Gdańsk, 23.06.2023

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**English translation of the Review of the doctoral dissertation for the Scientific Council of the Discipline of Automation, Electronics, Electrical Engineering, and Space Technologies at the Warsaw University of Technology - shortened version**

Dissertation Title: **Solid State Transformers for Microgrids based on Modular Multilevel Converters**
Author: MSc. Eng. Felipe Ruiz Allende

**1. The scope and the general characteristics of the doctoral dissertation.**

The aim of the dissertation was to develop a new configuration of a Solid-State Transformer (SST) with an output stage in the form of an MMC converter with increased power output on the low-voltage side. The dissertation involved a detailed theoretical analysis with the development of averaged models, the design of the control system, simulation studies, and experimental verification using a developed small-scale laboratory model.

The dissertation, written in English, consists of 158 pages divided into 5 chapters. Additionally, it includes a list of references, a list of figures, a list of tables, and the Appendix containing a description of the dynamic model of the MMC converter. Chapter 1, spanning 17 pages, provides an introduction to the dissertation topic and an extensive review of Solid-State Transformer (SST) topologies described in the literature. Due to the fact that Solid-State Transformers are characterized by a three-stage structure comprising an active input stage, an active isolation stage, and an active output stage, a separate review of isolation stage topologies was also conducted, as their topology and control method have a significant impact on the bidirectional energy flow processes in the Solid-State Transformer. The global literature analysis and state of the art knowledge were appropriately conducted. At the end of Chapter 1, the thesis statement was formulated, which pertains to the proposed control method for the output stage of the Solid-State Transformer with an MMC converter topology. The thesis has already been put forward at this point of the dissertation, although the review of MMC converter topology applications in Solid-State Transformer and the analysis of existing problems are presented in the following chapter. Chapter 1 concludes with a summary of the author's original contribution ((according to the reviewer, it should be included only at the end of the dissertation) and a synthetic description of the content of all five chapters of the dissertation.

In Chapter 2, based on the literature, concepts of Solid-State Transformers utilizing the MMC converter topology were presented. Subsequently, a proprietary architecture of a Solid-State Transformer (SST) based on the MMC converter topology was proposed, ensuring increased output power by employing parallel-connected sub-modules, i.e., transistor bridges, in each arm of the MMC converter. The parallel connection of n sub-modules in each arm of the MMC converter results in an n-fold increase in the output current compared to the solution where a single transistor bridge is present in each arm.



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In the further part of Chapter 2, the model of the active input stage of the Solid-State Transformer (SST) in the form of the medium-voltage MMC converter was presented, along with the control system of the input stage and simulation results. Subsequently, the model of the isolation stage of the Solid-State Transformer (SST) and simulation results were presented, followed by a theoretical analysis of the operation modes of the Solid-State Transformer (SST), supported by the simulation results of the input stage and isolation stage. The simulation results were presented correctly and convincingly.
In Chapter 3, a detailed analysis of the output stage of the Solid-State Transformer (SST) in the form of the MMC converter with arms containing parallel-operated transistor bridges was presented. An original model of cross-coupling currents between the connected sub-modules in the arm of the MMC converter was proposed. The small-signal modeling technique was used to develop the model, which significantly facilitates the inclusion of a larger number of parallel-connected sub-modules in the model. The developed averaged model can include an arbitrary number of n parallel-operated sub-modules. An analysis of the operation of the parallel-connected sub-modules was conducted, in which, in the proposed structure of the Solid-State Transformer (SST), each sub-module is supplied from a separate isolated DC voltage source.

The dissertation modeled the phenomenon of cross-coupling currents between sub-modules for any number of parallel-connected sub-modules used in the arm of the output stage MMC converter of the SST. Cross-coupling currents were not included in the circuit-based averaged model, but in the mathematical description of the model, an algebraic operator Δ was introduced to determine the cross-coupling currents not directly from the matrix equations describing the dynamics of the variables of the averaged MMC converter model, but based on algebraic equations that include variables from the dynamic model. The adopted assumptions are justified and allowed the author to develop small-signal models of cross-coupling currents, which were analyzed for various scenarios, taking into account component tolerance uncertainties, including differences in pulse width of individual transistor bridges and changes in the intermediate DC circuit voltage of each transistor bridge. The analysis was convincingly confirmed by experimental verification using a single-phase small-scale laboratory model.

In Chapter 4, the author described the synthesis of the control system for the MMC converter with cross-coupling current compensation using a Proportional-Integral-Resonant (PIR) controller and presented a brief description of the stability analysis of the controller using the Root-Hurwitz criterion. The operation of the controller was verified through experimental tests using the single-phase small-scale laboratory model. In the further part of Chapter 4, simulation results of the low-voltage output stage of the developed transformer converter (SST) were presented.

The dissertation concludes with Chapter 5, which summarizes the dissertation and restates the thesis with its justification. Again, similar to Chapter 1, the summary of the author's original contribution is mentioned once more. Chapter 5 ends with a description of proposed future research directions that serve as a continuation of the dissertation.
The attached bibliography of the dissertation contains 183 references, including one publication co-authored by Felipe Ruiz Allende.

**2. General Remarks**

Regarding general issues arising from reviewing the doctoral dissertation, the following points are worth discussing:

1. On page 114, 'Figure 4.2' is an exact duplicate of 'Figure 3.9' on page 89. Similarly, on page 115, 'Figure 4.3' is an exact duplicate of 'Figure 3.10' on page 90. What was the purpose of duplicating these figures? Is it an editorial error?



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2. As the author rightly pointed out in the dissertation summary, further work should focus on incorporating voltage transistor pulse width modulation (PWM) in the developed models and control method. As the author correctly observes, averaged models do not account for common-mode currents. However, in a real system, under certain rates of change of voltage (dv/dt) for SiC transistors and with parasitic ground capacitances in the individual components of the Solid-State Transformer (SST), parasitic common-mode currents will flow to charge/discharge these parasitic capacitances. Does the author have a concept of methods that could eliminate these common-mode currents? Will the application of these methods affect the developed models and the control method for the MMC converter with cross-coupling current compensation?

**3.Detailed Remarks**

The dissertation is carefully edited. The results have been presented clearly and concisely. The carefully prepared figures deserve particular attention. While there are some editorial errors in the dissertation, it is understandable that it was challenging to avoid them, especially in the first part, which involves a literature review and a comparison of numerous different topologies of input stages, isolation stages, and output stages of Solid-State Transformers (SST).

- In the abstract in Polish, at the beginning of the dissertation, there is a lack of a definition of cross-circulating current; only a mention is made: "*In both configurations, an undesired current, known as cross-circulating current, flows between parallel-connected SST modules, adversely affecting the system's operation*". However, the English and Spanish abstracts include a definition: "*In both configurations, the circulating current is defined as the current that flows through the closed path between the parallel converters and is not reflected in the load/output.*"
- On page 6, in the caption under 'Figure 1.3,' instead of the label 'Fig.1.3o)', 'Fig. 1.3m)' is repeated.
- In the same section, the descriptions under figures 1.3a) to 1.3o) are separated by periods in some cases and semicolons in others.
- On page 11, in the second paragraph, the sentence "The modular topology shown in Fig.1.3 i)" lacks a predicate.
- On page 11, in the second paragraph, the topology mentioned in the description is *'Modular Multilevel Converter (MMC)'*, although the figure referenced in that paragraph, 'Fig.1.3i)', pertains to the *'Modular three-stage ISOP'* topology.
- On page 14, in the third paragraph, the statement "*It is important to notice the output stage must be properly controlled to avoid circulating currents among inverters*" is mentioned for the first time in the literature review, even though the author does not introduce the reader to the concept of cross-coupling currents or explain why they are an undesired phenomenon until later in the dissertation.
- On page 29, in the first paragraph, "(...) *and a common mode voltage*" should be "(...), *and a common mode current.*"
- On page 55, for the subtitle "*Simulation of AC-MV/DC-MV input stage and DC-MV/DC-LV isolation,*" there should be a separate numbering.
- On page 67, for the subtitle "*Impact of parameters mismatch,*" there should be separate numbering.
- On page 67, for the section title "*The unequal inductance,*" there should be a separate section number. Similarly, for the subsequent section titles "*The unequal Resistance*" on page 69 and "*Voltage Deviations*" on page 70.
- On page 71, in the third paragraph, the symbol for cross-circulating current is given as '$\Delta_i$', but it should be 'Δi'.



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- On page 71 and onwards, in Subsection 3.2, in the description of equation (3.2.3), the symbols for matrices and vectors are not bolded, as was adopted in the notation used in the earlier part of the dissertation.
- On page 90, in 'Figure 3.10,' all the modules of the converter model are labeled as "*Converter 1*." Shouldn't they be labeled as "*Converter 1*," "*Converter 2*," "*Converter 3*," "*Converter 4*"?

**4. Evaluation of the Dissertation**

The reviewed doctoral dissertation presents a comprehensive approach to modeling and analysis using averaged models for a highly complex system, namely the Solid-State Transformer (SST). The chosen SST topology (designed to be three-level and modular) consists of an active input stage for controlling the network voltage parameters on the medium-voltage side, an active isolation stage for bidirectional energy flow control, and an active output stage for regulating the network voltage parameters on the low-voltage side. The medium-voltage input stage is implemented using the MMC converter topology with n series-connected transistor bridges in each phase leg branch. The active isolation stage is realized as n isolated bidirectional full-bridge DC-DC converters. The output stage of the SST is the low-voltage MMC converter.

In analyzing the structure of the Solid-State Transformer (SST), the author considers a single transistor bridge as the basic sub-module of the primary SST module. Adapting the commonly used approach of configuring SST modules, which involves series connection of module inputs on the medium-voltage side and parallel connection of module outputs on the low-voltage side, the author proposes parallel connection of sub-modules, i.e., transistor bridges, in the arms of the output stage MMC converter of the SST. This is an original solution that provides a favorable increase in the current capacity of the low-voltage side of the SST, but it also results in the occurrence of cross-coupling currents between the sub-modules in the arms of the MMC converter. In the case of parallel-connected power electronic converters powered from the same voltage source, the analysis of cross-coupling currents between the parallel-connected converters is well-described in the literature. However, in this dissertation, there is a case where the sub-modules, which are connected in parallel in each arm of the MMC converter, are powered from isolated voltage sources. Therefore, the development of models and analysis of cross-coupling currents between the sub-modules required the author's original contribution. The author analyzed the influence of selected parameters of the SST output stage, including different sub-module inductances, different equivalent conduction resistances of the sub-modules, different sub-module duty cycles, and different DC voltage values of individual transistor bridges, on the values of cross-coupling currents between the sub-modules. Ultimately, the author proposed a control system for the SST output stage with the aim of minimizing cross-coupling currents between the sub-modules, i.e., transistor bridges, in the arms of the MMC converter, demonstrating the validity of the chosen topology for the Solid-State Transformer.

I acknowledge the following author's achievements in this dissertation:

- Development of a modular three-level Solid-State Transformer (SST) topology, consisting of a medium-voltage input stage using MMC converters with n series-connected transistor bridges in each phase leg branch, an isolated bidirectional full-bridge DC-DC stage, and a low-voltage output stage using MMC converters. A notable aspect of the dissertation is the inclusion of parallel-connected sub-modules, i.e., transistor bridges, in the arms of the converter, which provides increased current capacity on the low-voltage side of the entire system.
- Development of an averaged model for the output stage, which includes parallel-connected transistor bridges with individual DC voltage sources in the arms of the MMC converter, and



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conducting analysis using developed small-signal models of cross-coupling currents between the parallel transistor bridges in the MMC converter.

- Development of a control system for the SST output stage that minimizes cross-coupling currents between the parallel transistor bridges in the MMC converter of the SST.
- Conducting simulation studies of the developed control system, which provides cross-coupling current compensation between the parallel transistor bridges in the MMC converter, and validating the results through experimental verification using a simplified single-phase low-power model.

**5. Final Conclusion**

The doctoral dissertation titled "**Solid State Transformers for Microgrids based on Modular Multilevel Converters**" by Felipe Ruiz Allende presents an original solution to a scientific problem, demonstrates the candidate's overall theoretical knowledge, and constitutes an independent contribution to the field of power electronics within the discipline of Electrical Engineering (a sub-discipline of Automation, Electronics, Electrical Engineering, and Space Technologies). It contributes to the expansion of knowledge in the analysis and control methods of Solid State Transformers (SSTs).

**Considering that the reviewed doctoral dissertation meets all the conditions and requirements specified in Article 13 of the Act on Academic Degrees and Scientific Titles, I recommend its approval for public defense.**