Final report

1. Project details

Project title	Improving power quality using energy storage: Case rail-way transformers
File no.	64016-0058
Name of the funding scheme	EUDP
Project managing company / institution	DTU Energi, Danmarks Tekniske Universitet
CVR number (central business register)	30060946
Project partners	DTU Energi, DTU Elektro, Wattsup Power A/S, Banedanmark
Submission date	15 November 2022

2. Summary

Danish summary:

Målet for dette projekt var at demonstrere anvendelse af et svinghjulenergilager til den elektrificerede jernbane. Ideen i projektet var, at svinghjulet kunne levere spidsbelastningseffekten når et elektrisk tog skal starte, i stedet for at trække denne effekt fra det elektriske net, da dette kan forsage store problemer for det samlede elnet. Svinghjulet skulle leveres af Wattsup Power, og benytte et nyt og mere stabil magnetisk leje udviklet af DTU Energi. DTU Elektro skulle udvikle kontrolsystemet for svinghjulet og efterfølgende teste svinghjulet, inden dette endeligt skulle testes på Banedanmarks transformerstation i Andst på jernbanelinjen til Esbjerg.

I projektet udviklede DTU Energi det nye magnetiske leje, og DTU Elektro realiserede et kontrolsystem til svinghjulet. Dette arbejde resulterede i to publicerede videnskabelige artikler og to videnskabelige artikler til konferencer. Uafhængigt af DTUs arbejde var Wattsup desværre ikke i stand til at levere et fungerende flywheel til projektet. Det svinghjul som Wattsup først producerede til projektet, blev leveret to år for sent til test på DTU. Situationen blev dog endnu værre, da de elektriske komponenter inde i svinghjulet brændte af da Wattsup startede svinghjulet op første gang på DTU. Wattsup testede i stedet et nyt svinghjul på deres lokation i Avedøre, men dette viste sig at være klart utilstrækkeligt i forhold til at være relevant for test på Banedanmarks transformerstation. I stedet brugte DTU Elektro deres ressourcer i projektet på at undersøge om eksisterende hardware kunne løse problemet med spidsbelastning, og viste at dette er muligt og potentielt en billigere løsning end et svinghjul.

Projektet har været udsat for massive forsinkelser og udskydelser, fordi der intet svinghjul har været som kunne testes. Samlet er projektet blevet forlænget fire gange. EUDP har været bekendt med projektets status

på en ugentlig basis igennem de sidste par år af projektet og projektet afsluttes nu uden testresultater med EUDPs godkendelse.

English summary:

This project was about demonstrating a flywheel energy storage for an electrical railway application. The idea was that flywheels could supply the peak power needed to start electrical trains, instead of drawing this fully from the electrical grid, as this can cause a severe unbalance in the grid. The flywheel was to be supplied by Wattsup Power, with a new more stable passive magnetic bearing developed by DTU Energy. DTU Elektro was to develop a control scheme for the flywheel as well as test this before the flywheel was to be tested at the Andst transformer station by Banedanmark.

In the project, DTU Energy successfully developed a new passive magnetic bearing and DTU Elektro realized a control scheme for the flywheel. This work was published in two scientific papers and two papers for scientific conferences. However, Wattsup was not able to make a working flywheel for the project. The flywheel that Wattsup was to produce for the project was delivered two years late to DTU Elektro for test. Worse, the electrical components inside this flywheel burned when Wattsup powered it up for the first time. Wattsup instead tested a flywheel at their premises, but this was far inferior in performance to be tested by Banedanmark. Instead DTU Elektro made a comparison study of existing hardware and showed that this could also be used to solve the voltage unbalance problem.

The project has suffered multiple delays and extensions, because of the lack of a flywheel to test and characterize. In total the project was extended four times. EUDP has been informed of the status of the project on a weekly basis throughout the last couple of years and the conclusion of the project without test results of a flywheel is with EUDPs approval.

3. Project objectives

The main objective of the project was to demonstrate that a magnetically levitated flywheel, which is a large cylindrical mass spinning at high RPM, is a suitable way to store energy for peak power shaving for electrical grids, here specifically electrical railways. The flywheel is at the core of this project and thus an explanation of the working principle of this technology is in order. A flywheel stores energy in the form of kinetic energy, by spinning up a mass to as high RPM as possible. Simply put, the energy stored scales linearly with the mass of the spinning object but squared with the angular velocity, thus the higher speed the more energy is stored. The problem is that when a flywheel is spinning at many thousand RPM, the friction in the bearings holding the flywheel will be huge. Therefore, state-of-the-art flywheels use magnetic levitation to float the spinning mass, by having a set of permanent magnets in the rotor repel a similar set of permanent magnets in the stator. Here it is important to understand that a mass cannot be levitated magnetically in a stable way without an active control system. Thus, a magnetic flywheel has both a passive magnetic bearing that provides the lift necessary to levitate the flywheel, and an active magnetic bearing that continuously adjusts the magnetic force to keep the flywheel levitated stably.

The problem targeted in the project is that fluctuations in power consumption on the large Danish (132/150 kV) electrical grid is a problem that increases in severity the shorter the timescale of the fluctuations. An area where very large but brief power consumption is seen is in the electrified part of the Danish railway system, where starting trains draw a very large but brief power from the electrical grid. This is a problem, especially in light of the planned large-scale electrification of the Danish railway. At present transformer stations that supply the required 25 kV DC power from the 132 kV AC grid are severely over dimensioned in order to provide the necessary peak power.

The objective in this project was to install a 3.3 MW magnetically levitated flywheel, designed and produced by Wattsup Power (hereafter Wattsup) that will continuously draw power from the 132 kV grid and quickly be able to supply this power to the electrical train system when a train starts. This will reduce the peak load on the overlaying electrical grid.

To realize this objective in the project, the then-current magnetic flywheel must be adapted to the large voltage at railway transformer stations and be made to resist the vibrations from the passing trains. In the project this would be done through researching optimized power electronics and vibration-resistant magnetic bearings. The power electronics will allow the flywheel to quickly respond to the requested load and be able to operate at 132 kV, while the optimized magnetic bearing will allow the flywheel to last more than 20 years in the vibrating transformer environment.

Once the optimized flywheel had been designed, the objective was to construct and subsequently test it, first at a small-scale test setup at DTU Elektro, and then at an electrical railway transformer station at Andst in Jutland. Here the flywheel was to be tested to demonstrate its real-world abilities to provide peak power shaving and energy storage.

The roles in the project were clear: DTU Energy would design the new magnetic bearing for the flywheel, DTU Elektro would design the power electronics for the flywheel, research the optimal control scheme and test the flywheel before commissioning at Andst, Wattsup would build the flywheel and associated electrical components and Banedanmark would provide the real-world testing facilities and evaluate the performance of the flywheel.

4. Project implementation

The short description is that the project did not go according to plan, and that the project is terminated, with EUDPs approval, before having reached the project goals. In the following the chronological progress of the project is described. This will be followed by an analysis of what went wrong and has been learned in the project. It is emphasized that since 2019 regular weekly meeting have been conducted in the project and minutes of these has been sent to EUDP every week. Thus, the evolution of the project, described in the following section, has been, unless where it is stated otherwise, to the full knowledge of EUDP.

The project began in December 2016. As specified in the initial GANTT diagram, the project began with DTU Elektro hiring a PHD-student to perform data collection on the railway grid and to perform initial modelling work to test the control of the flywheel to be delivered by Wattsup. At roughly the same time DTU Energy started working on modelling a new passive magnet bearing for the flywheel. The key goal here was to realize a passive magnetic bearing that was less unstable and provided more lift than the existing bearing in the Wattsup flywheel.

The project proceeded as planned for the first one and a half year, where DTU Energy and DTU Elektro worked on the scientific parts of the passive magnetic bearing and the power electronic control system, as discussed subsequently in section 5. After both problems had been satisfactorily solved and discussed with Wattsup the time came for Wattsup to deliver a flywheel for test at DTU, so that the researched control scheme could be tested. This was to happen in June 2018 according to the original plan. However, this was postponed by Wattup, as they, contrary to what was promised in the project, simply did not have working flywheel that could be delivered to DTU. There were numerous problems with the flywheel, all discussed in the yearly report and multiple extension requests were filed to EUDP because of this, as will be discussed subsequently. The fact also remains that it is hard to pinpoint exactly why Wattsup could not deliver a flywheel – on the regular weekly meeting Wattsup regularly promised to deliver a flywheel, but the promise was never kept, and the delivery date kept getting postponed with a new excuse.

It should be stressed that Wattsup's failure to deliver a working flywheel to the project was not even considered a risk in the original project description. The project partners were under the clear impression that Wattsup had a working flywheel at the beginning of the project, and that while this would be optimized in the project, especially with respect to the passive magnetic bearing, the flywheel was nevertheless in full working order.

As just stated above, the flywheel to be delivered from Wattsup Power to be tested at DTU was postponed numerous times. The following is the list of promised delivery dates by Wattsup:

- June 2018
- September 2019
- November 2019
- December 2019
- February 2020
- March 2020
- November 2020

Finally, in November 2020, the flywheel was delivered to DTU. However, Wattsup did not deliver the electrical converter, vacuum system and active magnetic bearing needed to make the flywheel operational. The delivered flywheel as shown in the image to the right.

The flywheel delivered by Wattsup to DTU, installed on the foundation made by DTU Elektro.

The flywheel that Wattsup delivered to DTU, termed by Wattsup the Deneb002 mk was hand build at Wattsup. Wattsup claim that the flywheel was successfully powered up at their own test facility before shipment to DTU, although no initial test reports have been shared in the project on its performance, nor how it was tested. However, during the first power up at DTU by Wattsup personal only, there was a flash over and hereafter a short circuit in the active magnetic bearing structure on the stator, inside the flywheel. This permanently destroyed the active magnetic bearing. The active magnetic bearing is mounted on the stator by a shrink fit, i.e. the active magnetic bearing is heated up, and the stator is cooled down. When they reach the same temperature again, the active magnetic bearing is firmly connected to the stator. Unfortunately, this also means that the active magnetic bearing cannot be separated from the stator in a non destructible way. This meant that the flywheel at DTU could only be operated on it's backup bearings, which limits the maximum speed of operation to approximately 2.000 rpm.

It is stressed that the burned component, the active magnetic bearing, was a component solely made by Wattsup. It is <u>not</u> related to the passive magnetic bearing developed by DTU in the project, and no failure was experienced by this component. It also needs to be stressed that the information concerning the fact that the flywheel could not be repaired was not made clear to the other project partners (DTU Energy and DTU Elektro) until the final project meeting with EUDP in June 2022.

The project was made aware that the active magnetic bearing was burned, but the project still wished to test the flywheel spinning on the backup bearings. However, this was not possible as Wattsup could not deliver an electrical converter that could make the flywheel spin. Furthermore, Wattsup was not willing to put in the technician time needed to fix the flywheel, as they felt that further tests of the flywheel were not valuable.

In the meantime, Wattsup had built a new version of the flywheel that was located at Wattsup facility in Avedøre. This had been tested internally at Wattsup, but Wattsup was not interested in moving this new flywheel to DTU for tests, as Wattsup stated that they had already learned what they could from testing the flywheel. However, the test reports from this testing were not shared with the project until spring 2022.

As a consequence of Wattsup's failure to deliver a flywheel for test, and subsequently making the flywheel work, the project has been extended numerous times and as a consequence the end date of the project has been moved. The original end date of the project was 31 May 2019, the first extension due to not delivering the flywheel to DTU was 31 May 2020, the second extension end date was 30 November 2020, on which Wattsup delivered a flywheel. The third extension end date was 31 August 2021, to allow for testing the flywheel and finally, the last end date of the project was 28 February 2022. However, the project did not end at this date, as EUDP required that the project test a flywheel. However, following a discussion with EUDP on the status of the project during the spring and summer of 2022, this final report was handed in on July 15th.

Because of Wattsup's failure to deliver a flywheel the milestone regarding testing the flywheel, as well as subsequent milestones, was not completed.

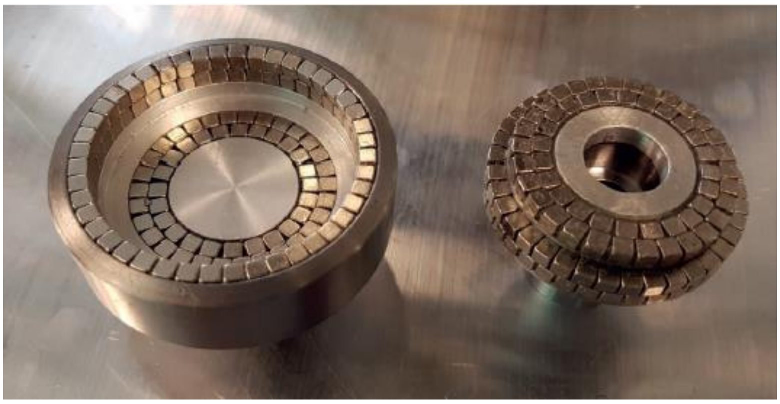
For Banedanmark, even though interesting results were generated in the project, as also described in section 5, the situation is that Banedanmark has completed projecting all new transformer stations in Denmark, and most of these are either now in operation or under refurbishing. Therefore, the idea of realizing a flywheel energy storage of new transformer stations on the Danish railway is no longer of particular interest, and thus there is no longer an incentive for Banedanmark to see the project demonstrated.

5. Project results

As described in section 4, the project was not successfully completed, and the project results are thus lacking compared to the original ambitions. The main shortcoming is obviously that a flywheel was not delivered to DTU that could be tested. Therefore, this section instead describe the project results in three separated main sections, namely on the passive magnetic bearing researched at DTU Energy, the peak power compensation for electrical railway researched at DTU Elektro and the flywheel tests done at Wattsup Power facilities.

5.1 The passive magnetic bearing researched at DTU Energy

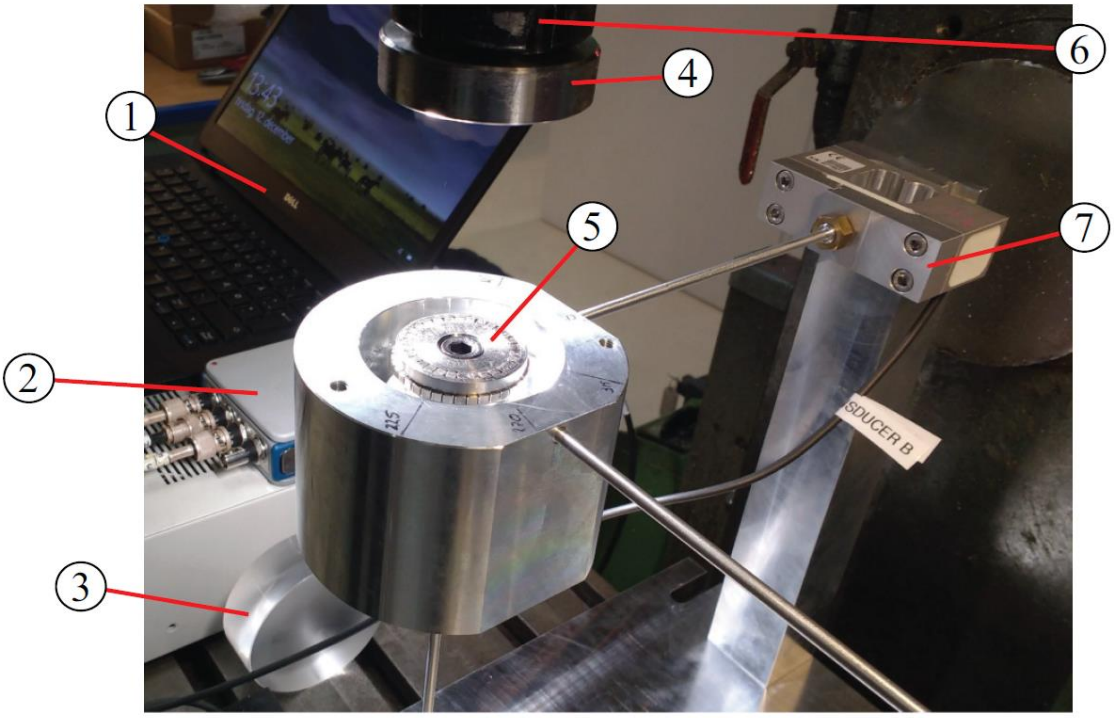
As described in Section 3 it was DTU Energys task to design a new passive magnetic bearing for the flywheel that could withstand the vibrations near the railway. Furthermore, DTU Energy, after discussion with Wattsup, also wanted to realize a passive magnetic bearing that could provide more lift. The key idea in a passive magnetic bearing is to arrange the set of permanent magnets in the rotor and stator so that these repel each other as strongly as possible.



A passive magnetic bearing developed by DTU Energy in the project. The bearing consists of a stator and a rotor part.

Using a numerical model DTU Energy tried various design of passive magnetic bearings and compared these with the existing Wattsup bearing. After decided on the design that provided the largest degree of stability (i.e. being the least unstable as such bearings will always be) with the largest lift, four different sets of experimental bearings were realized based on this design. These had varying number of magnets. An example of one of these experimentally realized bearings is shown in the image to the right.

These experimental bearings were then subsequently tested in a force measurement setup shown below, and then compared to the numerical results. This work was published in [Nielsen, K. K., Bahl, C. R. H., Dagnæs,



The setup for measuring the force on the bearing. 1) Computer used with LabView to measure and process data, 2) Analog-to-digital converter, 3) Calibration cylinder (30 mm in height) for measuring the radial displacement, 4) Stator, 5) Rotor, 6) Shaft that can be moved vertically and horizontally in both directions, 7) Strain gauge used for measuring the radial and axial forces on the device.

N. A., Santos, I. F., Bjørk, R., *A passive permanent magnetic bearing with increased axial lift relative to radial stiffness*, IEEE Transactions on Magnetics, 57, 8300108, 2021.]. However, before publication DTU and Wattsup decided that the passive magnetic bearing design was worth patenting, so Wattsup filed a patent application (WO2020084345A1), which has now been published and is in the national phase in Germany, Canada, Brazil, Europe, Australia and World. This is also why the paper was first published in 2021, as this could not happen until the patent was made public.

Following this work, the bearing was integrated into the Wattsup flywheel design, which DTU Energy also assisted with. It was then an objective in the project that Wattsup provide test data back to DTU Energy, to evaluate the performance of the bearing. This never happened although DTU Energy repeatedly asked for this. Wattsup did communicate orally that the bearing design had a high clocking torque and that the mechanical stiffness in the bearing varied.

In order to fix these two issues, DTU Energi designed a new type of bearing based on a bowl-shaped design. In this design the rotor fits “into” the stator. This design is shown in the figure to the right. Using a numerical model, DTU Energi showed that such a bearing has a constant mechanical stiffness, which is very desirable in a bearing. However, Wattsup did not wish to integrate this new design into their flywheel. This work on the conically shaped bearing was published in [Bjørk, R., and C. R. H. Bahl., *A conical passive magnetic bearing with constant stiffness*, Scientific Reports, 12, 4130, 2022.] and also presented as an oral presentation at the 2021 IEEE International Magnetic Conference (INTERMAG).

5.2 Peak power compensation for electrical railway

It was DTU Elektros task with the aid of Banedanmark to study the peak power compensation for the electrical railway. As the Danish railway system is a single-phase load connected across two phases of the transmission grid, a voltage unbalance (VU) is created at the point of connection (POC). It has been demonstrated that a single-phase load creates an equal amount of positive and negative-sequence currents (PSC and NSC respectively) in the grid lines. While the PSC is commonly found in balanced power systems, the NSC is responsible for voltage unbalance in the grid lines, negatively affecting the performance of the other components powered by the same grid. Typically, only a relatively small amount of VU is allowed by the transmission system operator. In the case of the Andst railway system, which was singled out as a target for this project, the largest allowed VU specified by Energinet is 1.08%.

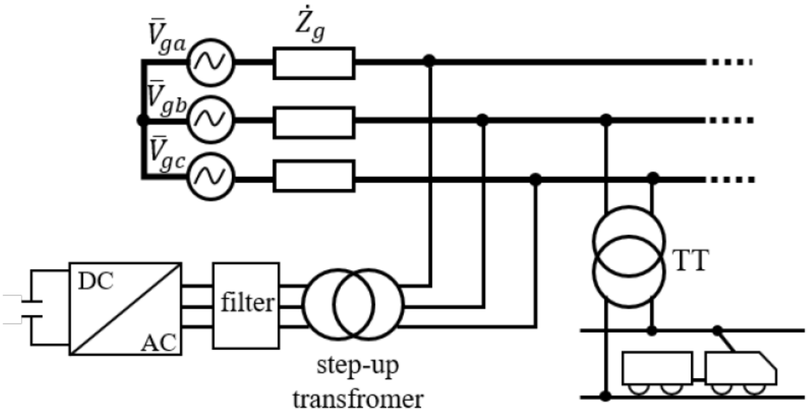
When the railway system operates at full capacity, with the traction load reaching 35MVA which is the nominal rating of the traction transformers at Andst, a VU of 1.77% is generated at the POC of the traction transformer to the transmission lines. As this VU is above the imposed restrictions, countermeasures are required to attenuate its level which was the primary motivation of BaneDanmark in the proposed flywheel technology. Accounting for safety margins, the VU limits translate in to RMS NSC propagated by the railway system should not exceed 66A, which corresponds to an equivalent traction load of 19MVA, meaning that any load exceeding 19MW of traction transformer will cause VU larger then allowed. DTU Elektro has evaluated 3 possibilities for mitigating the VU issues caused by:

- Non-Energy Storage solution: Negative Sequence COMpensator
- Energy Storage solution: Flywheel energy storage
- Hybrid solution

These individual solutions are discussed below in detail and subsequently compared.

<u>Non-Energy Storage solution: Negative Sequence COMpensator (NSCOM)</u>

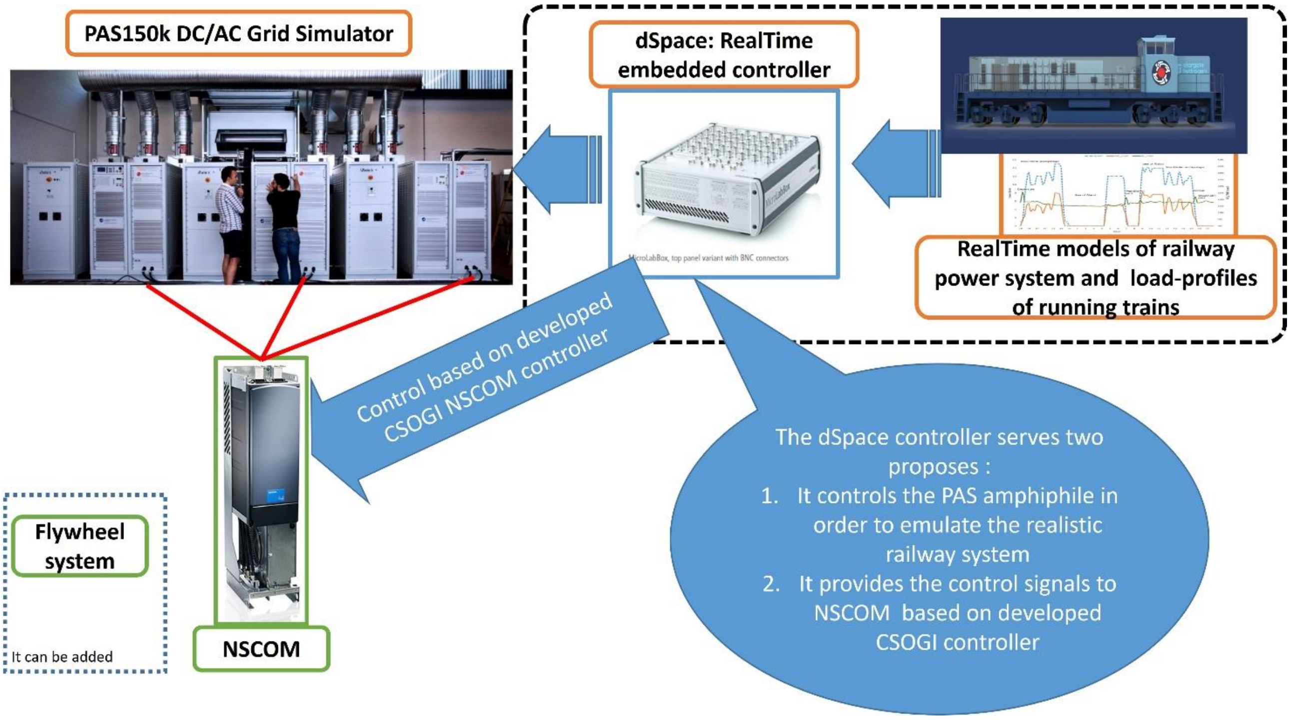
The NSCOM is an AC/DC converter connected across the lines of the transmission grid, in the proximity of the concerned railway system, illustrated in the figure below. The designed control strategy implemented in the NSCOM is able to track and compensate the NSC generated by the railway system, attenuating the VU at the POC. This approach effectively transforms the train and railway system from single phase load into a symmetric 3 phase load, eliminating the VU issue.



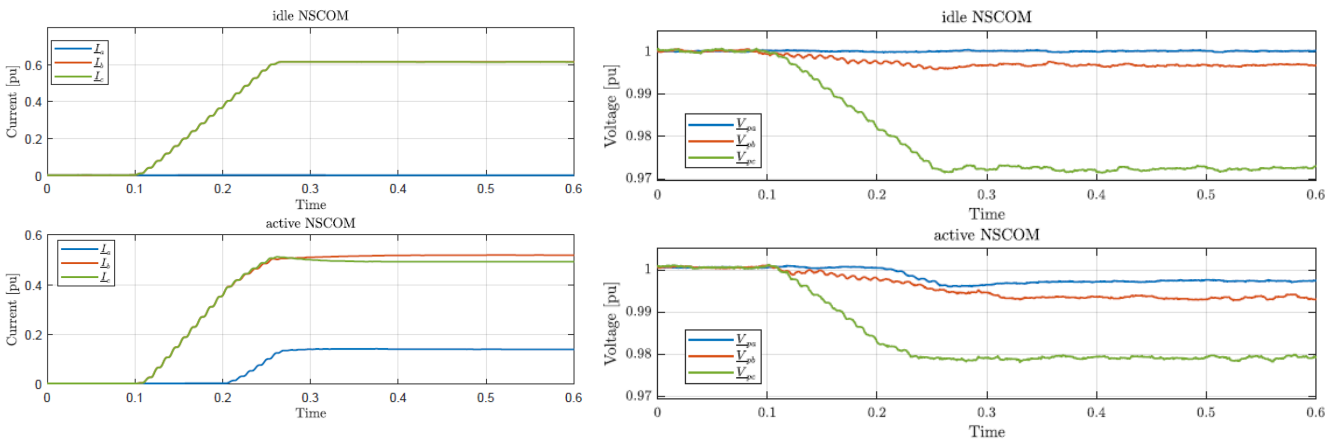
Circuit diagram representation of the NSCOM solution. A three-phase AC/DC VSC is connected across the lines of the grid through a filter and a step-up transformer

In the project, we developed a control function for tracking the NSC, based on the implementation of a Cascaded Second-Order Generalized Integrator (CSOGI), and investigated its performance in laboratory settings. The choice of CSOGI for NSC tracking was made as it allows good harmonic rejection and an accurate estimation of the amplitude and the phase of the NSC. The NSC generated by the NSCOM, instead, is controlled by a Proportional-Resonant (PR) controller. The choice of the PR controller has been driver by its great performance in controlling NSC and PSC and acting as a low-frequency harmonics filter. Illustration of the experimental validation of this approach is show in the figure below. In short, the experiments were performed by controlling a power converter at the lowest level of hardware. Then a power amplifier is connected which emulates the power system based on the developed models. In this way it was investigated how a control scheme would behave in the various scenarios.

The current and voltage distributions with and without the NSCOM solution is shown below. As can be seen from the figure, with the NSCOM active, the discrepancy between the voltage levels is reduced, as the VU at the POC is attenuated. From the obtained results, the NSCOM required to be installed at Andst has been rated at 16MVA, with an estimated capital cost of 2.4M€ (all cost figure cited here are purely for comparison purpose and stem from techno economical assessment of the primary CAPEX of each investigated solution. It is not based on market quotation.).



The testing setup for the control schemes, including Power Hardware-in-the-Loop

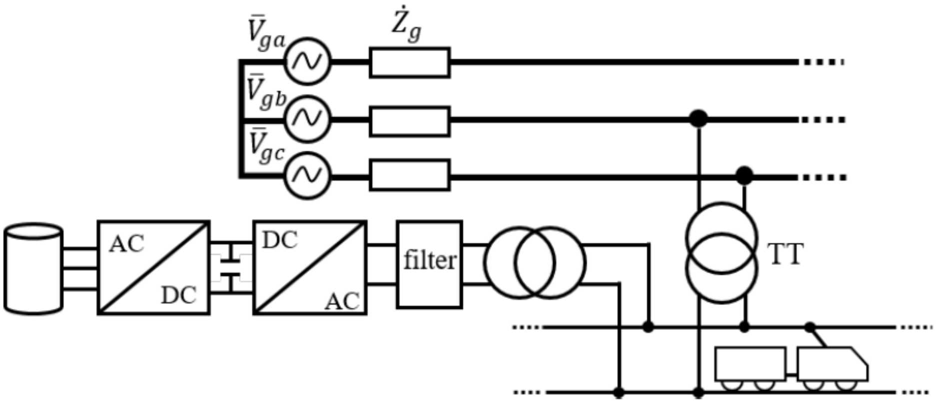


Right: RMS distribution of the current in the grid lines. When the NSCOM is not operative, the traction current is only located in phases *b* and *c*. With the NSCOM active, instead, the current is more evenly distributed among the lines of the grid, having phase *a* loaded as well.

Left: RMS voltage distribution at the POC. With the NSCOM active, the discrepancy between the voltage levels is reduced, as the VU at the POC is attenuated. It should be noted that NSCOM control was only compensating for VU which was exsessive (larget then 1.08%), hence some VU is pressent as seen in the figure.

Energy Storage solution: Flywheel energy storage (FES)

The FES is connected across the lines of the railway system through a back-to-back converter, whose main objective is to curtail the peaks of the traction load using the power stored by the FES itself, as illustrated in figure below. In this approach, the flywheel energy system is used to compensate any power railway system would need that exceeds 19MW, the limit that would cause higher then allowed VU.



Circuit diagram representation of the flywheel solution described in this section. A flywheel is connected across the lines of the railway system through a back-to-back converter, a filter and a step-up transformer.

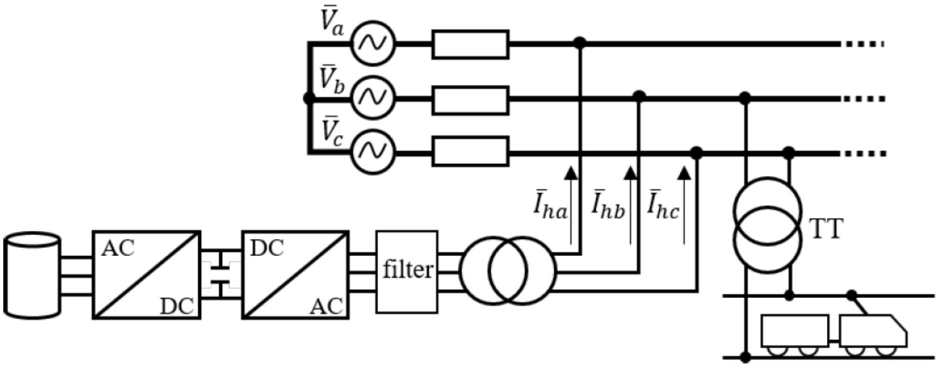
DTU Elektro initial attention was focused on the single-phase phase-locked loop (PLL) used to synchronize the converter with the voltage of the railway system as a critical control element of this approach. The implemented PLL is based on a CSOGI filter, able to provide good time performance and being immune to the harmonics typically found in the railway system voltage. A tuning procedure was developed for the CSOGI-PLL, where tuning parameters are defined based on the harmonic rejection capability of the PLL itself. All tuning of the CSOGI filter and PLL has been done based on an electromagnetic time domain simulation of the railway system including main components such as: train, overhead catenary lines which varying length, traction transformer, transmission system presented with Thevenin source and impedance and the proposed solutions e.g. flywheel system (where the simplified flywheel system is presented as a current source).

Following this, the attention was then moved to the control of the curtailing power and of the charging and discharging cycles of the FES. It was demonstrated that for the application intended in this work, a FES operating at constant torque mode minimizes the capital expense of the flywheel system while providing a satisfactory compensation of the traction load.

It is estimated that flywheel system can be placed at the railway station of Andst with an investment cost of 7.8 M€ (all cost figure cited here are purely for comparison purpose and stem from techno economical assessment of the primary CAPEX of each investigated solution. It is not based on market quotation.). As expected, the cost the flywheel system is higher than the NSCOM, since two converters and a FES are required. The higher cost could be justified by the ability of the flywheel system to power the railway system independently for short periods in the cases of power outage or localized faults, although this was not identified as favourable objective by Banedanmark.

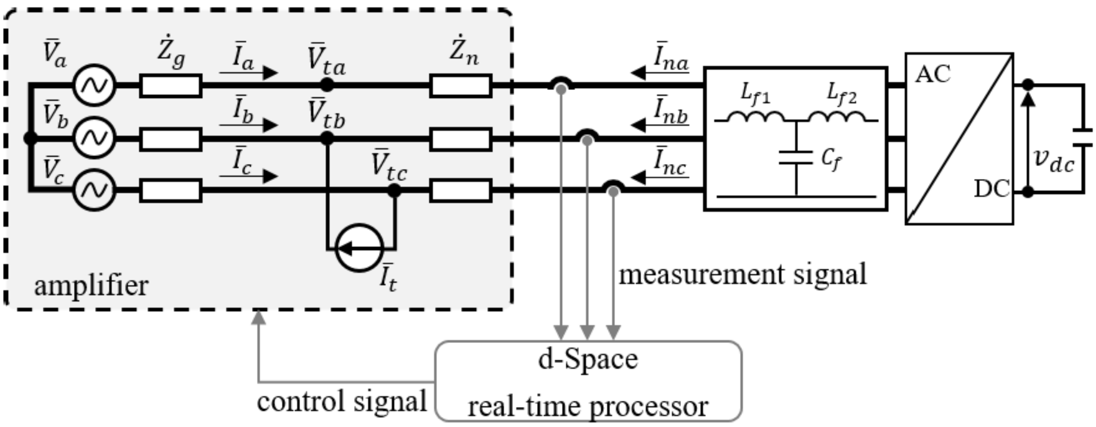
Hybrid solution

The third and final approach to the voltage unbalance mitigation merges the benefits brought by the NSCOM and flywheel solutions, leading to the creation of the hybrid system. The hybrid system consists in a FES connected across the lines of the transmission grid through a back-to-back converter, in the proximity of the analysed railway system, as illustrated in figure below. The main advantage of the hybrid system is the ability to compensate the NSC and PSC absorbed by the railway system independently, thus being able to provide the same VU attenuation of the flywheel solution with the use of a smaller FES. The tuning of the control strategy of the hybrid system is finalized to maximize the attenuation of the PSC while maintaining a capital cost lower than the flywheel solution. The hybrid system is economically more advantages compared to flywheel system if the compensated PSC are not larger than 85% of the compensated NSC, reaching an investment cost of 7.5M€(all cost figure cited here are purely for comparison purpose and stem from techno economical assessment of the primary CAPEX of each investigated solution. It is not based on market quotation.). Finally, the control strategy applied to the NSCOM has been tested in the laboratory through experimental results.



Circuit diagram representation of the hybrid system

The experimental test consists in a Power Hardware-in-the-loop (PHIL) simulation applied to an AC/DC converter connected to an amplifier, emulating the response of the railway system, as illustrated in figure below. The algorithm employed for the implementation of the PHIL simulation has been based on the root-matching integration technique, showing excellent performance and relatively low computational burden. The obtained results have confirmed the possibility of using an AC/DC converter as a NSCOM for the compensation of the NSC caused by a railway system and the attenuation of the VU in the power system.



PHIL testing block& circuit diagram representation of the electric system simulated and tested in the laboratory.

Comparison of solutions

While it was unfortunately not possible to test the flywheel energy storage system physically at DTU and thus verify the developed control strategies, the research performed instead comparing the non-energy storage solution to the flywheel technology. The results proved very interesting and showed that the flywheel technology needs to be reduced in cost for it to be of interest for this specific application.

The work described above was published in two articles at international conferences, namely [D'ambrosio, A., Guest, E., Mijatovic, N. & Agelidis, V. G., *Design of Power Peak Shaving Controller for Single-Phase AC Railway Systems*, Proceedings of 2018 53rd International Universities Power Engineering Conference. IEEE, 6 p. 8542032, 2018] and [D'ambrosio, A., Mijatovic, N. & Agelidis, V. G., *Lumped Parameter Model of a 2x25 kV Railway System Based on Root-Matching Method*, 2018 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific). IEEE, p. 1-5, 2018]

Banedanmark has followed the results produced by DTU Elektro with interest, and has also aided in discussions with the PhD-student.

5.3 Flywheel tests at Wattsup Power facilities

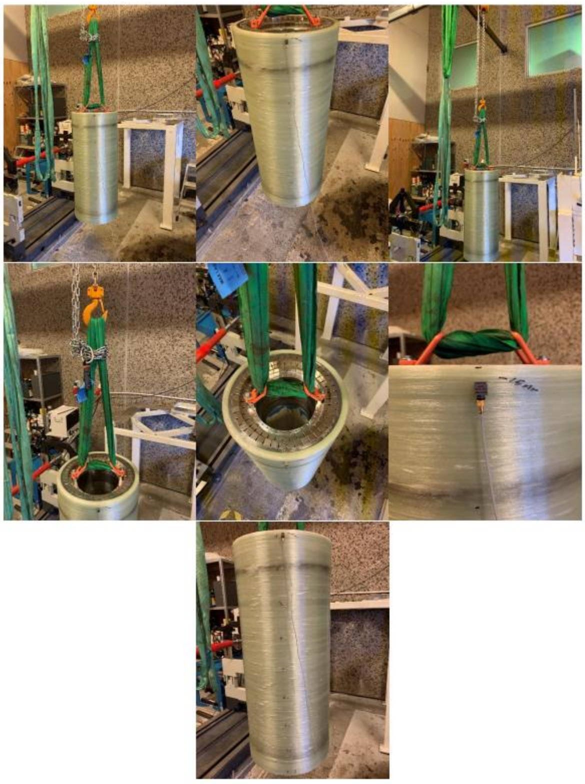
It was Wattups responsibility to produce and perform an initial test of a flywheel for the project. Wattsup in the following did not describe this procedure in detail but have chosen to focus on presenting tests of the produced flywheel for the project These are described by Wattsup as follows using information available only to Wattsup:

5.3.1 Deneb rotor modal test

Modal test was performed to identify natural frequency and hence the damping ration for the rotor. This test is done to ensure that the flywheel rotor is balanced during operation at high speeds. The test is carried out with impact hammer and accelerometer.

The rotor is suspended from an overhead crane connected with a sling to two with two eye bolts. The weight of the eyebolts is considered negligible. The rotor hammer impacts are made perpendicular to the plane made from the two eyebolts and the crane, to mitigate any stiffness added from the support.

It is not possible to properly impact the rotor inside when suspended in the overhead crane, thus a series of tests has also been carried out with the rotor horizontal supported on rollers as shown in the figure below.



Suspension of flywheel rotor

Suspension of flywheel rotor

Node positions

9 (node 1-9) points were added on the outside of the rotor equally distributed over the length of the rotor. 5 points (node 10-14) were added on the inside of the rotor, 1 in each bearing center (11,13), 1 in each radial position sensor center (10,14), and 1 in rotor center (12). See Deneb 000 rotor initial modal test nodal positions Rev 2020-03-16.pdf for locations. The outside points were distributed as follows (from support end):

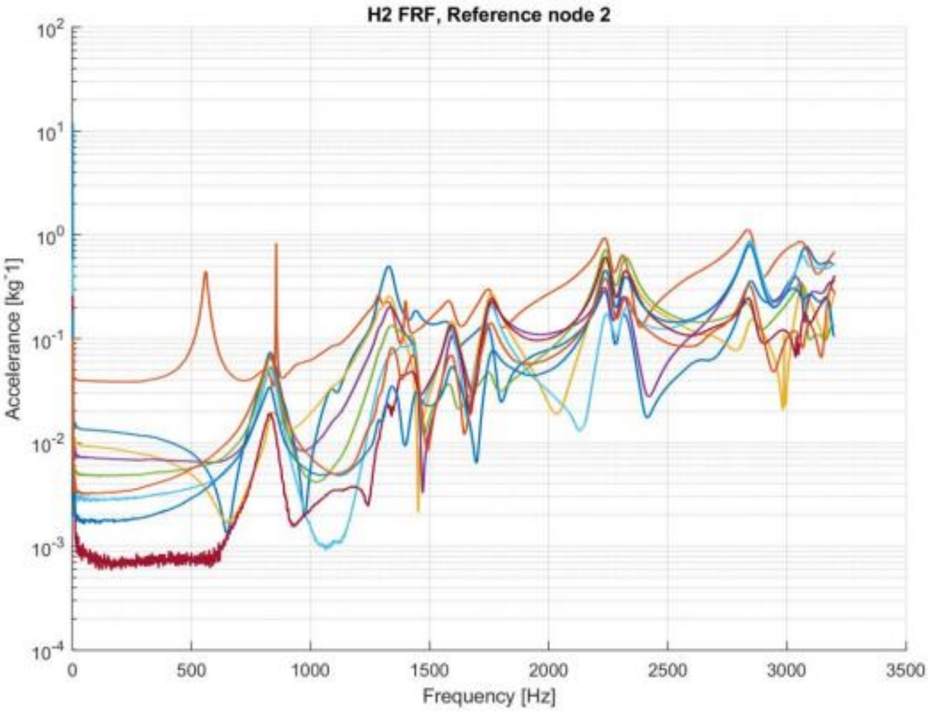
The outside points were distributed as follows (from support end):

1	2	3	4	5	6	7	8	9
15mm	116mm	233mm	349mm	465mm	581mm	697mm	813mm	912mm

Table 5.3.a: Descriptions of node positions

Results:

The impact measured on reference node 2 can be shown in the figure below as well as the natural frequency and hence the damping ratio is tabulated in the table below.



Reference node 2

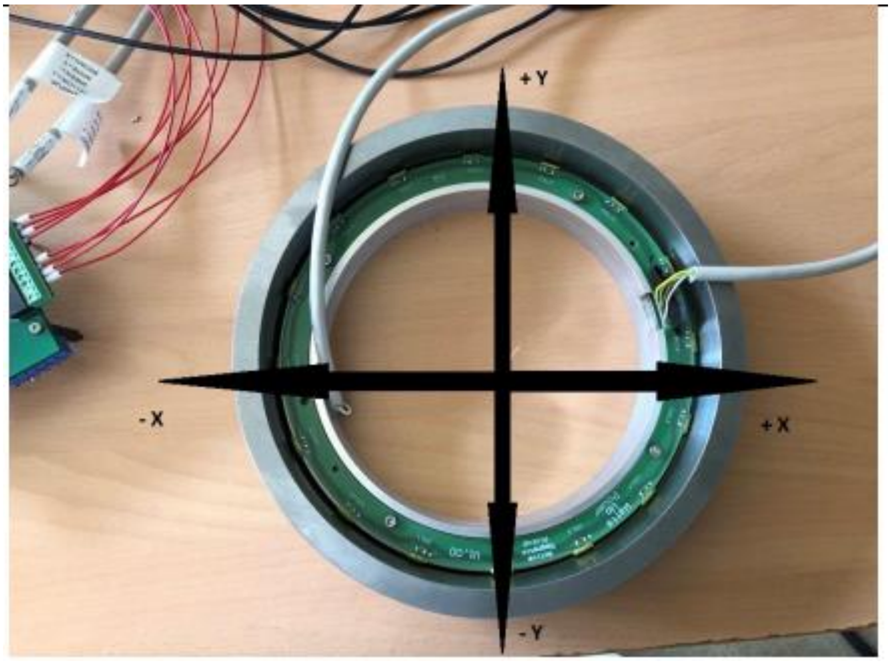
Reference 2					
Natural frequency [kHz]			Damping ratio [%]		
lsce	lsrf	pp	lsce	lsrf	pp
1.1716	0.8308	0.8306	5.17%	2.13%	2.49%
1.2571	1.3342	1.334	3.41%	1.51%	2.38%
1.2571	1.4354	1.4094	3.41%	1.75%	2.65%
1.2571	1.5949	1.5907	3.41%	1.70%	1.81%
1.9826	1.7541	1.7584	13.23%	1.61%	2.05%
2.3522	2.2404	2.237	8.59%	1.00%	1.10%
2.3522	2.3167	2.3245	8.59%	1.11%	1.35%
2.7318	2.8463	2.8443	3.05%	1.05%	1.06%
3.142	3.0746	3.0574	2.18%	0.77%	1.05%

Natural frequency and damping ratio obtained for node 2

Conclusion: The information about the natural frequency and damping ratio obtained from the fly-wheel rotor is used for the tuning of AMB (Active Magnetic Bearing) controller from Siemens during commissioning of the same.

5.3.2 Functionality test for AMB radial position sensor

The objective of the test is to check the functionality of AMB radial position sensors with Siemens electronics for AMB. Radial position sensors play a important role as they provide the AMB with the information in order to keep the flywheel rotor centered during operation. There are two radial positions, one for each AMB located at top and bottom of the flywheel.



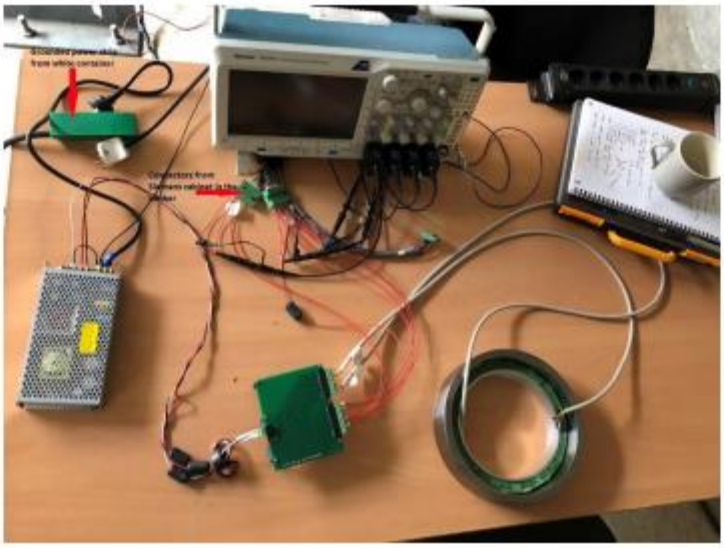
XY coordinate system used as reference for the test

The XY coordinate system used in the figure above is used as a reference while moving the sensor left, right, up and down. When the sensor is moved in the + X direction, the signal for the X channel on the oscilloscope should be – X indicating that the rotor is pulled in the – X direction and vice-versa. Similarly, when the sensor is moved in the + Y direction, the signal for the Y channel on the oscilloscope would be in – Y direction indicating that the rotor has been pulled in – Y direction.

The top and bottom AMB radial position sensors are installed in the in the flywheel as designeated and the connections are made accordingly.

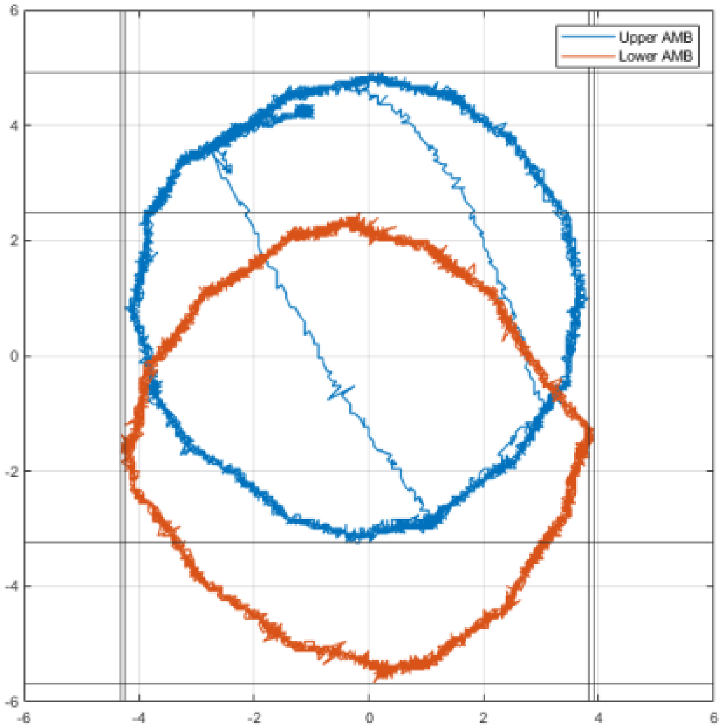
The probes from the oscilloscope are connected to the signal conditioning board for X1, GND, Y1, GND, X2, GND, Y2 and GND. Both top and the bottom AMB radial position sensor can be connected at the same time and the oscilloscope can display the results for X and Y for both the sensors.

The signals are captured in X and Y direction the sensors while the flywheel is in operation to capture full circular path traced by the sensor. A similar test setup to the sensors installed in the flywheel is shown in the figure below



Test setup similar to setup of the sensors in the flywheel to Siemens controller

Results and conclusion:

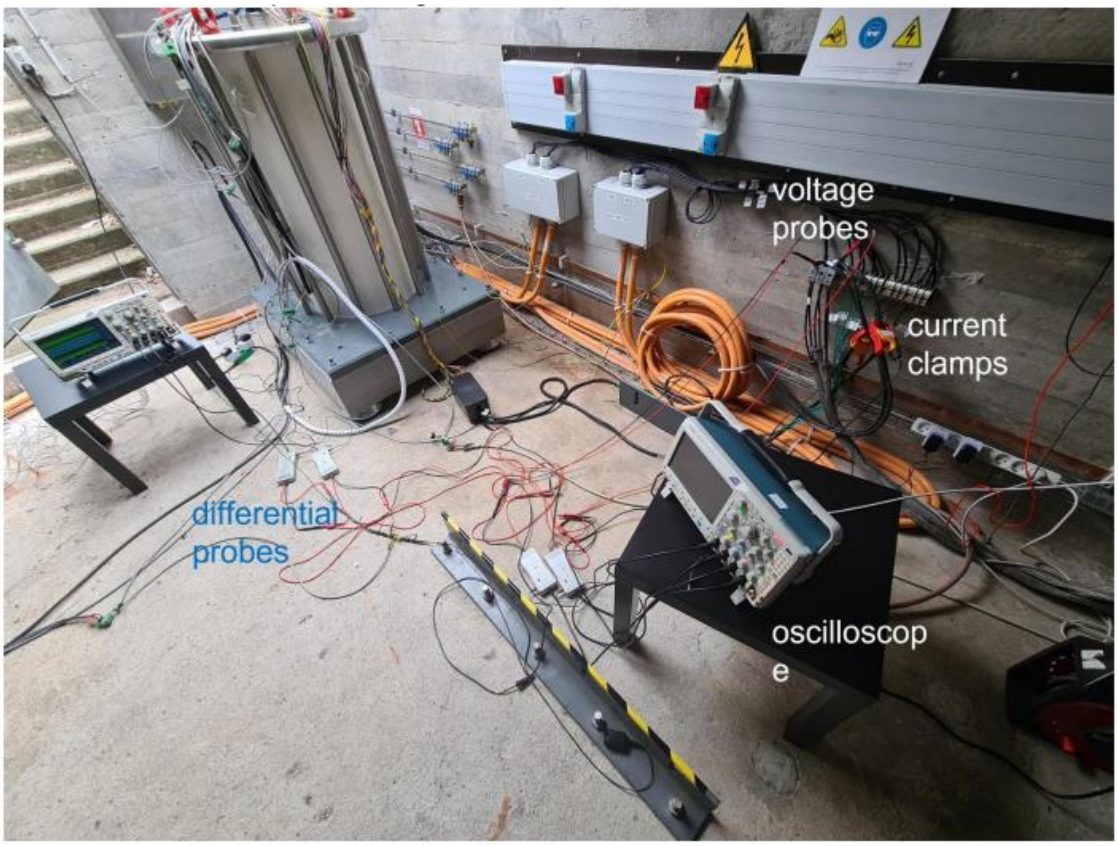


Path traced by top and bottom AMB radial position sensor

The functionality of the AMB postion sensors are validated. The signals from these sensors are fed to Siemens controller for AMB to control the AMB.

5.3.3 To perform constant current test for the flywheel.

To perform test for constant current test for the flywheel motor/generator and perform an FFT analysis of the same. The test setup can be shown in the figure below.



Overview of test setup

Constant current set at 15A

As a first step, the current is set at 15A in the Scott Drive controller. In Figure 5.3.H, it is possible to observe the measured current together with the rotational speed of the flywheel. A particular of the startup is shown in Figure 5.3.I. The measurement shows an initial overshoot, mainly due to the low impedance of the stator winding. After the overshoot, the current shows a trend similar to a square wave, probably due to particular startup control settings in the converter. As the flywheel reaches 120rpm, the current turns into a sinusoidal shape (see Figure 5.3.I). As the flywheel reached 1000rpm, the controller speed limitations triggers, interrupting power supply to prevent the speed from reaching 1000rpm. However, as the power supply is interrupted, the idling losses would prevail, slowing the flywheel down. The speed decrease would enable back the power supply, pushing the flywheel speed to 1000rpm one more time and causing another power interruption. This process would lead to a pulsating current in the motor windings, as shown in the last part of the graph in Figure 5.3.H.

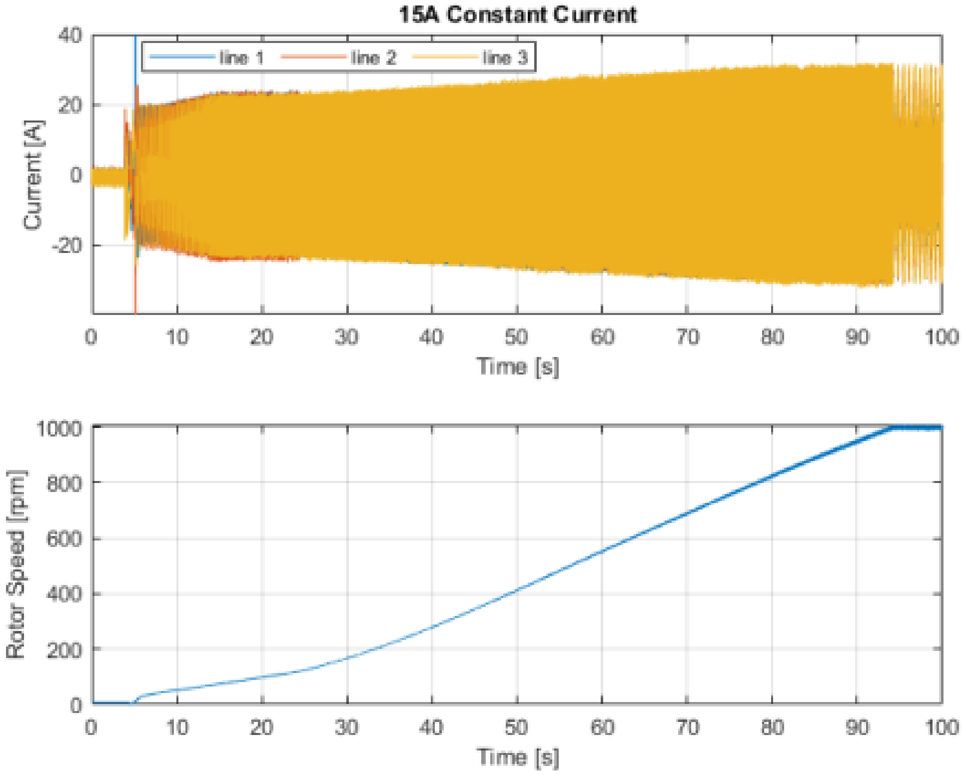


Figure 5.3.H: Measurement of flywheel speed and current with current controller set at 15 A

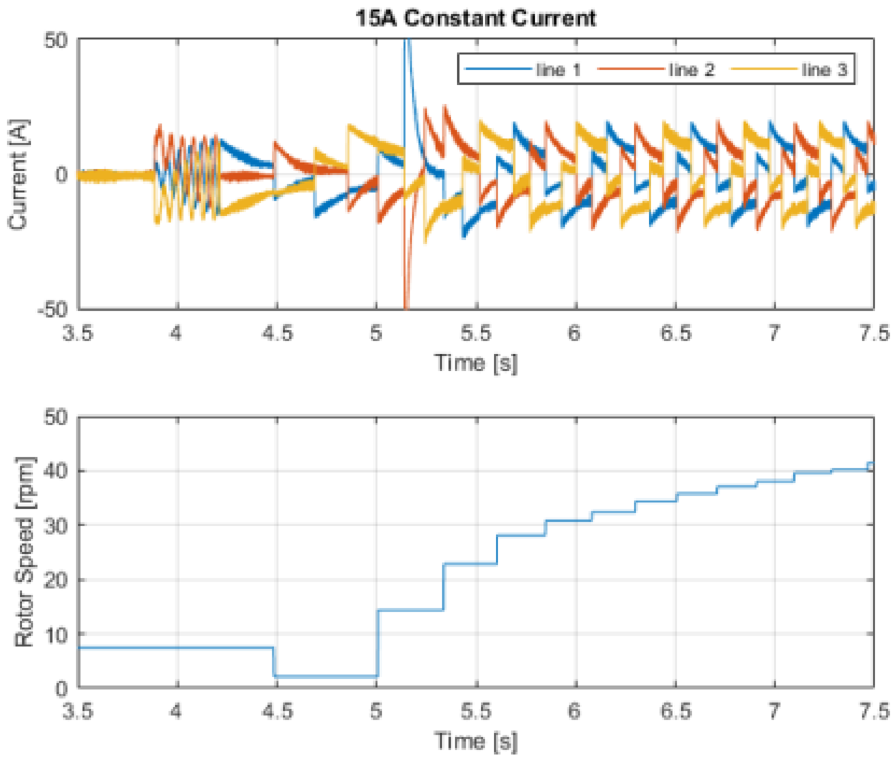


Figure 5.3.I: Particular of the startup current

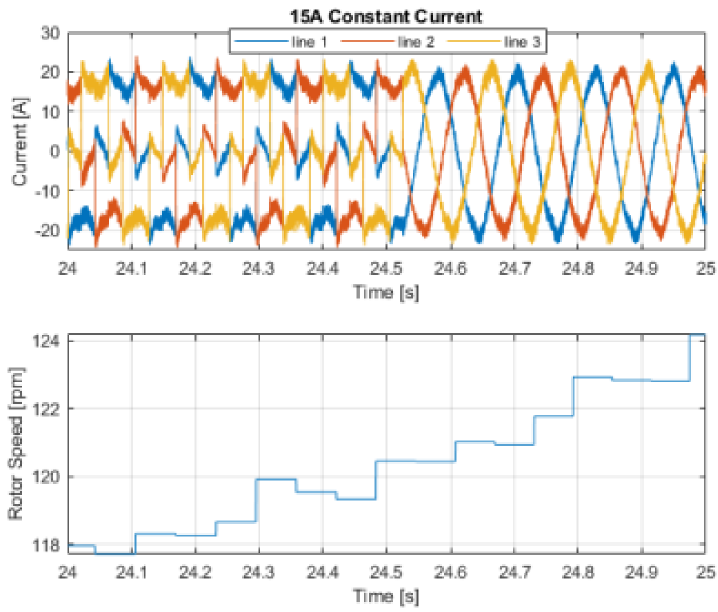


Figure 5.3.J: Particular of the current profile shifting from square to sinusoidal shape

A particular of the armature current at different speeds is shown in the graphs of Figure 5.3.K, Figure 5.3.L, Figure 5.3.M and Figure 5.3.N. As the speed of the flywheel increases, so does the harmonic content of the current in the stator winding. Such increase in the harmonic content is due to the modulation index of the Scott Drive. As the flywheel accelerates, the amplitude of the back-emf induced in the stator winding grows. Consequently, the fundamental voltage generated by the Scott drive should also increase to maintain a stable voltage drop across the motor winding and generate the required current. The amplitude of the fundamental voltage is controlled by the modulation index, being one proportional to the former. As the modulation index increases, so does the width of the pulsating voltage at the terminals of the Scott Drive (PWM). A larger pulse width would increase the ripples in the current, causing an increment in the harmonic content.

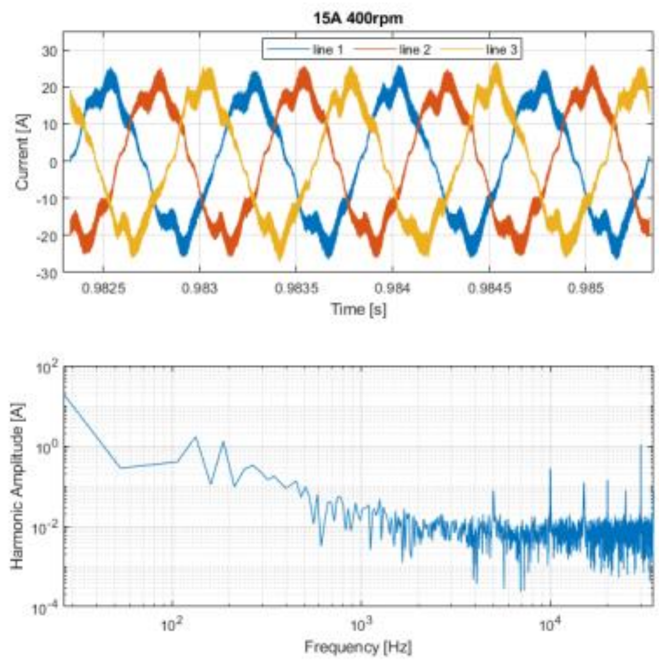


Figure 5.3.K: Representation of the measured current at 400 rpm (top) and FFT analysis (bottom)

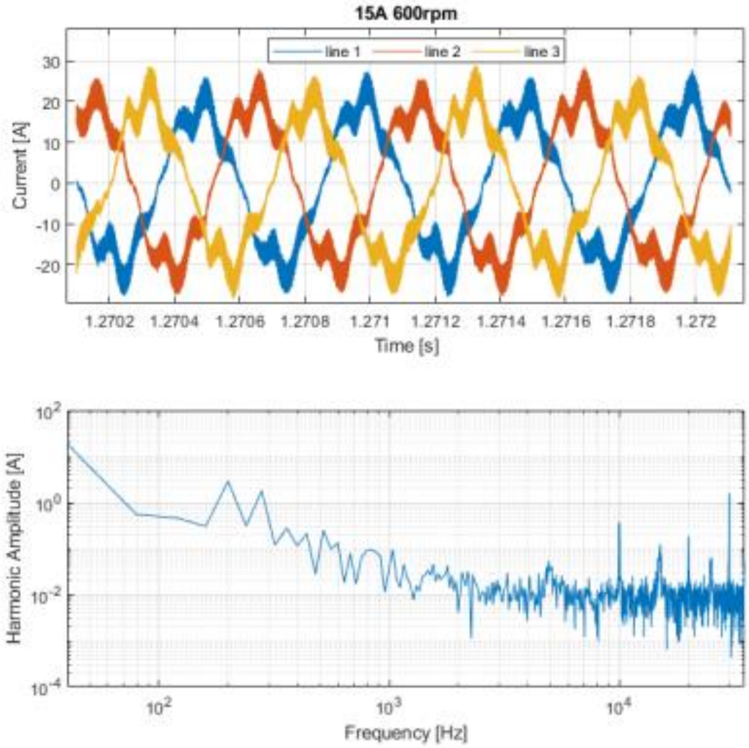


Figure 5.3.L: Representation of the measured current at 600 rpm (top) and FFT analysis (bottom)

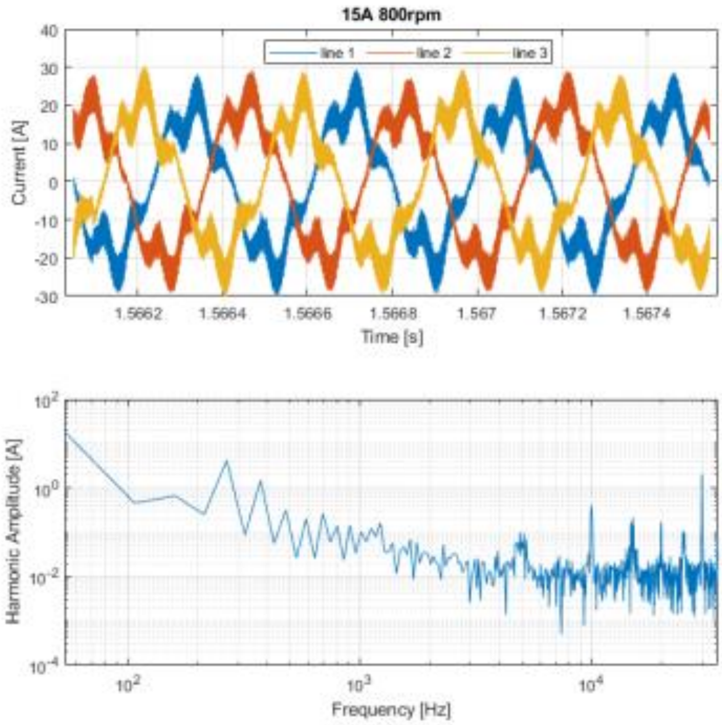


Figure 5.3.M: Representation of the measured current at 800 rpm (top) and FFT analysis (bottom)

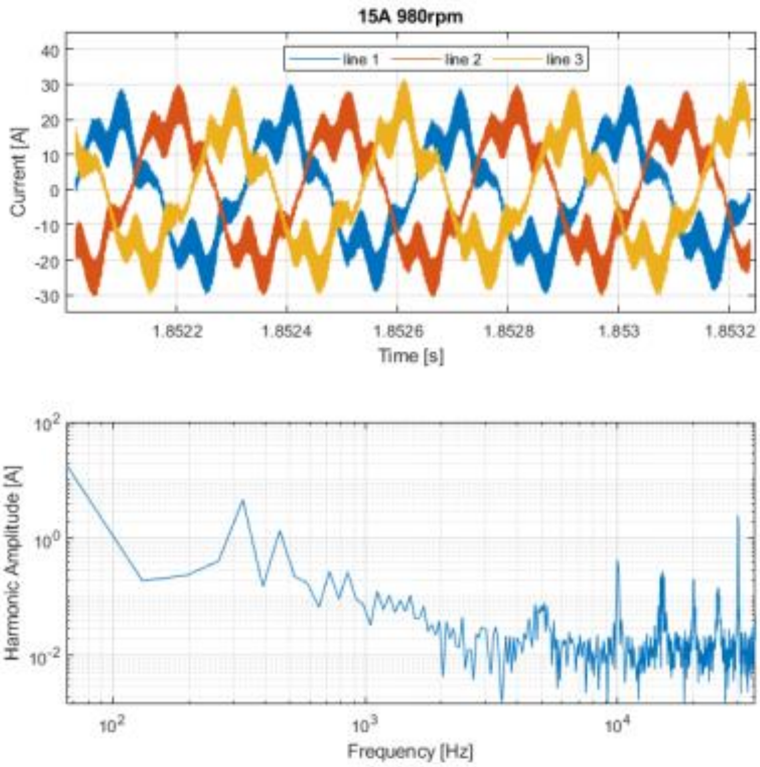


Figure 5.3.N: Representation of the measured current at 980 rpm (top) and FFT analysis (bottom)

Finally, the table below shows the total harmonic distortion (THD) up to the 7th harmonic.

Speed [rpm]	THD [%]
400	11.28
600	18.87
800	24.41
980	26.68

As expected, the THD would increase with the speed, as so does the harmonic content.

5.4 Dissemination

Regarding dissemination, in the project was published two scientific papers in international journals and two conference articles at international conferences, as well as three presentations at conferences, as described above. Furthermore, the project has a webpage located at https://www.flywheel.dk/ . As the project never managed to test an actual flywheel at DTU facilities, the overall promised dissemination strategy in the project application could not be fulfilled.

6. Utilisation of project results

As described above, the project did not successfully demonstrate peak power shaving in flywheels, nor did it demonstrate energy storage in said flywheels outside of WUP laboratory facilities.

For DTU Energy, the research on passive magnetic bearings are being used already in future research on magnetic levitation, but so far only for academic purposes.

The sections on Future market analysis and tFuture technological development below are provided by Wattsup and rely solely on information available only to them.

6.1 Future market analysis

The increasing demand for sustainable energy is still ongoing, and it goes hand in hand with the demand for energy storage. Due to the local and the European variability of energy production and consumption, storage is one of the most critical challenges behind the green transition.

However, energy storage for the biggest Danish industries like marine or wind is currently almost 100% based on batteries build outside of Europe. The World Energy Council reports that the energy storage in Denmark as a whole, is dominated by chemically derived on-site technologies like batteries (high capacity, low peak power) and super capacitators (low capacity, high peak power) technologies. This is suboptimal, as sustainability and the energetic safety and independence leads through diversity.

Many applications, incl. transport (from cars to large ships), small and medium-sized wind farms or more recently enforced by the transition, aerospace. Flywheel energy storage can be a decisive alternative, either as an independent solution or complementary to other systems. In such applications, which account for the ever-increasing demand for energy storage, the chemical-based solutions are limited by a number of parameters like rare earth materials, limited operation lifespan and weight and footprint penalty solutions. These are not the usual trademarks for Denmark.

When this project was launched, there was a perfect match with the beginning of the electrification of the Danish Railway. As described above, Banedanmark was worried for not being able to comply with the grid-imposed codes. As the electrification has progressed, this uncertainty has been clarified, and for now, the need for reducing the unbalanced load, which is typical for the 2-phased connection of an electrified railway, is dramatically reduced. This fact, in combination and the situation where few electrical trains will be running on the newly electrified rails for the next 5 -7 years has postponed the need for peak shaping solutions. The fact that the absolute main part of the railway seen from a worldwide perspective is electrified a long time ago, and operating under much different conditions than Banedanmark with respect to grid codes, the railway market is longer in the focus of Wattsup, due to highly lowered market expectations.

Due to this specific change in the local market requirement, Wattsup has during the past two years changed and focused more onto peak power leveraging and grid stability applications in cases of fast charging applications for the electrification of the transport sector in Europe and in the US. And as suggested by World Energy Council reports, Wattsup's new focus has now led to a number of orders for fast charging energy storage systems specifically for smaller 400kW electrical ferries is being delivered both in Denmark and in Norway. This new marketing segment is now considering the need from the markets focusing on electrification of the sea, as a much more promising market segment.

WattsUp has rectified the first certifications and will in the near future ramp up production of commercial flywheels for long term energy storage. The following part of this final report is WattsUp plan to go to market and their projections for the near future of the technology. WattsUp has 2 types of flywheels a 70kWh version with a 250KW output power and a 250kWh version with a 1MW output power. Both products are currently being approved for maritime use with a resistance of+/- 2g of acceleration (North Sea approval)

The current flywheel unit is based on the proprietary developed combination of s-glass composite and carbon-fiber composites. This unit can hold 250kWh of energy and 1MW of power. The unit rotates around 37.500 RPM at max Energy storage and stores energy from 9.000 RPM at min energy.

On the current road map for WUP production release will during 2023 be a 50.000 RPM product of 500kWh and a 75.000 RPM version in 2025 of 1MWh

All key components of the flywheel are currently produced at the WUP HQ facility in Hvidovre, Denmark and two new production facility is currently being planned in Norway and Louisiana for the US market.

Although the core technology and much of the actual product is the same for a variety of use cases there will be minor technical variations in the final products for different use cases. Moreover, there will likely be investors and market partners for different use cases and to manage the variety of joint venture contacts and/or investor obligations it is necessary to separate commercial units for the different markets. It is therefore likely that a few strategic business areas will be established. Wattsup will have a dedicated business unit manager serving each partner and business area when these are established.

CUSTOMERS

DELIVERED/ORDERED AND PIPELINE

WattsUp Power

DELIVERED/ORDERED	- 2020	2021	Q1-22	Q2-22	Q3-22	Q4-22	TOTAL 2022
Østensjø Rederi						8	8
BaneDanmark	1 (Test)	1(Test)				6	6
SCANDLINES						6	6
Danieli Group						6	6
Spinning Energy AS/ECO					4	10	14
PILOT PROJECTS	9				4	8	12
SUM	9	1	0	0	8	44	52

PIPELINE	2023	2024
Østensjø Rederi	60+	120
BaneDanmark	6	12
SCANDLINES	48	96
Danieli Group	36	72
Spinning Energy AS/ECO	88	976
SUM	238	1276

SCANDLINES – 248 flywheels in total during the project
Danieli Group – 280 Flywheels in total during in the project

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6.2 Future technological development

Wattsup has learned from the development and tests done on the flywheel produced for the project. The main findings are that the developed passive magnetic bearing has a very high cocking torque and this combined with the very little iron in the motor stator of the current Wattsup flywheel means that the flywheel has a very low starting torque. Because the resistance from the backup bearings, on which the flywheel is resting when it is not spinning, it is very difficult to start the flywheel without having access to the rotor, in order to give it a starting push. Based on the above learnings a new flywheel has been designed at Wattup the main difference compared to the flywheel used in the project is:

- Professional made active magnetic bearing (by EAAT Germany)
- A reduced design of the passive magnetic bearing with one layer of magnets
- An increased amount of iron in the motor

This version of the WattsUp flywheel is the one for which data is provided in section 5.

However, this prototype also suffers from several design failures. The main problems are:

- Very poor cooling system, with soft and weak water tubes. The result is lack of cooling, which limits the period of operation to 15 min at RPMs below 5.000, after which the flywheel must cool down for app. 4h.
- The rotor is spun on a huge solid electrically conductive aluminium cylinder. This leads to very high losses in the stator, caused by circulating eddy currents.

Based on the lessons learned Wattsup is currently producing a new generation of flywheel. Prototypes and first production series are ongoing but Wattsup does not much to provide details on these in this report.

7. Project conclusion and perspective

This project has been running for 6 years and have not succeeded in testing a flywheel. It can therefore only be considered unsuccessful. However, the two DTU partners have successfully completed their individual subprojects and Wattsup has used the knowledge gained in the project to develop a new generation of flywheels.

Furthermore, since DTU Elektro could not test a flywheel, instead time was spent investigating alternative solutions to the voltage unbalance problem. Here, a novel but currently cheaper solution to the problem was found by using existing hardware.

In section 6, the future projections from Wattsup both on the marketing and technological side were laid out. It is also clear that without the project Wattsup would not, in the future, be able to produce and sell a new generation of flywheels.

On Banedanmark part, information of the peak power usage and subsequent compensation has been gained, as a result of the initial measurement in the system and the subsequent PhD thesis by DTU Elektro. Banedanmark also wish to note that they have received no compensation for their tasks done in the project, as these could be naturally fitted into the tasks done as part of the electrification of the Danish railway and because no flywheel as tested on a transformer station.

8. Appendices

The two scientific articles published in international journals by DTU Energi are included as appendices. Two conference articles published by DTU Elektro are included as appendices. Two test reports provided by Wattsup is included as appendices.