Energy efficient propulsion technology based on permanent magnet synchronous motors

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Energy efficiency and the optimization of total cost of ownership (TCO) for rail vehicles are increasingly important aspects. An important element to fulfill these requirements is the permanent magnet motor technology. Propulsion systems based on permanent magnet synchronous motors and well aligned traction inverters optimized on system level show many benefits for high-speed, metro and commuter rail trains.

Energieeffiziente Antriebstechnik mit Permanentmagnet-Synchronmotoren

Energieeffizienz und die Optimierung auf Total-Cost-of-Ownership für Schienenfahrzeuge werden immer wichtiger. Ein wesentliches Element zur Erfüllung dieser Anforderungen ist die Permanentmagnet-Motortechnologie. Antriebssysteme mit Permanentmagnet-Synchronmotoren und optimal abgestimmten Stromrichtern optimiert auf Systemebene zeigen viele Vorteile im Einsatz in Hochgeschwindigkeits- und Metrozügen sowie im Nahverkehrs-Bereich.

Technologie d’entraînement économe en énergie avec moteurs synchrones à aimants permanents

L’efficacité énergétique et l’optimisation du coût total de possession des véhicules ferroviaires deviennent de plus en plus importantes. Un élément clé pour répondre à ces exigences est la technologie des moteurs à aimants permanents. Les systèmes d’entraînement avec moteurs synchrones à aimants permanents et convertisseurs de puissance parfaitement adaptés et optimisés au niveau du système présentent de nombreux avantages lorsqu’ils sont utilisés dans les trains à grande vitesse et les métros ainsi que dans le domaine des trains de banlieue.

1 Introduction

The demand for energy efficiency, smaller carbon footprint as well as the optimization of total cost of ownership (TCO) for rail vehicles is increasing. This tendency is reflected more and more by current rail vehicle tenders. Siemens Mobility developed efficient propulsion systems based on permanent magnet synchronous motors (PSM) for high-speed and metro trains. Both vehicle types are ideal applications of PSM propulsion technology to generate ecological and economic benefits over lifetime because of their operational characteristics and typical duty cycles.

For commuter rail vehicles with long coasting time periods within the typical duty cycles, simulations of propulsion systems based on a mix of asynchronous motors (ASM) and permanent magnet synchronous motors show clear advantages in terms of energy efficiency and initial investment. This propulsion system will also be introduced in this article.

2 Development

The development of the PSM propulsion technology made by Siemens Mobility started more than 20 years ago [1] with laboratory prototypes and permanent magnet motors for field tests, an example being the successful *SYNTEGRA* train for the Munich metro system [2].

Starting in 2005, large quantities (>8 000 pcs) of permanent magnet synchronous motors in the 160 kW power range were built by Siemens for hybrid and electric buses. These water-cooled motors have data and characteristics very similar to traction motors for metro trains in terms of maximum and continuous power, maximum speed and starting torque.

In 2015 and 2016, a PSM for high-speed train application was tested in a *Velaro* train [1]. The self-ventilated motors of type *1DB2222* with 680 kW power and their control system performed without any problem. The train with the two test motors operated in regular passenger operation and covered about 480 000 km in roughly one year.

Based on these experiences, two PSM propulsion systems for high-speed and metro trains were developed and tested.

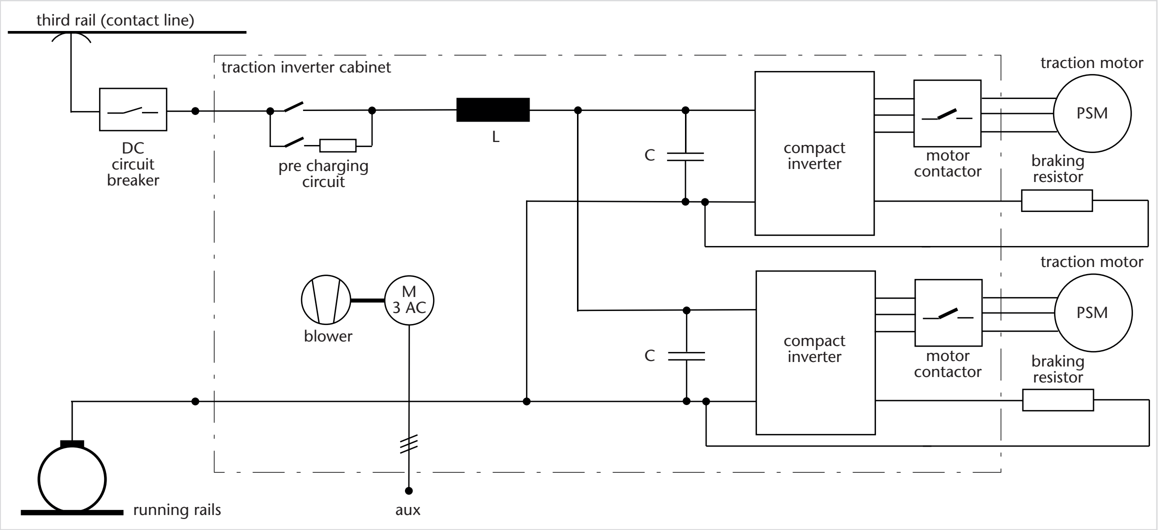

Figure 1:
Main circuit diagram for one power bogie and power supply system DC 750 V third rail (All Figures: Siemens Mobility, partly modified *eb*).

3 Permanent magnet synchronous motor propulsion technology for metro

3.1 General

The PSM propulsion system was developed for lighter metro trains with up to approximately 15 t wheelset load and DC 750 V power supply. The system can also be employed in high-floor light rail vehicles. It consists of a force ventilated traction inverter for underfloor or roof-mounted arrangements feeding two PSM drives (motor and gear unit). Figure 1 shows the main circuit diagram for the metro propulsion system of one power bogie for the power supply system DC 750 V with third rail.

The entire system was designed for high efficiency over the whole operating range considering typical duty cycles for lighter metro trains, including full load as well as partial load. Compactness, lightweight design, robustness, reliability and maintainability were other important system requirements for the design.

3.2 Traction inverter

The traction inverter cabinet (TIC) houses two independent compact inverters with their individual control units, each suppling one PSM drive. The motor contactors for separating the PSM from the three-phase traction inverters are also part of the TIC; moreover, the line choke (L) is integrated as well. Each compact inverter is built with a braking chopper enabling the high dynamic electric braking capability in case the DC 750 V power supply cannot accept the energy from regenerative dynamic braking, thus avoiding the use of the train's mechanical friction brakes. This helps to ease maintenance and reduces wear and dust emissions. The compact inverter for about 200 kW motor power is depicted in Figure 2. The same traction inverter topology can be expanded to higher power demands; the compact inverters are scalable in a modular way.

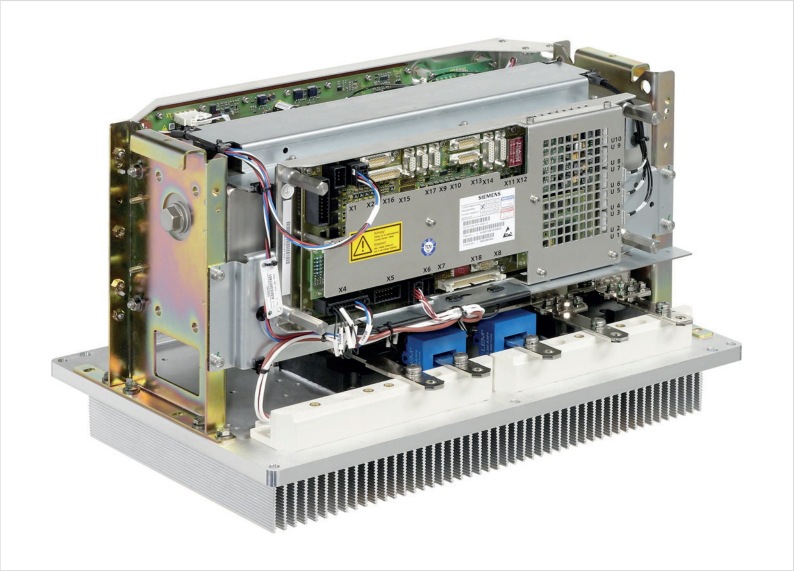

Figure 2:
Compact inverter for PSM metro application.

To realize the requirements high efficiency, lightweight and compact design, the two compact inverters and the line choke are force-ventilated by a blower drawing cooling air through a filter unit to keep the air ducts and the components clean over a long time period.

The TIC can be designed for different redundancy levels depending on customer requirements. The current electrical design shares the line choke and has a common DC link being optimized for a compact and lightweight TIC and to avoid complexity coming from additional components like contactors.

The *SIBAS* control units are integrated into the compact inverter assembly. The control of motor torque and speed is highly dynamic and realizes a full protection concept for inverter and motor (e.g. monitoring of the limits of voltage, current, temperature). The *SIBAS* control for the PSM application was successfully field tested in the *Velaro* high-speed train [1].

3.3 PSM traction drive for metro

3.3.1 Mechanical design

The drives as the other main components for the PSM propulsion system were designed for compactness and lightweight. The first drive variant built and tested for metro application is a fully suspended motor and gear unit with a high level of integration (Figure 3). The torque can be transferred by a cardan hollow shaft (variant A) or a single coupling (variant B) from the bullgear to the wheelset of the power bogie. This supports the reduction the of the bogie's unsprung mass by separating the mass of the drive from the wheelset. In case of the cardan hollow shaft coupling (variant A), the drive is entirely suspended by the bogie frame. Variant B with the single coupling leads to a three-point suspension: in two locations by the bogie frame close to the motor and the third suspension point on the wheelset shaft by the rotating coupling which is radially and axially flexible.

The space between motor and wheelset shaft for the couplings which are located concentrically to the wheelset shaft is given by the two-stage gear unit. The height of the motor-gear-unit is also minimized by the two-stage gear. The housing of the motor and the gear unit is made of spheroidal cast iron. Finite element simulations with many different load cases were performed to optimize strength and weight of the structure. Aluminum material is also used for smaller parts in order to reduce the weight even further.

Figure 3:
PSM drive – motor *1DB1619* and gear unit.

Table 1

Motor data of the metro PSM (continuous rating).

Siemens motor type		1DB1619-0GA04
Pole number		8
Rated power	kW	156
Rated speed	min^{-1}	2 300
Rated efficiency	%	97,5
Maximum speed	min^{-1}	5 200
DC link voltage	V	590
Starting torque	Nm	1 250
Cooling		Self ventilation

3.3.2 Permanent magnet synchronous motor

The PSM was designed and optimized for high efficiency within the propulsion system considering typical duty cycles of metro applications. The traction motor is built with the proven and very reliable stator winding insulation system *Micalastic THD* thermal class 220 which is used for all Siemens traction motors, including asynchronous motors. The permanent magnets are safely buried in the rotor lamination using a potting system. The magnet sizing, material selection and the arrangement of the magnets were part of the extensive optimization process. The torque is generated by the electromagnetic flux of the permanent magnets but also by reluctance built into the rotor design. This minimizes the field weakening current in the d-axis of the PSM at higher speed and increases the efficiency in the typical metro duty cycles. Table 1 lists important motor data.

The rotor design with its lamination, end rings, magnets and potting system was qualified by a long test sequence comprising of thermal aging, thermal cycling, mechanical vibrations (simulating mostly the gear excitation) and speed cycling. After this lifetime simulation, dismantling of the rotor assembly showed that the mechanical integrity including the lamination (e-steel), the magnets and the potting system is assured. The permanent magnet properties, especially the magnetization (remanence), remained unchanged.

The fully enclosed active part of the motor, stator with winding and the permanent magnet rotor, is air cooled by a shaft mounted fan which is located at the non-drive end of the motor. To further enhance the cooling, a second inner cooling circuit was integrated within the enclosed part of the motor. The inner cooling circuit lowers the overall temperature of the stator and the rotor, enhances the cooling of the stator winding overhangs and balances the temperature profile in the active part by avoiding distinct temperature hot spots. The cooling system supports the energy efficiency of the motor, reliability and a long lifetime. Attention was paid to the fan losses in the outer and inner cooling circuit and the trade-off to lower stator winding copper temperatures and their impact on the stator copper losses, finding the optimum between mechanical fan losses and stator copper losses.

Mechanically driven motor fans are a robust, simple and reliable solution which ensures the motor cooling in all cases. This is important because a PSM will generate motor speed dependent no-load losses especially in the stator lamination unlike an asynchronous motor. This requires a certain level of cooling to keep temperatures at a safe level when the PSM separated from the traction inverter (traction motor cut-out).

The extensive and complex optimization process of the traction motor considered aeroacoustic effects at high motor speed, magnetic noise including magnetic forces in the airgap caused by current harmonics due to the inverter power supply. The optimization aimed to low motor noise emissions over the entire duty cycle while not compromising the cooling and efficiency of the motor. The heat run conducted as part of the motor type test for the rated operating point (Table 1) shows low temperature rise of about 90 K for the stator winding and 80 K for the permanent magnets.

3.4 DTUP London PSM propulsion system

The first application of the PSM metro propulsion system is for the underground trains for Transport for London (TfL) within the Deep Tube Upgrade Program (DTUP) [3]. The London Underground metro system requires trains for very tight tunnels with limited clearance and demanding environmental conditions like relative high temperature levels in the tunnels. The propulsion system of the DTUP trains is optimized for the characteristic duty cycles achieving low energy consumption. This also reduces the tunnel heating caused by the losses of the electrical components. Another important aspect for the customer TfL is a very reliable operation of the metro system, along with high passenger capacity and high train frequency in the core network which was considered in the design of train and propulsion system.

The compact traction inverter cabinet for underfloor installation with low height and low weight is shown in Figure 4. The optimized and compact traction drive has a two-stage gear with a ratio of $i = 6{,}1$ and a very high integration level with the power bogie. This includes the complete single flexible coupling to the wheelset which carries part of the weight and transfers the torque.

Figure 4:
Traction inverter cabinet for DTUP London.

A complex system test of the DTUP propulsion system including the motor and gear unit type test was conducted. The simulated predicted energy consumption for the DTUP duty cycle was measured precisely and the results were even better than predicted by the simulations.

The compact PSM propulsion system for the DTUP trains generates clear customer benefits: energy efficiency, high reliability, enabling the track friendly bogie concept and high power for increased passenger capacity.

4 Permanent magnet synchronous motor propulsion technology for high-speed trains

4.1 General

The PSM propulsion system for high-speed trains is designed for high power density based on a water-cooled, modular traction converter system supplied by an AC overhead line and a traction transformer. The DC link is connected to the transformer secondary windings by a four quadrant chopper. Figure 5 shows a typical main circuit diagram for the propulsion system with four three-phase power modules supplying four PSMs. Some details like the precharging circuit are not depicted in Figure 5.

4.2 Traction inverter

For the power electronics, the modular and lightweight traction inverter with high power density uses Siemens WL3 power modules [4] utilizing the

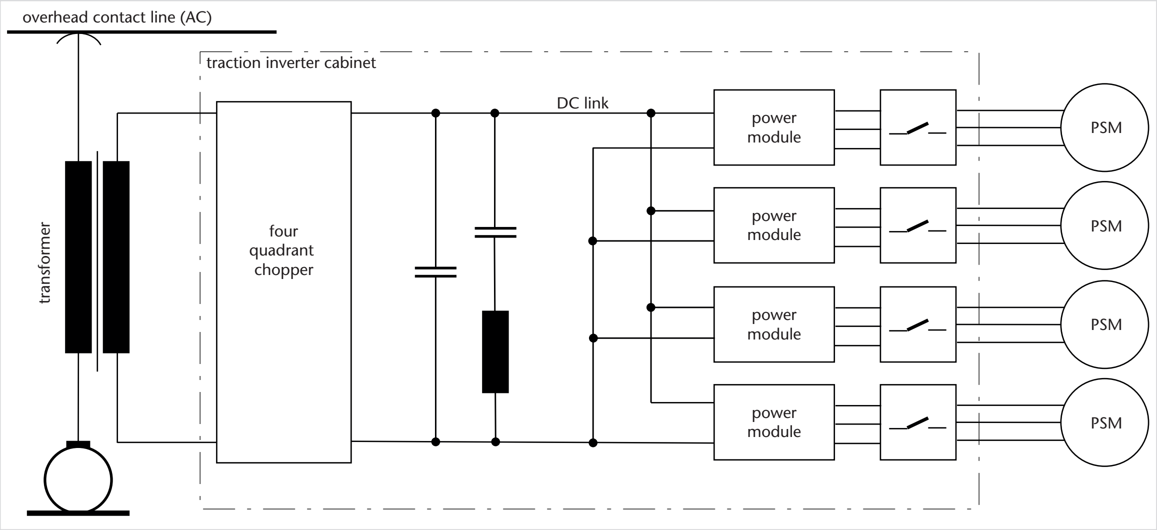

Figure 5:
Main circuit diagram for a PSM propulsion system supplied by an AC overhead contact line.

new 3,3 kV power semiconductor generation. These innovative 3,3 kV IGBT devices offer higher switching frequencies and lower switching losses compared to 6,5 kV IGBT. If required, the *WL3* power modules can utilize the high voltage power semiconductor class of 6,5 kV, for example in multi-system high-speed trains including DC 3 kV power supply. The *WL3* power modules are water cooled and offer different numbers of phases and parallel IGBTs depending on the required power per phase in the application (Figure 6).

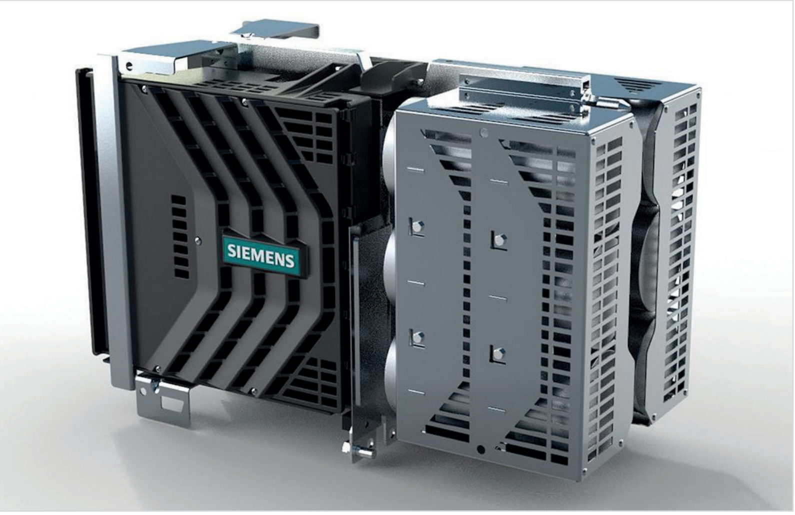

Figure 6:
WL3 power module.

Figure 7:
PSM *1DB2221* for high-speed trains.

The modular inverter design is suited well for PSM because each motor requires its individual three-phase power supply. Depending on the power and current requirement of the PSM, a single WL3 power module can feed one or even two PSMs. Hence, the WL3 power module can provide up to six phases, supplying two PSMs. Higher switching frequencies and lower switching losses are ideal for the power supply of PSM since they are designed with higher pole numbers which require higher fundamental electrical frequencies in comparison to the typical four pole asynchronous motors.

The converter control for the four quadrant chopper, the traction inverter feeding the PSM and other components and functions (e.g. protection, operation of switches and contactors) is the proven *SIBAS* control system which is used in all traction applications.

4.3 Permanent magnet synchronous motor for high-speed trains

4.3.1 General

The rated continuous power of the PSM for the high-speed train is 800 kW. A lightweight gear unit is used to drive the wheelset. The motor itself is fully suspended by the bogie frame and transmits the torque

Table 2

Motor data of the PSM for high-speed trains (continuous rating).

Siemens motor type		1DB2221-0GA04
Pole number		8
Rated power	kW	800
Rated speed	min^{-1}	5 583
Rated efficiency	%	97,4
Maximum speed	min^{-1}	6 283
DC link voltage	V	2 000/3 600
Starting torque	Nm	3 128
Cooling		Force ventilation
Mass *	kg	720

* for the Siemens standard motor suspension.

with a coupling to the pinion of the wheelset mounted gear unit.

The air cooled PSM (Figure 7) is force ventilated and is designed for high power density, high efficiency and low weight. The high power rating of this motor design is especially suitable for very high-speed trains with velocities over 350 km/h. The choice of materials - like electrical steel and permanent magnets - and the electromagnetic and thermal optimization aimed to achieve low losses and high efficiency even above 6 000 min^{-1} for an eight pole design. The eight pole design leads to a high stator bore volume, compared to six pole designs, maximizing the torque output for a given motor envelope. The high rotational speed increases the mechanical power output.

4.3.2 Electro magnetical design

The PSM had to be developed for a given envelope in a compact high-speed train bogie with a strict weight limit; therefore, high power density was imperative. The optimization of the motor was conducted specifically for high efficiency at high motor speed and for high power – a typical operating point of high-speed train applications (Table 2). Due to the eight pole design and the high fundamental electrical frequency of 400 Hz at 6 000 min^{-1}, special attention was given to reduce eddy current losses in the stator copper winding and the losses in the electrical steel lamination of stator and rotor.

Besides of the operating range at high rotational speed and high power, a few challenging duty cycles were checked during the design process to avoid exceeding temperature limits of stator and rotor.

The enclosed traction motor shares general design features and principals with the Siemens traction motors and is built with the already mentioned stator winding insulation system *Micalastic THD* thermal class 220. The rotor lamination safely holds the buried magnets with a durable high temperature potting system. Besides of the magnetic flux of the permanent magnets, the built-in rotor reluctance also contributes to the motor torque.

The electrical design process was carried out for a DC-Link voltage of 2 000 V (3,3 kV IGBT) as well as for a DC link voltage of 3 600 V employing 6,5 kV IGBTs. The latter DC link voltage can be raised to 3 800 V for higher non-continuous power demands. The adaption to the different DC link voltages is done by changing the number of turns of the stator winding and the insulation system *Micalastic THD*. The insulation system was developed and qualified for the different DC link voltage levels of 2 000 V and 4 000 V, additionally to the 1 000 V system which is

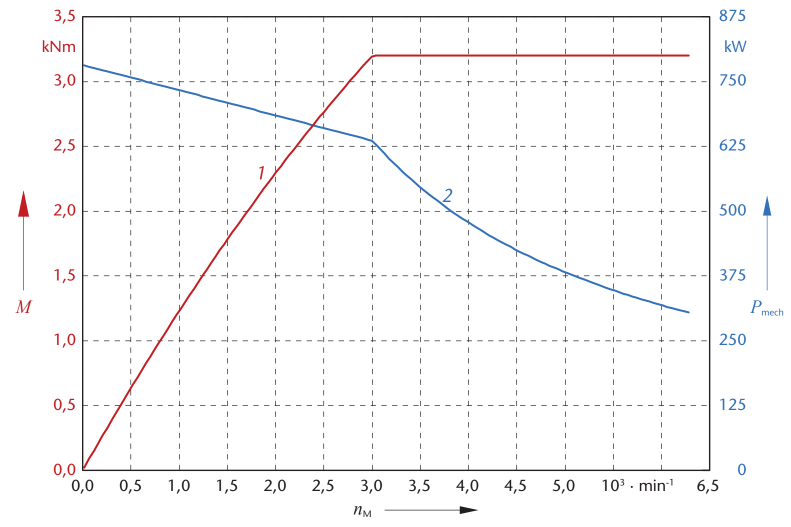

Figure 8:
Calculated characteristic curves of motor *1DB2221* – torque (*1*) and mechanical power (*2*) at 100 % load versus rotational speed (driving, DC link voltage 2 000 V).

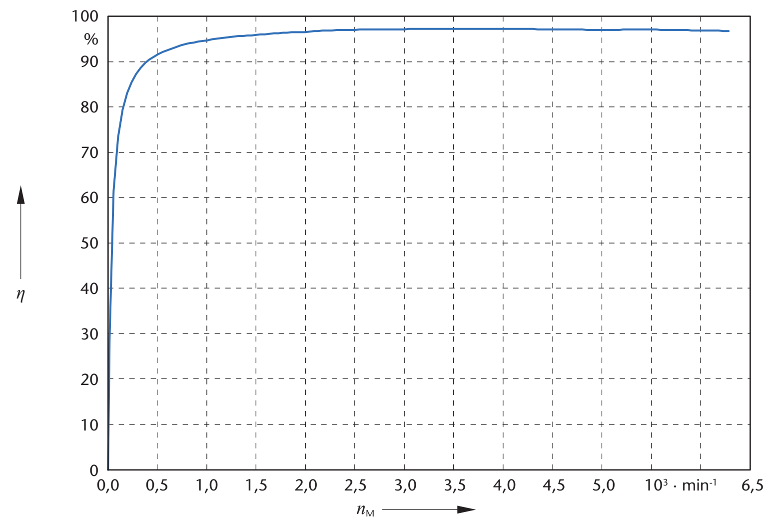

Figure 9:
Calculated characteristic curve of motor *1DB2221* – efficiency at 100 % load versus rotational speed (driving, DC link voltage 2 000 V).

used for example for the lighter metro applications as described above.

The Figures 8 and 9 depict the calculated characteristic curves of the PSM type *1DB2221* for torque, mechanical power and efficiency versus motor speed. The motor shows a wide range of high efficiency of 96 % to 97 % and above from one-quarter of motor speed to maximum motor speed.

4.3.3 Cooling

Extensive Computational Fluid Dynamics (CFD) and Conjugate Heat Transfer (CHT) simulations were conducted in order to optimize the cooling system in terms of pressure loss and temperature rise of the enclosed active parts e.g. the stator winding and rotor magnets. In this process, a unique, patented cooling system for an externally force ventilated PSM was developed [5].

The distribution of the incoming cooling air flow on top of the motor housing is carefully aligned into two separate air flow streams to both motor end shields at drive and non-drive ends (DE and NDE). This ensures an optimized cooling of the rotor and the stator and is accomplished without compromising the maximum pressure loss of the motor which was another important and challenging design limit. The inside of the rotor is cooled by the external cooling air flowing from DE to NDE. The NDE shield distributes both air flow streams to four cooling ducts located in the corners of the motor housing cooling mostly the stator yoke. The four stator cooling ducts terminate at the DE shield. An inner cooling circuit within the enclosed active parts of the motor supplements the efficient cooling system.

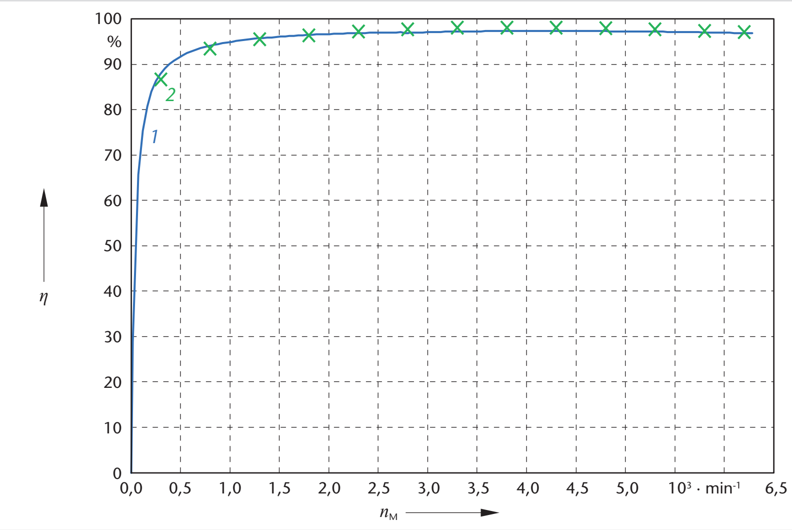

Figure 11:
Calculated (*1*) and measured (*2*) characteristic curves of motor *1DB2221* – efficiency at 100 % load versus rotational speed (driving, DC link voltage 3 600 V).

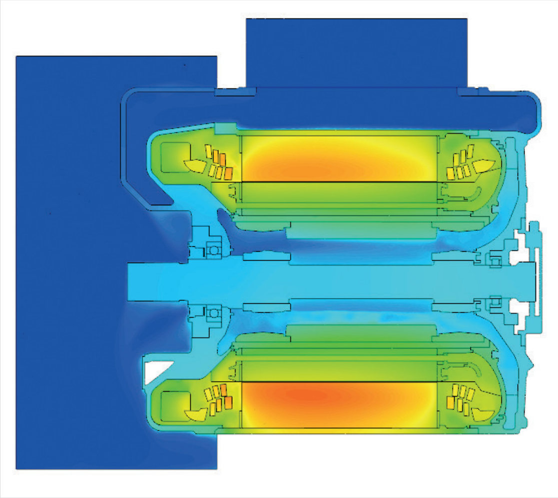

Figure 10:
Simulated temperature distribution of the motor (*left*: drive end of the motor).

To provide sufficient cooling of the motor at no-load in case the external blower fails, a small auxiliary motor fan, driven by the motor shaft is incorporated at NDE. This allows the operation of the motor at no-load up to maximum speed without the forced ventilation which is needed for normal operation.

The predicted temperature distribution of the motor for 27 °C ambient temperature is shown in a longitudinal section in Figure 10. The mean stator winding temperature is below 190 °C, the mean magnet temperature is approximately 150 °C for the operating point stated in Table 2. This was verified by the measurements during the type test.

4.3.4 Type test

In 2019 the motor was successfully type tested according to standard IEC 60349-4 [6] and fulfilled all requirements. The motor tests were carried out with the motor design for 3 600 V DC link voltage. The test setup was back-to-back on a traction converter with the specific pulse patterns. The high performance, efficiency (Figure 11) and temperature values could be proven with the measurements.

Based on the successful temperature rise test with 800 kW at 5 583 min^{-1}, a short time temperature rise test with higher power was performed. For a short time, with an increase of the DC link voltage to 3 800 V, it is possible to operate the PSM with 900 kW at 5 583 min^{-1}. The following time limits were reached:

- from cold state: 1,5 h
- from hot state: 0,8 h

Eight force-ventilated motors of type *1DB2221* with 800 kW power are being tested in a high-speed train, also in a speed range over 400 km/h. The mileage of the test train is nearing 100 000 km.

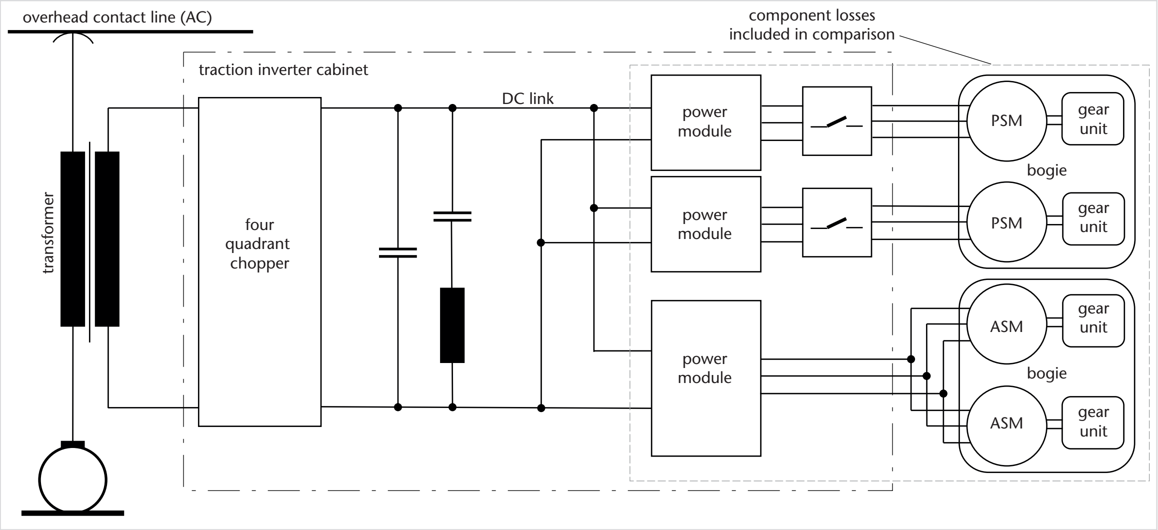

Figure 12:
XSM propulsion system diagram of an AC commuter rail vehicle with 2 000 kW power at wheel.

4.3 Customer benefits

The PSM propulsion system for high-speed trains described above offers a modular water-cooled traction inverter with high power suitable for permanent magnet motors. The inverter is easily integrated into vehicles. The air cooled, compact and lightweight motor with high power is especially designed for trains with velocities over 350 km/h saving energy and supporting lightweight train concepts. However, the inverters and motors can be used for high-speed trains with lower maximum speed (e.g. 300 km/h) and power demand, allowing the reduction of powered wheelsets leading to lower numbers of inverters, motors, gear units etc. The gear ratio can be adopted accordingly. The lower number of components offers savings of capital and operating expenses (CAPEX and OPEX).

5 Mixed propulsion system for commuter rail application

For applications with typical duty cycles containing long coasting time intervals with no or low power at the wheel, a propulsion system based on a mix of asynchronous motors (ASM) and permanent magnet synchronous motors (PSM) is a very attractive technical solution in terms of energy efficiency and initial investment. The inherent excitation of permanent magnet motors cannot be turned off during these coasting phases; therefore, the PSM will have losses in the stator iron and additional losses in the copper stator winding in the field weakening range even though the motors do not produce mechanical power. This is in contrast to the asynchronous motor which can be electrically shut down when not needed for propulsion by stopping the pulsing of the traction inverter power module.

In commuter rail and lighter metro applications, coasting time intervals often account for 20 % to 40 % of the overall operating time of a duty cycle. These long coasting intervals have a negative impact on the energy savings of PSM system in comparison to ASM in commuter rail and metro applications.

The patented propulsion system XSM [7] combining PSM and ASM will mitigate this disadvantage. A motor car can be equipped with two PSM and two ASM (Figure 12). The ASM can be shut down in time intervals at constant train velocity and the PSM can be used to maintain the velocity.

Figure 13 shows the energy savings for 100 % PSM and XSM propulsion systems in comparison to the consumed energy (component losses over the entire duty cycle: driving, braking, coasting etc.) of a 100 % ASM propulsion system of a commuter rail vehicle. Both self ventilated traction motors – ASM

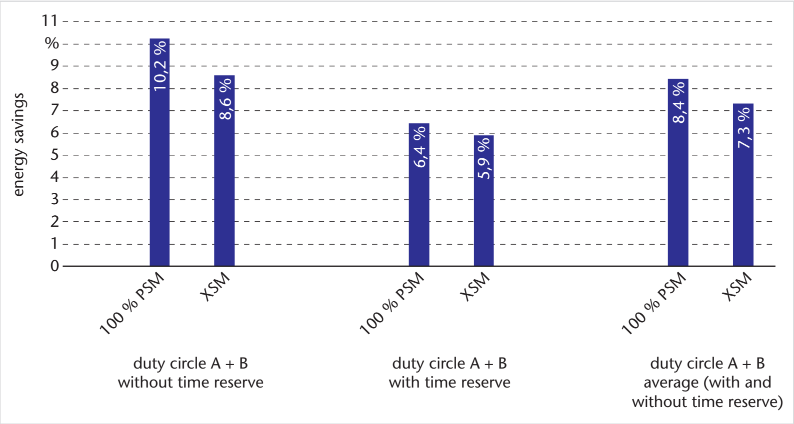

Figure 13:
Energy savings of a 100 % PSM and XSM propulsion system in comparison to a 100 % ASM system for commuter rail duty cycles.

and PSM – were designed for 500 kW mechanical power and optimized for high energy efficiency. The tractive effort versus speed characteristics are the same. The traction inverter power modules consist of conventional IGBT semiconductors.

The losses were calculated for the three different propulsion systems with four powered wheelsets consisting of the three-phase power modules, the motors, and the single stage gear units. Two duty cycles A and B, each about 100 km long, were simulated at first with time reserve (2 h with a coasting time interval of about 40 %) and second without time reserve (1,75 h, coasting time interval of about 20 %). The savings are greater for duty cycles with shorter coasting time intervals: The PSM system saves 10,2 % of the energy consumed by the pure ASM system whereas the XSM system saves 8,6 % compared to the ASM system. The savings of the XSM system are on average one percentage point lower compared to the PSM system.

Initial costs of the XSM system (CAPEX) are lower compared to the 100 % PSM system because of the group drive for the ASM (one three-phase power module for two ASM, no motor contactors) and the cost of the ASM itself. Maintenance costs as part of OPEX are also reduced because of the less complex ASM group drive as part of the XSM system. However, the higher number of spare parts (e.g. for the two motors types) must be considered.

The XSM propulsion system for commuter rail trains provides high flexibility and energy efficient adaption to different duty cycles. This is advantageous for a mix of shorter and longer distances between station stops operating through urban, interurban and rural areas. Even faster intercity trains can be a possible application.

6 Summary

The Siemens PSM propulsion technology with well aligned components – inverters and motors – and innovative systems such the XSM system offers numerous customer benefits. The systems for metro, commuter rail and high-speed trains enable innovative train and power bogie concepts optimized for reducing the total cost of ownership, addressing capital and operating expenses at the same time. Besides of high power density, energy savings are generated in comparison to propulsion systems applying asynchronous motors only. The modular traction converter designs and the compact and lightweight motors allow optimal integration into train cars and power bogies.

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