Gdynia, 15th July 2021

Assessment

of the PhD thesis entitled: „Microgrid energy management systems with hybrid optimizers, embedded deep learning forecasters and e-vehicle charging stations"
submitted by MSc Eng. Vishnu Suresh

This opinion has been prepared on the basis of Resolution of the Academic Discipline Council, Automation, Electronic and Electrical Engineering, Wroclaw University of Science and Technology dated on 19th April 2021 concerning my nomination as a reviewer of the submitted doctoral thesis as well as of the letter of Chairman of the Academic Discipline Council, Automation, Electronic and Electrical Engineering, Wroclaw University of Science and Technology dated on 30th April 2021 with a request for elaboration of the opinion about the related doctoral thesis.

The opinion was prepared as in detail justified assessment of fulfilment by the above mentioned doctoral thesis the conditions defined in Art. 13 para. 1 of the Act dated on 14th March 2003 "Act on academic degrees and academic title and degrees and title in art" (together with subsequent changes). The opinion includes, first of all, the references to the following questions:

- Importance and topicality of the research theme and subject of the thesis,
- Formulation of research questions/hypotheses,
- State of the art including a critical approach to other researchers' results,
- Methodology,
- Experiments and numerical simulations,
- Research contributions and quality,
- Quality of the conclusions,
- References,
- The weaknesses and the detailed remarks concerning doctoral thesis,
- Final conclusion.

1. Importance and topicality of the research theme and subject of the thesis

The area of power system research is fast evolving and exploring especially considering renewable energy sources microgrids and electric vehicles. The once predictable and consistent power network is now becoming stochastic and much more complex, among others, because of the increased share of renewables in the energy mix, which leads to uncertainly or even hazard in the power output making the problem of energy balancing more and more difficult. This has created the need for improved forecasting, optimization and control activities into managing the power system. In the wake of the aforementioned circumstances an importance and topicality of the research theme addressed to modern electrical power systems is commonly accepted and intensively explored. Optimizing the power system involves deployment of optimization algorithms modelled specifically for intended power networks, for example such as microgrids. In this context I am deeply convinced that the research problem, undertaken by candidate in his doctoral thesis, concerning the applicability of the advanced optimizers equipped with deep learning forecasters to support microgrid energy management systems belongs to a very present and topical subjects.

2. *Formulation of research questions/hypotheses*

Author has correctly stated that a critical part of a microgrid is its Energy Management System (EMS) embedded with forecasters and optimizers. The related responsibilities and operations of the EMS resulting from them are mainly focused on:

- analysing and conducting the optimal allocation of resources based on the maximization of the fixed objective,
- taking into account the unpredictability of the renewable energy-based in its network,
- maintenance of electrical network parameters such as voltage magnitude, frequency and others within specified limits according to standards,
- implementing specified programs such as responding to demand and flexibility according to the needs of the local situation.

The aforementioned challenges create the research questions addressed to current optimization and forecasting methods implemented in Energy Management System. This is why, the importance and the need of the submitted dissertation is to improve upon the current optimization and forecasting methods implemented in EMSs.

In consequence, the thesis of this dissertation (p. 6, Introduction) is formulated as follows:

"Application of hybrid optimization algorithms embedded with deep learning forecasters enables optimal energy management of electrical networks".

Thesis focus, covering the segments of forecasting and optimization as a part of the typical energy management system, is clearly illustrated in Fig. 2, p. 10, Introduction.

3. *State of the art including a critical approach to other researchers' results*

A state of the art, covering the development of modern electrical power system, concerning the short overview of the main terms and notions related to microgrids energy management systems that is microgrid concept (section 1.1), forecasting (1.2) divided into solar power forecasts (1.2.1), wind power forecasts (1.2.2) and load forecasting (1.2.3) as well as an optimization (1.3) including conventional and meta-heuristic optimization algorithms (1.3.1 and 1.3.2, respectively), is adequate and sufficiently comprehensive for the needs of this dissertation.

The introduction section presents the microgrid concept and provides the literature review behind the existing methods for optimization and forecasting involved in power systems, together with their advantages and disadvantages. Some important elements of critical approach are visible as the Author's explanations and comments to the presented forecasting and optimization models and algorithms (1.2.1, 1.2.2, 1.2.3 and 1.3.2, 1.3.2, respectively).

It's worth mentioning the Author's remarks (1.1) that "Microgrids enable the concept of active distribution networks and realise the implementation of smart grid" and "Microgrids quite often are equipped with Energy Management System (EMS) that are capable of managing both generators and loads in a way that is economical and sustainable" are research signposts in the presented dissertation.

4. *Methodology*

Methodology applied in this dissertation is based on the classical patterns and covers theoretical analysis and experimental research as the complementary components. In fact, this study uses a combination of both real and modelled data obtained from installations available locally and collaborating institutions abroad. All the power flows calculated are based on the alternating-current model. The thesis provides research concerning two critical parts of an energy management system for microgrids which are the forecasting and the optimization.

The thesis is being implemented in the following logically planned and consequently executed steps:

- literature review covering the existing approaches to optimization and forecasting,
- new approaches to the same are proposed upon the existing approaches and providing an explanation as to why they will be better,
- implementation of the proposed new approaches and application of the same to pre-existing electrical network and related data,
- comparison of the proposed methods with the existing methods from the literature to establish superiority,
- finally, an application of the new proposed methods to obtain optimal operational conditions of the microgrid based on real data from Wroclaw University of Science and Technology and optimal location of the Electrical Vehicle Charging Station (EVCS) in the microgrid.

All the aforementioned steps are described in a comprehensive and communicative way.

5. *Experiments and numerical simulations*

As it was mentioned earlier, this study uses a combination of both real and modelled data obtained from installations available locally, that is from Wroclaw University of Science and Technology. The thesis provides theoretical and experimental research concerning two crucial parts of the energy management systems for microgrids which are the forecasting and the optimization. Theoretical analysis together with numerical simulations were implemented to solve the problems of Solar Forecasting, Energy Management in the meaning of both optimal power flow and economic dispatch as well as the problem of EVCS and its optimal location.

With regard to forecasting, related analysis and numerical simulations explore novel deep learning architectures for 10-min ahead and 1-hour ahead forecasts. The considered models include the CNN, multi-headed CNN, CNN-LSTM and LSTM autoencoders. The results of all the approaches carried out were compared with each other and an ARIMA model for the specific data set. Finally, it was concluded that the LSTM autoencoder developed by the Author of dissertation provided the most accurate and the quickest forecasts.

During the process of forecasting numerous data processing techniques were incorporated and a sliding window approach was utilized to feed data into the deep learning algorithms. Author has noted that "Even during the time, the current thesis is being written, new deep learning models that are faster and more efficient are being introduced which could potentially pave the way for improved solar forecasting models for EMS applications and others". This observation allowed the Author to formulate an imperative to explore appropriate models for the higher time horizons.

With regard to optimization, this thesis focuses particularly on the meta-heuristic optimization approaches to OPF (Optimal Power Flow). It started with the description of power flow, numerical solvers for power flow and considered both meshed and radial networks for obtaining the steady state solution of the network. Afterwards, the Author has successfully applied the traditional meta-heuristics for optimization such as the GA (Genetic Algorithm), PSO (Particle Swarm Optimisation) and MICADO (Mixed Integer Distributed Ant Colony Algorithm). Next, the application of two novel optimization algorithms as the PO (Political Optimizer) and LA (Lichtenberg Algorithm) were introduced. All the optimization algorithms were integrated with MATPOWER for improved performance. The results were compared with other conventional non-heuristic optimization approaches. It was proofed that the most balanced and effective algorithm was MICADO, when the conclusions based on the value of the final solution and the speed of convergence to a solution were made.
With regard to ED (Economic dispatch) and their application to microgrids, their scheduling and energy management MICADO with MATPOWER was chosen as the optimization algorithm. The best performing optimizer was used for energy management in a modern microgrid modelled upon the installation present at Wroclaw University of Science and Technology with the objective of minimizing the Levelized Cost of Energy (LCOE). The installation consists of renewable energy sources such as solar PV modules, micro-hydro power plant, li-ion battery storage systems and fuel cells with hydrogen storage tanks. It was seen that the LCOE of the micro-hydro power plant was the lowest and that the fuel cells with hydrogen storage tanks was the highest.
E-mobility problems are solved by implementing coordinated charging in Electrical Vehicle Charging Stations (EVCS) in order to manage the sudden increase in energy demand and finding the optimal location for such an EVCS within the existing network. Several charging scenarios were introduced where the optimal power delivery was determined by "fmincon" of MATLAB within the EMS of the microgrid. In this case the objective function was modified and the import of power from the main grid was minimalized. Different charging scenarios were considered where the minimally charging rate was set at 25%, 50% and 75% of the maximum rated power delivery of the charger. From the results, it was concluded that the range of power delivery between 50% its maximum rated power delivery and maximum rated power delivery was optimal.
Experimental research part covering theoretical analysis together with numerical simulations is a really strong side of this dissertation, taking into account the planned scenarios, carried out research, well-documented results of experiments and finally extracted findings.

6. Research contributions and quality

The contributions of the thesis can be summarised as follows:

- the development of hybrid optimization algorithms which leverage the superior solution search capabilities of meta-heuristic algorithms and conventional optimization algorithms,
- deep learning neural network models to achieve better performance than conventional forecasting models for short term forecasting needs,
- an EMS tailored for optimal operational management of the Microgrid present at Wroclaw University of Science and Technology,

- identification of an optimal operational scenario of the EVCS taking into account the interest of both the consumer and the power system, and then finding its optimal location in the microgrid.

Taking into account the research with the use of combination of both real and modelled data obtained from physical installation shortly characterized in previous section, I am of the opinion that the key point of this part deals with highlighting the impact of appropriately chosen advanced methods and algorithms to develop the hybrid optimizers, embedded deep learning forecasters and e-charging stations on the effective and sustainable operation of microgrid energy management systems under consideration. The results obtained and shown in sections 2, 3, 4 and 5, respectively, confirm that the project objectives have been met in the satisfactory measure.

7. Quality of the conclusions

The conclusions are sufficiently supported which I have expressed in sections "Experiments and numerical simulations" and "Research contributions and quality". Formulated conclusions are well-balanced and carefully formulated. They also support and confirm previous Author's statement (1.1), that "The difference between microgrids and regular distribution networks with RES (Renewable energy sources) is mainly with regard to controlling the operations of the network".

The link between research problems and results/conclusions is strong, logical and well-documented.

8. References

The problem of references has been solved by the Author by assigning the related set of references to each section of the dissertation separately. According to this solution the number of references assigned to Introduction section is equal to 56 and to the consecutive sections of dissertation, that is to section 2, 3 and 4, this number is equal to 15, 46 and 10, respectively. To the last, section 5, being in fact a local case study, no references have been appointed.
The division of references into appropriate sections is logical from the point of view of the content analysis of a given dissertation section. On the other hand, a noted disadvantage is that a total sum of references aggregated from all sections is overestimated referring to the real number of cited publications. Bearing in mind all the aforementioned circumstances, the solid references have been used properly. I have no objections concerning this aspect. It is worth underlining, that a majority of the cited positions have been published after 2012, but many of them in the years 2015-2020. Another observation is that 4 positions cited in reviewed thesis have been published by or with cooperation of the thesis Author in such well recognized journals and conference materials as Energies, IEEE Access and Transactions on Environmental and Electrical Engineering as well as IEEE Conference EEEiC/I&CPS Europe.

9. The weaknesses and the detailed remarks concerning Doctoral Thesis.

<u>The weaknesses</u>

a) I consider the organization of certain elements of the structure of the submitted doctoral dissertation to be a weakness. A disadvantage of this organization is very uncomfortable for the readers the system of numbering and description of figures, tables and formulas, treated, separately for each section. It leads to the same number of different elements (for example, such as figures) in different sections. In consequence, we have the numerous errors and misunderstandings resulting from the proposed and introduced by Author system of designations and description. But even assuming that proposed style of structure organization of the doctoral dissertation is acceptable, the Author erroneously numbered the figures inside a given section (the examples are cited in the detailed remarks).

b) Dissertation is very complex and concerns the numerous methods and algorithms connected with forecasting and optimization, and in this context I feel a lack of clear and strong underlining Author's own contribution to solved problems.

The detailed remarks – exemplary cases

1) p. 8, line 24 up – Author used the wording "voltage angles". What does it mean? Is it a term related to voltage phase asymmetry or it is simply "phase angle" which describes the phase shift between a voltage and an electric current in the analysed circuit?
2) p. 6, line 15 down and p. 8, line 24 up – power quality standards are described in two places in the different way. Could you comment this situation?
3) With regard to "the weakness" point a) we have Fig. 1 at p. 9, Fig. 1 at p. 32, Fig. 1 at p. 56 etc., next Fig. 2 at p. 10, Fig. 2 at p. 32, Fig. 2 at p. 57 etc. The same concerns tables and formulas.
4) p. 36, Fig. 5 and p. 37, Fig. 6 (section 2) – they have wrongly the same description, but concern different CNN architectures.
5) p. 43, line 5 up – wrong numbers of equations are cited.
6) p. 44, line 8 down – It seems, that the sentence "... in this study to compare the result with ..." should be completed.
7) p. 44 – the equations (11), (12) and (13) should be numbered as (15), (16) and (17).
8) p. 47 – Fig. 12 should be numbered as Fig. 14, at the same p. 47, line 12 down – A cited Fig. 13 should be changed to Fig. 15.
9) p. 48 – Fig. 13 should be changed into Fig. 15 (Fig. 13 was shown at the p. 46)
At the same p. 48 in the text line 18 down, line 14 down, the numbers of Fig. 14 and Fig. 15 should be changed into Fig. 16 and Fig. 17, respectively.
10) p. 49 – Fig. 14 should be numbered as Fig. 16 and Fig. 15 should be numbered as Fig. 17.
11) p. 50 – Fig. 8 erroneous designation (probably corresponding to Fig. 8 from p. 40), it should be Fig. 18. At the same p. 50, line 1 up – a cited Fig. 16 should be changed into Fig. 18.
12) p. 57-Fig. 2 – The arrow between the boxes "Load data: solar PV, load and line data" and "Generation < load" is appointed in a wrong direction. But the most important doubt is about the next steps from the boxes ending the left and the right column, that is: "Add load equal to increased amount of energy" and "Reduce of energy stored by amount generated". Those steps are not clear. It seems that related loops from the aforementioned boxes should be closed. Could you comment and explain this battery management algorithm?

10. Final Conclusion

Bearing in mind that firstly, the submitted doctoral dissertation demonstrates the candidate's general theoretical knowledge in a discipline Automation, Electronic and Electrical Engineering well covering the previous requirements concerning the discipline Electrical engineering and the ability to conduct research independently, and secondly, the subject matter of the doctoral dissertation is an original solution to a scientific problems, and thirdly, my partial assessments expressed in points from 1 to 9,
I am of the opinion that submitted doctoral thesis has fulfilled all requirements included in the currently being in force Act dated in 14th March 2003 "Act on academic degrees and academic title and degrees and title in art" (together with subsequent changes) an in my opinion, the doctoral dissertation of Vishnu Suresh should be submitted to a public defence.