approaches has an impact on the optimization problem structure and its solution time. The non-linear non-convex programming (NLP) model at 231.3 seconds is solved a hundred times slower than its linear counterparts, while the mixed-integer linear programming (MILP) model requires 143.3 seconds for its solution. The fastest model is the ideal linear programming (LP-ideal) one, where the power limits and efficiencies are considered constant. However, as discussed in Section 2.5.2, the reliability of the derived battery scheduling for the LP model is compromised by its assumptions. It must be noted that even though the proposed linear approximation (LP-Approx) model introduces additional variables and linear constraints to represent more accurately the battery performance across it operating region, it provides optimal solutions considerably faster, 3.4 seconds, than the NLP and MILP models.

Comments on Chapter 3

Comment 3.1:

(Section 3.2.3) Can the relationship between the generated heat and power in each area always be represented as a convex region? I doubt so, so it would be helpful to explain if this is this an approximation/what assumptions it is based on?

Response:

As the reviewer points out, the relationship between the generated heat and power cannot always be represented as a convex region. A unit's operating region depends on the configuration of its thermodynamic cycle. The presented approximation through linear boundaries was introduced by Guo et al. for power system problems [5] and allows the general representation of cogeneration units, convex and non-convex ones. However, even this representation cannot capture the non-convex relationship between the generated energy and the primary fuel consumption. For this purpose, it is necessary to use mixed-integer linear programming approaches as that proposed in [6] and employed in our work [2].

The assumption of convexity in the representation of the operating region for cogeneration units permits us to use convex duality theory for the pricing of the exchanged heat and the use of the presented distributed optimization algorithm.

Comment 3.2:

(Page 72) The model assumes the solution would automatically enforce that an area does not export and import heat at the same time. Will this always be true? A more detailed discussion would be appreciated.

Response:

As highlighted by the reviewer, the model's solution does not automatically guarantee that an area would export and import heat from another area at the same time. The uniqueness of the transfer direction can only be ensured with the use of binary variables or the the presented disjoint constraint (3.5c). However, for most practical applications, the heat transfer efficiency between two nodes of a heating network is below 100%, which would deter the solution from having a simultaneous import and export of heat since this would result in wasted heat, unless there is an economic incentive in the objective function to do so. Common economic incentives that would impact the uniqueness of the direction of heat exchange are:

- The introduction of constraints or costs related to emissions or primary energy savings.
- The saturation of the interconnection capacity between microgrids for heat exchange, combined with high local electricity consumption and high electricity import prices.
- The presence of power-to-heat technologies power from excess renewable generation, whose heat generation exceeds the local demand and interconnection capacities.

The above-mentioned scenarios, alone or in conjunction, could prompt a solution in which it is more economically efficient to waste the generated heat via simultaneous import and export.

Comment 3.3:

(Page 75) I realize that it is convenient for your analysis to not impose restrictions on h_{ab}. However, can you include a discussion of the implications of this assumption? Does it impact the results?

Response: I think the reviewer might be referring to not imposing constraints on $h_{ab}^{(b)}$ in Model 4 (page 78). The use of such constraints would result in a redundancy of the model constraints, which it would not impact the scheduling results and the exchanged heat quantities. However, the use of redundant constraints duplicates the number of dual multipliers associated with the transfer limits, resulting in a degenerate solution of the dual problem, which is an issue if dual pricing is to be adopted. Therefore, using redundant constraints can lead to diverse price values for each participant of the decentralized market, complicating the economic settlement process.

Comment 3.4:

(Page 88) You state the that JP-ADMM algorithm is guaranteed to converge. What solution will it converge to?

Response:

The JP–ADMM algorithm has optimality convergence guarantees for exchange ADMM problems, i.e., problems in which each area (agent/block) must consider the values of exchanges with other areas in its local optimization problem.

Comment 3.5:

Eq (3.25) Where did this update come from (i.e., why is it defined this way)?

Response:

Equation (3.25) corresponds to the dual multiplier update, i.e., heat price update, that each area performs in the JP–ADMM algorithm for the exchange coordination as presented in [7]. Each area updates its offered heat price based on its locally optimized values of exported and imported heat in the current iteration of the coordination algorithm.

Comment 3.6:

(Section 3.5) I found it hard to understand which method was used to generate the results that are discussed. Is it using the centralized method? The distributed method?

Response:

For the numerical tests, I implemented the decentralized method presented in Section 3.4.

Comments on Chapter 4

Comment 4.1:

Can you discuss the implications and motivation for using deterministic line flow constraints in the problem formulation?

Response:

The use of deterministic line flow constraints is done to facilitate the derivation and interpretability of the energy and balancing prices for the proposed market formulation. Given that the electricity generation obeys a stochastic process, the use of deterministic line flows could make way for infeasible balancing orders due to network constraints, leading to a redispatch of the balancing resources.

However, given that most power systems in the world employ deterministic operation scheduling frameworks, the proposed market with asymmetric stochastic balancing would improve the balancing provision, and if line limit violations occur during the real-time operation, there already exist in the power systems progressive intraday market mechanisms that ensure the feasibility of the load flows. For this reason, we have decided to focus on understanding the impact that representing asymmetric forecast errors, evidenced in real system operation, would have in generation dispatch and reserves allocation. A more complete formulation based on joint chance constraints and stochastic line flows for understanding the impact of asymmetric balancing in line flows is not so straightforward mathematical extension of our work, and one that we are currently evaluating adapting existing methodologies as that developed in [8] or with a data-driven approach as proposed in [9].

Comment 4.2:

Where did the analysis for the Node-to-node (OPF-N2N-AB) come from in Table 4.1?

Response:

Table 4.1. summarizes the 4 types of markets presented in Section 4.4, Symmetric and System-wide Markets. The Table allows for the comparison of the price formation in the different market formulations.

I thank **Prof. Terzija** for his comments that allow me to present in a clearer manner this work's motivation and presented methodologies. I respond to his comments below.

Comment 1:

To provide more details about different definitions of power/energy system flexibility.

Response:

I have added the following definitions of flexibility for power and energy systems:

> **Page 2, Chapter 1 Introduction**
> A general and adequate definition of flexibility is also given by Alizadeh *et al.*: "the ability of a system to deploy its resources to respond to changes in the net load, where the net load is defined as the remaining system load not served by variable generation" [10].
>
> Additionally, Chicco *et al.* define the flexibility in multi-energy systems as "the technical ability of a system to regulate multi-energy supply, demand, and power flow subject to steady-state and dynamic constraints and while operating within predefined/desired boundary regions for certain energy vectors" [11]. This definition extends the electric net load balancing to include the management of the energy flows of the interconnected energy systems through space and time.

Comment 2:

Results presented in Fig 2.11 are based on a "day ahead" forecasting approach. Would it be applicable and why to undertake additional "hourly modifications" in reaching optimal solutions?

Response:

As the reviewer points out, the optimal scheduling operation of the distribution system presented in the Test Case 2 (Section 3.6) can be performed in practice in a rolling-horizon manner. In a rolling horizon approach the forecasted values are updated in real-time at every time step and the scheduling problem is run anew to obtain more precise solutions via the more accurate information obtained from the new forecasts. The presented Test Case 2 can be seen as a snapshot of this procedure for a fixed time step.

Comment 3:

In page 11 few details are given about gas systems. I would appreciate more comments about potential approaches for using gas system and busting system flexibility.

Response:

Following the reviewer suggestion, I have added the following additional explanation on the flexibility obtainable from gas systems:

Page 11, Section 1.2.5 Flexibility from multi-energy systems - Power-to-gas
Due to its compressibility, natural gas pipelines can be used to store gas for its later use by controlling the internal pipeline pressure. Additional synthetic gas could also be injected in periods of excess electric renewable generation. Therefore, gas systems can be operated as temporary primary energy storage to balance net load fluctuations in the power system [12].

Comment 4:

In page 41 a linear storage model is presented. The optimization problem has been solved, but I'd appreciate if a block diagram, in which input and output variables are used in the optimization procedure, could be presented. If possible, do the same for the OPF optimization.

Response:

I have added the following explanatory figure to the description of the energy storage model. I have opted out of providing a similar diagram for the OPF, since this is a standard model in the literature and its critical new component is the proposed energy storage characterization, provided in the figure below.

Page 45, Section 2.4 Linear Reformulation Approach
As seen in Figure 2.5, the proposed battery characterization model receives as an input the sampling point for the discharging and charging processes derived from the employed exact battery model and by their linear combination, derives the battery power and energy state.

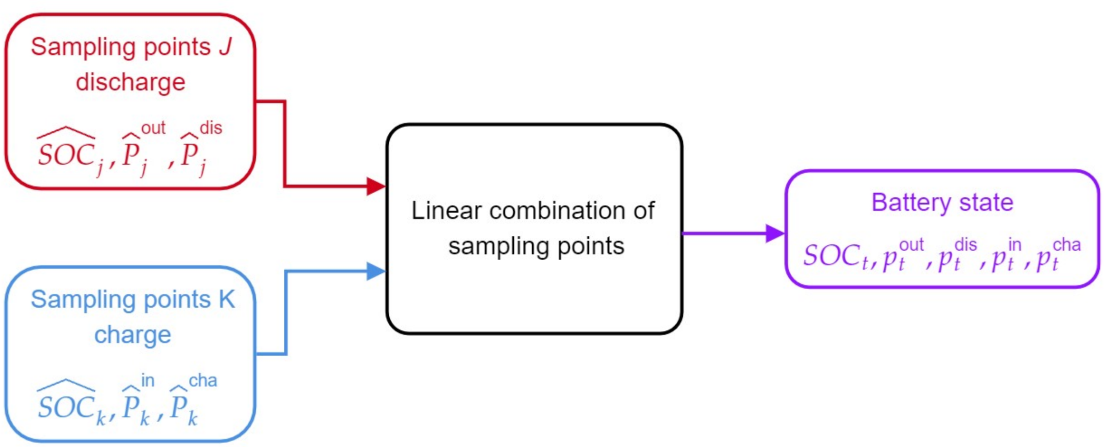

Figure 1: Block diagram representing the proposed battery characterization model.

Response to Prof. **Petr Vorobev**

I thank Prof. **Petr Vorobev** for his review of this thesis and the proposed steps for its future implementation in industrial projects. I look forward to this new step in which we can test in real Russian systems the proposed operation methodologies and models.

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