## Abstract

This habilitation thesis synthesizes the research activities and results obtained after the completion of the doctoral thesis entitled *"Problems regarding current collection from the contact line for electric traction vehicles"*, defended in 2003 at the *"Gheorghe Asachi" Technical University of Iași*, Faculty of Electrical Engineering, in the field of Electrical Engineering, under the supervision of Prof. Dr. Eng. Lorin Cantemir, Dr. H.C. of the Technical University of Moldova and member of the Romanian Academy of Technical Sciences.

The habilitation thesis, entitled *"Contributions to the modeling and electrical and thermal analysis of traction equipment powered by renewable energy sources"*, is structured into two parts. The first part contains summaries in Romanian and English, while the second part highlights the main scientific and professional achievements, as well as future career development plans. This second part is organized into three sections: the first comprises five chapters, the second consists of one chapter, and the third presents the bibliographic references underlying the synthesis of the author's achievements following the completion of the doctoral studies. The thesis also includes a table of contents, a list of figures, a list of tables, and a list of notations.

Chapter 1 outlines the motivation for the research directions addressed in this habilitation thesis, by substantiating investigations in the field of electrical systems for rail and road transport. It emphasizes the importance of developing integrated solutions aimed at increasing energy efficiency, ensuring operational safety and reliability, and significantly reducing environmental impact by lowering the carbon footprint. Based on these considerations, several research directions are identified:

- current collection in railway systems, where the pantograph–catenary interaction directly influences the quality of energy transferred to the electrical and electronic equipment of the traction unit;
- optimization and control of the pantograph through an electromagnetic model based on a linear induction motor, highlighting that high-quality energy transfer depends not only on the characteristics of the contact wire–collector strip interface, but also on the real-time dynamic response of the pantograph system;
- generation and integration of renewable energy through the electrical and thermal modeling and analysis of photovoltaic systems intended for electric traction applications;
- improvement of the energy performance of electric vehicles by investigating methods for increasing the energy efficiency of auxiliary systems in passenger transport applications.

This substantiation is based on both the relevant bibliographic sources from the specialized literature and the author's own research, conducted as sole author, first author, or co-author.

In Chapter 2, the pantograph-catenary interaction was considered in order to identify the parameters that ensure the continuity of energy transfer from the contact wire to the motor/locomotive unit. In this sense, the critical speed is a central parameter in the operation of the pantograph-catenary system, determining the dynamic response of the contact wire and the stability of current collection. The approach of the train speed to this value determines an increase in the amplitude of the catenary oscillations, generates pronounced variations in the contact force and amplifies the dynamic effects, negatively affecting the quality of energy transfer. The analysis of the critical speed allows the evaluation of the operating limits and the behavior of the system in critical regimes. The modeling of the contact point trajectory is based on a simplified differential equation, considering the system as an assembly of elastic masses with one vertical degree of freedom, neglecting train vibrations, pantograph friction and aerodynamic effects. Also on the dimension of the interaction of the pantograph - catenary system, the identification of the thermal behavior of the electrical contacts (pantograph wear bars and contact wire)

was considered, for which a thermal model was proposed for the evaluation of the temperature distribution in the electrical contact area made of different materials, under steady-state conditions. In this sense, the thermal contact model allows the establishment of heating values near the contact point, for different values of the electric current, contact force and ambient temperature. The model can also be used to evaluate the maximum heating of the pantograph-catenary contact and to design new types of contact materials, with a more uniform distribution of heating under different conditions of mechanical or electrical stress. These studies were based on some of the author's achievements, as sole author or co-author, as follows:

- **C. Nițucă**, *Thermal analysis of electrical contacts from pantograph–catenary system for power supply of electric vehicles,* Electric Power Systems Research, Volume 96, March 2013, Pages: 211–217. Doi: dx.doi.org/10.1016/j.epsr.2012.11.009, ISSN: 0378-7796, eISSN: 1873-2046, JIF (2024): 4,2, Q2, WOS:000315612100025, (Indexat Science Direct, WOS, Scopus).
- **C. Nițucă**, *Alimentarea şi captarea energiei electrice în tracţiunea feroviară,* Editura Performantica, Iaşi, 2009, 260 pagini, ISBN 978-973-730-628-9.
- G. Chiriac, D. Cuciureanu, **C. Nițucă**, *Critical Speed Impact over the Pantograph-Catenary System's Behaviour*, Indian Journal of Science and Technology, 2016, Volume: 9, Issue: 40, Article number 86736, **ISSN:** 0974-6846**,** DOI: 10.17485/ijst/2016/v9i40/86736 (Indexat Scopus).
- L. Cantemir, **C. Nițucă**, G. Chiriac, A. Rachid, *Unconventional Current Collecting of the Electric Energy from a Contact Line for the Electric Traction Vehicles,* International Conference on: Pantograph-Catenary Interaction Framework for Intelligent Control - PACIFIC 2011, December 8th 2011, Amiens, France, pp. 48-53, Conference Paper, Code 92659, EID: 2-s2.0-84866320723 (Indexat Scopus).

Chapter 3 addresses the conditions required to ensure high-quality electrical energy transfer from the contact wire to the traction unit by means of the pantograph. The main function of the pantograph is to maintain stable and continuous contact with the contact wire under varying catenary geometry and the influence of locomotive-induced disturbances. To perform this function effectively, the pantograph must exhibit low mass and inertia, high mechanical stability, and the ability to maintain an appropriate contact force under both static and dynamic conditions. From a structural and functional perspective, the pantograph can be modeled as a nonlinear articulated mechanism composed of arms and kinematic joints, whose vertical motion is generated by an actuation system responsible for lifting and maintaining the contact force. The position of the elastic spring or actuator significantly influences the dynamic response of the system. In practice, the lifting force is achieved through mechanical or pneumatic solutions, as well as passive systems incorporating elastic and damping elements.

To improve the dynamic performance of the pantograph, various active and passive suspension solutions have been proposed. One modern research direction focuses on the use of a bilateral linear induction motor with a plate-type inductor (LIM) for pantograph actuation. This approach enables precise control of lifting, lowering, and contact force, thereby improving current collection, reducing wear of both the contact strip and the contact wire, and minimizing local contact losses. However, the operation of the LIM under oscillatory conditions involves significant thermal stresses, which may lead to structural deformation and performance degradation. In this context, the relationships governing temperature variation at critical points were determined, and a correction to the graphical estimation of the heating time constant was introduced, allowing for a more accurate characterization of heating curves under different operating conditions and at different locations within the LIM. Furthermore, a thermal model of the LIM was developed for two configurations: one with a compact plate reinforcement and another with a segmented plate reinforcement featuring longitudinal cutouts, in order to obtain a detailed thermal profile and predict the temperature distribution. These studies are based on a number of the author's contributions, developed as sole author, first author, or co-author, as follows:

- **C. Nițucă**, G. Chiriac, D. Cuciureanu, C. Dumitrescu, Guoqiang Zhang, Dong Han, A. Plesca, *Thermal modeling of a linear induction motor used to drive a power supply system for an electric locomotive*, Thermal Science, 2019, Volume: 23, Issue: 2, pp. 589-597, part. A, https://doi.org/10.2298/TSCI180420190N,

https://thermalscience.rs/2019/2/15, ISSN: 0354-9836; eISSN: 2334-7163; JIF (2024): 1,1, Q4, WOS: 000462414100015, (Indexat WOS, Scopus).

- **C. Niţucă**, *Thermal analisys for a double sided linear induction motor*, European Scientific Journal, ESJ, March 2013, vol.9, No.9, pp. 38-50, https://last.eujournal.org/index.php/esj/article/view/904 , ISSN: 1857 – 7881 (Print) e - ISSN 1857-743, DOI: https://doi.org/10.19044/esj.2013.v9n9p%25p (Indexat EBSCO, PROQUEST, Copernicus, Urlich's).
- **C. Niţucă**, G. Chiriac, *Pantograph driven with a linear induction motor with adaptive fuzzy control* , Journal of Energy Technology: Vol. 12 No. 1, April 2019, https://www.fe.um.si/images/jet/JET_april_2019_splet.pdf DOI: https://doi.org/10.18690/jet.12.1.41-54.2019 (Indexat INSPEC, PROQUEST, EBSCO).
- **C. Niţucă**, *Alimentarea şi captarea energiei electrice în tracţiunea feroviară,* Editura Performantica, Iaşi, 2009, 260 pagini, ISBN 978-973-730-628-9.
- D. Cuciureanu, **C. Niţucă**, G. Chiriac, *Force Estimation of an Asymmetrical Pantograph for Different Damper Positions*, Indian Journal of Science and Technology, 2016, Volume: 9, Issue: 40, Article number 88878, ISSN: 0974-6846, DOI: 10.17485/ijst/2016/v9i40/88878 (Indexat Scopus).
- L. Cantemir, A. Rachid, **C. Niţucă**, *Etudde concernant sur le amplacement de ressort entre capteur et la manivelle,* 4th International Conference on Electrical and Power Engineering – EPE 2006, Iaşi, România, 12-14 octombrie 2006, Buletinul Institutului Politehnic Iaşi, Tomul LII (LVI), Fasc. 5 A, pp. 531-536, ISSS 1223-8139.
- L. Cantemir, A. Rachid, **C. Niţucă**, I.C. Bărbânţă, G. Chiriac, A.P. Alexandrescu, *Echipament de acţionare electromagnetică a unui culegător de curent de tip pantograf*, **Brevet de invenţie**, Nr. 128199, RO 128199 B1, Data depozit 23.08.2011, Data eliberării 28.02.2018.

Chapter 4 focuses on the mathematical modeling of photovoltaic cells and modules, based on which the influence of key parameters—such as temperature, solar irradiance, and series and shunt resistances—on the energy characteristics of photovoltaic devices (I–V, P–V, and P–I curves) is analyzed through simulation. The model incorporates the real parameters of a photovoltaic panel, allowing for the estimation of series and shunt resistances and the evaluation of module performance under various operating conditions. From a thermal standpoint, a dedicated thermal model was developed and used to simulate the behavior of a real photovoltaic panel. The simulation results were compared with experimental data, highlighting the discrepancies between theoretical predictions and measured values. Additional analyses address the impact of temperature variations and manufacturing defects on the energy performance of photovoltaic panels. A further comparison between simulated results and experimental measurements carried out in an actual photovoltaic park is also presented. In terms of energy generation, electricity production in different locations was analyzed, enabling the identification of vulnerable factors that may lead to reduced output. Furthermore, in the context of the increasing integration of photovoltaic systems into green energy infrastructures and the expansion of electric mobility, a significant part of this chapter is devoted to the analysis of a hybrid charging system for electric buses with an autonomous power supply. A solution is proposed for the use of renewable energy to recharge the batteries of an electric bus (Bus E321), through a photovoltaic-powered traction substation. Based on the configuration of the photovoltaic system within the substation and the onboard battery system of the bus, a hybrid charging architecture with autonomous capability was designed and analyzed. To ensure operational flexibility, the photovoltaic traction substation was structured into three independent fields of panels, each equipped with its own hybrid inverter and connected in parallel to the grid. The charging station control system is fully automated, enabling real-time monitoring of operating parameters. These studies are based on a number of the author's contributions, developed as first author or co-author, as follows:

- **C. Niţucă**, G. Chiriac, D. Cuciureanu, Guoqiang Zhang, Dong Han, A. Plesca, *Numerical Analysis of a Real Photovoltaic Module with Various Parameters*, Hindawi, Modelling and Simulation in Engineering, Volume 2018, Issue 1, Article ID 7329014, 12 pages, 2018, https://doi.org/10.1155/2018/7329014 , ISSN: 1687-5591; eISSN: 1687-5605, JIF (2024): 1,3, Q3, WOS: 000429430400001, (Indexat WOS, Scopus).
- **C. Niţucă**, G. Chiriac, C. I. Gatu, D. Cuciureanu, I. Murgescu, *Design and Experimental Studies on Laboratory Photovoltaic Concept for Mechatronics System of Solar Electric Application*, 10th International Conference and Expositions on Electrical and Power Engineering, EPE 2018, pp. 932–936, Iasi, Romania, OCT 18-19, 2018, WOS: 000458752200182, DOI: 10.1109/ICEPE.2018.8559792, (Indexat WOS, Scopus, IEEE *Xplore*).
- **C. Niţucă**, G. Chiriac, C. I. Gatu, D. Cuciureanu, I. Murgescu, *Laboratory Off-Grid Photovoltaic System with Two Axes Orientation*, Proceedings of the 2018 10th International Conference and Expositions on Electrical and Power

Engineering, EPE 2018, pp. 846–849, Iasi, Romania, OCT 18-19, 2018, WOS: 000458752200165, DOI: 10.1109/ICEPE.2018.8559755, (Indexat WOS, Scopus).

- **C. Nițucă,** I. Nucă, A. T. Plesca, G. Chiriac, V. Cazac, M. Burduniuc, *Improving the cross-border public transportation using electric buses supplied with renewable energy,* (în limba engleză), Editura Tritonic Books, Bucureşti, 2022, 220 pagini, ISBN 978-606-749-584-3.
- G. Chiriac, **C. Nițucă**, D. Cuciureanu, I. Murgescu, *Analysis of Hot-Spots Effects on the Performances of a Photovoltaic System Used in Romania*, International Conference on Electromechanical and Power Systems (SIELMEN-2017), Iasi, Romania, OCT 11-13, 2017, Pages: 239-244, WOS: 000426906000047, DOI: 10.1109/SIELMEN.2017.8123325 (Indexat WOS, Scopus, IEEE *Xplore*).
- D. Cuciureanu, **C. Nițucă**, G. Chiriac, D. Sticea, *Analysis of the Photovoltaic Panels Currently in Use in Different Locations,* 9th International Conference and Exposition on Electrical and Power Engineering (EPE), Iasi, Romania, OCT 20-22, 2016, Pages: 888-893, WOS: 000390706300174, DOI: 10.1109/ICEPE.2016.7781464 (Indexat WOS, Scopus, IEEE *Xplore*).
- Ilie Nuca, Cazac V. Burduniuc M., **Nițucă C**., Chiriac G., Gabor G., *A Hybrid Charging System Design for Electric Vehicles with Autonomous Power Source*, Sielmen 2021, 11th International Conference on Electromechanical and Energy Systems, pp. 487–490, DOI: 10.1109/SIELMEN53755.2021.9600328 (Indexat Scopus, IEEE *Xplore*).

Chapter 5 addresses the minimization and optimization of energy consumption by auxiliary loads in an electric bus. In this context, a bus model characterized by reduced energy consumption for both cabin climate control (heating and air conditioning systems—HVAC) and auxiliary systems such as lighting, doors, windows, sunroof, and windshield wipers is analyzed. The selected vehicle that meets the specified requirements is a high-capacity trolleybus intended for intercity passenger transport (Bus E321), modernized by Regia Transport Electric Chișinău (RTEC), Republic of Moldova. By identifying the specific energy consumption of auxiliary systems and applying a thermal balance approach, mathematical relationships were derived to describe the main heating and cooling loads, which were then integrated into a relatively simple and computationally efficient mathematical model. Based on these relationships, several coefficients specific to the thermal behavior of the electric bus were considered, accounting for heat transfer mechanisms such as conduction, convection, and radiation. The resulting thermal model of the bus cabin environment was developed to optimize passenger comfort conditions while reducing thermal losses. On the basis of simulations, the cabin thermal model was further refined by incorporating various heat loss mechanisms, including losses through windows, laminated side walls, floor, roof, and through doors during station stops. Model validation was performed by comparing the simulated thermal map with temperature measurements obtained using an infrared camera. These studies are based on a number of the author's contributions, developed as first author or co-author, as follows:

- **C. Nițucă,** I. Nucă, A. T. Plesca, G. Chiriac, V. Cazac, M. Burduniuc, *Improving the cross-border public transportation using electric buses supplied with renewable energy,* (în limba engleză), Editura Tritonic Books, Bucureşti, 2022, 220 pagini, ISBN 978-606-749-584-3.
- **C. Nițucă**, I. Nucă, Horga Cristina, A. T. Plesca, G. Chiriac, G. Gabor, Daniela Gârlea, Maria Zagoreț, V. Cazac, M. Burduniuc, A. Moldovan, *Improving of the energetical performances for electric bus used in urban and interurban transport*, (în limba engleză), Editura Tritonic Books, Bucureşti, 2022, 40 pagini, ISBN 978-606-749-585-0.
- **C. Nițucă**, G. Chiriac, I. Nuca V. Cazac, M. Burduniuc, *Geometry design and analysis of an electric bus for the interior ther-mal modelling* , Journal of Energy Technology: Vol. 14 No. 2 (2021): October 2021, https://journals.um.si/index.php/jet/article/view/3433/2471 DOI: https://doi.org/10.18690/jet.14.2.47-55.2021 (Indexat INSPEC, PROQUEST, EBSCO ).
- G. Chiriac, D.D. Lucache, **C. Nițucă**, A. Dragomir, S. Ramakrishna, *Electric Bus Indoor Heat Balance in Cold Weather,* APPLIED SCIENCES-BASEL, Volume 11, Issue 24, Article Number 11761, https://doi.org/10.3390/app112411761 Published DEC 2021, https://www.mdpi.com/2076-3417/11/24/11761 , eISSN: 2076-3417, JIF (2024): 2,5, Q4, WOS: 000735789500001, (Indexat WOS, Scopus).
- G. Chiriac, D.D. Lucache, **C. Nițucă** and G. Gabor, *Aspects Regarding the Heating of Electric Buses*, SIELMEN 2021, 11th International Conference on Electromechanical and Energy Systems, pp. 481–486, DOI: 10.1109/SIELMEN53755.2021.9600435 (Indexat IEEE *Xplore*).

- Ilie Nuca, Cazac V. Burduniuc M., **Niţucă C**., Chiriac G., Gabor G., *A Hybrid Charging System Design for Electric Vehicles with Autonomous Power Source*, Sielmen 2021, 11th International Conference on Electromechanical and Energy Systems, pp. 487–490, DOI: 10.1109/SIELMEN53755.2021.9600328 (Indexat Scopus, IEEE *Xplore*).

Chapter 6 presents a concise overview of the author's career development and professional trajectory, highlighting the main scientific, academic, and professional achievements obtained after the completion of the doctoral thesis, as well as the future career development plan. The professional and teaching section outlines key stages of the academic and professional evolution, including didactic achievements such as books, textbooks, course materials, and supervision activities. Academic responsibilities are also emphasized, together with both formal and informal activities carried out with students and doctoral candidates. Research activity is presented through a selection of scientific papers published in internationally visible journals and conference proceedings, as well as research projects in which the author has acted as project director or team member. Another important aspect addressed in this chapter is the recognition and impact of the research activity, reflected by citation metrics. A significant part of this chapter is dedicated to the career development plan, outlining future directions for teaching activities, collaboration with students, doctoral candidates, and colleagues, as well as the further development of scientific research activities.

The habilitation thesis concludes with a Bibliography section comprising 143 references that support the chapters of this work.