International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0615

ENERGY EFFICIENT OPERATION OF PERMANENT MAGNET SYNCHRONOUS MACHINES POWERING A RAILWAY ELECTRIC VEHICLE

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ABSTRACT

This study aims to determine the losses of a permanent magnet synchronous machine used for propulsion of a railway electric vehicle in no-load and low-power operation conditions, found during vehicle coasting and low acceleration/deceleration speed profile. The simulation results are showing that it would be preferable to operate the electric machine at low power instead cutting the power from inverter.

Keywords: railway electric vehicle, reference power distribution, direct drive system, no load operation losses.

NONMENCLATURE

Abbreviations	
PMSM	Permanent magnet synchronous machine
SURV	Suburban railway vehicle
FEA	Finite element analysis

1. INTRODUCTION

Electric railway vehicles have a long history behind and a certain future ahead. The arguments behind this affirmation lies in the high energy efficiency and zero local emission (drive system) for this type of vehicle.

There are three main types of pure electric railway vehicles: those dependent on external power feeders, those equipped with energy storage systems [1] and a combination of the first two, constituting the hybrid vehicles [2].

The propulsion systems have evolved from DC motor to AC induction or PMSM. AC propulsion machines have higher efficiency, reliability and lower weight/power ratio. Usually, a mechanical transmission is used to power one axle from one electric machine. The axle is attached to both wheels present at each end and drives the wheels (Fig. 1). This solution has the benefits of lower number of drive systems and lower implementation costs, but also some drawbacks: the need of a transmission gearbox and higher losses and wear due to additional friction between the inner wheel and rail in corners. Another solution is to drive directly each wheel with independent electric machines (Fig. 2). This configuration eliminates the need of a transmission gearbox but adds complexity (double number of machines and power converters) and costs to the drive system. This direct drive solution has another advantage compared with the one presented in Fig. 1, increased redundancy.

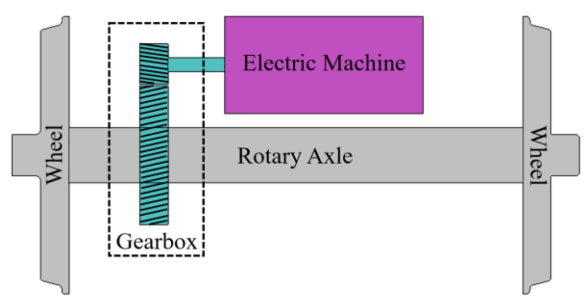

Fig 1 Drive system with transmission

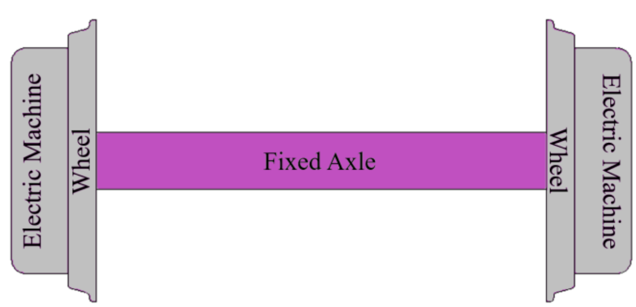

Fig 2 Direct drive system

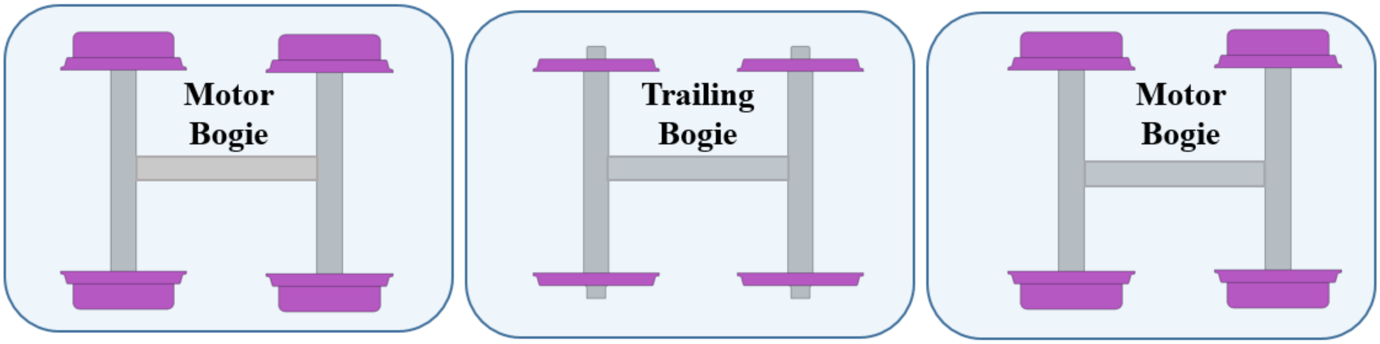

Fig 3 SURV contruction topology

This paper presents the simulation results at no-load and low-power operation conditions with the objective to determine improved energy efficiency conditions. Section 2 presents the context of the study including a short description of the PMSM, Section 3 the simulation results and Section 4 a discussion about the results.

2. SUBURBAN RAILWAY VEHICLE

2.1 Short presentation

In one construction topology, the SURV has two motor bogies and one trailing bogie (Fig. 3). Each motor bogie accommodates 4 PMSM, driving the wheels independently. In Table 1 are presented the main SURV parameters. These parameters where used to determine the necessary traction effort by the drive system.

Table 1 SURV parameters

Parameter	Values	Units
Vehicle total mass	45	t
Equivalent frontal area:	11.8	m^2
Aerodynamic coefficient	0.35	
Acceleration up to 40 km	1.1	m/s^2
Maximum speed	100	km/h

Table 2 Axial flux PMSM structure and dimensions

Parameters		Values	Units
Number of stator slots		21	
Number rotor poles		16	
Stator core	External	433.16	mm
	Inner diameter	309	mm
	Axial length	120	mm
Rotor disc	External	456	mm
	Inner diameter	280	mm
	Axial length	30	mm
Permanent Magnet	Length	60	mm
	Width	60	mm
	Height	25	mm
Other	Total axial length	176	mm
	Airgap	1	mm

It was determined that the installed electrical power should be around 600 kW, distributed between 8 electric propulsion machines. Thus, each machine must have an installed power of 75 kW. Knowing the speed at which the electric train has to travel and the outer diameter of the wheels (600 mm), the required nominal rotational speed of the propulsion machine is 1000 rev/min.

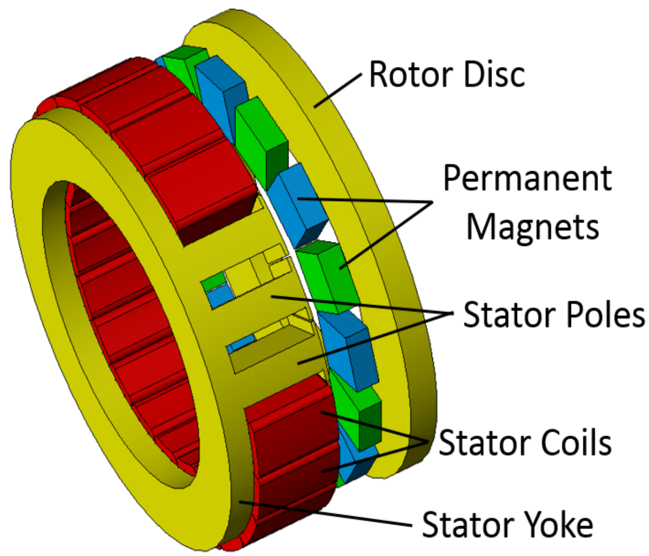

Fig 4 Outline of the axial-flux PMSM topology

2.2 Propulsion electric machine

The main parameters and geometric dimensions of the PMSM are presented in Table 2. The active components of the PMSM are showed in Fig. 4. These dimensions and structure where determined in earlier studies [3], in which the electric machine was simulated using FEA software JMAG. The combination of 21 stator slots and 16 rotor poles was chosen in order to reduce the cogging torque and to facilitate the manufacturing by keeping the number of permanent magnets to be mounted and number of coils to be wound to a minimum.

3. DETERMINATION OF NO-LOAD AND LOW POWER OPERATION LOSSES

During no-load or low power operation, Joule windings losses are absent or very low. Thus, core losses are predominant. These losses appear in the stator iron core, in rotor iron core and in permanent magnets. Core losses can be determined analytically or by simulation [4], [5].

In order to determine the losses in the PMSM at no load operation, several simulations where made using JMAG finite element simulation software. The stator and rotor magnetic losses that where identified during simulations are: stator core losses in steel laminations, eddy current rotor core losses and eddy current permanent magnets losses. In the following figures, some simulation results that show these losses are presented. The worst case scenario was considered, when the machine is working at maximum speed 1000 rev/min.

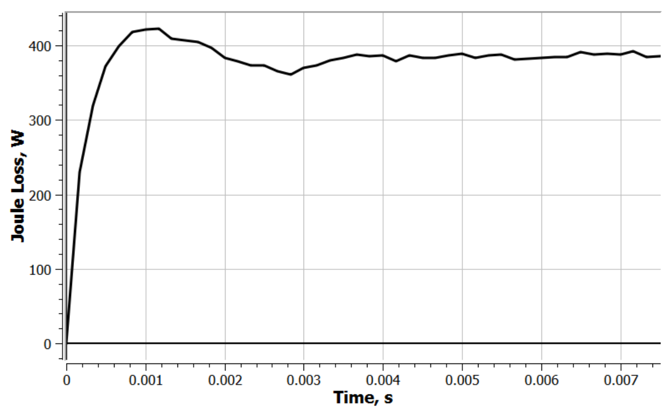

Fig 5 Rotor eddy currents Joule losses

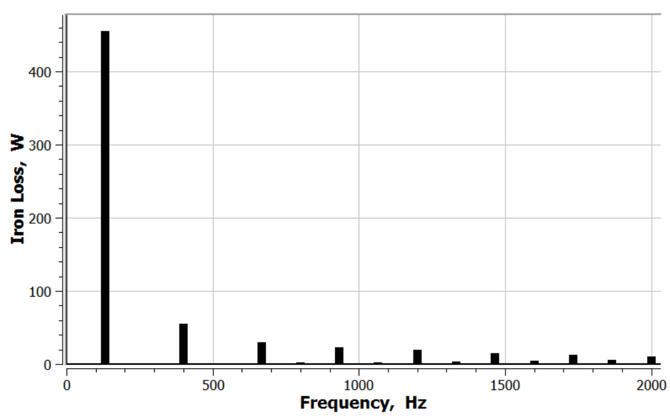

Fig 6 Stator iron losses

Figs. 5 and 6 are showing that the total losses (rotor disc and permanent magnets) at rotor level are around 385 W and, in the stator, magnetic circuit almost 675 W. Thus, the total amount of energy loss is around 1060 W.

Next, the simulation results for low power operation are presented. The electric machine works at around 5.9 kW.

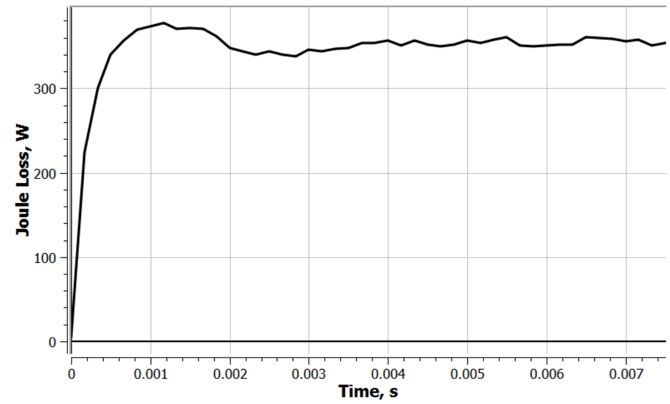

Fig 7 Rotor eddy currents Joule losses plus stator windings Joule losses

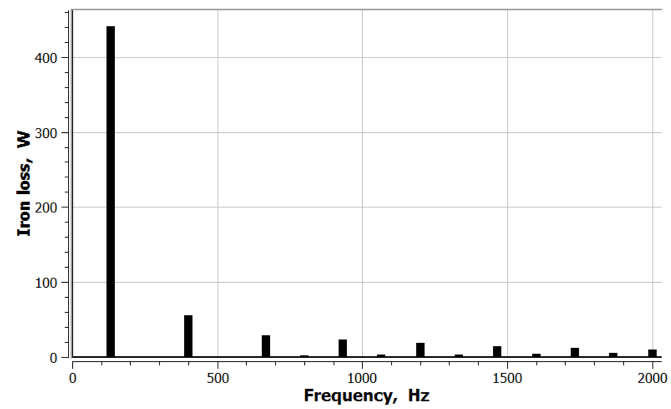

Fig 8 Stator iron losses

From Figs 7 and 8 we determine that the total losses for a low power operation is 1012 W. In Table 3 are summarized the simulation results for several power levels operation of the electrical machine. The rotor speed is 1000 rev/min.

Table 3 Axial flux PMSM structure and dimensions

Reference phase current [A]	Mechanical power [kW]	Stator iron losses [W]	Joule losses (coils + rotor) [W]	**Total losses [W]**
0	negative	672	386	**1058**
2.5	2.74	664	368	**1032**
5	5.9	657	355	**1012**
7.5	9.1	649	348	**997**
15	18.8	627	365	**992**
25	31.9	601	472	**1073**

Simulations where made also for lower rotor speeds. In Fig. 9 are presented the no-load losses for the entire speed range of the propulsion machine. As expected, when the rotor speed reduces the losses are smaller.

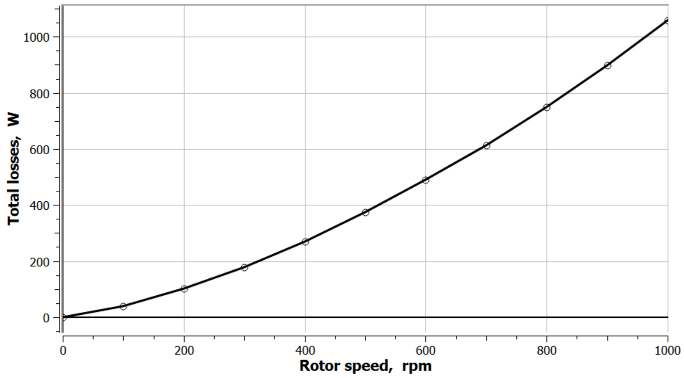

Fig 9 No-load losses for the entire rotor speed range

4. DISCUSSION

Considering the railway vehicle with 8 propulsion electric machines, usually, the total power developed by the drive system is divided equally between the ones in normal operating conditions. This is mainly true in high accelerations or decelerations. But during reduced accelerations/decelerations and constant speed operation, the electric power of the drive system is a fraction of the nominal one. To increase the efficiency of the drive system and knowing the individual PMSM efficiency map (Fig. 10), it would be obvious that some of the machines should work at higher power and others should be shut down. During coasting there are not easy solutions to solve the problem.

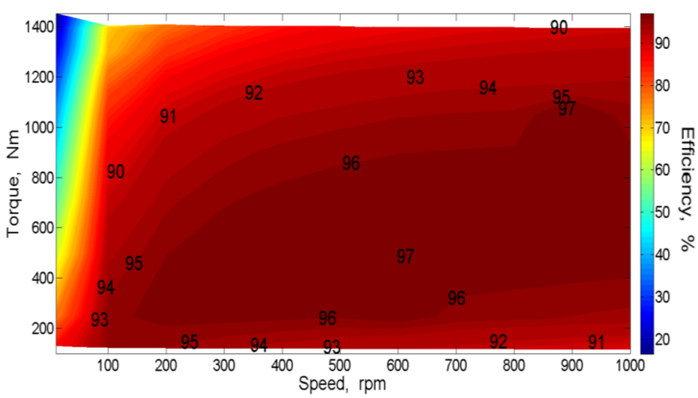

Fig 10 PMSM eficiency map [3]

But, considering the results presented in Table 3, it seems to be more appropriate to balance the power between all the machines. This is true at high speed operation due to high losses in stator core, rotor core and permanent magnets. At reduced power the PMSM losses are even lower compared with the no load operation condition. This could be explained by the reduction of magnetic flux variations when a stator magnetic field is generated from stator coils, thus, lower stator and rotor (including permanent magnets) losses will emerge. By comparing the operation of the electrical machine at no-load condition and almost half of the nominal power (Table 3 - first and last lines) one can observe that the total losses have similar values. To conclude, at high speed operation, the propulsion machines should work at low power instead at no load.

For the above considerations it was assumed that in the case of no-load operation, the PMSM stator voltage peak level was inferior to DC-link voltage from which the inverter is feeding the coils, thus the machine was not operating as a generator. Also, the inverter losses where not considered in this study.

Future work will stress on finding an optimal power distribution between the propulsion machines, for the entire speed range, in order to increase the overall efficiency of the drive system.

5. CONCLUSIONS

This study has showed that the losses of a PMSM used for propulsion of a railway electric vehicle in no-load and low-power operation conditions are similar, thus, instead of cutting the power from the inverter it would be preferable to operate the electric machine at reduced power.

ACKNOWLEDGEMENT

This work was supported by the project “Advanced technologies for intelligent urban electric vehicles”- URBIVEL-Contract no.11/01.09.2016, project co-founded from the European Regional Development Fund through the Competitiveness Operational Program 2014-2020.

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