FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS UNIVERSIDAD DE CHILE

Review Report of the Doctoral Dissertation

Solid-state State Transformers for Microgrids based on Modular Multilevel Converters

1. Introduction

The thesis of Mr Felipe Ruiz addresses topologies and control systems for Solid State transformers. This is an important topic considering the advantages of SSTs over conventional transformers not only in terms of volume, weight and specific power density. The SST allows multi-frequency operation in its input/output ports, operation at unity or variable power factor, fast control in the currents simplifying fault ride-through etc. If the SST is implemented using modular multilevel converters, then providing robustness again faults in the power electronic modules is relatively easy to achieve by using redundancy in the power cells located in each arm of the MMC.

Microgrids are a relatively new paradigm for the distribution of electrical energy. A Microgrid typically is composed of several generators (many of them based on renewable energy sources), loads, energy storage elements and a control unit; the microgrid can be operated, in an islanded and/or grid-connected mode, in a defined area to facilitate the provision of supplementary power and/or maintain a standard service. MGs are becoming increasingly popular considering their efficiency, reliability, flexibility and expandability. Nevertheless, the operation and control of microgrids have still many challenges to overcome to fully achieve their potential.

As stated in the thesis of Mr Felipe Ruiz, SSTs may be used to solve some of the challenges still present in the distribution of electrical energy, including the reliable operation of microgrids. SSTs can be used to interconnect microgrids operating at different frequencies and voltages, regulating the power flow between them. Interconnection of Battery Energy Storage Systems

(BESS), to provide inertia to systems largely composed of power converters, is also possible considering the dc ports typically available in SSTs. However, to take full advantage of the large flexibility of solid-state transformers, it is necessary to implement relatively complex control systems to regulate the circulating currents, balance the energy in the MMC converters, and control the transfer of power in the isolation stage. In summary, the control of SSTs is much more complex than the control of conventional devices and some of these control issues are discussed in this thesis work.

2. Thesis Content

In my opinion, the thesis correctly identifies the control and topologies issues which have to be addressed to improve the performance of a multi-port SST. The issues considered in this work are studied using theoretical analysis, simulation work and experimental validation. The thesis is organised into five chapters in addition to the bibliography. An Appendix is also considered at the end of the thesis.

Chapter 1 is the introduction and discusses the topology of a typical SST. Chapter 1 also proposes a new classification of the SST structures reported in the literature. This classification methodology is defined by the isolation stage. Chapter 2 discusses the utilisation of the MMC to implement a fully modular SST for MV/LV grid-connected applications.

Chapter 3 addresses the small-signal modelling of a separate DC-link parallel full-bridge, considering cross-circulating currents for an arbitrary number of parallel converters. The proposed model is validated using experimental and simulation work. Chapter 4 discusses the control systems proposed to eliminate/mitigate the cross-circulating currents. Stability issues are addressed and a stability analysis is performed using the Routh criterion. The performance of the proposed controllers is verified using simulation and experimental work.

Chapter 5 presents the conclusions of this work as well as summarises the contributions of this thesis. Future work avenues are also discussed and suggested. Finally, an appendix is used to explain the modelling of the MMC utilised in the thesis, as well as discuss the dynamic of the circulating currents.

3. General Comments

The research work has a good theoretical and experimental level, discussing new control systems and providing their validation. Nevertheless, I have some general comments.

- The design of the control systems is not fully addressed. For instance, those proposed for the cross-circulating currents are not discussed e.g., in terms of closed-loop bandwidth or dynamic performance. Moreover, small signal models are used to obtain a suitable plant. When small linear models are required, usually the gain of the plant changes and this certainly changes the dynamic performance of the closed loop system.

In my opinion, additional discussion about the design of the control systems has to be provided. It is recommended that at least the intended bandwidth and the methodology used to obtain the controller's gains and other parameters of the PI and PR controllers (for the cross-circulating currents) have to be presented.

- It is mentioned in the title of the thesis that the proposed SST is intended for Micro-grid applications. However, in low-voltage microgrids, harmonic distortion and imbalances are usually present in the grid and these currents and voltages may produce harmonic content in the cross-circulating currents and capacitor voltages, among other issues.

I understand that it is not possible to address everything in a single thesis, but (in my opinion) at least some comments discussing how to identify and address these issues, have to be provided in the work.

-To analyse and study the LV control systems, it is assumed that synchronised PWM, without interleaving, has to be used. It seems to me a rather important limitation. I) What happens to the proposed cross-circulating currents if interleaved PWM is applied? II) Is the proposed control system still operative?

4. Detailed comments

- In my opinion, English requires more corrections and editing in the document.
  - For instance, in the caption of Fig. 2.12, "competent" seems to be "component".
  - In Section 2.4.3 the sentence, "The third control use of communications" is difficult to understand.
  - Fig. 2.21 "Pot Cell".
  - At the end of page 63, chapter 3, "having models allows the research of circulating currents"??.
  - Page 62, "can be handled with common proper control" is difficult to understand.
  - Page 80, after (3.3.31), " The products between the Δ are depreciated"?
  - Page 128, first line, "the behaviour of the LVDC port is held constant by the control at 1KV" is incorrect. Do you mean the voltage is held constant?
  - In "Conclusions", at the end of the first paragraph "Paralyzing LV sub-modules?

These are just a few examples of many more. I recommend the edition and correction of the English in the whole thesis.

- Please clarify in Section 2.3, if the dc inductance (L_{dc}) of Fig. 2.5 is parasitic or is considered as an added element in the design of the SST.
- Below (2.3.7) it is stated "The same transformation used for the current is applied…". Where is the transformation?

- Section 2.3.1.1, above (2.3.11) it is stated, “The transfer function between Vdc and the total output power obtained by…”. I do not see the output power being used in (2.3.11).

- Resistances are not well identified in Section 2.3.1. In (2.3.5) there is r, r_{dc} and r_{sc} (not shown in Fig. 2.5). After that in (2.3.15) it is used R (ESR of the capacitor?). Please clarify in the text of the thesis.

- Section 2.3.1.2. Before showing the simulation results, the software used (PLECS?) and the parameters of the power converter and simulation rig have to be discussed. What is the *H* value of the MMC?
- Page 38, second paragraph. Please explain the meaning of “The voltages of the capacitors of the positive and negative branches of the same phase are balanced. However, the voltages of the positive and negative branches of the same phase are balanced”.

- Fig. 2.11. What is the purpose of using arbitrary references in a SST?. Is this realistic or just a theoretical exercise?, What is intended to demonstrate with these results?

- Page 54, at the end of the second paragraph, it is stated, “In this mode, the SST operates in grid-supporting mode and provides many additional functionalities for the grids and local customers”. In my opinion, this has to be further elaborated explaining the most important functionalities expected from the proposed SST operating in this mode.

- Page 59, first paragraph. Please explain the meaning of “It should be noted that the dynamics of the voltage in the MMC capacitors do not lose their intrinsic dynamics, despite being connected to a DAB”. I do not understand the sentence, Why the MMC capacitors can lose their intrinsic dynamic?

- Page 66. The term “circular current” seems to be incorrect.

- Page 67. The sentence, “ Generally a series equivalent circuit is a better model of a low-impedance circuit”, needs more justification and referencing.

- Fig. 2.20. I can understand why a resonant controller is required to regulate Ioref, due to the term cos (ωt) multiplying at the top of the figure. But I do not understand very well why a PR controller is used to regulate ΔI_z. Is a double-frequency sinusoidal reference obtained at the output of the PI controller regulating Ez? Please elaborate on that and clarify the issue in the thesis.

- Page 67. It does not seem completely realistic to operate an MMC-based SST with a switching frequency of 50Khz. Why are you using such a large frequency? What happens if a smaller switching frequency is utilised? Please elaborate on that.
- Please check the line dashing and colours in Figs. 3.2, 3.3 and 3.4. There are many additional figures in the thesis where the colour and type of line used (dasher or solid ones) do not correspond to the variable depicted in the graphics.

- Table 3.2. Why the caption is Simulation Cases?

- Fig. 3.13. In the caption..h), ..j) after b), why?

- In (4.1.13). The term $K_0/(\tau_0 s + 1)$ has to be explained and discussed. The meaning of the time constant has to be discussed.

- Fig. 4.1. There are two controllers in this figure. Do they have (both) the same topology? This is not discussed in the work. The design of a single controller is addressed

- Table 4.1. Case 2 is repeated as a column title.

- Page 123, below Fig. 4.8. Something seems wrong with this sentence. "The control scheme depicted in Fig. 4.9 is implemented using PI controllers. Due to its sinusoidal tree-phase nature, the control for the output component is implemented using a linear controller in dq coordinates"

I could not see any dq control system in Fig. 4.9.

- Fig. 2.1. The caption seems to be incomplete.

- In Section 3.5, related to the experimental validation of the small signal model for the cross-circulating currents in, it is stated, a couple of times in the section, that:

"…In the same way, as was predicted in the previous simulations, a greater variation implies a greater deviation of the currents concerning the average current. Therefore, it can be concluded that the current amplitude is directly proportional to the tolerance of the components."

Notice that this is not a single sentence stating that there is a linear relationship between the tolerance of different components and the amplitude of the circulating currents. Similar sentences are elsewhere in chapter 3.

I think these sentences are mistaken. If the current amplitude has a linear relationship with the tolerances (directly proportional is said), a small signal would not be necessary?. Small signal models linearise a non-linear model.

5. Please answer the questions and concerns depicted below.

1) The control system of Fig. 2.15 is non-linear. The effect of the nonlinearity is a variable gain which, at least theoretically, has values between -1 to 1. What are the effects of this non-linear system on the dynamic performance of the closed-loop system? Can these non-linear effects be compensated to avoid variable closed-loop poles in the control system?

2) I do not understand very well why there is a PI controller to regulate the dc link voltage of the LV-MMC in Fig. 4.9. The output of the PI is a DC-current reference.

Unless I am not understanding everything, it seems to me that the dc link voltage of each cell, in the LV-MMC, is simultaneously being regulated by:

a) The DAB operated using the control system of Fig. 2.15.
b) The control of Vdc in Fig. 4.9.In addition , I do not understand very well the reason to manipulate the DC-current to regulate the LVDC voltage in Fig. 4.9.

Moreover, having more than one PI controller (in both Figs 2.15 and 4.9) regulating similar variables could affect the stability of the system, because both integral controllers may "fight". Please clarify.

3) How is the double-frequency reference signal for the I_z component of the current generated in Fig. 2.20? Without a sinusoidal reference, there are no good reasons to use a PR controller.

4) Operating with synchronized carriers for the sub-modules of the LV-MMC seems a rather strong limitation. The interleaved operation allows the elimination of harmonics. Is it very complicated to modify the algorithm presented in Chapter 3, to relax the restriction of synchronized PWM operation?

5) For the Laplacian matrix presented in (3.2.3), what information can be obtained from the eigenvalues? In particular, the Fiedler value of a Laplacian is typically used in micro-grids to obtain information about the dynamic. Please elaborate if there is useful information to be obtained in this case and how is the impact (if any) of this eigenvalue in the dynamic of the cross-circulating currents.

6) The non-linear effects of the dead time, which produces harmonics in the synthesised voltages and, eventually, will produce distorted cross-circulating currents were not

addressed in chapters 3-4. How can these types of distorted circulating currents be mitigated or eliminated?

7) The Routh-Hurwitz analysis presented in section 4.1.4 is neat and well-performed. However, stability on its own is not sufficient to ensure good dynamic performance. How is the controller of (4.1.14) tuned to ensure a good performance in the whole operating range?

8) The thesis is entitled “Solid State Transformers for Microgrids based on Modular Multilevel Converters”. However, there are not many issues related to the operation and control of microgrids in the thesis. For instance, the output could be unbalanced and distorted. What kind of modifications to the cross-circulating control systems are required, to operate with harmonics and imbalances?

6. Assessment and conclusions.

Despite all my comments and concerns, it is my opinion that this thesis fulfils the requirement of a PhD with clear contributions to the state of the art. In addition, to validate the work the author has discussed a large number of experimental and simulation tests which have been presented and extensively discussed in the thesis. The original contributions to this doctoral work are at least the following:

- To propose a new fully modular SST topology based on an MMC with parallel sub-modules on the LV side.
- To propose a small signal model for the cross-circulating current produced in the *n* paralleled sub-modules of the LV side of the MMC.
- To propose a controller topology for regulating the cross-circulating current to zero in the *n* parallel sub-modules. The stability of the proposed controller is analysed using the Routh Hurwitz criterion.

FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS
UNIVERSIDAD DE CHILE

- To propose a control system for the bidirectional operation of the SST.

In my opinion, Mr. Felipe Ruiz has achieved a good knowledge of the power electronics and control issues related to the design, operation and control of SSTs based on MMCs. Therefore I recommend him as a candidate for the PhD degree.

Jesús Roberto Pedro Alejandro Cárdenas Dobson

Digitally signed by Jesús Roberto Pedro Alejandro Cárdenas Dobson
DN: C=CL, O=E-Sign S.A., OU=Terms of use at www.esign-la.com/acuerdoterceros, CN=Jesús Roberto Pedro Alejandro Cárdenas Dobson, E=jesus.cardenas@uchile.cl
Reason: I am the author of this document
Location: Tupper 2007 UCHILE
Date: 2023.07.28 15:29:42-04'00'
Foxit PDF Editor Version: 12.0.0

J. Roberto Cárdenas Dobson
Bsc. Msc. PhD, full professor
Jesus.cardenas@uchile.cl, WebPage
Electrical Engineering Department
University of Chile