Skoltech
Skolkovo Institute of Science and Technology

Thesis Changes Log

Name of Candidate: Fernando Dávalos Hernández

PhD Program: Engineering Systems

Title of Thesis: Supercapacitor Energy Storage System based on Modular Multilevel Converter with embedded self-balance control

Supervisor: Associate Professor Federico Martin Ibanez, Skoltech

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

Dear Jury Members,

Thank you for your thoughtful and professional comments on my thesis. I have carefully reviewed all the observations, comments, recommendations, and changes proposed by the reviewers. Accordingly, the thesis has been revised, incorporating the suggested improvements.

Reviewer: Prof. Elena Gryazina

This thesis focuses on analysis and design of a specific energy storage system by adopting the modular multilevel converter. The novelty of this work resides in the selection, design of the power converters and the proposed techniques to use them as balancers, DC/DC, and DC/AC converters simultaneously. The author makes a detailed literature review, develops the model of the system, builds two laboratory prototypes (with single supercapacitor per submodule and with 4 supercapacitors per submodule) and provides its experimental validation.

Comments:

1. *Thesis contains a lot of acronyms. I suggest to make a list of acronyms in the beginning.*

Response: Thank you for your comment, the list of abbreviations is now added after the Table of Contents.

2. *In the thesis significant attention is devoted to the number of SC per SM. So what is the optimal number SC per SM? Will it depend on particular application?*

Response: The hypothesis of using the MMC approach for creating an ESS with the novelty of using all the needed stages of a traditional ESS (energy storage, cells balancing, DC/DC and DC/AC conversions) in a single stage (Submodules) was validated with the first prototype. However, it was noticed that the efficiency was not as good as traditional ESSs (around 88%). Mainly because of the low voltage and high currents involved in the Submodule. For this reason, a sensitivity analysis is proposed in Chapter 3.4.1, which evaluates the efficiency of the proposed ESS when using more than 1 SC per SM. However, when assessing a particular Case application, the parameters for the sensitivity analysis need to be updated based on the components and power constraints. Chapter 3.4.2 details a Case study using 3000F SCs for a single-phase system with a power output of 6.7kW. In this Case study, 4 SCs placed in series in each SM improved the efficiency by almost 4% in comparison to a single SC per SM. Therefore, the optimal number of SCs or cells will depend on the power constraints or the targeted ESS, and the sensitivity analysis will evaluate all the losses involved in the system for an optimal selection of the cells.

3. *One of the declared benefits of the proposed design is the reduction of losses. What is the actual loss reduction (both theoretical and experimental)? What is the proper way to assess the reduction of losses?*

Response: This benefit is declared in Chapter 1.5. This claim is made since a traditional Energy Storage System is composed of multiple stages. Each of those stages will have a given efficiency value, and the whole ESS efficiency has to consider all the losses involved in the stages. Based on your comment the Thesis Chapter 1.5 first paragraph is corrected to guide the readers in better understanding the loss reduction and how this reduction can be assessed later in the simulation and experimental results sections in which the whole efficiency for both theoretical (Fig. 41) and experimental (Fig. 50) for the proposed ESS is detailed, the changes are highlighted:

In a traditional SC-based ESS, four stages are needed: the energy storage devices, the balancing system, and the DC/DC and DC/AC converters that connect the storage devices to the grid. Being the main source of losses the DC/DC and DC/AC converters. Since all the energy will flow from the SC cells to the AC grid across these converters or vice versa. If each stage has an efficiency of up to ~97%, the total efficiency for the whole ESS will be ~94%. The main contribution of the proposal is an SC-based ESS which reduces the number of stages by adopting the Modular Multilevel Converter (MMC). Thus, it is possible to create an ESS with increased efficiency since fewer losses from the stages are present and this single-stage efficiency will determine the whole MMC-based ESS's efficiency.

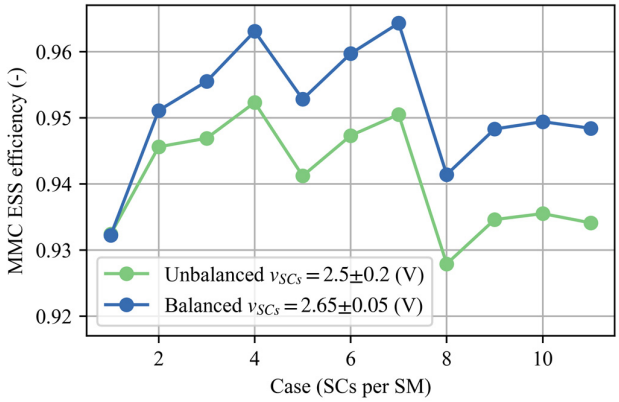

Fig. 1 CDF Energy Efficiency plot for (a) unbalanced and (b) balanced initial conditions for all Cases.

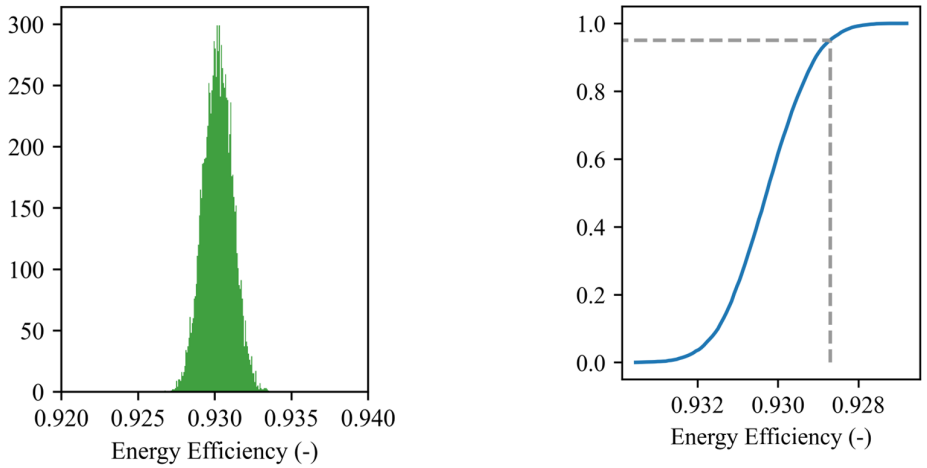

Fig. 2 Probabilistic study based on the extracted SM efficiency from the prototype, (a) histogram and (b) CDF plot.

4. *Table 6 reports the characteristics of each SM with an efficiency of ~94%. Where this efficiency come from*

Response: Thank you for your comment, the efficiency was first mentioned without telling the reader that the efficiency of the SMs was tested and shown in Fig. 49. The Thesis was corrected to avoid confusion when the reader reaches this chapter.

Reviewer: Prof. Pallavee Bhatnagar

I congratulate the candidate and his guide for such an innovative work. The work is well explained, simulation and experimental results validate the proposed concept. The work proposed is showing many future applications. I recommend the thesis with minor changes as given below.

Response: Thank you for your appreciation and recognition of my work. I agree with you that the work has many future applications and I hope to explore them further in my future research.

Comments:

Few observations from English/grammar:
1. Page 7, 2.5 it should be comparison not comparative
2. 3.1 Principle instead of Principles
3. Page no 18 (Based on Fig. 4 it is possible to infer that if we moved in a diagonal from the left bottom to the upper right the volume would start to decrease,) it should be move
4. Page 18. (Depending on the application, the energy storage device must be selected based in a techno-economic analysis). It should be on instead of in
5. Page 19. (Therefore, they are very suitable for maintain the power quality in the grid for a period of time in the second's range.). It should be maintaining
6. Page 22 (Due the nature that the majority of energy storage devices only store energy in the form of DC, it is not possible to directly interconnect them to the AC grid.) needs correction.
7. Page 23. (Since ESSs already have the required energy buffer for successfully operate in the
grid-forming control, they can also be used as to provide frequency support and black start services) to successes fully operate.
8. Page 35: (One solution is two put the transistors in series and switching them exactly at the same time) two or to???
9. Page 36: (Multi-level converters are a solution) a remove a.
10. Page 36:(Although the first application of a multi-level converter were in the field of a) was instead of were.
11. Page 36: (the idea of synthetizing a higher voltage waveform from various voltage sour) synthesizing
12. Page 50 (Finally, other authors ……..created a hybrid ESS by) have to be included.
13. Page 68: (Boost-mode consists of five-time intervals.) this sentence needs correction.
14. Page 83: (The first simulation consisted of a discharge process). Consist of.

Response: Thank you for your observations, all the changes are now added to the thesis as suggested.

Comments:

Few technical observations:
1. I would suggest the scholar to avoid using reference like [3], [4], [7]–[10]. The scholar has used reference in this style lot many times. This is not recommended mostly.
2. Page 26: There are so many other advantages of MMC when integrated with grid. I would suggest scholar to add more advantages.
3. Page 27 : It is observed that at many places scholar has used the past tenses and future tenses like (Simulations were done using Matlab Simulink and LTSpice or HSpice,

Python), (In this section, several types of topologies for DC/DC converters and DC/AC inverters will be covered)
It is always recommended to use present tenses.
4. Why fig. 9, 10, 11, 12……..are called proposed converters? Proposed word mostly is used while introducing your own work
5. Page 37: (transistors are used instead of diodes bidirectional power flow can be) I would recommend MOSFET instead of transistor. As in the topology shown in figure 14 uses MOSFETs ant transistors, also transistors are unidirectional. At many other places also word transistors is used please check.
6. Explanations given in 3.1.1 and 3.1.2 are good.
7. Some formatting corrections needed in Page 71
8. Page 81: Fig 35. Needs more explanation, as it is not clear from the given description.
9. Page (and an Iref signal) this Iref is differently used at different places please check.
10. Excellent simulation work. Results are properly explained.
11. Page 89: Formatting corrections are required
12. Methodology is well explained and implemented
13. Fig. 42 needs some formatting corrections
14. Experimental results validates the proposed objectives, if possible please check the labeling of the experimental figures. The labels and the resolution of the figures need improvement.
15. Conclusion is well written.
16. Sufficient and relevant references.

Response: Thank you for your technical comments on the thesis, I modified the thesis according to your observations.

Reviewer: Prof. Vedran Perić

The thesis provides a contribution to the domain of power electronics by providing a detailed design of a MMC converter to be used with a supercapacitor energy storage. The proposed MMC topology has several advantages. The best quality of the thesis lies in the detailed assessment of the proposed topology and its experimental validation. From the structure point of view, the thesis provides all necessary details, but it can also be improved in the sense that the main novelty of the thesis comes relatively late in the manuscript (after roughly 50% of the text). I would recommend considering moving a lot of literature review from the beginning, where the operation of conventional topologies is described, to the appendix, as this material is known and just puts additional burden to understanding the main contribution of the thesis. In addition, a lot of text goes to the context, which is in my view not necessary for the thesis and spoils the flow of reading. For example thermal energy storage description is not relevant for this work. In addition, the issues bulk power systems are facing are too extensively discussed.

Response: Thank you for your thorough review of the thesis, I have modified the thesis according to your observations from the separate comments file.

Reviewer: Prof. Henni Ouerdane

The doctoral thesis manuscript is composed of 5 chapters, including the Introduction and Conclusion over 100 pages. The thesis contains more than 50 figures illustrating some statements and showing block diagrams and numerical results. The list of references is fine and covers a sufficient number of relevant works that help substantiate the points made in the thesis. The literature review chapter in particular provides an interesting and useful overview of the thesis' research field. The proposed approach to the problem stated in the Introduction is presented in Chapter 3, and Chapter 4 provides experimental results and the validation of the results of the preceding chapter. The main criticism concerns the writing style that shows that the writing was somehow rushed, which lowers the overall quality of the thesis that otherwise contains good scientific and engineering works.

Work is needed to polish the thesis manuscript. The following is a non-exhaustive short list of revisions to do to improve the manuscript:
- IRINA in the caption of Fig.1, page 14, should be corrected: IRENA.
- The page number of publication 4 listed page 5 should be given for proper reference.
- Given the number of abbreviations used throughout the thesis manuscript, a nomenclature would be useful as a reference.
- Chapters should be separated and not follow each other like sections of a paper.
- "Low-voltage" is mentioned throughout the text, but to what range this applies, is never explicitly stated.
- I also strongly advise that the whole thesis manuscript is proofread after the revisions

Response: Thank you for your feedback, I have implemented all the minor revisions and also asked a native English speaker to review the thesis and correct grammatical errors.

Reviewer: Prof. Petr Vorobev

The thesis is dedicated to topology design, theoretical analysis, numerical simulation, and experimental assembly and validation of a multi-level converter for use with super capacitors (SCs).

The Thesis is well structured and easy to follow. It contains a comprehensive literature review on different types of converters, with the proposed converter topology justified from the point of view of the required performance. The review is sufficient to provide the background for the research presented.

The theoretical analysis is performed using methods, well established in the power electronics field. Different converter switching states are considered separately with the subsequent build of an averaged model which is used for small-signal stability analysis. The theoretical analysis is then validated using numerical simulations with a standard PSIM software package.

Experimental study is done using a lab-scale converter prototype connected to real super capacitors and different modes of operation are tested.

In my opinion, all the parts – theoretical, numerical, and experimental are performed according to the existing well-established academic standards in the field of power electronics, so the work definitely corresponds to the standards of a PhD thesis.

The publications are two journal and two conference papers. I would especially note the publication at the IECON conference – which is the top conference of the society for industrial electronics. This confirms the value of the thesis results.

Response: Thank you for your thorough review of the thesis, I have modified the thesis according to your observations from the separate comments file.

I have few minor questions/suggestions, that are fully optional.

Comments:

1. *Maybe it makes sense to add references to the figures in the literature review, whenever they are borrowed from the papers cited in the text. This would make it easier to navigate the text.*

Response: Thank you for your suggestion, the Figures now contain the references that were needed.

2. *How fast is your converter in terms of the bandwidth of your control? Alternatively, if you make a step input, what would be the speed of response?*

Response: Each SM has a switching frequency of 100 kHz and uses a type-III controller, providing more than enough bandwidth to recreate a 50Hz or 60Hz sine wave. Therefore, the MMC master or main controller can be implemented with a PI controller. See Fig. 28 for the details.

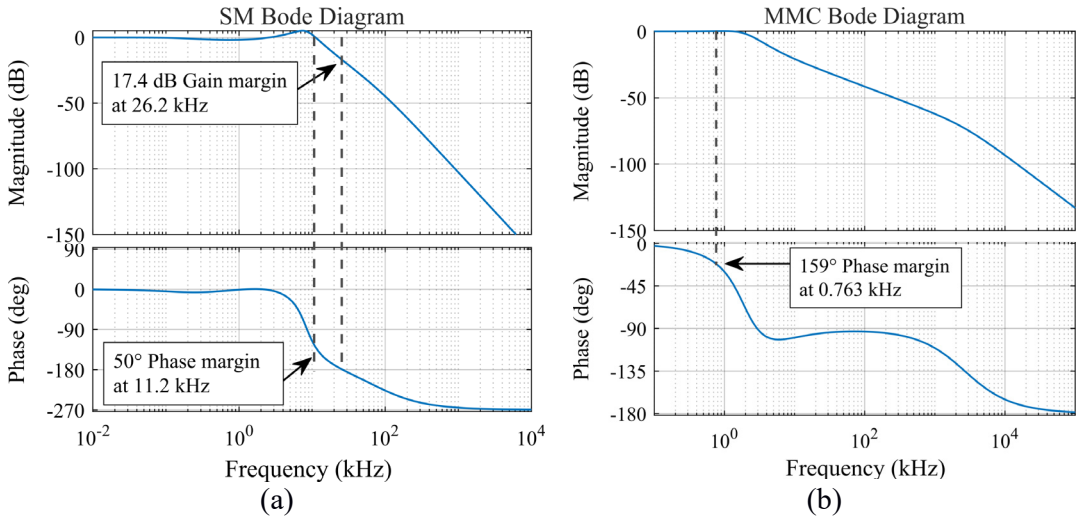

Fig. 3 Closed loop transfer function for (a) SM using a type-III controller and (b) MMC using a PI controller.

The step-response was tested at the MMC level with the first prototype (4 SMs), and the results are as Fig. 45 shows, there is a sharp response mainly because the oscilloscope was recording at low speed to track the 50Hz sinewave:

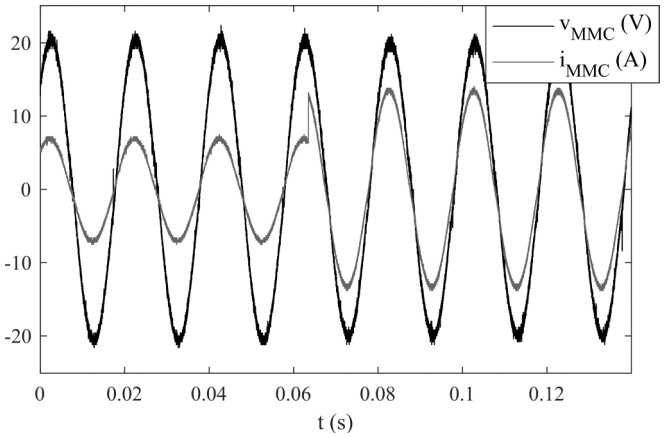

Fig. 4 MMC output voltage and current for a step change in the load.

3. *Is there any difference in efficiency when operating with different power factors?*

Response: Although the efficiency was only tested with resistive loads the power factor will affect the efficiency since the SMs are based on DC/DC converters. Hence, if the power factor deviates from 1 the efficiency of the SMs will be determined by the apparent power rather than the real power, as the current will increase, and some portion will be dissipated through the transistors.

4. *Is efficiency very important for SC operation? Maybe there are some other characteristics that are more important specifically for SCs?*

Response: Not only efficiency is important when using Supercapacitors, but the converter needs to operate in a wide voltage range since the supercapacitors can go from Vmax to Vmax/2 to extract at least 75% of the stored energy. For these reasons, the SMs are based on a full bridge with an active clamp, which can operate in the wide voltage range and provide good efficiency values in the entire range.