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Innovative Railway Traction System

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Abstract

This article describes the future Alstom railway traction systems developed as part of "Shift2rail". This innovative system is based on silicon carbide (SiC) high power density converters, high efficiency transformers, increased speed motors to improve the whole traction system efficiency. SiC semiconductors (MOSFET) have lower losses than silicon IGBT and will operate at higher junction temperature **(175°C)**. The reduction of the power converters' losses **(-50%** total losses) enables the cooling system to be simplified and compacted. Globally, we expect important achievements in terms of train energy consumption **(-10% at train level)**, mass and volume reduction, positive impact regarding the reliability (elimination of cooling pumps and fans), better availability and noise reduction, in order to design innovative, environmentally friendly, economy efficient rail solutions.

Keywords: Railway traction system; Silicon carbide; Shift2rail.

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1. Introduction: Shift2rail objectives

The European railway industry is being increasingly challenged by the changes and perspectives of the future society. Demographic projections show that the global population will reach 9.8 billion people by 2050, with 70% living in urban areas. The public authorities are now very concerned about the environmental impact of regional and urban transportation. At the same time, alternative means of transport are becoming more popular such as car-sharing, low-cost buses and low-cost airlines, promoted by digital technologies breakthroughs. The main railway manufacturers such as Alstom underlined the necessity to respond to these challenges with a more attractive and cost effective railway system. Under the coordination of the Association of the European Rail Industry (UNIFE), an EU industrial research cooperation program has been organized called Shift2Rail which is part of Horizon 2020. Shift2Rail has ambitious targets with the following major Key Performance Indicators (KPI) for the whole railway system (infrastructure, signalling, rolling stock):

- Life Cycle Cost : -50%
- Reliability : +50%
- Capacity : +100%

These KPIs have been declined to the different railway sub-systems and for the traction system there are 7 KPIs summarized in the following table (Fig.1-Table 1):

Table 1. Keys Performance Indicators [1]

Railway System	Train traction system	Alstom objectives
Life Cycle Cost	Capital Cost	**-10%**
	Maintenance Cost	**-20%**
	Train Energy Consumption	**-10%**
Reliability	Reliability	**+15%**
Capacity	Weight	**-10%**
	Volume	**-5%**
	Noise	**-5%**

In Shift2rail Alstom will develop a new traction system for regional trains up to prototype demonstration in an operational environment (Technology Readiness Level 7). The objective is the introduction of better trains to the market (quieter, more comfortable) at a lower life-cycle cost, with more capacity to cope with growing passenger mobility demand [2].

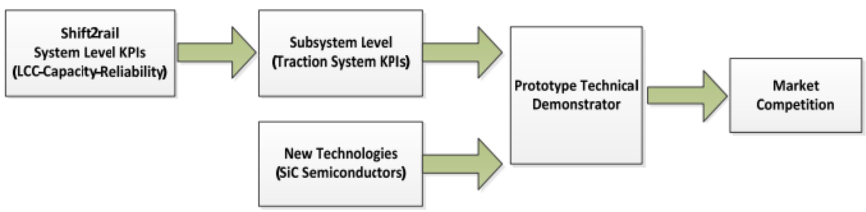

Fig.1 Shift2rail program

2. Regional trains: traction system overview

The traction sub-system is one of the main components of a train, it has an essential role during operation and it is crucial for the train efficiency, reliability and availability. In this study it is very important to define the boundary of the system to allow a calculation of the KPI improvements. In this article the traction system consider the following components from the pantograph to the wheels for an AC catenary voltage (Fig.2):

- Transformer

- Traction Case-Power Converters (4 QC rectifier, three-phases inverter)
- Traction Motor

The typical regional train configuration is a four cars unit with distributed traction. In fact the modern trains can have more than one traction system installed according to the maximal speed and acceleration performances (Fig.3-Table 2).

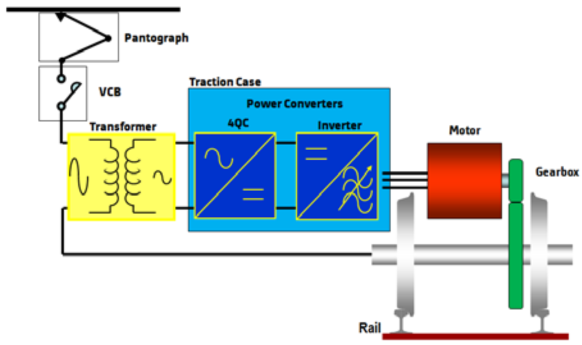

Fig.2 Traction system

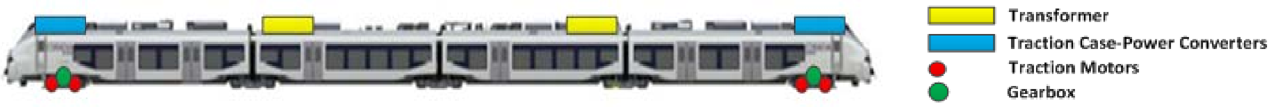

Fig.3 Alstom regional train

Table 2. Train data

Propulsion Configuration	Bo-2-2-2-Bo
Max Speed (km/h)	160
Train Weight LCC Load (t)	179
Number of driven axles	4
Nominal Voltage (kV)	25 (50Hz)
Maximal Traction Power (MW)	1.8

The baseline traction system is based on an independent traction DC link (direct current) per motorized axle. On the train we have two independent traction drives. Each traction drive has one traction transformer with two secondary windings on which a 4QC converter is connected. On each 4QC converter, a traction inverter is connected with one motor.

3. Silicon Carbide Semiconductor

The objectives fixed in Shift2rail are very ambitious and to reach them it is necessary to introduce technological innovations. Since first introduction in railway traction approximatively 50 years ago, power semiconductor devices have always been the key lever to introduce innovation in traction system and pull improvement of performances. Higher voltage capability, higher power density and lower losses have been reached over the years by power semiconductor devices used in railway traction (from thyristor to Insulated Gate Bipolar Transistor (IGBT)) bringing substantial weight, volume and cost reduction at converter level. All of these static switches were built from silicon (Si). Si based power devices are approaching their physical limit and further improvement of performances is therefore limited. Wide band gap power semiconductors are emerging and their performances are promising to pursue the trend towards lower losses and higher power density. SiC (compound of silicon (Si) and carbon (C)) based semiconductor, particularly promising for railway traction are under focus as they are reaching good maturity level. SiC material has interesting physical properties to design high voltage, high power switches with low losses (Table 3).

Table 3. Semi-conductors data

Properties	**Si**	**SiC**	Characteristic Impacted
Energy Gap (eV)	1.12	3.26	Junction Temperature
Electric Breakdown Field (MV/cm)	0.3	3	Switching Speed-ON resistance
Thermal Conductivity (W/cm°C)	1.5	4.9	Junction temperature
Electron Mobility (cm²/Vs)	1400	900	ON resistance

4. Power modules for railway traction system

Use of multi-chips power modules including several Si_IGBT dies for transistor part (for switch function) and several Si_diode dies in antiparallel (for freewheeling function) is today state-of-the-art and covers all needs of railway traction in terms of voltage and current.

4.1. Si Power Modules

The most common transistor device for power applications (high current-high voltage) is the IGBT (Fig.4). This transistor is an association of MOSFET and bipolar transistor providing good conduction performances and easy driving (MOSFET input stage). The low resistance during conduction phases is obtained with the injection of minority carrier (conductivity modulation) in the drift region (ν region). During switching-off these carriers recombine in the drift region and this increases the switching losses and increases turn-off time (tail current).

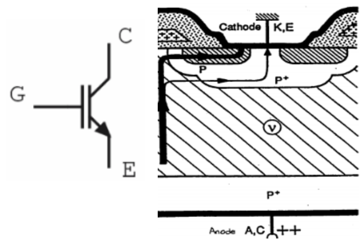

Fig.4 Si-IGBT

The Si freewheeling diode (Fast Recovery Diode) is a PiN diode, minority carrier diode as well and it means that it is impacted by very similar phenomenon to that of the transistor such as high switching off losses. This is because minority carriers accumulated in the drift layer contribute to conduction until their lifetime ends.

4.2. SiC Power Modules

Due to SiC properties it is possible to change the transistor and diode structure with significantly better performances in terms of losses and switching speed. As a consequence of material physical properties shown in table 3 (especially higher electrical breakdown field), it is possible to build SiC based MOSFET with voltage capability above 3300 V with attractive characteristics thanks to thinner drift layer (ν region) that reduces the resistivity during on state phases. MOSFET is a majority carrier device (unipolar) with low on resistance and fast switching capability, in principle zero tail current with very low switching losses (Fig.5). The larger bandgap guarantees operation at higher junction temperature (175°C) if properly packaged.

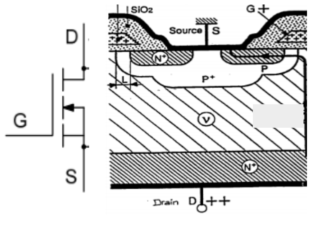

Fig.5 SiC-MOSFET (n-channel)

The MOSFET can also be used in reverse conduction mode in freewheeling phases. In theory, external diode can therefore be removed but for high voltage, suppliers tend to keep it to avoid excessive stress in MOSFET structural body diode. The SiC diode is a SBD (Schottky Barrier Diode) which is a majority carrier device (unipolar device) that does not use minority carriers for conduction. It means that it has the same advantages as the MOSFET such as very low switching off losses and high switching speed.

4.3. Comparison between Si and SiC power modules

The main properties of SiC power module in comparison to Si power modules are listed in the table 4.

Table 4. Power module main data

Properties	**Si power module**	**SiC power module**	System impacted
Rated Current (A)	1500	2x750	
Voltage (V)	3300	3300	
Switching losses (p.u.)	1	0.3	Cooling
Voltage Switching speed (p.u.)	1	>3	Insulating system (transformer-motor)
Current Switching speed (p.u.)	1	>3	Switching cell design
Junction Temperature (°C)	150	175	Cooling - Gate drive
Short circuit time	>10 µs	< 10 µs	Gate drive
Turn Off Current	2xIn	> 2xIn	Power converter design
Baseplate surface (mm²)	140x190	140x100	Power Converter Mechanical Design
Active switch are (p.u.)	1	0,6	
Diode area (p.u.)	1	0,4	
Switch	1 (IGBT)	2 (MOSFET)	
Diode	1 (FRD)	2 (SBD)	

The switching losses are showed in Fig.6, where SiC power module has almost zero tail current and zero diode recovery losses.

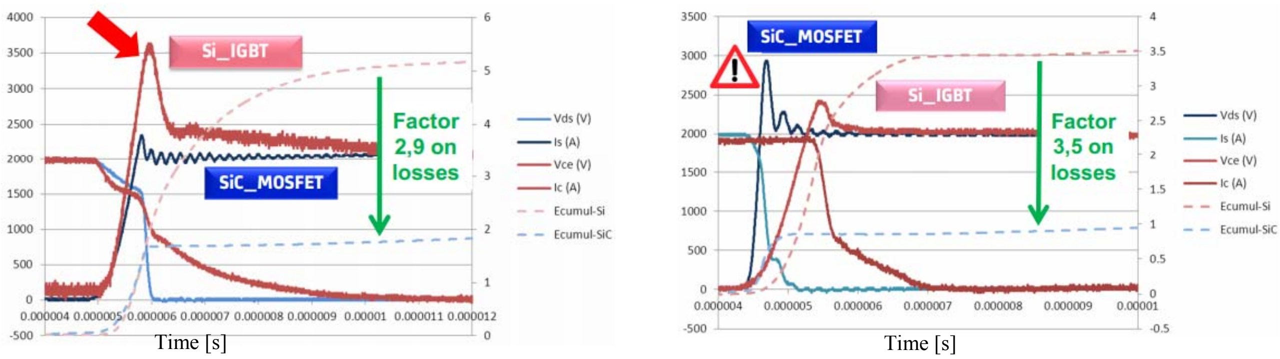

Fig.6 Switching ON - switching OFF losses comparison

5. Traction Case - Power Converters

In this chapter we will analyze how SiC properties affect the design of the power converters.

5.1. Switching loop

The switching loop is one of the most important parts for the performances of a power converter. The SiC device has a very fast switching speed (dI/dt) and for this reason the stray inductance (Ls) must be minimized (40-

50nH) to reduce the over-voltage during switching (Fig.7). The design of the switching loop must ensure that overvoltage generated during turn-off because of parasitic inductance will not exceed device safe operating area (SOA) and will also guarantee a good current distribution between paralleled modules.

Fig.7 Stray inductance comparison

This constraint has some important impacts on the design of the converter as showed in Fig.8. To reduce the circuit's stray inductance, some possible solutions are: optimize the busbar between the main capacitor and the legs or include decoupling capacitors to reduce the switching inductance and have a good current distribution between the power modules. The best design solution can be found with accurate 3D modelling techniques.

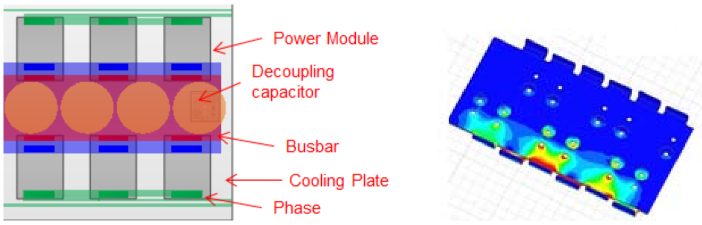

Fig.8 Converter switching loop (left) - busbar current distribution (right)

5.2. Gate Drive

The SiC MOSFET can reuse the same base of the gate driver defined for the IGBT, but with some necessary adaptation due to the highest dv/dt and new protections needed to protect the SiC module (voltage and current). The control voltage for switching-on is +17V instead of +15V for an IGBT in order to decrease the resistivity during conduction phase to compensate the lower carrier (electrons) mobility in silicon carbide (Table 3). The control voltage for switching-off is -7V instead of -12V for an IGBT.

5.3. Cooling System

The reduction of losses (up to -50% in a real traction power cycle) and the increase of the maximal junction temperature allow a simpler cooling system to be used (lower acquisition costs and lower maintenance costs). The target is to use a passive (heat-pipe or similar) wind speed cooling system instead of the current water cooling system (Fig.9). By doing this we will remove the water pump, fan, pipes, which will also save energy, noise, cost, and improve the reliability of the system.

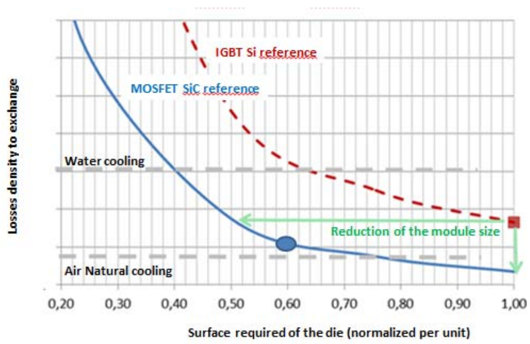

Fig.9 Comparison Si-SiC power density

These main changes imply new challenge related to the wind speed cooling on the train roof, which implies many CFD (Computational Fluid Dynamics) simulations to predict the airflow (speed-pressure) (Fig.10). The train runs in both directions, the main challenge is to design a wind speed system with the same performances in both directions.

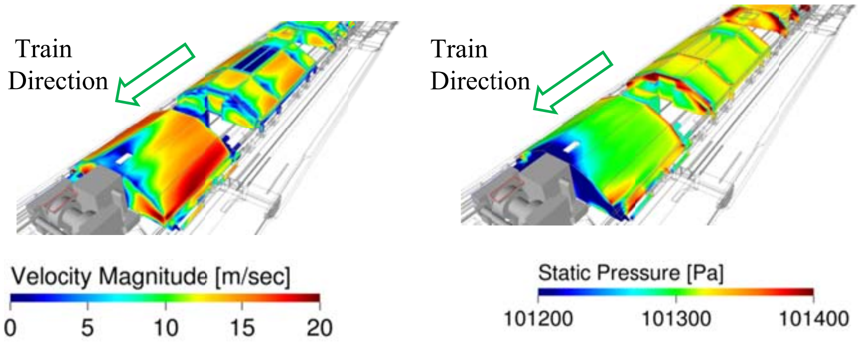

Fig.10 Air speed-pressure CFD results on the train roof

The results have a direct impact on the traction case mechanical design, for example small wind deflectors could be necessary to deflect the air flow inside the heat-exchanger.

5.4. Mechanical Design

The SiC power modules introduce many challenges for the design engineers to find the best compromise between these different constraints:

- double power density means smaller cooling power module surface (Fig.11a)
- higher junction temperature (175°C) increases the temperature of the bus bars, gate drives and capacitors around the module (Fig.11b)
- wind speed cooling system tends to increase the volume of the heat-exchanger.

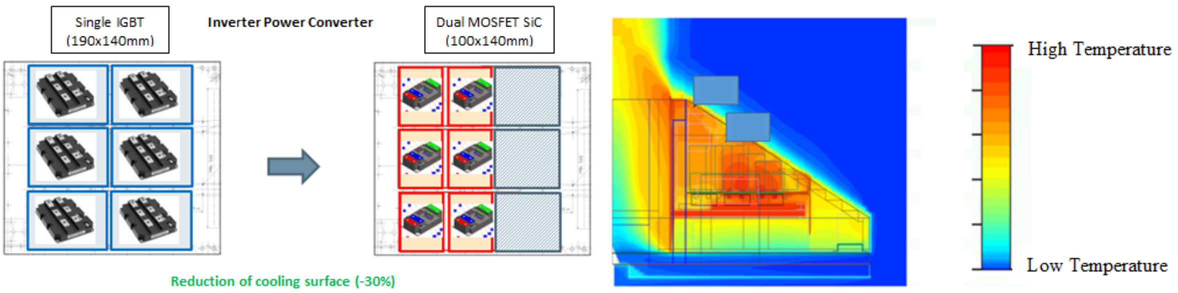

Fig.11a Cooling plate [3] – 11b thermal simulation inside the traction case

The first simulation shows high temperatures inside the traction case (+20% than Si power converters). Solutions to manage this constraint are being studied.

6. Transformer

The SiC power module permits an increase of the switching frequency (f_{sw}) of power converters. This is possible because of the very low switching losses of SiC modules. The f_{sw} has a direct impact on the load connected to the converter (main transformer and traction motor).
The 4QC converter rectifies the catenary alternative current to provide the DC-link, for this reason it employs a PWM (Pulse Width Modulation) pattern with a switching frequency. The relation between the f_{sw} and the L_s (secondary winding leakage inductance) define a current with sinusoidal waveform as shown in Fig.12.

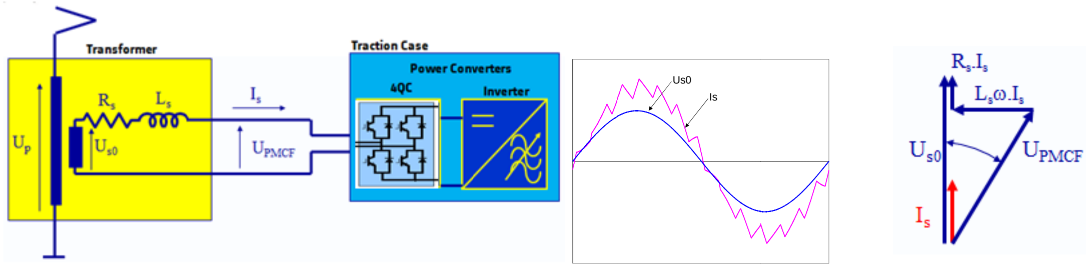

Fig.12 Transformer-4QC

The catenary current harmonic content (F_f) must respect the railway standards and it depends on (Eq.1):

$$F_f = \frac{I_1}{I_{rms}} \approx \frac{Transformer\_Power}{Ls \cdot fsw} \tag{1}$$

F_f: current harmonic content index
f_{SW}: switching frequency [Hz]
L_s: leakage inductance [mH]
I_1: catenary fundamental current [A]
I_{rms}: catenary rms current (fundamental+harmonics) [A]

It means that if we maintain the current harmonic content index constant, the product $L_s{*}f_{sw}$ remains constant. Therefore if f_{sw} increases (for example +30%) L_s decreases proportionally (-30%). L_s is a parameter and it depends from the transformer physical parameters (winding turns) as explained in Fig.13.

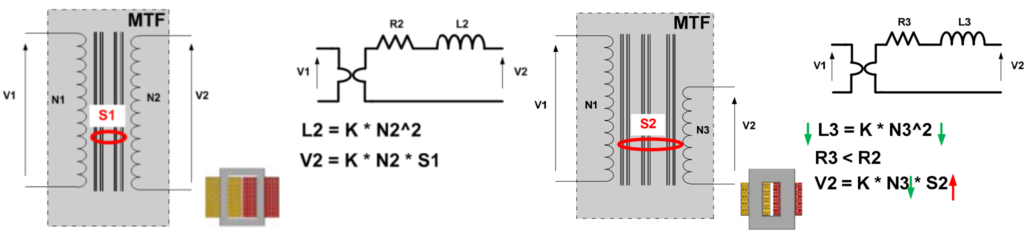

Fig.13 Current solution (left) - solution under design (right)

In conclusion, a reduction of L_s decreases the transformer joule losses (less turn windings-N3) with a risk of a heavier transformer (bigger magnetic circuit-S2) and a higher f_{sw} increases transformer harmonics losses. The objective is to find the best trade off to have a more efficient transformer. A reduction of the total losses could help a development of a wind speed cooled transformer without a cooling fan and this solution is under study. In the future it will be possible introduce an electronic transformer based on high voltage SiC power module (>15kV). This option is also under study but at the moment this kind of power module are not yet available.

7. Traction Motor

The inverter generates a chopped voltage waveform on the motor windings (Fig.14). These PWM patterns generate additional losses on the motor and are also a source of electromagnetic noise. These additional losses, called harmonic losses, increase the temperatures of motor. This increase of temperature has a direct impact on the lifetime of the windings insulation materials. By using SiC devices, it is possible to increase the switching frequency of the traction converters and thus generate a more sinusoidal waveform applied on the motor. Thus, the harmonic content and the losses inside the equipment are reduced and the motor efficiency is increased.

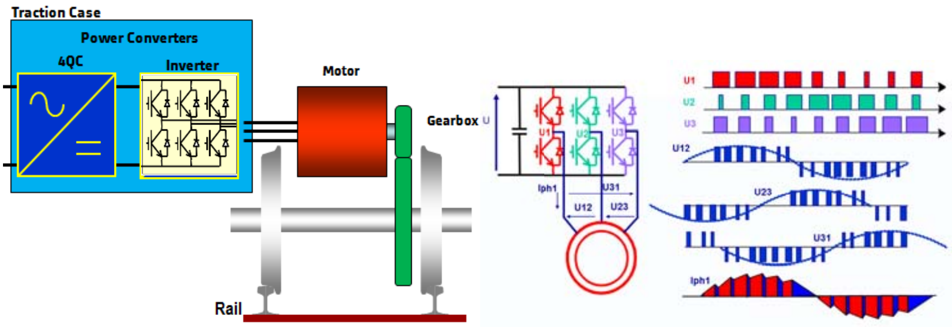

Fig.14 Inverter - traction motor [3]

The harmonic losses can be expressed with the following equation (Eq.2), where n is proportional to f_{sw}:

$$Harmonic\_Losses \approx 3 \cdot \frac{K}{fs} \sum_{n=2}^{\infty} \frac{Un^2(T\mathrm{mod}, PWM)}{n} \tag{2}$$

U_n: motor phase voltage [V]
f_S: stator frequency [Hz]
k: motor parameters
n: harmonic rank

This higher switching frequency could also be employed to increase fundamental frequency (f_s) therefore the motor speed, which means a volume and weight reduction according the following equations (Eq.3-4-5):

$$N(\sim wr) = \frac{60 \cdot f_S}{p} \tag{3}$$

f_S: stator frequency [Hz]
2 p : motor poles number
N: magnetic field rotational speed [rpm] = wr (motor speed-synchronous motor)

The motor has the same mechanical power, thus the torque decreases proportionally to the speed increase (Eq.4):

$$Pmot = T \cdot wr \tag{4}$$

Pmot: motor power [kW]
T: motor torque [Nm]

The smaller torque reduces the motor weight and volume (Eq.5):

$$T \approx k \cdot D^2 \cdot L \tag{5}$$

k ~ windings current-cooling system-magnetic material
D: rotor diameter (m)
L: rotor length (m)

It is important to highlight that the gearbox is also under re-design because of the change of the motor speed. It is necessary to apply a multi-parameter approach to find the best trade-off between the motor losses, inverter switching frequency and the converter cooling system.

8. Implementation of the innovative traction system on existing trains

The final objective is to be able to implement the innovative traction system without major changes on the existing regional trains ("plug and play"). It means that the main constraints are to design the new system with the same volume and mechanical interfaces than the existing ones.

9. Case study: Regional Train on real profile

This chapter describes how the innovations presented could affect the performance of the traction system in term of KPIs. The table 5 and fig.15 show the KPIs evaluation for this traction system and highlight the main points that must be improved during the detailed design.

Table 5. KPIs evaluation

		Alstom Objectives	Preliminary Study	Comments
Life Cycle Cost	Capital Cost	**-10%**	Under evaluation	Strongly Affected by SiC price estimation
	Maintenance Cost	**-20%**	Under evaluation	Strongly Affected by SiC price estimation
	Train Energy Consumption	**-10%**	**-10%**	Better Global Efficiency
Reliability	Reliability	**+15%**	**+10%**	Simplified cooling system
Capacity	Weight	**-10%**	**-9%**	High speed motors
	Volume	**-5%**	**-7.2%**	No fans - less motor volume
	Noise	**-5%**	Under evaluation	No fans

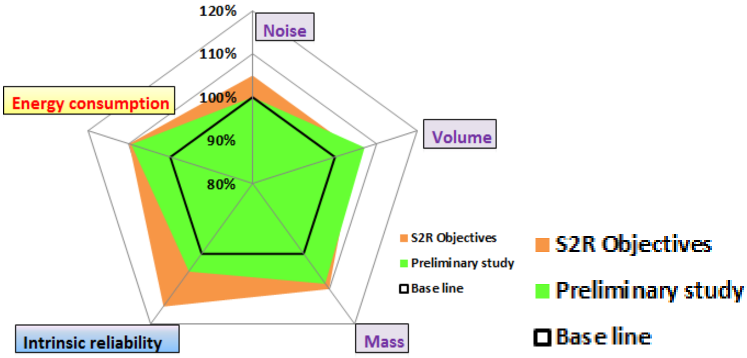

Fig.15 KPIs radar [3]

10. Conclusions

According to these preliminary results we have important achievements in terms of train energy consumption (-10% at train level), mass and volume reduction (higher train capacity), positive impact regarding the reliability (elimination of cooling pumps and fans) and better availability. The cost estimation of this system is strongly affected by the cost of the SiC power modules but thanks to the reduced energy consumption the break-even-point, the payback time, is between **3 and 7 years** according to different SiC price scenarios. The SiC price has to be further analyzed in the future in collaboration with suppliers to find the best trade-off between performance and cost. The introduction of the electronic transformer and smart maintenance will be evaluated. Alstom is on track with the design of the next generation innovative and environmentally friendly traction system, based on latest generation of power semiconductors, then bringing substantial system benefits.

11. References

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