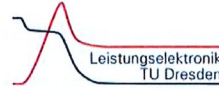




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Dresden, August 15th 2024

Expertise

to the doctoral dissertation

„Control of a Hybrid Transformer to Improve the Power Quality in a Distribution Network“

submitted by Mr. Alvaro Carreno Henriquez

Topic, goal and research methods of the Ph.D. thesis

The necessary reduction of CO₂-emissions requires a transformation of the electrical energy supply into a sustainable system. The entire electrical grid has to be developed to avoid CO₂ emissions including the supply and use of electrical energy. Power electronics is a key technology within this transformation.

Distribution grids are an important part of the electrical grid with Distribution Transformers (DT) as key component. Distribution transformers are the coupling elements between the Medium Voltage and the Low Voltage grid. Measures of the grid transformation at distribution level like

- the increasing installation of onshore windfarms, PV- and battery storage systems,

- the increasing share of nonlinear loads or loads with power converters as grid interface and
- new applications like vehicle charging stations and heat pumps

change the operating conditions of distribution grids. An increase of electric power and power fluctuation, bidirectional energy flow, grid voltage variations, power quality requirements and the provision of grid services are essential challenges for the future development of distribution grids.

The Ph.D. thesis of Mr. Alvaro Carreno Henriuquez introduces the concept of a Hybrid Distribution Transformer (HDT) as a "combination of a distribution transformer and one or more power electronic conversion stages which are designed to operate at a fraction of the nominal power of the distribution transformer". Depending on the topology, the operating principle and the control algorithm HDTs feature interesting characteristics like inrush current mitigation, increase of power, improvement of power quality, influence of grid voltage, provision of grid services, integration of renewable energy sources and a decentralized control capability.

In chapter 1.7 the author formulates the goal of thesis:

"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 condition of its main Low-Frequency Transformer. "

This topic is very interesting, relevant and challenging from both, scientific and the application's point of view.

The author proposes an analytical and simulation based approach followed by experimental verifications on the basis of a laboratory setup.

This approach is very well suited for the afore mentioned scientific task.

Structure of the Ph.D. thesis and literature

Chapter 1 introduces existing and future challenges of distribution grids. The introduction and definition of the HDT concept is the basis for an overview about the different

topologies, structures, characteristics and applications. This overview and classification is an interesting summary of the State of the Art in this field. The introduction of a new HDT topology, the motivation to investigate this topology and the outline of the thesis complete the chapter.

Chapter 2 considers the analytical model of the HDT consisting of a series converter (2L-VSC) with LC output filter connected to the MV side and a parallel converter (2L-VSC) with LCL output filter connected to the LV side. The LV grid features both, a 3-wire and a 4-wire configuration.

The control system and the internal stability of the HDT are presented in Chapter 3 assuming balanced operation. In a first step the control system for the two converters of the HDT is described. Then the stability of the HDT is shown using the equivalent series converter impedance model, the parallel converter admittance model, a combined model and the Nyquist Criterion. Experimental results of a three phase voltage sag at the MV side demonstrate the correct function of the converter control.

Chapter 4 describes the so called Circulating Active Power Flow (CAPF) phenomenon including its impact on the HDT efficiency. The first two sections discuss the efficiency of the DT and the model of the CAPF. Section 4.3 presents the model and design of the DC - link considering the oscillating power caused by unbalances in the grid, the HDT and the load. Due to its negative impact on the HDT efficiency Chapter 4.4 constitutes two CAPF reduction methods. Simulation results and experimental investigations proof the correct function of the HDT and the converter control, the CAPF phenomenon as well as CAPF reduction methods.

Chapter 5 presents the discrete-time control of the series connected and the parallel connected converter for a 3 wire and 4 wire grid configuration. Both converter controls apply the discrete-time Linear Quadratic Regulator (LQR). The proper function of the HDT including converter control to improve the power quality of the distribution grid is verified by simulations and experimental investigations. The experimental results for the conditions of distorted load currents, balanced voltage sags and swells, an unbalanced voltage sag, distorted grid voltage and load steps are impressive.

The flux regulation of the transformer is considered in chapter 6. Voltage disturbances like voltage sags and swells influence the transformer flux which could lead to trans-

former saturation and undesired high grid currents which jeopardize the proper function of the grid. This chapter presents a concept, in which the series converter injects a voltage to eliminate the DC - offset of the flux and provides rated flux to the main low frequency transformer. After the introduction of the magnetic model of the HDT and a discussion of voltage sag effects the flux regulation including the required control structures are described. Simulation results in selected operating points (no load operation, nonlinear load) proof the correct function of the concept.

Chapter 7 summarizes the basic structure of the thesis, important results and original contributions. A summary of potential future research tasks completes this chapter.

The appendix summarizes selected aspects and details of the linear quadratic regulator (Appendix A), the experimental set setup (Appendix B) and simulations (Appendix C).

This excellent structure of the thesis enables a clear, comprehensive, complete and precise presentation of the topic.

Literature

The bibliography contains 116 references including 3 journal publications and 5 international conference publications with Mr. Alvaro Carreno Henriquez as first author. The listed references base on high quality international journals and conferences. The references reflect the state of the art on the highest international scientific level.

Research results and original scientific achievements:

This Ph.D. thesis presents the following original scientific achievements and contributions:

- Novel HDT configuration with series converter on the MV-side and parallel converter on the LV-side,
- Derivation of mathematical and simulation models of the proposed HDT for different relevant operating conditions,

- Novel discrete time control structure of the HDT to improve the power quality of the main transformer, grid and load,
- Analysis, modelling and experimental verification of losses and loss distribution of the proposed HDT,
- Analysis of the energy flow through main transformer and converter configuration and proposal of two methods to optimize this energy flow (called: Circulating Active Power Flow (CAPF) by the author)
- Proposal and investigation of control concept to improve the flux and the behavior of the main transformer at voltage disturbances like voltage sags and swells,
- Development of an experimental setup of the considered HDT to verify the basic functions and characteristics of the proposed HDT including converters, filters and control in different operating points and working conditions

Both quality and quantity of the original scientific achievements and contributions are impressive. The proposed concept of a novel HDT is an interesting further development of active filters and power electronic solutions for distribution grids. The results of the Ph.D. thesis are an innovative and original solution in the field of distribution grids.

Research methods

The basic approach of this Ph.D. thesis can be roughly structured in the following steps:

- Introduction and motivation of the scope of the thesis
- Derivation of sub – topics and tasks,
- Definition of assumptions and requirements, problem analysis including analytical and simulation modeling,
- Derivation of solutions and integration in superordinate topic,

- Scientific investigation of partial and combined solutions by mathematical analysis, simulation and experimental investigations.

Simulations and experimental investigations are restricted to relevant operating conditions. The State of the Art (SoA) is considered in every step. The applied scientific methods like e.g. modelling of electric and magnetic configurations on the basis of Kirchhoffs-Laws, space state representation, stability assessment with Generalized Nyquist Criterion, derivation and design of converter control on the basis of a discrete-time state feedback controller, stability analysis, verification of models and concepts by simulations and experimental investigation in characteristic operating points correspond to the State of Art. The applied methods are perfectly suited to successfully work on the considered topic. The mathematical analysis, the application of the different afore mentioned methods in the relatively new field for power electronics (distribution grid and transformer) and the discussion of the results are excellent. The theoretical knowledge of Mr. Alvaro Carreno Henriquez in the area of power electronics and converter control and his ability to work scientifically in a new field are excellent. The applied methods show, that Mr. Alvaro Carreno Henriquez knows the state of the art models and methods and he is able to apply them successfully in new areas and topics.

Practical applications of the research results

The research results are verified by numerical simulations (mostly based on MATLAB including toolboxes) and experimental investigations in relevant operating points for defined operating conditions. The good compliance of analytical results, simulation results and experimental investigations proof the correct function of the concepts. Differences of the different investigation levels are caused by the deviating assumptions and clearly declared. The challenging laboratory setup and the convincing experimental results show a high degree of technical and practical skills.

It is remarkable, that the proposed novel HDT configuration has a considerable potential for industrial applications. This is a remarkable result for a Ph.D. thesis in the field of Power Electronics.

Evaluation of structure, formal presentation and expression

The structure of the thesis is excellent. It enables a clear, comprehensive, complete and precise presentation of the topic. The content is presented on the basis of a correct mathematical description. The chosen stylistic expression corresponds to a scientific work. Figures and diagrams effectively support the understanding of the text. Summarizing structure, formal presentation and expression are excellent. I did not find irregularities, mistakes or imprecise statements within this thesis.

Questions for Mr. Alvaro Carreno Henriquez in the defense of the Ph.D. thesis:

Grid transformation changes the operating conditions and requirements of distribution grids. The HDT is an interesting power electronic configuration to respond to these changes.

1. Could you mention important alternative solutions to the concept of HDTs for future distribution grids?
2. How do you evaluate the chances for an application of the proposed HDT in distribution grids? What are potential specific applications? What are the most important criteria and requirements for such an application of HDTs?

Conclusion:

The Ph.D. thesis submitted by Mr. Alvaro Carreno Henriquez is a valuable contribution to the further development of power electronics in distribution grids.

The goal of thesis:

“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 condition of its main Low-Frequency Transformer. ”

is completely achieved and verified. The investigation of this topic and the application of state of the art scientific methods necessitates an extensive knowledge and experience in the field of power electronics. Both quality and quantity of the scientific achievements are excellent.

Mr. Alvaro Carreno Henriquez has published 3 journal papers (2 in the internationally renowned IEEE Transaction on Industrial Electronics) and 5 conference papers (including one best paper award) as first author within the scope of this thesis. The publications shows, that the achieved results are accepted and appreciated by the international scientific community.

Mr. Alvaro Carreno Henriquez has submitted a Ph.D. thesis which fully meets the requirements of a Ph.D. thesis. I fully accept the work for the final defense of this thesis.

Considering all the circumstances, I hereby grade the Ph.D. thesis with

Magna Cum Laude (Very Good).



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