

PM SYNCHRONOUS MOTOR FOR CITY BUS OF 30 PASSENGERS CARRYING CAPACITY: DESIGN AND PERFORMANCES

PM СИНХРОННЫЙ ДВИГАТЕЛЬ ДЛЯ ГОРОДСКИХ АВТОБУСОВ ИМЕЮЩИХ ГРУЗОПОДЕМНОСТИ ДЛЯ 30 ПАССАЖИРОВ: КОНСТРУКЦИЯ И ЭСПЛУАТАЦИОННЫЕ КАЧЕСТВА

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Abstract: This paper presents the design results of power and traction system for electric bus, with carrying capacity of about 30 passengers, working in aboveground urban public transportation grid. The power architectural foresees two permanent magnet synchronous motors, one for each wheel, fed by an inverter that is linked to the batteries. The main components have been designed according the requirements related to the work of bus; the performances of motor have been evaluated and presented.

KEYWORDS: ELECTRIC BUS, SYNCHRONOUS MOTORS, PERMANENT MAGNETS

1. Introduction

The organization and the planning of the public transport in the urban areas requires to be faced in a viewpoint which has, as its principal components, the demand, the offer (network, vehicle, operating) and the costs (economical and environmental). The contents of this study concerning the realization of particular systems of vehicular propulsion, are placed in a wider context of research which has produced the idealization and the realization, in all its principals components, of a system of urban public transport, highly efficient, called "Dense Grid" [1].

The system is characterized by a gridwork, extended to all urban areas, which has short and regular stop spacing not greater than 400-500 m, and by segments covered by "shuttle-type" small sized vehicle vehicles with high operating frequencies.

The urban route on the grid implies a cyclical and not homogeneous motion composed by additional phases which include acceleration, maintains constant speed, deceleration and stop time to allow passengers to get on and off.

It is necessary to underline that the environmental aspect assumes considerable importance as in the urban areas the difficulties caused by the increase of traffic pollution are growing. Authorities from different countries have been persuaded to take into consideration drastic measures aimed, in the next future, to the exclusive use of electric vehicles.

For these reasons this study examines a small sized city bus with electric traction only powered by batteries.

A battery electric vehicle produces zero vehicular emissions where it works; however emissions are produced at the generation site if the source fuel is converted into electrical power. The amount of pollution create by electric vehicle's depends mostly on the source of the electricity used to charge them.

2. System configuration

In this preliminary investigation, a small sized city bus with a carrying capacity of about 30 passengers with a full mass (tare and pay load) of 5000 kg has been considered. The proposed configuration foreseeing an Interior Permanent Magnet (IPM) synchronous motor powered by batteries has been carried out and investigated. More in detail the power configuration contemplates two IPM motors each of one is coupled to wheel by a reducer (R); the motors are fed by an inverter that is linked to the batteries: a suitable control strategy allows to optimise the motor performance in a wide range of speed. Electrical energy of battery is used to power the electric motor which then turns the wheels and provides propulsion.

A simplified scheme of the system configuration is shown in Fig.1. In this contest IPM motor represents a very efficient solution [2] thanks to its characteristics as low inertia, high power-to-weight ratio and acceleration performance. This represents an innovative solutions of traction motor, in relation to traditional electric motors (series wound brushed DC, brushless DC, shunt wound DC, AC)

[3]. Power electronics have revolutionized motor drives, offering higher reliability and better performance.

Recently, variable speed applications and operating limits for IPM synchronous motor drives have been widely studied and investigated.

The main advantages for adopting an IPM motor are that:

- the arrangement of the PM inside the rotor makes it a robust structure, allowing high speed operation ;
- the armature reaction causes low effects on PM demagnetization ;
- the saliency into rotor magnetic circuit is profitably used to produce reluctance torque term.

The possibility to set in motion the vehicle in correspondence of 4% road grade at full weight and to reach the maximum speed of about 40 km/h at zero road grade represent the constraints of system project.

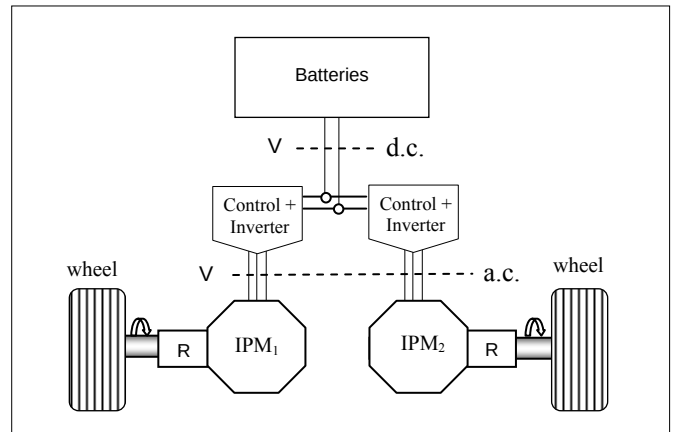


Fig. 1 – System configuration scheme

3. Design and performance

The IPM motor, whose cross section is shown in Fig. 2 has been adopted and analysed.

The motor has four poles with Ne-Fe-B permanent magnets arranged inside the rotors interacting with dynamic field produced by AC windings distributed in the stator slots.

This motor requires an accurate speed control with a current-regulated inverter [4],[5]: that is crucial to the efficiency and operation of the electric vehicle, and speed controllers should be rated according to the voltage and amperage range.

The proposed design procedure combines a preliminary analytical evaluation of motor size together with a fine Finite Element analysis, that allows to test the motor performance in the whole speed range: this has allowed to verify the specifications of electric bus in terms of speed and acceleration performance.

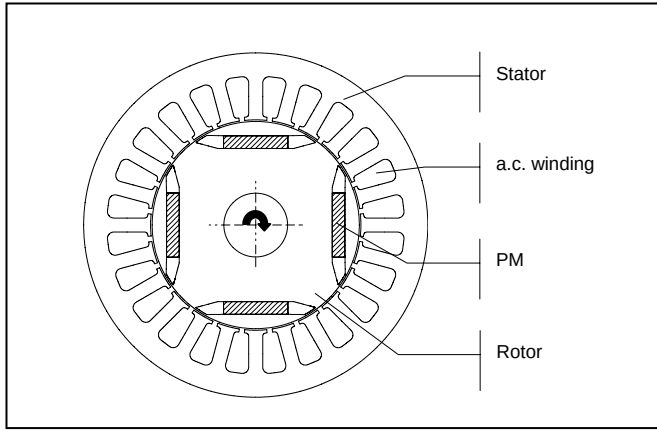


Fig. 2 - Cross section of the IPM synchronous motor

The steady-state IPM motor equation of rated torque is [6]:

$$T = \frac{3}{2} p [\phi_m \cdot I_q + (L_d - L_q) I_d I_q]$$

where p is the pole pair, ϕ_m is the flux linkage (due to the permanent magnet), I_d and I_q the axis-currents and L_d and L_q are the d and q-axis inductances.

The operations of an IPM motor drive can be divided in three operating regions, as shown in Fig.3.

- I: Constant torque region
This occurs up to the base speed v_b ; the torque limit is constant and equal to the rated torque, delivered by constant I_d and I_q chosen so that maximum torque-to-current ratio is achieved.
- II: Constant power region
Operation in this region is limited by the rated current and the rated voltage: the speed increases from v_b to v_M , the latter being therefore the maximum speed of the constant volt-ampere region.
- III: Ultra-high speed region
This is a decreasing volt-ampere region and the speed is higher than v_M .

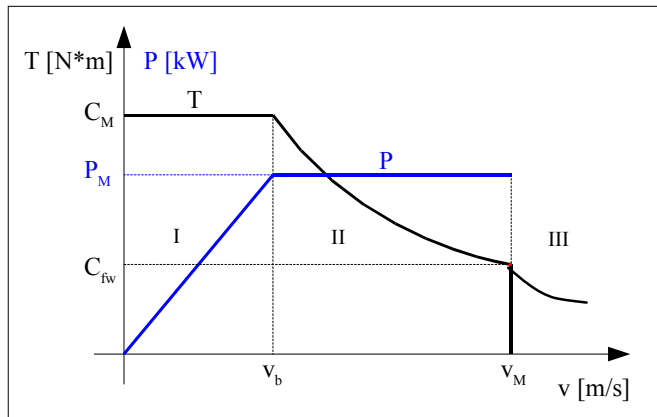


Fig. 3 - Various operation regions in the IPM motor

Once torque, current and phase voltage are fixed, the design is carried out starting from this values and imposing the thermal and magnetic limits. The main motor dimensions are reached by solving a system of non-linear equations [7]. From the system of equations the rotor diameter D , stack length L , numbers of turns N_t , PM dimensions and air-gap length can be obtained. By adopting a simplified thermal lumped network, the copper over temperature can be estimated as a function of D , L , electric loading, the stator copper surface and specific thermal resistances.

The design of the motor is thus completed. However, since the stator winding resistance as well as iron saturation and losses have been neglected in defining the motor parameters, a refinement of the design could be required. Taking advantage of the analytical form of the procedure, the motor design can be easily implemented in a computer. However, since the flux leakage lines and the saturation effects of the IPM motor are not taken into account, the performance do not fully satisfy the required specifications.

Once the motor main dimensions are fixed, an accurate analysis is possible by means of the Finite Element Method (FEM) approach. It permits to refine the motor design in order to satisfy the required specifications [6,7]. Then, the 2-D FEM model of the IPM motor may be certainly used in the motor design procedure.

In order to satisfy the bus requirements, the proposed approach has been used for the design of a 35 kW, 100 V, 4 poles IPM synchronous motor, with a typical stator frame. The main data of the final design are shown in Tab.1.

The chosen permanent magnet is the rare-earth materials neodymium-iron-boron (Nd-Fe-B) that presents higher coercive force (900 kA/m) and remanent magnetic flux density (1.2 T), while the material for the stator and rotor core is a “low loss” electrical steel.

Several simulations have been carried out with different values of axis currents (I_d , I_q) that correspond to a maximum phase current values of 240 A, while the phase voltage is 100 V.

The maximum torque value is obtained at 870 rpm; with reference to this speed, the torque is 380 Nm and power is 34.6 kW, with an efficiency of about 94% and a power factor of 0.98. The maximum speed range is about 3 times the rated speed: this results confirms the goodness of the proposed design.

The maximum flux density in the teeth does not exceed 1.8 T, while in the stator yoke is about 1.6 T.

Table 1 – Main data of each IPM motor

Number of poles	4
Stack length	250 [mm]
Outside stator diameter	310 [mm]
Outside rotor diameter	200 [mm]
Number of slots	36
Number turns x phase	48
Weight of motor	130 [kg]
<i>Performance @ 870 rpm</i>	
Rated torque	380 [Nm]
Phase voltage	100 [V]
Power	34.6 [kW]
Phase current (max)	240 [A]
Efficiency	0.94
Power factor	0.98

The resultant torque-speed and power-rpm characteristics of the two IPM motors are shown in Fig. 4 and Fig. 5. It is evident a wide speed range at maximum torque (760 Nm) from zero to 870 rpm; then, the torque reduces in the “flux weakening region” (region II) and the operation in this region is limited by the rated current and the rated voltage. The maximum speed is about 2400 rpm.

Figure 5 refers to the power obtained by the use of two IPM motors.

A reducer of 5 ratio has been employed where each IPM motor is coupled to the wheel whose diameter is 0.546 m.

Figures 6 and 7 show the performance of vehicle in correspondence of full weight at different work conditions. Figure 6 shows the thrust vs. speed of vehicle at five different road grade; it is evident how the bus can operate until a road grade of about 4%.

Figure 7 shows the acceleration vs. speed of vehicle at five different road grades; the acceleration and maximum speed at 0 road grade are respectively about 0.47m/s² and 50 km/h. It confirms that the project requirements are fully satisfied.

The batteries have been sized taking into account a d.c. voltage of 170 V and a maximum current of 240x2 A: the Nickel-Metal Hydride (Ni-MH) modules has been chosen, with enhanced specific energy and energy density, usually employed in the electric vehicle. The calculated total weight of batteries is about 520 kg.

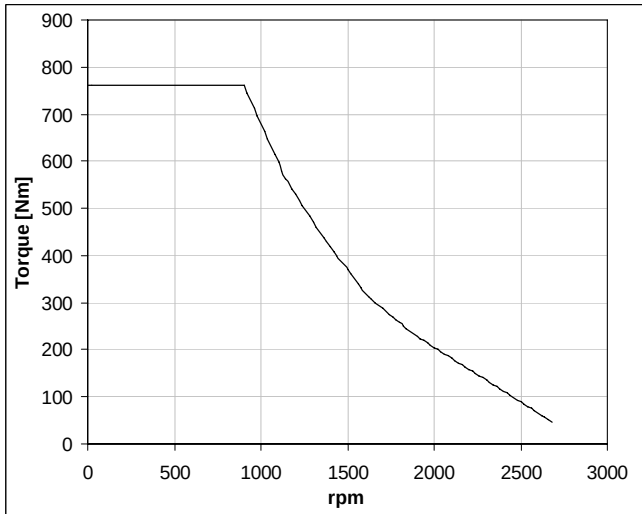


Fig. 4 – Resultant Torque vs. speed characteristics

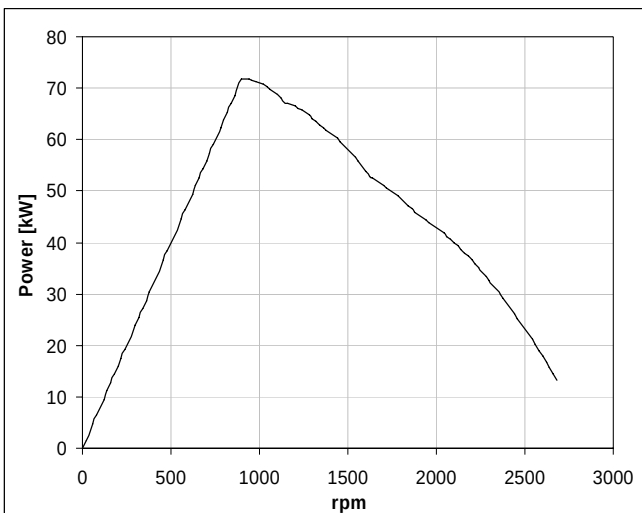


Fig. 5 – Resultant Power vs. speed characteristics

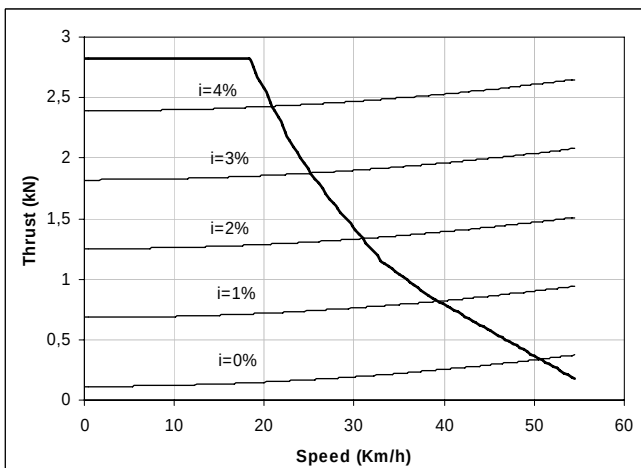


Fig. 6 – Thrust of vehicle vs. speed at different road grades

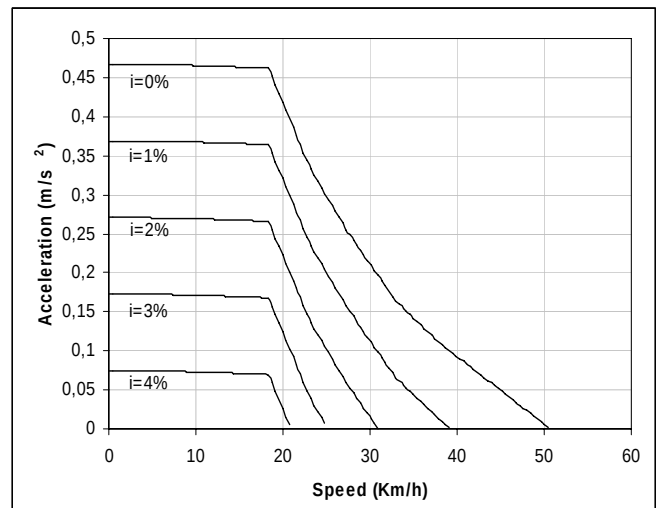


Fig. 7 – Acceleration of vehicle vs. speed at different road grades

4. Conclusions

The design of power system employing IPM motor supplied by a batteries, for small sized electric bus has been carried out and investigated.

The proposed design procedure combines a preliminary analytical evaluation of motor size together with a fine FEM analysis, that allows to test the motor performance in the whole speed range: this has allowed to verify the specifications of electric bus in terms of speed and acceleration performance.

The procedure has been applied to the design of two 35 kW IPM motors, demonstrating good results with a good efficiency and power factor.

The results highlight that the IPM motor, owing to their low inertia, high power-to-weight ratio and acceleration performance, can represent a valid solution for applications in the small sized electric vehicles, respect to the traditional induction motors or DC motors.

5. References

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