

Jasmin Smajic

Lecturer and scientist at Institute of Electromagnetic Fields (IEF)

Swiss Federal Institute of Technology (ETH)

smajicj@ethz.ch

Simulation Based Development of the Hyperloop Innovation Award Winning Linear Motor

This story dates back to November 2017. At the time, I was aware of SpaceX' Hyperloop idea, but I did not know there was a team at ETH Zurich called Swissloop that planned to participate in the Hyperloop competition in LA. This is why I was very positively surprised by a proposal of one of my master students, Christopher Timperio, who was a member of the Swissloop team. He expressed his enthusiasm to pursue his master thesis under my supervision on the topic of linear motor development for the Hyperloop competition.

Our former master student Christopher Timperio, now working as an RF Engineer at Vector Launch Inc. in Huntington Beach, CA, was most likely inspired by Elon Musk's 2013 white paper on Hyperloop [1], in which a linear induction motor was mentioned. Christopher was, however, the only one in the Swissloop team in 2018 seriously considering the idea to employ a linear induction motor (LIM) for the Hyperloop competition. From the beginning, I found Christopher's proposal very interesting and promising and therefore accepted to supervise his master thesis [2].

Linear motors usually have a larger air gap between the stator and rotor when compared to their rotating counterparts, which inevitably results in lower efficiency. On the other hand, a linear induction motor uses the rail as its "rotor" (moving part) separating the electromagnetic losses and heat induced in the rail from the vehicle. Consequently, the losses in the moving part do not increase the motor temperature, allowing for higher power density. Furthermore, the LIM, in addition to its traction force component, also offers a considerable repelling or lifting electromagnetic force - this feature simply comes "for free". The lifting force of the LIM has not been used at the Hyperloop competition so far, but it will certainly be used in the future for developing levitating pods without wheels, capable of reaching even higher speeds, as friction losses would also be eliminated.

Developing a high-speed linear induction motor that can reach speeds of 500 km/h and power of almost 600 kW in 10 seconds is not a trivial task. If the pod has a mass of around 300 kg (including the motor, structure, shell, batteries, and electronics), the required traction force of the motor should be slightly above 4 kN, which is a considerable force. Our former master student Christopher Timperio proposed to develop such a motor from scratch, having no experience in motor design and with very limited experience in low frequency electromagnetic simulations. Because of that, the proposed project looked like mission impossible, but I did not (and could not) tell that to Christopher. I accepted his proposal instead, looking at his happy face and keeping my worries to myself.

As a simulation specialist, I have had many national and international projects with industry designing and optimizing electric motors [3]-[7]. This has, without exception, always been with rotating machines. The reason is very simple - there are almost no commercially available high power linear motors around, with the exception of a few experimental train applications (see for example [8]), military applications (electromagnetic launch systems), and rollercoasters.

With the unpleasant initial conditions related to the lack of concrete knowledge and experience, the project had a considerable risk of failing, but we happily ignored the risk and started this adventure in December 2017. That is the beauty of a university job.

Shortly after the start of Christopher's master thesis, the Swissloop team decided not to pursue the use of our linear motor under development for the competition in July 2018, instead choosing to employ conventional rotating permanent magnet synchronous motors. Needless to say, we were disappointed, but we understood the decision. The risk of waiting for us to

develop the LIM was too high for the team at that point, as they were preparing for the fast approaching competition carefully, having many other uncertainties to resolve. The Swissloop team wanted a solution with low risk for their new pod “Mujinga”. The team, however, recognized the potential of the LIM and they encouraged us to continue the development of the motor, as it could be used for future Hyperloop competitions.

After Christopher Timperio spent months with analytical modeling and numerical simulations, the first LIM1 prototype emerged, becoming ready for manufacturing. At this stage of the project we contacted one of our long-term partners, Gebrüder Meier AG in Regensdorf, who became a partner of the Swissloop team for LIM manufacturing shortly thereafter. The team of Gebrüder Meier AG (Michael Drpic – project leader, Patrice Gosteli – technical expert, and Angie Pletscher – winding manufacturing specialist) managed to translate our virtual theoretical models and drawings into the practical motor manufacturing language. How they did that remains a secret, even to us, until this very day.

The manufacturing team faced several issues, as our winding structure was everything but standard, as visible in Fig. 1. I remember from that time that the manufacturing team produced a full-scale plastic motor model in order to properly determine how to position our complex windings into the stator core slots. After endless hours of discussions and trials, they managed to assemble the plastic motor model, which looked so realistic and well fabricated that Christopher and I could not recognize that it was only plastic and thus wanted to test it (this anecdote is still circulating among the manufacturing team and their customers in Regensdorf – I hope without mentioning the names).

Perhaps it is worth explaining here how the cable spaghetti visible in Fig. 1 functions. The winding system, made of insulated copper wire and distributed in the slots of the iron core, is connected to a three-phase voltage source. This system produces the so-called traveling magnetic field, which is visible in Fig. 2. The traveling speed of this field is determined by the frequency of the three-phase voltage source and this is the way to control the speed of the motor.

The traveling magnetic field shown in Fig. 2 induces eddy currents in the aluminum beam (the rail) which together with the traveling field produce the magnetic thrust force that accelerates the motor fixed to the pod. The thrust force accelerates the motor in the opposite direction of

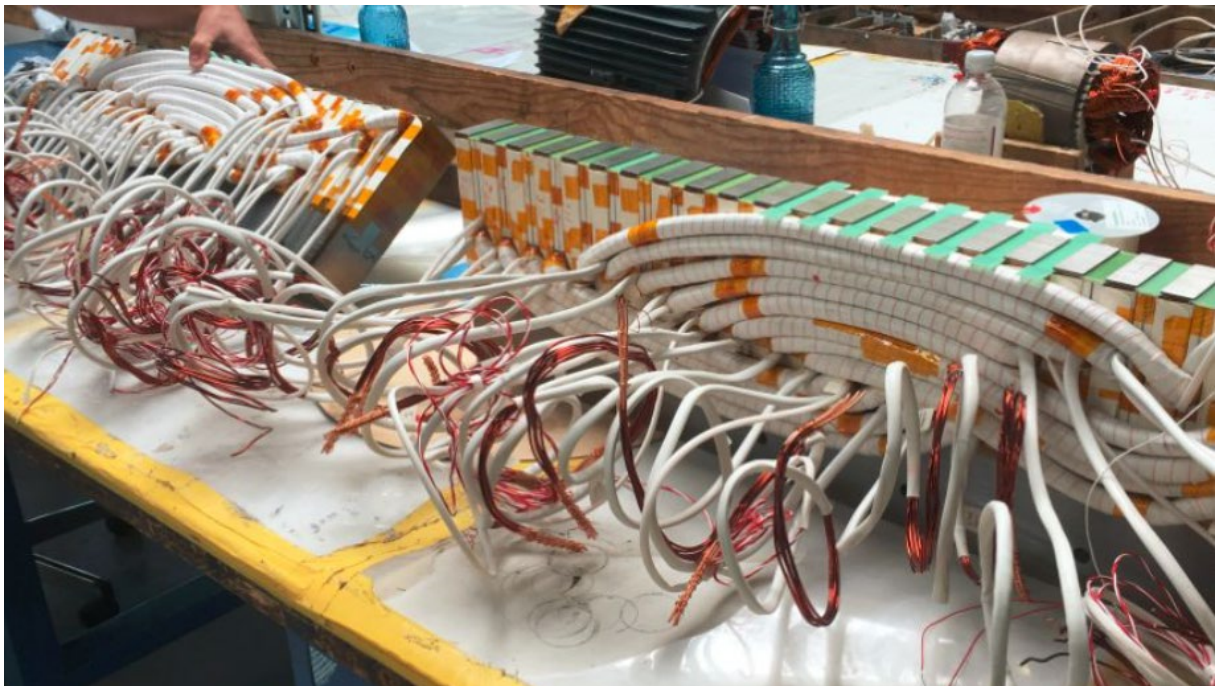


Figure 1. Double sided linear induction motor (LIM1) in its final stage of production at Gebrüder Meier AG in Regensdorf.

the traveling field. It sounds simple, but it is not so straightforward. Such a motor requires a high quality mechanical design of the whole system. A tiny air gap between the rail and the motor must be maintained during the drive because the traction force depends heavily on the air gap thickness. On the other hand, a too small gap increases the risk of collision between the motor and the rail, which means motor damage and disaster. The whole system is in vacuum, therefore the convective heat transfer between the motor and the environment does not exist. The only reasons why the coils do not burn is their own thermal capacity and the short driving time. The dielectric withstand capabilities of low pressure air in the tunnel of SpaceX is very low (its behavior is described according to the so-called Pachen curve [9]), which sometimes leads to electric discharges between open contacts. In other words, there are many possibilities for things to go wrong.

The LIM 1 prototype was never tested at high speed. It was used mainly to measure its traction force and to validate and characterize our calculations and simulations. Its effect was more psychological, as it was used to justify our high expectations, hopes, and ambitions as well as to test our patience - we could do it (but we could not drive with it).

The Hyperloop completion in 2018 unfortunately revealed an unexpected problem in an electrical subsystem of the Swissloop pod "Mujinga". The low air pressure in the SpaceX tunnel caused an electrical discharge in the inverter (due to the mentioned Pachen law [9]) and consequently the pod could not perform the final run.

After the Hyperloop competition in 2018 was over, the new Swissloop team 2019 was formed. They turned their attention to our LIM development and the existing prototype. After several discussions and evaluations, the new team decided to use the LIM concept for their new pod "Claude Nicollier". The arguments for this important change of strategy were numerous: (a) no traction-based acceleration limit, (b) LIM is a more promising solution for a real Hyperloop system, as it has no problems with the centrifugal forces typical for rotating motors at high velocities, (c) the competing teams TU Munich and TU Delft based their pods on rotational motors and the Swissloop wanted to develop their own recognizable and innovative concept, (d) the spirit of student competitions is to take risks and introduce new innovative technologies, (e) the existing LIM1 was proof that it can be done, and (f) a psychological effect, as a vehicle without rotating motors looks like science fiction to the public, even today.

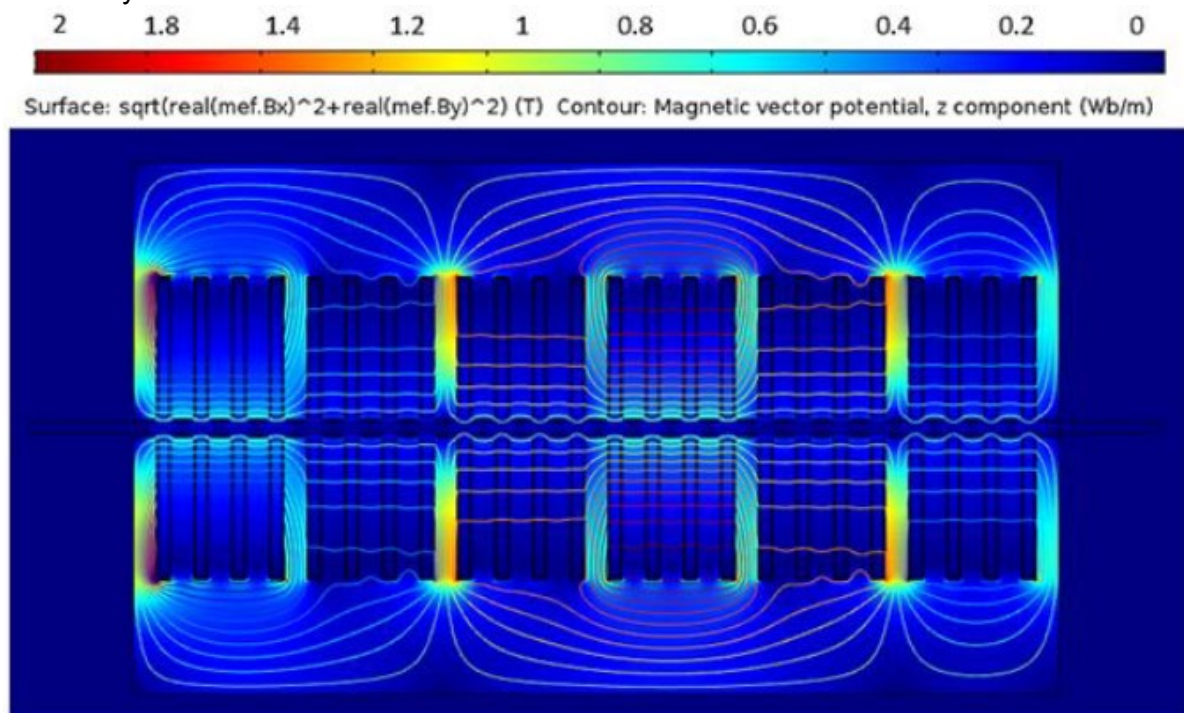


Figure 2. 2-D simulation model of the LIM1 presented in Fig. 1 is shown. The magnetic flux density (B) in one arbitrary chosen moment of time is depicted. The aluminum beam (the rail) between the motor halves is visible. More details can be found in the text.

The era of LIM in Swissloop has finally started. In September 2018, I had the first meeting with the new team members Nicolas Marchal and Samuel Sadok, who were responsible for the LIM implementation. I tried to convince them to use the existing LIM1 prototype with few simple improvements. The existing LIM1 prototype worked quite well, had a robust winding that could withstand the thermal and mechanical stress of the harsh vacuum environment, but, as everything in the world, also had a “small” problem, namely its weight. Due to the special core, manufactured by laser cutting, we needed to order the core several months before our simulations for LIM1 were finished. To ensure the motor would work, we “slightly” oversized the core. I told this to Samuel and Nicolas, suggesting a simple solution to cut unnecessary core regions off, which is possible even without removing the winding system. I was of the opinion that this would be optimal for us, would minimize the risk of failure and we would have a motor at an early stage of the project and plenty of time to optimize and test its control until the Hyperloop competition in July 2019. I also had an additional argument. Actually, the weight of LIM1 is not a problem as long as it can produce a sufficient traction force. The trick is, as with everything in life, to find a balance between two opposing effects, in this case between the weight of the motor and its traction force.

The process of testing and characterization of LIM1 was performed by the whole electrical team, coordinated by Vlad Niculescu, and it played an essential role for designing the new prototype. After testing the existing LIM1 and reading its documentation, Nicolas and Samuel came to me with a proposal – a new LIM2 is needed and they intend to develop it (oh no, not again I thought, this time I got two Christophers at once...). They wanted to make the motor lighter, they wanted to increase the number of magnetic poles and consequently to increase the fundamental frequency of the inverter, they wanted to design a more complicated winding structure, they wanted to implement dynamic switching frequency in the inverter for the sake of efficiency, etc. In short, they wanted to change everything in order to win the competition, unaware of the fact that they increased the failure risk by several orders of magnitude with their decision. I agreed, and to be able to sleep after that I said to myself - after all this is a student competition, they should make decisions, and they are allowed to fail.

After a while, I noticed that Samuel and Nicolas progressed very quickly in improving the motor design. They quickly learned the required theory, the simulation procedure that Christopher described in his master thesis [2], and they went even further by inventing their own methods and algorithms. With every week of our collaboration, they needed less and less support from me, and they compensated their lack of experience with their talent, enormous energy and student motivation. Looking back at this time, I must say, they are clearly among the most talented students I have ever worked with.

The final product of all their theoretical and simulation efforts is presented in Fig. 3. Evidently it is a considerably more complicated design than LIM1 and it could produce the same traction force weighing less than half of LIM1.

It is here worth emphasizing the additional features of LIM2 compared to LIM1: (a) due to its special design (which we do not want to disclose here in detail), LIM2 is capable of producing considerably more thrust than LIM1 at high speeds (for example, two times more at 300 km/h), (b) LIM2 is considerably thinner than LIM1 and fits into the given I-beam without problems, (c) despite being considerably lighter, LIM2 is twice as long as LIM1, and (d) having a smaller cross-section, LIM2 survived all the runs without damage and could be (will be) used after the competition for further tests back at home (in contrast, the winning pod of TU Munich was damaged during the final run).

The manufacturing went smoother than with the LIM1 prototype. The team at Gebrüder Meier AG (Michael Drpic – project leader, Patrice Gosteli – technical expert, and Ralf Dambach and Guido Sternad – winding manufacturing specialists) did not need a plastic model for practice this time. The unusual aspect ratio between the slot height and the yoke height, along with the limited space given by the I-beam, presented a considerable manufacturing challenge. These features of LIM2 resulted in a considerably longer end-winding region, requiring an innovative solution from the manufacturing team to produce and mount the coils. Based on their experience with LIM1, they produced LIM2 within a short time and delivered it to the Swissloop team for testing. In Fig. 4 the LIM2 is presented during its manufacturing (top) and on its mounting in the pod (bottom).

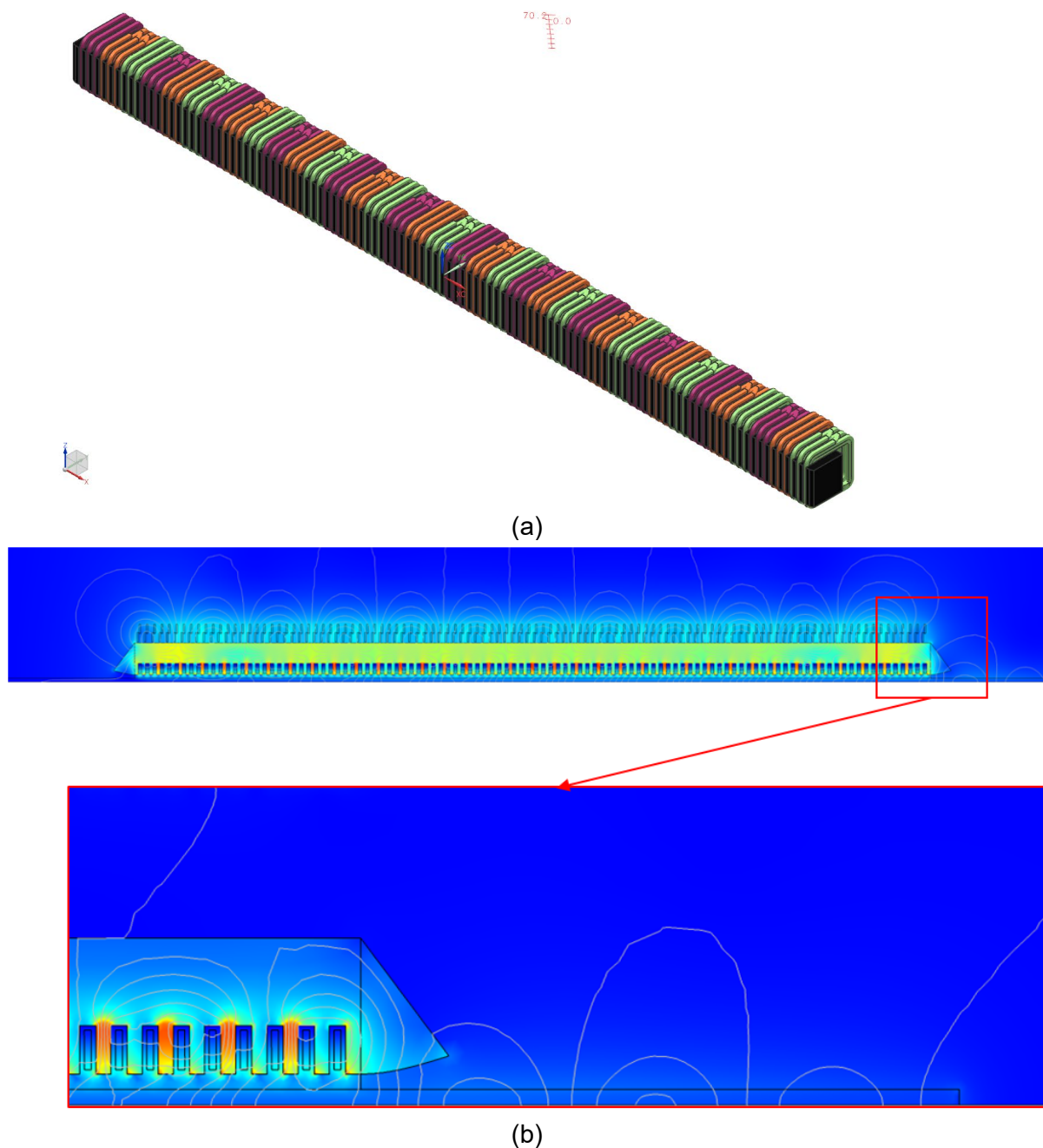


Figure 3. 3-D CAD model of LIM2 (a) along with its B -field distribution over the middle symmetry plane (b) is shown. The magnetic flux density (B) in one arbitrary chosen moment of time is depicted. More details can be found in the text.

Here it is worth mentioning an important detail of LIM2. Its winding structure is very complex and consequently required a high number of slots in the stator core. Thus, the stator core teeth were thin and fragile. However, they still needed to transmit the traction force to the pod. Therefore, a question arose whether they could actually withstand the corresponding mechanical stress. This question along with the question how to withstand a considerable attraction force between two sides of the LIM were answered through FEM simulation models of Daniel Kaufmann, yet another Swissloop member supporting the development of the electrical subsystem.



Figure 4. The core of the LIM2 (top) and one side of the LIM2 with the windings (bottom) is presented. More details can be found in the text.

In mid-June the pod was ready for testing. After several runs at the testing track at EMPA in Dübendorf, LIM2 accelerated the pod to almost 120 km/h. This was very encouraging, however, by performing the final test runs one of the three winding phases turned brown due to a considerable temperature rise. Not to kill the joy, we quickly convinced each other that this is normal (carefully avoiding why the other two phases remained white).

Let us have a look at the motor's performance at the competition. Although the motor should withstand even more current, the team limited the phase current amplitude to 400 A for the competition. In my opinion, this was a smart decision in order to prevent a possible thermal failure of the inverter. The acceleration lasted 12 seconds, and during this time, the inverter's switching frequency was gradually increased from 440Hz to 4kHz for the sake of efficiency. At the end of the acceleration, the pod's velocity reached the value 252 km/h. It accelerated from 0 to 100km/h within 2.35 seconds with the peak force reaching 2.8 kN. Given the total mass of the pod of 200 kg, the average traction force that LIM2 developed was around 1.2 kN and the mechanical power at the end of the acceleration time was 90 kW. In these simple calculations, the friction in the wheels and the air resistance in the tunnel (it was not ideal vacuum, of course) were neglected. Thus, the real motor parameters were even higher. The performance of the motor speaks for itself, as the team placed second in the overall speed competition, additionally winning an innovation award for the LIM a couple of weeks ago in LA. I am personally very proud of the achievement of the Swissloop team this year.

As stated above, the motor performance was very good, but can be considerably better. We presently see several possibilities for considerable improvement. It is, however, too early to elaborate on this in detail (we know that our competition is reading this carefully). Let us first enjoy the success for a while.

Last but not least, the Swissloop team and I, as their advisor for the LIM development, was permanently and generously supported by Prof. Juerg Leuthold, the head of IEF, and the ITET-management throughout the entire project. The LIM1 prototype was completely financed by the ITET and the LIM2 prototype was partially financed by the IEF and Prof. Leuthold. For the financial support, their permanent interest in our work, and their encouragement when we occasionally fail, I am very grateful.

References

- [1] SpaceX, "Hyperloop Alpha", https://www.spacex.com/sites/spacex/files/hyperloop_alpha.pdf, LA, 2013.
- [2] Ch. L. Timperio, "**Linear Induction Motor (LIM) for Hyperloop Pod Prototypes**", Master Thesis, ETH Zurich, July 2018.
- [3] J. Smajic, "**Electromagnetic Simulations of Synchronous Motors for Mill Drives**", **CTI project** with ABB minerals and Printing in Baden-Dättwil, Switzerland, 2012-2015.
- [4] J. Smajic, "**Entwicklung von effizienz- und lebensdaueroptimierten Antriebssystemen**", **InnoSuisse Projekt** mit B&R Industrie-Automation AG, Frauenfeld, Schweiz, 2018-2020.
- [5] J. Smajic, "**Dynamische elektromagnetische Analyse des permanenterregten Synchrongenerators**", ein Forschungsprojekt mit der Firma Vensys Energy AG, Neunkirchen, Deutschland, 2018.
- [6] C. Jäger, I. Grinbaum, J. Smajic, "[Dynamic Short-Circuit Analysis of Synchronous Machines](#)", **IEEE Transactions on Magnetics**, Vol. 53, No. 6, pp. 1-4, June 2017.
- [7] C. Koster, J. Schulze, T. Schmidiger, R. Pittini, J. Smajic, "[Field Simulation Approach for Computing the Commutation Angle Error of EC-Motors](#)", **IEEE Transactions on Industry Applications**, Vol. 53, No. 3, pp. 1942-1947, June 2017.
- [8] Bombardier Innovia Metro, https://en.wikipedia.org/wiki/Bombardier_Innovia_Metro.
- [9] A. KÜchler, "Hochspannungstechnik – Grundlagen, Technologie, Anwendungen", Page 170, 3te neu bearbeitete und erweiterte Auflage, Springer Verlag, Heidelberg, DE, 2009.