Green train

System Analysis of Permanent Magnet Traction Drives

FINAL REPORT PROJECT HK 06-1509/AL50

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Gröna Tåget
Trains for tomorrow's travellers

ROYAL INSTITUTE
OF TECHNOLOGY

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of
Permanent Magnet Traction Drives

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Project HK 06-1509/AL50

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Preface

When it was decided to test permanent magnet motors within 2 years on a train, it became clear that the newly started collaboration between KTH and Bombardier within the High Performance electrical machines and Drives (HPD) research program in EKC2 did not have enough human resources to cover the needs. Åsa Sandberg and I were really happy that we succeeded to organize some extra financing to support the PM project at Bombardier. It made it possible, among other activities, for my mobility from KTH to the company under spring 2008, with one day a week in Västerås, my colleague Oskar Wallmark's mobility being financed by HPD.

I have had many exciting moments. Sitting in a train with Joseph Riefel from Bombardier in Austria, going home from a meeting in early 2007 was one. I got really impressed when he explained he had designed the induction motors driving the Swiss train we were sitting in for some years ago. I was even more thrilled and proud going back and forth between Västerås and Grillby, cruising along at 250 km/h in a modified Regina train with its two PM motors I had contributed to put there on this summer day 2008.

Unfortunately, things got much more complicated when it was time to finish off the project. The PM motors had just being successfully tested in "ghost" traffic operation when I went on parental leave on my due date in 2009. I learned the hard way that mums of young children are also susceptible to short-circuits. I was lucky that my burn-out was due to a relatively short-time overload, not completely destroying the machine. The reparation work still took nearly one year to get completed. The completion of this project is clearly showing my train is rolling forward again, even though no speed record attempt will be part of the journey this time.

Juliette Soulard
Auckland, 2012-12-19

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Abbreviations

AC	alternative current
AGV	automotrice à grande vitesse (Alstom)
BT	Bombardier Transportation AB
DC	direct current
FEM	finite element method
HPD	High Performance electrical machines and Drives research program at KTH
IM	induction motor
KTH	Royal Institute of Technology
PM	permanent magnet
PMSM	permanent magnet synchronous motor
NdFeB	neodymium-iron-bore magnet material

Abstract

This report describes the activities in the project HK 06-1509/AL50 "System analysis of permanent magnet traction drives" conducted at KTH in collaboration with Bombardier Transportation between January 2007 and December 2010. The driving aim of the investigations was to support the testing of PM traction motors in the Green Train during summer 2008 and analyse the results.

The technology of traction electrical motors for train application has evolved from DC motors to AC drives with both synchronous and induction motors in the last decades. Three-phase permanent-magnet (PM) synchronous motors are both smaller and lighter than induction motors (IM) for a given torque with same cooling conditions. However, this also implies new system challenges to be solved.

Besides supporting the activities involving design, prototyping and testing of the PM motors in laboratory and vehicle environment, a number of theoretical investigations have been conducted by KTH researchers. Thermal modelling and loss calculation tools were developed. The main effort was dedicated to the investigation of winding failure and its possible consequences from original short-circuit to worst possible conditions of the PM motor after failure propagation without mitigation strategies. A new algorithm to implement sensor-less control of PM motor was also developed in a semi-parallel project and is therefore shortly described as well.

Keywords: laboratory test, losses, permanent magnet motor, thermal modeling, traction, vehicle tests, winding failure.

Sammanfattning

Rapporten beskriver aktiviteterna som genomfördes inom projektet HK 06-1509/AL50 ”Systemanalys av permanentmagnetiserade drivsystem för traktion”. Personal från KTH och Bombardier Transportation samarbetade mellan januari 2007 och december 2010 med test av permanentmagnetiserade (PM) motorer på Gröna Tåget under sommaren 2008 som mål. Analys av test resultat ingick också i projektet.

Teknologin av traktionsmotorer bytte från DC motor till AC motorer de senaste 20 år med både synkron- och asynkronmotorer. Trefasiga PM motorer har högre momenttäthet än asynkronmotorer vid samma kylning. Användning av den lättare och mindre motorn innebär dock visa system utmaningar.

KTH forskare gav support vid dimensionering, prototyp tillverkning samt testning av de PM motorer som byggdes. Teoretiska studier genomfördes vad gäller termisk modellering, samt förlustberäkningar. Huvudstudien handlade om lindningsfel med modellering av felsutveckling från kortslutning till den värsta tänkbara motor status utan felshantering strategi. Den nya sensorlös kontroll strategi som togs fram i ett närliggande projekt är också kort beskrivit.

Nyckelord: laborativa tester, förluster, permanentmagnetiserade motorer, termisk modellering, traktion, fordonstest, lindningsfel.

1. Introduction

During 2006-2008, full scale tests in speeds up to 275 km/h were to be conducted in the frame work of Green Train [AND12] and R&D *REGINA* 250. The objectives were e.g. to study and verify the operation of both a passive and an active suspension bogie and active lateral suspension. Besides, the train was equipped with bogie shields to reduce external noise. It was also decided to test electric drives with permanent magnet traction motors on the modified Regina train.

Before such test runs could be conducted on a train with this relatively new technology, design aspects of motor, converter and gear had to be studied as well as fundamental system issues for permanent magnet motor drives. For the system aspects, it was decided that this project would focus on mechanical robustness and fault handling, e.g. at short circuit. The last phase of the project comprised a comprehensive evaluation of the test runs.

This project was started in January 2007 and was planned to be finished in December 2008, with the participation of the division of Electrical Machines and Power Electronics at KTH and Bombardier Transportation. The driving force behind the organisation of the conducted activities was the tests of the new PM drives on the Green train during the summer tests in 2008.

This report starts with a short description of the known advantages and drawbacks of permanent magnet synchronous motors used in traction applications. It is followed by a presentation of the specifications and some characteristics of the motors tested on the Green Train in section 3, reporting the main results from the laboratory and different vehicle tests until May 2009. Section 4 describes shortly the theoretical investigations conducted at KTH within the project, followed by conclusions in section 5. The list of publications and involved personal are presented in section 6 and 7, respectively. The complete details of the references cited in this report can be found in section 8.

2. Why permanent-magnet traction motor?

The technology of traction electrical motors for train application has evolved from DC motors to AC drives with both synchronous and induction motors in the last decades. Three-phase permanent-magnet (PM) synchronous motors are both smaller and lighter than induction motors (IM) for a given torque with same cooling conditions. Therefore, it is not surprising that many of the bids for new rolling stocks could be seen to integrate PM motors after Alstom's AGV broke the world speed record with this "new" technology in April 2007 (see fig. 1).

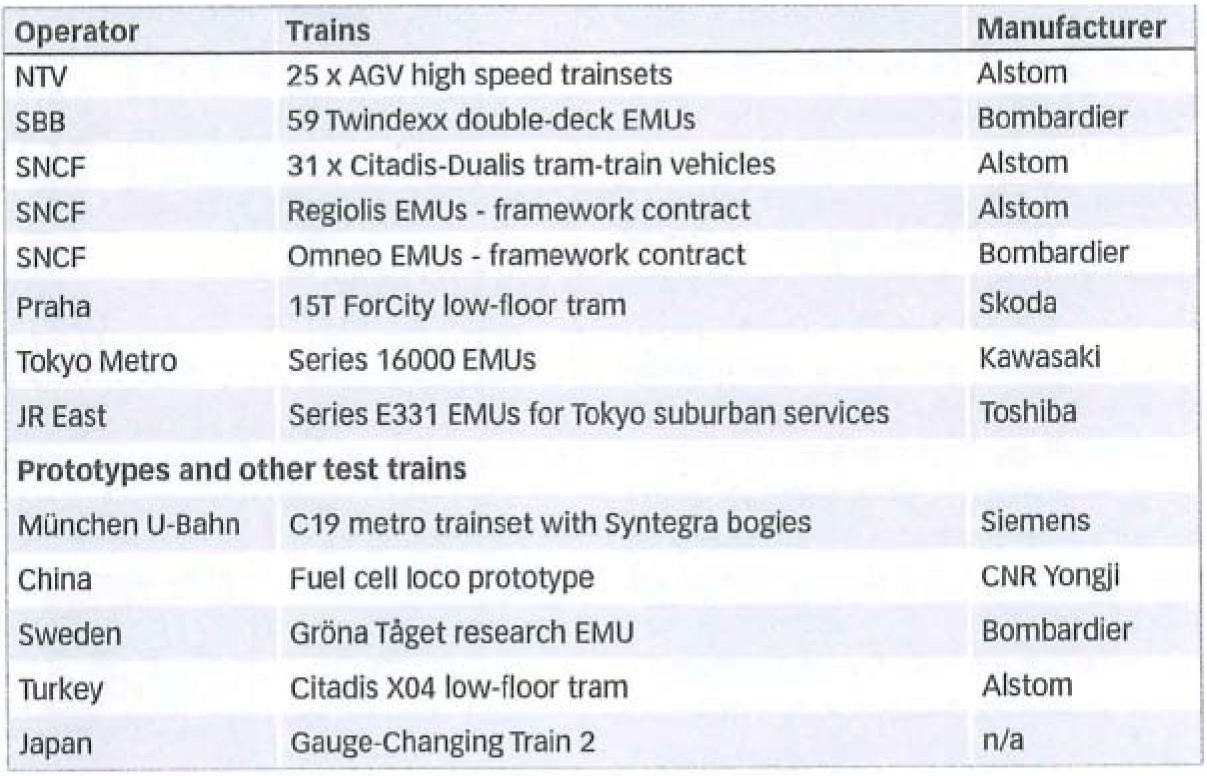
[HILL11] gives a really nice introduction to the difference between DC and AC synchronous (PM and wound) synchronous and induction motors for traction.

The significant advantages of PM motors compared to induction motors are:

- Higher efficiency: *"1 to 2% higher on 80% of the operating range"* according to [HIL11]
- Higher specific power: *"30% to 35%" leading to "25% smaller or lighter motors for the same power rating"* [HILL11]
- Reduced need for rotor cooling since the rotor magnetization is provided by magnets (currents in rotor bars in induction motor)
- Potentially more reliable drives since the PM traction motor needs to be enclosed.
- Regenerative braking is available down to really low speeds

[HIL11] also lists several main drawbacks:

- Due to limitations in the converter dimensioning, higher speeds can only be reached by a controlled strategy called field-weakening since the magnets produce a constant magnetization non depending on the speed. The field-weakening strategy involves higher copper losses in the stator winding to counter-act the magnet field.
- A major system aspect is that each PM motor requires its own converter due the synchronization needed between the rotor position and the currents fed in the windings.
- Even when not producing any torque, the magnets induce an AC field in the stator core and teeth whenever the rotor turns. This creates iron losses in coasting conditions.
- The magnetic properties of permanent magnet material are temperature dependent to such an extent that the temperature swing has to be monitored. The material is also relatively delicate mechanically, which makes to manufacturing more delicate.
- High dynamics of synchronous motors require a position sensor of high resolution. Reliability issues need to be dealt with. Sensor-less algorithms for converter control are also existing but researchers around the wold still try to improve certain characteristics.
- Permanent magnets are susceptible to de-magnetization by too high temperature and/or inverse magnetic field (possibly created by the stator windings).
- In case of partial or spread-out short-circuit in the stator windings, the intact magnets would induced circulating currents (therefore breaking torques), whenever the rotor turns (e.g. towing).



Operator	Trains	Manufacturer
NTV	25 x AGV high speed trainsets	Alstom
SBB	59 Twindexx double-deck EMUs	Bombardier
SNCF	31 x Citadis-Dualis tram-train vehicles	Alstom
SNCF	Regiolis EMUs - framework contract	Alstom
SNCF	Omneo EMUs - framework contract	Bombardier
Praha	15T ForCity low-floor tram	Skoda
Tokyo Metro	Series 16000 EMUs	Kawasaki
JR East	Series E331 EMUs for Tokyo suburban services	Toshiba
Prototypes and other test trains		
München U-Bahn	C19 metro trainset with Syntegra bogies	Siemens
China	Fuel cell loco prototype	CNR Yongji
Sweden	Gröna Tåget research EMU	Bombardier
Turkey	Citadis X04 low-floor tram	Alstom
Japan	Gauge-Changing Train 2	n/a

Figure 1: Selected trains using permanent-magnet motors [HILL11].

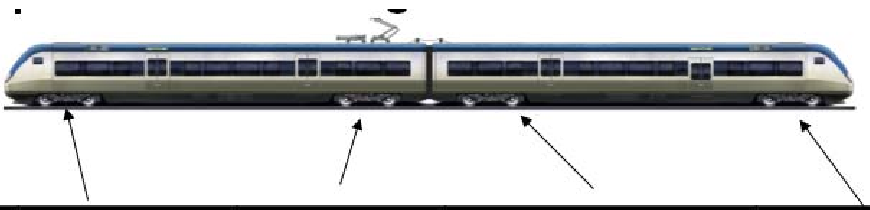
The research activities conducted at KTH focused on the last three items of the drawback list.

3. Permanent-magnet motors tested in Green Train

3.1 Design specifications

The dimensioning of the PM motors to be tested in the Green Train was initially conducted by Professor Andrea Vezzini from Bern University of Applied Sciences, Switzerland. Modifications were introduced by Bombardier in collaboration with KTH in later stages.

The set of specifications for each of the two PM motors to be tested on the Green Train were really stringent. Since PM motors require each their converter, 4 IMs of a normal *REGINA* train were replaced by 2 PMs, still keeping 4 IMS of the original set-up (see fig 2). The specified torque-speed curve took this into account, allowing as well for the possibility to attempt a speed record requiring increased high speed capability.



Year, tests	Bogie 1	Bogie 2	Bogie 3	Bogie 4
2008	Induction motors	Induction motors	🟩 PM motors	Non-driven
2006-2007	Induction motors	Induction motors	Induction motors	Induction motors

Figure 2: Configuration of *REGINA* train for tests June – September 2008.

The PMSM system was based on *MITRAC* systems developed for induction motors, merging the best of the existing motor design with the latest research on permanent magnet technology. The PM motors were designed to be compatible with the existing products like

- other *MITRAC* drive system components
- bogies
- brakes

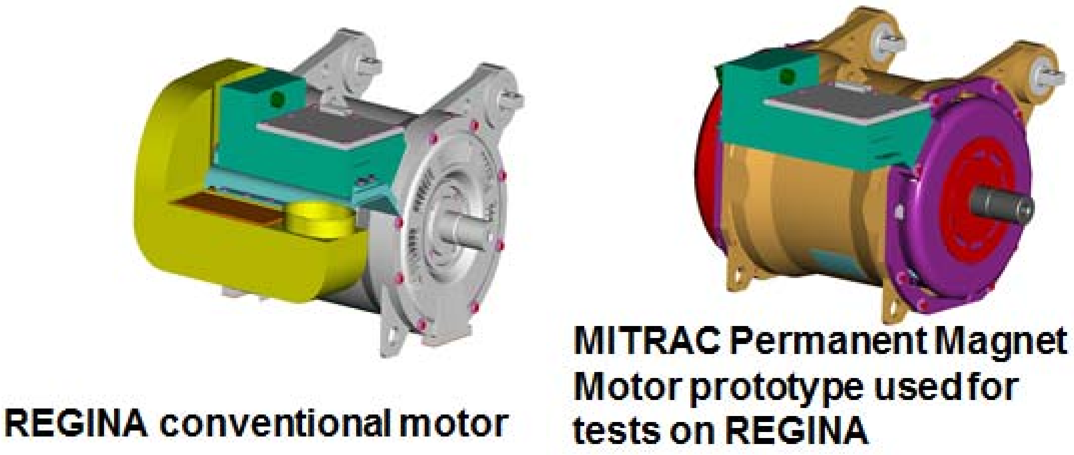


Figure 3: CAD drawings of IM and PM motors (source: Bombardier).

Basically, the IM and PM motors have the same weight and approximate outer dimensions and there are mechanically interchangeable (see fig.4). The external ventilation in yellow in the left figure has disappeared in the PM motor since it is self-ventilated.

Figure 4: The *MITRAC* PM motor mounted in the *REGINA* test train bogie.

3.2 Laboratory tests

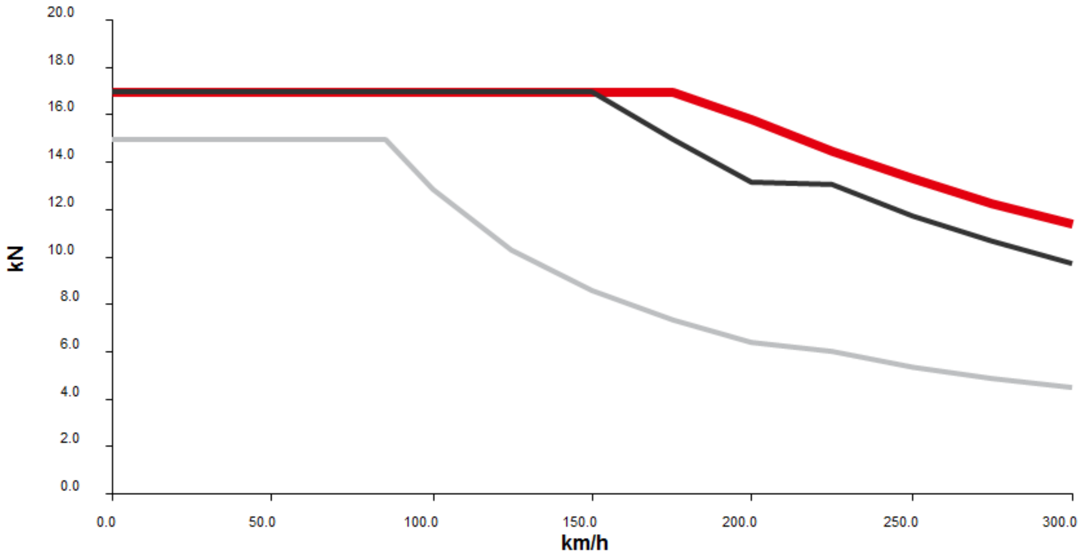
The results of the optimization of the PM motors at vehicle level in the same volume could be investigated in the laboratory tests. The design combined an increased power per motor for the same volume, together with an increased traction effort at high speeds (see fig. 5):

- 950 kW defined max power = 1.7 kW / kg, 1046 kW max measured power
- Max PM motor tractive effort** 2.6 times that of an induction motor

The resulting efficiency was 96.7% at rated power (302 kW), and 97.1% at maximal power (laboratory tests).

🟥 Max Tractive Effort per PM motor
⬛ Utilized Tractive Effort per PM motor
⬜ Utilized Tractive Effort per ASM motor

utilized = utilized in the 303 kph test run
max = calculated for max current and warm magnets, tested in the lab



More rail power with fewer motors

Figure 5: Traction effort versus speed for IM and PM motors of Green Train.

The focus of the laboratory tests were on performance and safety. Beside detailed measurements in well-controlled conditions of the tractive/braking effort and efficiency, the motor temperature distribution was investigated. To prepare for vehicle tests, over-speed tests were conducted successfully, testing as well safety and protection functions. Indicative tests of vehicle level characteristics were also run dealing with the control robustness, electromagnetic noise and electromagnetic compatibility.

3.2 Vehicle tests

The vehicle tests were run June-September 2008. They confirmed the robustness and compatibility of the PM drives on the *REGINA* train.

The accuracy, dynamics and robustness of the control were asserted in vehicle service conditions. Slip/slide on soaped tracks was tested as well as sensor-less control. It was verified that electric brake is possible to full stop.

Safety and protection aspects were also addressed by verifying the contactor functionality including supervision. Power interruptions were simulated involving the testing of back-up braking and the possibility to re-start the PM drive at high speed.

At vehicle level, the increased vehicle performance was confirmed (speed record). Noise level was measured as well as radiated emissions.

No reliability issues were encountered. Measurements confirmed electrical compatibility with *MITRAC* design and zero failures occurred.

3.4 Traffic operation

Reliability was in focus during the traffic operation conducted from September 2008 to May 2009 after the vehicle tests. Before the start of ”ghost” service in mid-October 2008, several activities were conducted. First, a disassembly of the PM motor and inspection confirmed the perfect function after 8 weeks of high-speed test. Special attention was given to the cooling channels, rotor balance, bearings, position sensors and maximal temperature indicators. The active suspension bogie and active lateral suspension were replaced by standard type bogie. The tractive/braking effort references were adjusted, leading to a reduced motor utilization as the train was run under conditions similar to commercial traffic.

The PM motors and drives faced a full spectrum of physical environment stress, to assess long duration impact. It included temperature swing (winter climate), vibrations, and moisture. The full conclusions are not presented here but it should be noted that zero failure occurred.

3.5 Conclusions on tests in Green Train with PM motors

The tests performed in Sweden were successful, exceeding expectations and confirming the expected advantages of *MITRAC* PM motor. The two PM motors increased the vehicle performance at high speed. The motor reliability, the control and protection functions, were verified.

The *MITRAC* PM motor clearly benefits from the experience of reliable and proven *MITRAC* induction motor. It has a general compatibility with existing systems. Furthermore, it offers a high degree of versatility for optimized utilization of complete system.

4. Theoretical investigations conducted at KTH

Several drawbacks were listed in section II about using PM motors in traction applications to replace induction motors. The last three points in the list were especially investigated at KTH. The permanent magnets’ susceptibility to de-magnetization by too high temperature and/or inverse magnetic field (possibly created by the stator windings) were studied by developing thermal models and working on loss modelling (section 4.1). The main effort was dedicated to possible winding failure and developing tools to predict worst case scenario and test mitigation strategies (section 4.2). Investigations of sensor-less control are only shortly reported in this report since they were financed by the HPD program, except for the work required by the implementation on the train and summer tests.

4.1 Thermal modeling and losses

The 4-pole motor with buried magnets, designed by Professor Vezzini from the Technical University of Biel, was used as case study in [FAI07]. As written before, the PM motor prototypes tested on the green train were modified from the original design.

Several thermal models were developed by the students. At first, two analytical thermal models for one single stator slot were developed. The first model considers one equivalent conductor per slot carrying the total current in the slot and the slot copper loss. The assumption was that there is no gradient of temperature within the slot or along the tooth (no radial thermal resistance). A temperature difference of 65°C was obtained between the copper and the stator yoke for 100 W of copper loss in the slot.

The second and more advanced model allows describing the possible uneven spreading of the copper loss in the n_s slot conductors and takes into account the grading of temperature in the slot and tooth. For the same conditions as for one equivalent conductor in the slot but with equally distributed copper loss in each of the 14 conductors in the slot, it was seen that there can be a difference of temperature between the conductors of 20°C. The coolest conductor is the one at the bottom of the slot. A gradient of 15°C was seen along the tooth.

A thermal model for the motor (stator + rotor) was then developed. The network represents actually $1/Q_s$ of the motor (based on slot thermal model), with Q_s the number of stator slots. The model for the rotor with the magnets is based on [ELR04]. The rest of the thermal model is based on [LIN99]. The thermal network is shown in figure 6.

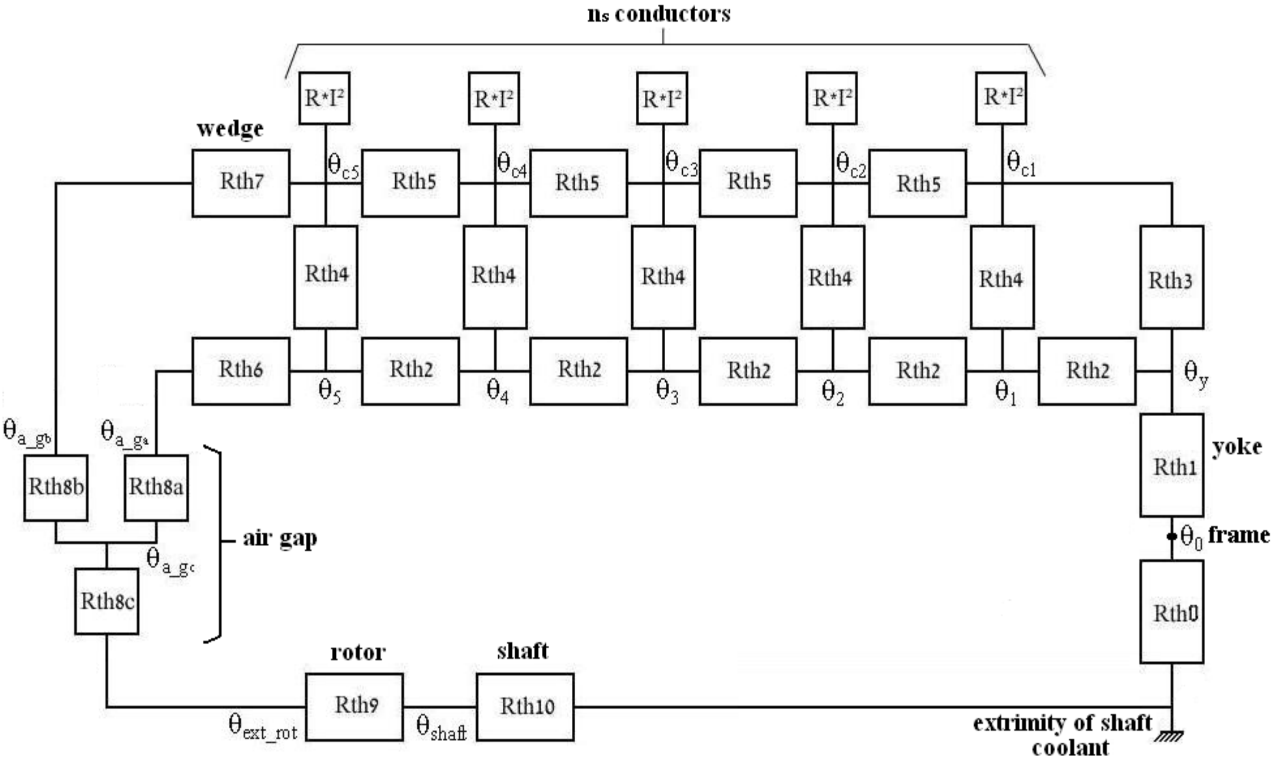


Fig. 6: PM motor thermal network. [FAI07]

Several resistances are difficult to calculate: R_{th10} and R_{th0} for example. Actually R_{th0} was back calculated so that the temperature of the shaft set to 40°C would be obtained with a frame at 120°C. With this model and at nominal torque, the temperature of the magnets was calculated to be around 137°C. This result has to be considered with some reserve. It should be noticed that the end-windings have not been modelled at all. The influence of the value of the thermal resistance of the air gap also needs to be investigated further as only conduction and no convection has been considered to take place in the air gap. No iron loss, nor magnet loss have been introduced in the network at this stage. The copper losses would also need to include skin and proximity effects.

At high frequency, eddy currents appear in the conductors of the windings. These eddy currents are due to skin effect and internal proximity effect (alternating magnetic field created by conductors lying nearby). The internal proximity effect is illustrated in figure 7, where it can be seen that the current is pushed on the outside parts of the coil, increasing by a factor close to 2 the current density in the outer conductors.

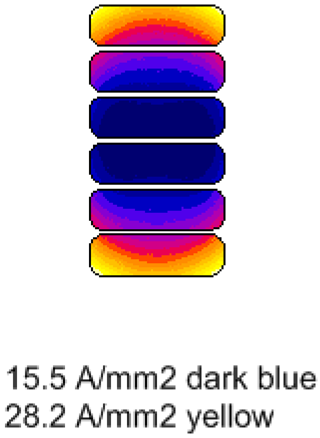


Figure 7: Current distribution in six conductors in parallel in air at -40°C and 400Hz.

The analytical model presented in [MAG04] to take into account the eddy current losses within the copper losses has been implemented in Matlab. FEM simulations were run with FLUX for the considered motor as well. The results from the analytical model and FEM simulations showed good agreement with higher values of copper losses obtained with the analytical models.

The increase of copper losses is not important in end-windings (less than 10% increase) compared to the increase in the active part of the winding. It was also shown that it is the proximity effect that has the major influence on the increase of losses. The values in table 1 for the copper losses (including the eddy current losses) and correction factors $k_T = P(f)/P_{DC}$ were obtained from the FEM simulations, for the part of the winding in the lamination stack (active part). At 400Hz and the minimum specified temperature, the losses are 253% higher than the DC losses (no skin and no proximity effect).

Table 1: Copper loss in one slot of the considered motor (per m of active part)

frequency	DC	50Hz		100Hz		200Hz		300Hz		400Hz	
Power/kT	W/m	W/m	kT	W/m	kT	W/m	kT	W/m	kT	W/m	kT
-40deg	295	303	1.02	324	1.10	409	1.38	550	1.86	747	2.53
20deg	391	396	1.01	412	1.05	476	1.22	583	1.49	733	1.87
200deg	675	678	1.00	687	1.02	724	1.07	786	1.17	873	1.29
240deg	737	740	1.00	749	1.02	783	1.06	840	1.14	919	1.25

Loss in permanent magnets created by variations of flux in the rotor can be a serious problem as high temperature reduces the remanent flux density of the magnet material (typically -0.01%/K for NdFeB).

Variation of flux in the rotor may occur due to harmonics in the current created by the switching pattern of the voltage and a reduced value of the inductance. In case the amount of harmonics cannot be influenced, one solution is to increase the number of magnets in each slot (applying the same principle that led to the use of iron laminations for the stator shown in fig. 8).

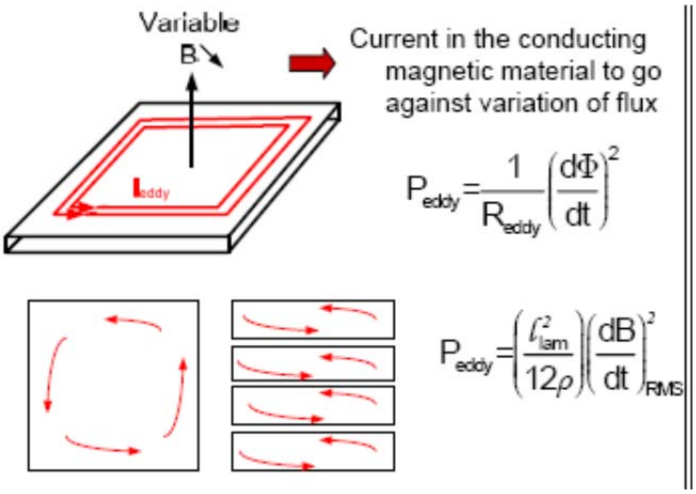


Fig 8: Cause and spatial position of eddy currents.

It is possible to calculate relatively simply the expected reduction of magnet loss by splitting the magnets both in the cross-section direction and in the axial direction.

The area available for magnet material in a slot is defined by two dimensions:

- the axial length of the machine L
- the width of the slot w_s.

Within this area, a certain variation of flux with time is created by the stator $d\Phi/dt$. In the following, it is assumed that the *variation of flux density is the same at each point.*

The eddy currents created in the magnets created by the time variation of flux are within the skin effect or penetration depth δ, given by:

$$\delta_p = \sqrt{\frac{\rho_{mag}}{\pi . \mu_0 . f}} ,$$

where f is the lowest frequency of the time variation of the flux, and ρ_{mag} the resistivity of the magnet material (and therefore depending of the temperature).

It can be assumed that the current is then circulating close to the border of the magnet within the penetration depth (see fig. 8).

Whatever the number of magnets in one slot, the eddy current loss in each magnet can be expressed as:

$$P_{mag} = \frac{\left(\frac{d\Phi_{mag}}{dt}\right)^2}{R_{mag}} = \frac{\left(\frac{d\Phi_{mag}}{dt}\right)^2}{\rho_{mag}.\frac{2L_m + 2w_m - 4.\delta_p}{\delta_p.h_m}}$$

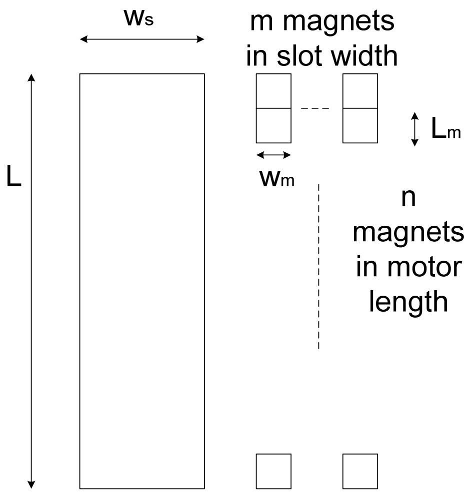


Fig. 9: Magnet splitting.

If the area for the magnets is split by *n* in the axial length and *m* in the slot width (see fig.9) then:

$$L_m = \frac{L}{n}; w_m = \frac{w_s}{m}$$

$$\frac{d\Phi_{mag}}{dt} = \frac{1}{n.m}.\frac{d\Phi_{tot}}{dt}$$

Then the total magnet loss in the slot is given by:

$$\boxed{P_{tot} = \frac{1}{n.m}.\frac{\left(\frac{d\Phi}{dt}\right)^2}{\rho_{mag}.\frac{2(L/n) + 2\left(w_s/m\right) - 4.\delta_p}{\delta_p.h_m}}}$$

Of course, this is valid as long as the assumptions are respected. For example, the magnets should be insulated from each other if no current is to be circulating from one to another.

4.2 Turn-to-turn windings failure

Winding failures occur really seldom in induction motors designed by Bombardier Transportation. However, the impact of a winding failure is limited since induction motors have the advantage to be non-active magnetically once the inverter is turned down. In PM motors, the magnets (if not demagnetized during the initial failure) may still energize the magnetic circuit and therefore create currents in short-circuited parts of the windings. It is therefore important to define a worst case scenario to investigate how PM motors behave under and after failure in spite of low failure frequency. In a long term, the developed models should allow to determine whether control strategies, supplementary equipment, motor design constraints or a combination of these solutions should be implemented to obtain a partly optimized system that guarantees the safety of passengers.

Different types of winding failures may occur and are described in [SOU08]. The cause of the turn-to-turn failure is not considered. A similar investigation as the one presented in [BON92] would need to be conducted for PM motors.

When no error has been committed during the construction of the windings (choice of insulation system and right end-winding dimensions), the rate of winding failure for BT's traction induction motors with form-wounded windings is less than 10 for 30 000 motors [FRÖ08]. In the motors that failed, different patterns of failures could be seen from single ground failure to completely burn-out windings.

A turn to ground fault implies that a current to the ground is created. If the detection level of the ground current is set to 1A (only possible when middle point in DC link is grounded), the winding does not suffer so much [FRÖ08]. A small hole (1-2mm) can be seen in the insulation between the conductor and the tooth at the top of the slot (closest the air gap) (see fig.10). If the detection level is around 100A (case without middle point in the DC link), the hole is larger (5-10mm). The location of the failure closest to the air gap can be explained by the fact that it is where the electric field is highest (slot leakage), and it corresponds as well to where the mechanical stress is highest [FRÖ08], [BRA08].

It is really rare to discover a single turn-to-turn short-circuit on its own in a faulty motor. The current in the short-circuited turn is really high and **leads really quickly to a ground failure** [BON92], [FRÖ08]. One turn may be initially short-circuited and then grounded but two adjacent turns might as well be short-circuited and grounded. From experience, the **single turn-to-turn failure always occurs in the end-windings** [FRÖ08]. Therefore the turn-to-ground failure cannot occur at the same place. In [BON92], it is described that the ground failure is situated 180 (electrical) degrees from the turn-to-turn fault.

If it is assumed that it is the voltage transients dv/dt that cause the turn-to-turn failure (as many do as it leads to dielectric failure), then the failure would occur where the stress is highest. The propagation of transient waves in winding machines is really complex and difficult to analyze [NAR89], [BRA08]. This is out of the scope for now so a **usual simplification** is to assume that the failure occurs where the voltage difference between turns is highest i.e. at the **entrance of the coil**. Figures 10 and 11 show more precisely in the slot and in the cross-section of the motor where the most plausible start of the turn-to-turn short-circuit is localized.

The initial investigations led to the following conclusions:

- When a turn-to-turn failure occurs, it is most likely to appear in the end-windings and it is usually assumed that it is then the first turn of the phase belt that is short-circuited.
- The value of the current in the short-circuited turn depends on the position in the slot.
- The current in the short-circuited coil is then really high and leads to a spreading of the failure to a ground fault by overheating of the insulation. A simple thermal model considering only the slot was used by [GER05].
- The only articles on PM motors (that have been found) considered motors with L_d=1p.u. which implies that after the failure has been detected, a balanced three-phase short-circuit is recommended to be applied. This solution would considerably reduce the level of flexibility to adapt the torque-speed curve to a given application.

The continued activities focused on developing models to predict the propagation of the initial winding failure to the rest of the windings. This involved FEM electromagnetic simulations combined with thermal modeling (lumped parameter models and FEM). These investigations have been published in [SME10]. More details are available in [SME08].

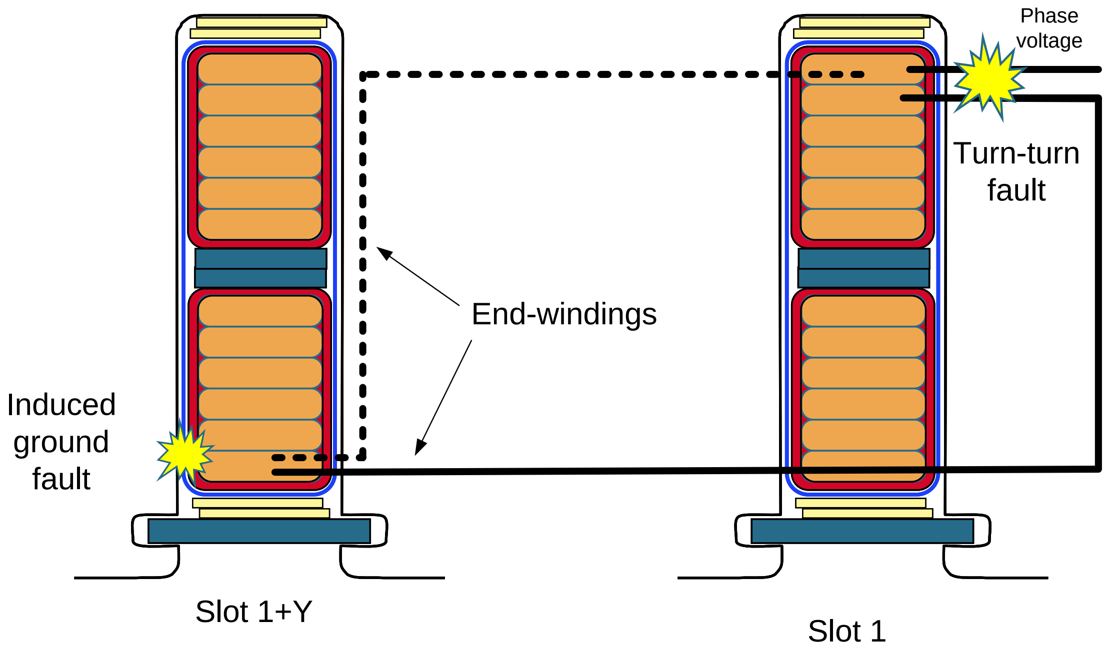


Figure 10: ASSUMED localisation of turn-to-turn failure in slots

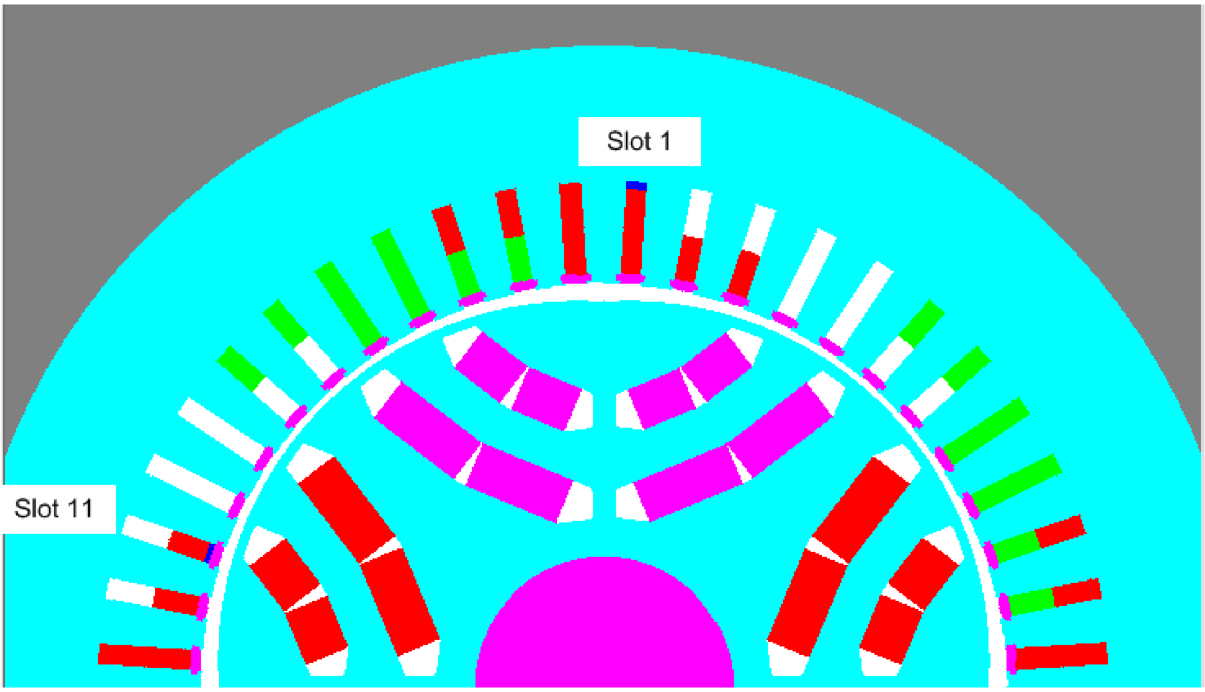


Figure 11: ASSUMED localisation of turn-to-turn failure in winding shown on 4-pole PM motor with buried magnets.

From the developed models, it could be concluded that the initial turn-to-turn failure most likely spreads into the other conductors in the same slot, finally leading to a turn-to-tooth failure if it is not detected in time. It should be noticed that the thermal assumptions made to the insulation material have not been verified experimentally. However, the interest of the investigation lies in the modeling principles and implementation of a highly non-linear combined electromagnetic and thermal system, rather than in the numerical results of the case study. These models should be verified experimentally. Once verified, they can be advantageously used to develop mitigation strategies.

4.3 Sensor-less control

High dynamics of synchronous motors require a position sensor of high resolution. The reliability issues were dealt with by extensive testing both in laboratory environment and during the vehicle tests. Sensor-less algorithms for converter control are also existing. A new algorithm was developed, implemented and tested in the Green Train. The investigations led to three publications [WAL_1], [WAL_2] and [WAL_3]. The delay from 2009 to 2012 is due to the sensitivity of certain aspects of the conducted investigations. [WAL_1] is available via IEEE explorer database. Interested readers may contact Oskar Wallmark to obtain access to the other two publications.

5. Conclusions

The possibility to test PM traction motors on the Green train during the summer tests in 2008 led to unique possibilities to test the technology. A journey of more than 505 000km was completed, including challenging winter conditions. No failure has been reported.

The collaboration between Bombardier and KTH has been extremely fruitful, not the least because two senior researchers were given the possibilities to mobility to the company in the most intensive periods before the tests.

If this project was a technical success, exceeding expectations, it was also really positive that it could lead to two record orders for Bombardier. *BOMBARDIER OMNÉO* for Régio2N for SNCF (France) was contracted in February 2010, including up to 860 double-decker trains. At least 129 trains have already been sold to 6 regions. The trains equipped with self-ventilated air cooled *MITRAC* PM motors will reach maximum speeds between 140 km/h – 200 km/h depending on the trip location. *BOMBARDIER TWINDEXX* are double-deckers for SBB (Switzerland). The contract signed in June 2010 includes 59 trains with option for 112 in addition, for a maximum speed of 200 km/h and will feature water-cooled *MITRAC* PM motors.

Figure 12: Bombardier *OMNÉO* and *TWINDEXX* (source: Bombardier)

6. Publications

External publications

- Johan Smeets, Juliette Soulard, Elena Lomonova, ”Analysis of a Winding Turn-to-Turn Fault in PM Synchronous Machine”, Proceedings of XIX International Conference on Electrical Machines - ICEM 2010, Rome, September 2010.

- Johan Smeets, “Study of turn-to-turn failure in permanent magnet traction motor for railway applications”, Royal Institute of Technology (KTH), report TRITA-EE 2008:068, December 2008.

- Juliette Soulard, “Turn-to-turn winding failure in PM motors - Literature study”, Royal Institute of Technology (KTH), report TRITA-EE 2008:069, December 2008.

- Wallerand Faivre d Arcier, Laurent Sérillon, “Thermal Modelling of Permanent Magnet Motor for Traction”, M.Sc. thesis, Ecole Navale de Brest (France)/KTH, December 2007,

Internal publications

- Juliette Soulard, “Turn-to-turn winding failure in PM motors - FEM models for investigation of electromagnetic transients”, Royal Institute of Technology (KTH), TRITA-EE 2008:070, December 2008.
- Juliette Soulard, “Turn-to-turn winding failure in PM motors - Lumped-parameter and FEM thermal models”, Royal Institute of Technology (KTH), TRITA-EE 2008:071, December 2008.
- Juliette Soulard**,** ”Investigation of eddy current loss in the winding of a traction motor with rectangular conductors”, internal report, Royal Institute of Technology (KTH)**,** report TRITA-EE 2007:042, July 2007.
- Henrik Mosskull, ’PM drive for Regina 250 train”, course EJ2221, final report, KTH, October 2008.
- Florence Meier, ”Design of a 10-pole 12-slot Permanent-Magnet Synchronous Motor for Traction Application”, internal report, KTH, March 2008
- Henrik Grop, ”Design of a surface-mounted PM machine for traction applications”, course EJ2220 final report, Royal Institute of Technology, October 2007.
- Alexander Stening, ”Theoretical design of a surface-mounted permanent magnet motor”, course EJ2220 final report, Royal Institute of Technology, October 2007.
- Dmitry Svechkarenko, ”Analysis of a surface-mounted radial-flux permanent magnet machine”, course EJ2220 final report, Royal Institute of Technology, October 2007.

Other communications

- Cooperation between KTH and Bombardier including within the Green Train highlighted in a three-page article in the Royal Institute of Technology & CO., KTH internal and alumni magazine in 2010.
- Participation at the conference International Conference of Electrical Machines in Italy (September 2010) with oral presentation held by Juliette Soulard.
- Johan Smeets presented his study of the Department Electrical Machines and Power Electronics in December 2008.
- Bombardier had also seminars on ECO4, the environmentally focused product portfolio in which the PM motors, the actively steered bogies and EBI driven are included plus a number of other technologies that are not tested in the Green Train.
- Presentation of at InnoTrans 2008, Germany, Berlin, 23. - 28. September 2008
- Press preview August 7 2008, focusing on summer tests with Green Train in general.

Related publications of the HPD program

- Oskar Wallmark and Johan Galic,, “Prediction of DC-link current harmonics from PM-motor drives in railway applications”, Int. Conf. on Electrical Systems for Aircraft, Railway and Ship Propulsion, Bologna, Italy, October 2012.
- Oskar Wallmark, Johan Galic, M. Jansson, and H. Mosskull, “A robust sensorless control scheme for permanent-magnet motors in railway traction applications”, Int. Conf. on Electrical Systems for Aircraft, Railway and Ship Propulsion, Bologna, Italy, October 2012.
- Alessandro Acquaviva, “Analytical Modelling of Iron Losses for a Permanent Magnet Traction Machine”, MSc thesis, Royal Institute of Technology (KTH), February 2012.
- Oskar Wallmark, Johann Galic, Henrik Mosskull, “Sensorless control of PMSMs adopting indirect self-control”, IET Journal of Electric Power Applications, vol 6, nr 1, pp 12-18, 2012.
- Bo Yang, “Development of thermal models for permanent-magnet traction motors”, MSc thesis, Royal Institute of Technology (KTH), July 2009.

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[SME08] J. Smeets, “Study of turn-to-turn failure in permanent magnet traction motor for railway applications”, Royal Institute of Technology (KTH), report TRITA-EE 2008:068, December 2008.

[SOU08] J. Soulard, “Turn-to-turn winding failure in PM motors - Literature study”, Royal Institute of Technology (KTH), report TRITA-EE 2008:069, December 2008.

[WAL12_1] O. Wallmark, J. Galic, H. Mosskull, “Sensorless control of PMSMs adopting indirect self-control”, IET Journal of Electric Power Applications, vol 6, nr 1, pp 12-18, 2012.

[WAL12_2] O. Wallmark, J. Galic, M. Jansson, and H. Mosskull, “A robust sensorless control scheme for permanent-magnet motors in railway traction applications”, Int. Conf. on Electrical Systems for Aircraft, Railway and Ship Propulsion, Bologna, Italy, October 2012.

[WAL12_3] O. Wallmark and J. Galic, “Prediction of DC-link current harmonics from PM-motor drives in railway applications”, Int. Conf. on Electrical Systems for Aircraft, Railway and Ship Propulsion, Bologna, Italy, October 2012.