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DOCTORAL DISSERTATION REVIEW

M.Sc. Eng. Alvaro Andres Carreno Henriquez
Dissertation title „Control of a Hybrid Transformer to Improve the Power Quality in a Distribution Network"

This review is written based on the Decision of the Board of Scientific Discipline Automation, Electronics, Electrical Engineering and Space Technologies of Warsaw University of Technology, No. 750/II/2024 dated 21.05.2024, as well as a letter from the Chairman of the Discipline Board, Prof. D.Sc Ph.D. Eng. Tomasz Starecki.

1. Relevance of the Dissertation Topic

The dissertation deals with the control of a distribution network hybrid transformer with a proposed original circuit structure. Research issues related to improving power quality in distribution networks have been studied for many years. The scale of implementation of power quality improvement systems has also been steadily increasing. This is due to both the increasing number and total power of connected nonlinear loads and the ever-increasing dynamics of the processes occurring in distribution networks. The development and increasing scale of renewable energy sources, such as wind farms and photovoltaic systems, which are characterized by significant variability in the power generated, play a fundamental role. In addition, such sources are distributed throughout the network. It becomes increasingly difficult to predict the direction of power flow at different points in the network. It is clear that the network has changed radically from its historical form, which consisted of large, stable power sources (power plants) and well-defined, predominantly linear loads. This trend is deepening and will continue to do so, making the implementation of regulatory processes in the network increasingly challenging.

Fundamental challenges and tasks in the broad area of power quality now include both global and local management of: stability, loads and load capacity, voltage levels, reactive power (an issue largely related to voltage levels), as well as the management of distortion of current waveforms and, as a result, of supply voltages as well. These tasks should be carried out with high dynamics, steplessly and under variable, often poorly defined operating conditions. Power quality problems typically propagate from the supply and distribution networks (low and medium voltage) to the transmission networks (high voltage). Therefore, it is advisable to apply technical solutions to improve power quality, by addressing the above-mentioned issues, close to the sources of these problems, i.e. in the medium and low voltage networks. A technical solution that appears to have significant potential for meeting the above-mentioned power quality improvement tasks is hybrid transformers. This is confirmed by the growing interest in hybrid transformers from both researchers and industry. Taking into account the above-mentioned points, I consider the research topic of the dissertation under review to be important, scientifically up to date, and highly applicable.

2. Scope and general characteristics of the dissertation

The dissertation is edited in English and is in the form of an internal publication of the Warsaw University of Technology. It runs to 205 pages comprising 7 chapters, 3 appendices and a bibliography of 116 entries. The independently numbered introductory part of the dissertation covers 23 pages and includes an abstract (edited in English, Polish and Spanish), table of contents, as well as lists of figures, tables and acronyms. The Author formulated the following thesis of the dissertation:

"The novel Hybrid Distribution Transformer configuration and control algorithm improve the grid and load power quality under varying conditions, as well as enable the better operation conditions of its main Low-Frequency Transformer". The author proves this thesis through, which is worth emphasizing, research conducted in a full cycle including theoretical analysis, simulation studies and experimental research on a laboratory model.

The seven chapters of the dissertation are organized as follows:

Chapter 1, entitled Introduction, outlines the power quality problems associated with actual distribution systems and the requirements of modern power systems. It also describes a general, already known concept of HDT. Then, various structures of HDT presented in the literature are thoroughly and critically reviewed. It is worth noting that the review presented in this chapter covers both the different main transformer circuit configurations and the power converter configurations, and demonstrates the author's knowledge of the current literature. This chapter also includes the motivation of the research scope and presents the original structure of the HDT with a series converter on the MV side and a parallel (shunt) converter in the LV side of the transformer. This configuration was chosen for the research studies presented in the dissertation. The chapter also contains the formulation of the thesis, the list of original achievements and the author's publications related to the thesis.

In chapter 2, entitled Model of the HDT, the Author derives the mathematical model of the HDT, including the main transformer and both converters. The model is formulated in state space representation and is the basis for further research documented in the following chapters of the thesis. An LC-type filter is used for the series converter, while an LCL is used for the parallel converter. The model for the LV side has been derived in both 3-wire and 4-wire configurations using $\alpha\beta$ and $\alpha\beta\gamma$ coordinates, respectively. The model formulated in rotating *dq* coordinates is also derived.

Chapter 3 presents the operation of the HDT under balanced conditions, using a controller system based on the *dq* coordinate system. In this chapter, the stability of the simplified model of the HDT is analyzed, considering the interaction given by the LC and LCL circuits. In this chapter, the phenomenon of CAPF is also pointed out. The CAPF is specific to the HDT studied in the thesis.

Chapter 4 is dedicated to a thorough study of the CAPF and its effect on the efficiency of the proposed HDT. The unbalanced operation of the HDT is considered, neglecting the load and the harmonic distortion of the network. The control of the HDT for unbalanced conditions is presented and two methods to reduce the CAPF are proposed. The first method is based on the generation of a series voltage at the MV transformer side, which is exclusively related to the reactive power. The second method uses an additional power source in the DC link in the form of a Battery Energy Storage System (BESS). The effectiveness of both methods in reducing CAPF has been proven.

Chapter 5 focuses on the application of the HDT to improve the power quality of the distribution network around the transformer, considering both 3-wire and 4-wire network configurations. For this purpose, the Author has derived and verified a dedicated control system. Due to the limitations of the laboratory system, the Author has also derived an estimators of the load current, the supply voltage and the capacitor voltage of the LC filter. It is worth mentioning that the chapter also contains simulation results and an extensive set of experimental results obtained for various operating modes and conditions.

Chapter 6 serves as a proof of concept for the application of the HDT to stabilize the flux of the main transformer during dynamic conditions related to voltage dips and swells, in order to avoid momentary saturation of the transformer core and, consequently, to limit the inrush currents. For this purpose, the Author has derived a model of the magnetic circuits of the main transformer. The concept was verified by simulations.

The results of the original research presented in the dissertation are summarized in its Chapter 7 entitled Conclusions. Author in this chapter also indicates the possible future research on the subject.

The structure of the dissertation is clear and well organized.

3. Critical and discussion remarks

1. Chapter 3: The Author uses the Generalized Nyquist Criterion to derive the stability regions of the system. The Author makes some simplifications of the system for this analysis, but still the system remains nonlinear, because there is no assumption of the infinite DC link voltage. The Author refers to "ideal DC sources", but this means only a voltage source with zero impedance. Was the stability derived for a linear or nonlinear system? What is the full list of model simplifications for this analysis?
2. In the dissertation, several variants of the HDT converter's control system is derived and investigated – from the simplest one (chapter 3), to the most complete (chapter 5), then further extended in chapter 6. Why the analyses and research results shown in the dissertation are not based solely on the most complete, single control system, with possibly some of its functionalities switched off for particular simulations and experiments?
3. Chapter 3.7: Statement "Moreover, after the system is interconnected and the external control loops such as the DC-Link voltage controller, and grid voltage compensator are taken into consideration, the system remains stable. The DC coupling and the presence of the CAPF do not destabilize the system." seems to be too general and therefore inappropriate. Stability in this case has only been confirmed for certain operating points for which experiments have been performed.
4. In the HDT system models presented in the dissertation, the load is modeled exclusively with equivalent current sources. This means that the voltage susceptibility of the loads is assumed to be zero. How would a load with significant voltage susceptibility affect the stability of the system and the operation of the HDT? For example, a load in the form of a diode rectifier with parallel connected capacitor and resistor on the DC side?
5. The series converter of HDT acts as a Dynamic Voltage Restorer (DVR). The Author examines its special mode of operation to limit the CAPF (with generating the voltage related to reactive power only), but it would be reasonable to refer to, apply and compare the methods well established for DVR, which means: pre-sag compensation, in-phase compensation and the minimum energy compensation.
6. The parameters of both the simulation models and the experimental setup are given in various places in the dissertation and seem to be incomplete. These parameters should be given in complete form (including information on the control hardware), in a selected place in the dissertation (e.g., in the appendix), and should be the same for all models, simulations, and experimental research. This would make the results easier to follow and compare.

7. What was the reason for the lack of measurements of (and control feedback from) the available physical quantities (such as capacitor voltage, supply voltage), and therefore it was necessary to use observers in the control system (Chapter 5)?
8. Why has been selected a relatively low transistor switching frequency (equal to 31.25 kHz) for SiC transistors?

4. Selected detailed remarks

- Page V, page 2 and others: the term „nonlinear currents" is used several times instead "distorted currents" or "nonsinusoidal current".
- Page VI and others: Author refers to primary and secondary sides of the transformer. I think, that it would be better to refer to MV and LV sides, as the transformer works in both power transfer directions (what is also investigated in the dissertation).
- Page 30: reference to Fig. 2.3 instead of Fig. 2.1.
- Page 30: reference to Fig. 2.3(a)-(b) instead of Fig. 2.1(a) and 2.1(b).
- Page 31: equation 2.2.1 suggests, that R_1 is the equivalent resistance of the L_1 inductors, but it is not shown in the drawings nor defined in the text.
- Page 32: equation 2.2.3 suggests, that R_{c1} is the equivalent resistance of the C_1 capacitors, but it is not shown in the drawings nor defined in the text.
- Page 34, equations 2.3.1 and 2.3.2: lack of definition of R_2 and R_s, respectively.
- Page 35, equation 2.3.3: lack of definition of R_{c2}.
- Page 38, equation 2.3.15: lack of definition of R_{dc}.
- Page 52, equation 3.0.1: Why is a delay assumed to be $1.5hs$?
- Page 54, chapter 3.1.2: should be H_{i2} instead G_{i2}.
- Page 66, chapter 3.6: what is the reason to not compensate the deatimes? What was the value of deadtimes?
- Page 77, chapter 4.1: Why transformer load related losses would depend only on "circulating currents" as the text suggests.
- Page 110, Fig. 4.15, DC-Link transients: why DC voltage is controlled to 351.7 V, not 350 V (as listed in Table 4.1)?
- Chapter 5 the Author uses the terms "observer" and "estimator" interchangeably. Although this is often considered correct, it is better to use one for clarity's sake.
- Page 134, chapter 5.2.4, also Fig. 5.1c on page 116: I suggest not using the term "estimation" when referring to current decomposition. Why is a multi-resonant system used for this purpose? How does it compare to e.g. DFT?

- Page 150 and 151, Fig. 5.13 and 5.14: some of the transients are doubled in these figures, regardless of the fact that the former figure contains oscilloscope waveforms and the latter obtained from the controller. The same applies to Fig. 5.15 and 5.16.
- Page 160, chapter 5.5: which cycle is referred to in the sentence: "(…) between half and a cycle"?
- Page 176: The thesis quoted at the bottom of the page is incorrect and inconsistent with the thesis of the dissertation.
- Appendix B: Figures B.1 to B.5 are almost identical. It would be better to show the variations in a single figure.

5. Some editorial remarks

- Page 3: author uses term „resources" instead of power "sources" (referring to e.g. wind power plants, PV).
- Page 19, chapter 1.5: word "latter" used instead of "former".
- Page 47: grammar is incorrect in phrase "(…) can trigger instabilities can be triggered".
- Page 66, the last paragraph: the tens with a sentence: "(…) when a robust control algorithm, such as LQR." is incomplete. It should read "(…) when controlled with a robust (…)".
- Page 73: should read "The work [10]", not "The work in [10]".
- Page 74, chapter 4.2: should read "which removes" or better "which suppresses", not "removes".
- Page 78, equation 4.2.11: the same caption of each equation section was incorrectly repeated.
- Page 116, Fig. 5.1b: output of v_g estimator is not marked.
- Page 119, above equation 5.1.8: wrongly repeated word "frequency".
- Page 124, chapter 5.1.4: The sentence: "The grid voltage is not measured in this chapter" is incorrect. Voltage cannot be measured "in the chapter".
- Page 134, chapter 5.2.4: I suggest avoiding the word "even" when referring to harmonics in general, as it can lead to confusion as to whether one is referring to the odd-even classification of harmonics.
- Page 144, chapter 5.4: should be "grid", not "gridk".
- Page 144, chapter 5.4: should be "recifier", not "recified" (mistake repeated two times).
- Page 144, Remark: Oscilloscopes information duplicated from Appendix B.

6. Evaluation of the dissertation

The reviewed dissertation deals with the up-to-date and important topic of structures and control of HDT systems. The dissertation is original, comprehensive and demonstrates the author's high research competence, including the selection of appropriate methods for modeling and analysis of circuits and systems, synthesis of the control, as well as practical skills necessary to perform experimental, laboratory tests. The results are clearly presented in the dissertation and show the high application potential of the proposed HDT circuit structure and also the developed control algorithms.

In my opinion, the Author's original achievements documented in the reviewed dissertation include:

- Hybrid Distribution Transformer (HDT) structure with a series/parallel converter on the MV/LV side, respectively,
- mathematical and simulation models of the proposed HDT for the different operating conditions,
- several discrete-time control algorithms of HDT, including one to improve the power quality around the main transformer – both on its network and the load sides,
- modeling and experimental verification of the losses and Circulating Active Power Flow (CAPF) model of the proposed HDT,
- proposal and application of two methods to reduce the CAPF,
- proposal of a control algorithm to improve the flux of the HDT main transformer,
- development of an experimental setup of the proposed HDT and experimental validation of the thesis.

It is noteworthy, that the Author has published a number of papers, including three high-scoring papers in peer-reviewed scientific journals, within the topic of the dissertation.

7. Final conclusion

The critical and discussion remarks included in this review do not alter my high rating of the Doctoral Thesis of M.Sc. Eng. Alvaro Andres Carreno Henriquez. I hereby confirm, that the reviewed dissertation exceeds the conditions and requirements indicated for doctoral dissertations, as specified in Article 187 of the Act of July 20, 2018 – Law on Higher Education and Science (*In Polish: w artykule 187 ustawy z dnia 20 lipca 2018 roku – Prawo o szkolnictwie wyższym i nauce)*, in relation to the Scientific Discipline of Automation, Electronics, Electrical Engineering, and Space Technologies. **Therefore, I recommend that the doctoral dissertation of M.Sc. Eng. Alvaro Andres Carreno Henriquez be accepted for public defense. Furthermore, considering the outstanding quality of the doctoral dissertation, I recommend that it be awarded a distinction.**