SWISSMETRO

Combined Propulsion With Levitation And Guidance

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Abstract

Swissmetro is a MAGLEV Project between the main cities of Switzerland, designed for a speed up to 500 [km/h] in two tunnels under partial vacuum. Two propulsion variants are considered: - the short stators of the linear homopolar motors are fixed with the tunnel tracks; - the stator of the motors is on board of the vehicles. The levitation, the guidance and the transfer of energy are independent.

The authors investigate the possibilities to combine the propulsion with the levitation and the guidance. Polarized inductors for the levitation and the guidance are studied. The electromechanical component designs are presented, considering the specificity of the tunnel partial vacuum.

1 INTRODUCTION

Actually, the electromechanical components of Swissmetro are based on two proposed variants A and B for the propulsion [1], as presented in Figures 1, 2, and 3:

A) the short stators of the linear homopolar motors are fixed with the tunnel tracks;

B) the stator of the motors is on board of the vehicles.

For these two variants, the Swissmetro will be propelled by linear homopolar synchronous motors. An air gap of 20 [mm] is considered for the propulsion, the magnetic levitation and guidance. The choice of classical linear motors implies short pole pitch, such as 231 [mm]. This value is necessary in order to decrease the motor end winding lengths. The maximum synchronous frequency is 300 Hz, which corresponds to today technology limits of power inverters. Such a frequency corresponds to a synchronous speed of 500 km/h. The motor optimization leads to an appropriate number of slots, poles and a given coil opening. The winding is based on a fractional number of slots per pole and per phase in order to decrease the reluctance forces and on a coil opening minimizing the harmonic winding factors. The winding uses technology permitting a high copper/aluminum filling factor (> 0.5).

The investigation [2] of the independent magnetic levitation and the magnetic guidance functions, both by attraction, showed typically technical issues to solve, such as:

- the attractive force between the stator and the reactive part (rotor) of the linear propulsion motor must be compensated by a double inductor structure.
- the levitation and the guidance inductors, being not polarized, the generated heat and its dissipation become an issue in tunnels with partial vacuum. The levitation and the guidance inductors request a cooling system, on board of the vehicle and an additional cooling system in the stations. The coefficient of convection, in partial vacuum atmosphere, is a key issue during the vehicle motion. Consequently, the aerodynamic behavior has to be known [3, 4];
- to decrease the levitation and the guidance drag force, a laminated reactive rail is necessary.

Based on the previous results, for long stator propulsion variant (stator fixed with the tunnel), there is an interest to consider the possible combination of different functions, such as:

- the propulsion with the magnetic levitation, by attraction;
- the propulsion with the magnetic guidance, by attraction.

The partial vacuum, the closed environment of the tunnels are considered during the new Variant C.

This paper presents only an overview of some design issues as a first order analysis of the concept.

2 COMBINED PROPULSION WITH THE LEVITATION

2.1 Design Considerations

Figures 1 to 3 describe the actual two variants A and B of the Swissmetro. Figure 1 represents the Swissmetro vehicle, which can bend in the curves, due to the flexible active joints. The vehicle comprises a tail, four cells and a tail. Figure 2 presents the spatial integration of the different electromechanical components. Figure 3 shows the transfer of energy to the vehicle which consists of a linear transformer [7].

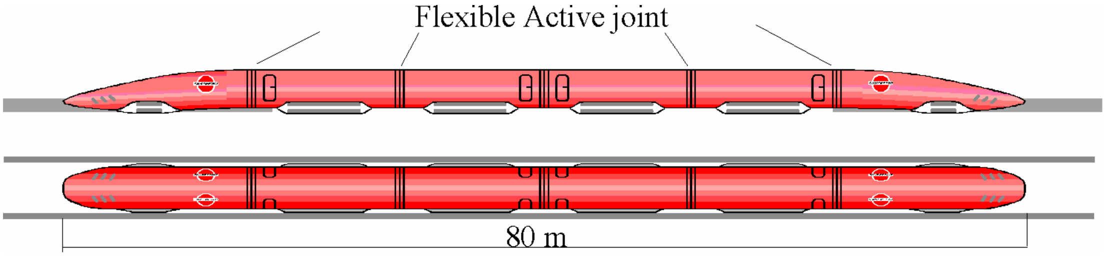
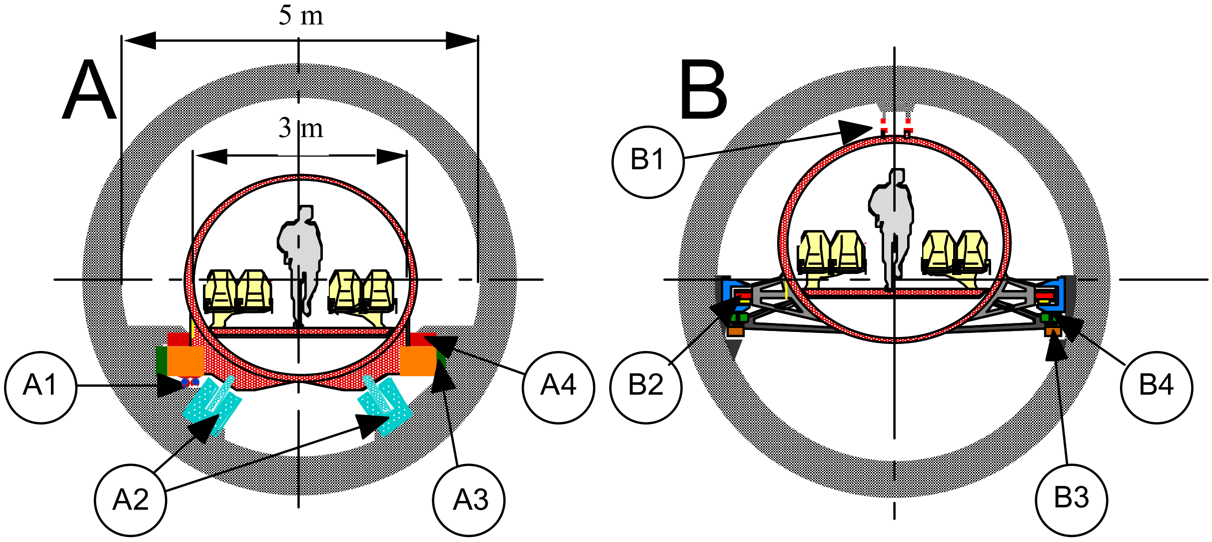
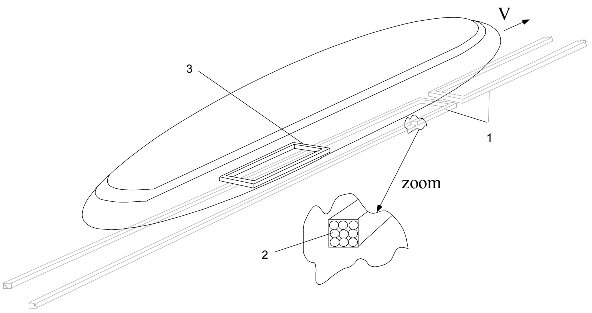


Fig. 1 Swissmetro vehicle: nose + four cells + tail.



Variant A: A1: transfer of energy to the vehicle, linear transformer
B: B1: transfer of energy to the vehicle, linear transformer
A2: fixed stators with the tunnel, rotor poles on board B2: rotor poles fixed with the tunnel, stators on board
A3: magnetic guidance per attraction B2: magnetic guidance per attraction following the stators
A4: magnetic levitation per attraction B3: inductors, urgency brake
B4: magnetic levitation per attraction

Fig. 2 Swissmetro cross section of the vehicle.



1: fixed primaries; 2: secondary linked to the vehicle; 3: turns, Litz wires

Fig. 3 Simplified principle: ironless linear transformer.

Combining the propulsion with the levitation and the guidance imposes to give up the homopolar linear motor (as chosen for the actual two variants A and B) and to choose a classical synchronous motor. The favorable tunnel environment permits to consider long stator motor with windings close to industrial motor, thus permitting to avoid the use of high voltage cables for the winding. High voltage cables impose a coil opening of three slots, for a three phase motor. In order to decrease the Joule losses created by the levitation and the guidance inductors, *a combination of polarized inductors with an additional DC winding is considered*. Furthermore, this combination is necessary if the same inductor is considered also as a rotor pole of the linear motor, with its excitation.

The combined propulsion with the levitation and the guidance reduces the number of active surfaces of the vehicle where a force is created. This permits a better mechanical integration of the electromechanical components, both fixed with the tunnel and on board of the vehicle.

3 MOTOR PRE-DESIGN

3.1 Mechanical Power

The motor total mechanical power is limited to 6 [MW], see Specifications, Table 2. The rotor poles are distributed in the four vehicle cells, on both sides. Consequently, each motor active part sees only an eight of the total force and of the total mechanical power. The motors produce a constant force until they reach their maximum mechanical power, than the acceleration is decreasing. The system performance specifications and the above considerations permit to define the design criteria and to investigate the motor characteristics. Figures 4 and 5 present the key characteristics. The obtained "real acceleration" will depend on the complete behavior of the vehicle, considering all aerodynamic forces and magnetic drag forces [3]. Consequently, the presented acceleration is the upper limit.

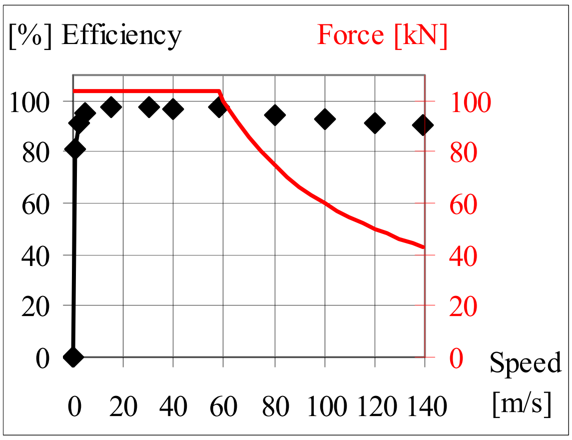


Fig. 4 Total propulsion force and acceleration.

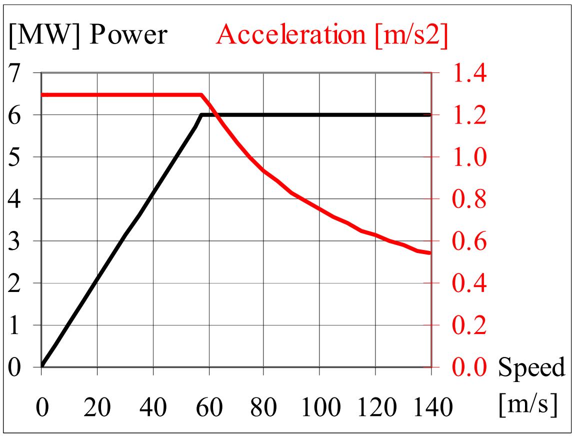


Fig. 5 Efficiency and total mechanical power.

Considering the long stator, the efficiency presented previously will be affected by the length of the stator section which sees one motor inverter. Mainly the Joule losses of the complete stator section are the key components of the losses of the stator part which does not see an active part of the rotor. The efficiency can be represented as a function of the length of the stator section. Computation results are presented in Figure 6. The efficiency, even, starting from a high value, decreases rapidly versus the length of the stator section energized by one inverter.

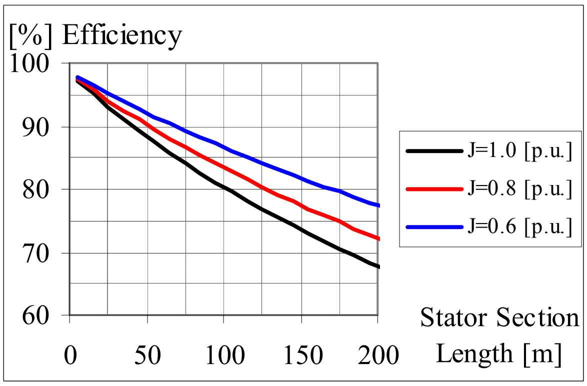


Fig. 6 Efficiency versus the stator section length, for different stator current densities.

Decreasing the current density in the stator winding improves the efficiency. However, the stator lamination stack and the armature winding volume increase and consequently the investment cost. There are design constraints to analyze between:

- the length of the stator section energized by one inverter, the number of inverters (investment costs);

- the energy consumption (exploitation cost).

3.2 Winding Configuration

Considering the motor combined with the levitation, there is a clear interest to have a non negligible number of rotor poles, which will be the inductors of the levitation. This necessity is due to the fact that the actual Variants A, B, showed that 24 levitation inductors are necessary. Consequently, the homopolar variant, since there is a pole each two pole pitches, is not considered for the new Variant C. The pole pitch is imposed to 0.231 [m] and the active length of the rotor poles of each vehicle cells is limited to 5.1 [m]. This defines 22 rotor poles on each side of one vehicle cell. For the winding configuration, a slot opening of one slot is investigated, thus permitting to reduce the end winding and permitting an industrial assembly concept. Taking benefit of the tunnel environment, classical winding are considered as shown in Table 1. Furthermore a high copper filling factor equal to 0.6 can be considered. Figures 7 and 8 represent the winding configuration of the motor for the different variants. In order to reduce the drag force and consequently the iron losses in the rotor, a laminated rotor is considered.

Winding	Zn0 [-]	Zn [-]	p [-]	m [-]	q [-]	s [slot]	Kw1 [-]
Variants A, B	57	54	7	3	1.86	3	0.9
New variant C	25	24	11	3	0.364	1	0.949

Table 1 Winding configuration.

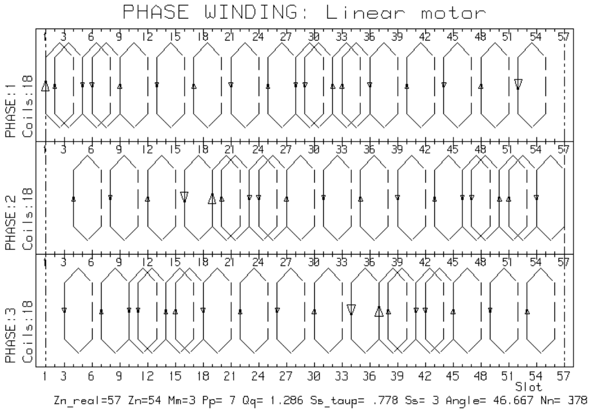


Fig. 7 Swissmetro winding configuration: Variants A and B.

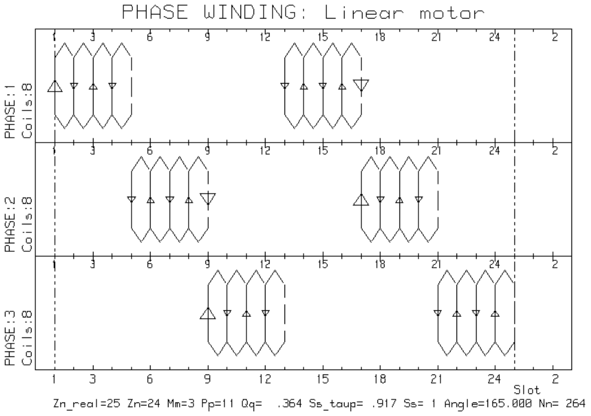


Fig. 8 Swissmetro winding configuration: Variant C.

3.3 Active Width

For this first order design, the active width of the motor is not a free parameter. Among all the specifications, the design must satisfy the *key specifications* such as:

- the propulsion force;
- the phase back EMF;
- the levitation force.

The corresponding iterative design process leads to an active width of 0.175 [m].

3.4 Permanent magnet MMF

The relative long pole pitch 231 [mm] and the air gap 20 [mm] lead to an important permanent magnet MMF and consequently, to a permanent thickness of 20 [mm] in the magnetization direction. The corresponding permanent magnet MMF is 18.7 [kA], for one rotor pole. The realization of one pole consists of several permanent magnet blocks put in parallel, having the same magnetization direction. High remanent flux density of 1.23 [T] is obtained with NdFeB magnet material.

3.5 Converters

The converter and inverter strategy is identical to the one defined for Variants A and B [10], the inputs of the motor inverters is a three level DC bus of 5, 0, -5 [kV]. The inverter is a three phase inverter with three voltage levels, with GTO thyristors of 4500 [V] and 4000 [A].

4 LEVITATION PRE-DESIGN

The permanent magnet of a polarized inductor produces the attractive force and will reduce the Joule losses during the permanent behavior. The additional inductor winding produces the necessary force complement (positive or negative) and assures the dynamic behavior of the inductor. The control acts on the currents of the additional rotor winding. The design criteria are not only the total levitation force to produce, but for a very small air gap, the attractive force due to the permanent magnet, only, should not result in a force higher than the vehicle weight with no passenger, but be a proportion of this weight. On the other hand, the total mass of the vehicle can vary between the masses without and with passenger, corresponding to a factor of 1.33, for the Swissmetro.

As one inductor defines one pole of the motor, including its excitation, the phase back EMF produced by the excitation should satisfy the motor design criteria and particularly the phase voltage.

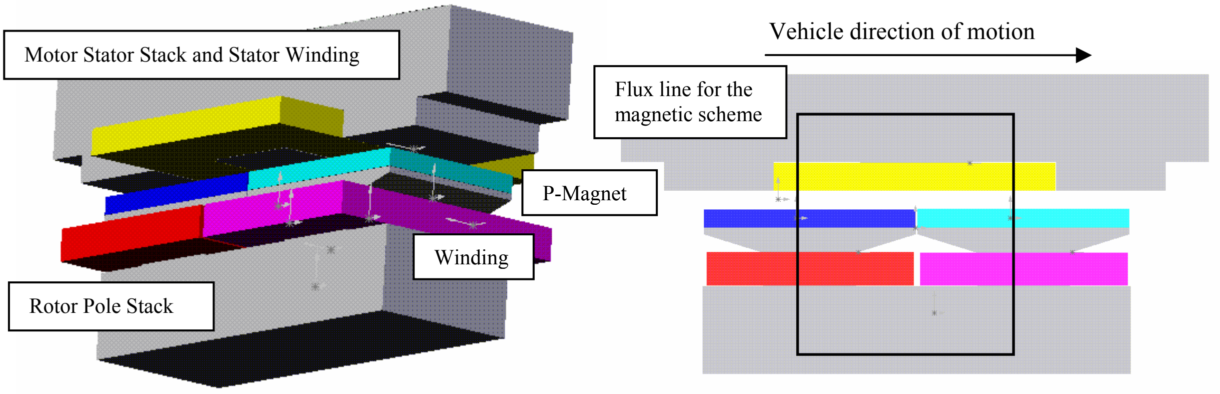


Fig. 9 Rotor Two Pole Inductors: levitation inductors.

Figures 9, 10 show two consecutive pole inductors. The permanent magnet MMF is in serial with the rotor inductor winding MMF. A first order design of the levitation inductors with permanent magnet shows some advantages of the approach. The gain in heat dissipation is a clear advantage, which could overcome the increase of the inductor cost. Assuming that the motor propulsion force is produced when the stator currents are in phase with the corresponding motor phase back EMF, then, the power supply produces a current only in the transverse axis (axis q) of the motor. This current component has no effect in the direct axis (axis d). Consequently, the behavior of the levitation can be considered as an independent function, for a first order analysis. Due to the control strategy, the saturation level in the stator and in the rotor poles are maintained to a low values. This permits also to determine a simplified magnetic scheme, where the iron parts are not considered versus the air gap permeance and the permanent magnet permeance.

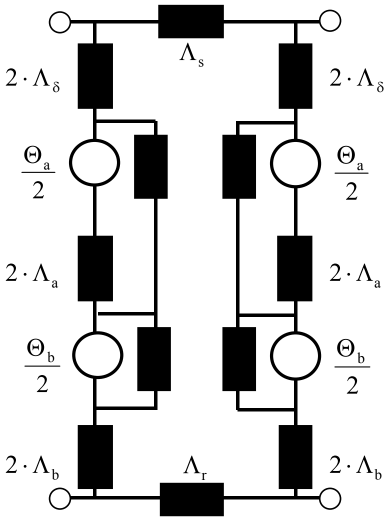


Fig. 10 Equivalent Magnetic Scheme
Rotor pole inductors.

4.1 Permeances Of The Inductors

Considering the previous assumptions, the following equations, permitting to analyze the inductors, are obtained:

$$\Lambda_\delta = \mu_0 \cdot \frac{A_{\delta\text{pole}}}{2\cdot\delta} \qquad [\text{H}] \qquad (4.1)$$

$$\Lambda_{aa} = \Lambda_{bb} = \Lambda_{\delta\delta} = \Lambda_{ab} = \Lambda_{ba} = \Lambda_{a\delta} = \Lambda_{\delta a} = \Lambda_{b\delta} = \Lambda_{\delta b} = \frac{\Lambda_a \cdot \Lambda_\delta}{\Lambda_a + \Lambda_\delta} \quad [\text{H}] \qquad (4.2)$$

$$\frac{\Lambda_{aa}}{d\delta} = \frac{\Lambda_{bb}}{d\delta} = \frac{\Lambda_{ab}}{d\delta} = \frac{{\Lambda_a}^2}{(\Lambda_a + \Lambda_\delta)^2} \cdot \frac{d\Lambda_\delta}{d\delta} \qquad [\text{H/m}] \qquad (4.3)$$

The air gap δ is the magnetic air gap, considering the variation of the air gaps due to the presence of the stator teeth. The Carter's factor permits to determine the air gap δ.

4.2 Attractive Force

The attractive force is determined knowing the different MMF produced by the inductor windings and the permanent magnets:

$$F_\delta = \frac{1}{2} \cdot \frac{C_{aa} \cdot d\Lambda_{aa}}{d\delta} \cdot \left(\Theta_a + \Theta_b\right)^2 = \frac{1}{2} \cdot \frac{d\Lambda_\delta}{d\delta} \cdot \theta_\delta^{\,2} \quad [\mathrm{N}] \qquad (4.4)$$

Where θ_δ is seen on two air gaps. The attractive force F_δ becomes:

$$F_\delta = \frac{1}{2} \cdot \frac{\Lambda_a^{\,2} \cdot \left(\Theta_a + \Theta_b\right)^2}{\left(\Lambda_a + \Lambda_\delta\right)^2} \cdot \frac{d\Lambda_\delta}{d\delta} \qquad [\mathrm{N}] \qquad (4.5)$$

4.3 Per Unit Values

As Λ_δ, $\frac{d\Lambda_\delta}{d\delta}$ and Θ_a are "known" from the motor design, the following factors k_a, k_θ are defined as:

$$\left.\begin{aligned} \Lambda_a &= k_a \cdot \Lambda_\delta \\ \Theta_b &= k_\theta \cdot \Theta_a \end{aligned}\right\} \qquad (4.6)$$

Then the attractive force F_δ is written as:

$$F_\delta = -\left(1 + k_e\right)^2 \cdot \frac{\mu_0}{4} \cdot \frac{k_a^{\,2}}{\left(k_a + 1\right)^2} \cdot \frac{A_{\delta pole}}{\delta^2} \cdot \Theta_a^{\,2} \qquad [\mathrm{N}] \qquad (4.7)$$

Defining the force Fa_δ as the Reference Attractive Force, which corresponds to the attractive force without current in the inductor winding. This force is equal to:

$$Fa_\delta = -\frac{\mu_0}{4} \cdot \frac{k_a^{\,2}}{\left(k_a + 1\right)^2} \cdot \frac{A_{\delta pole}}{\delta^2} \cdot \Theta_a^{\,2} \qquad [\mathrm{N}] \qquad (4.8)$$

$$Fa_\delta \equiv 1 \qquad [\mathrm{p.u.}] \qquad (4.9)$$

Considering the air gap of 20 [mm] as the nominal value, Figures 11, 12 are obtained.

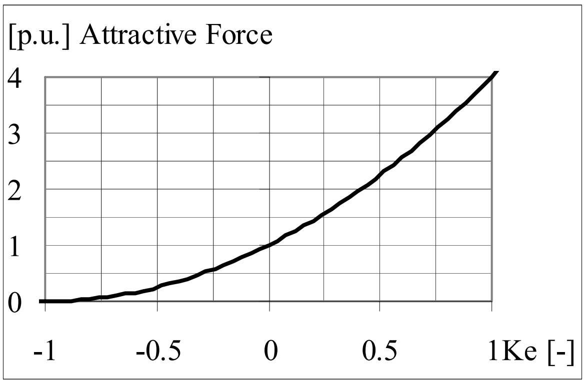


Fig. 11 Attractive force versus the factor Ke.

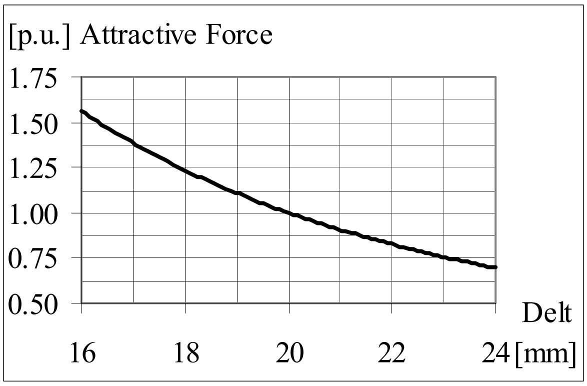


Fig. 12 Attractive force versus the factor Ke.

4.3.1 Limit Condition

Figures 11 and 12 indicate there is a clear interest to limit the range of possible variation of the air gap. For a constant attractive force F_δ, the relation between the inductor current and the variation of the air gap is a linear function, expressed as:

$$k_e = \delta \cdot 2 \cdot \frac{k_a + 1}{k_a} \cdot \frac{1}{\Theta_a} \cdot \sqrt{\frac{\left|F_\delta\right|}{\mu_0 \cdot A_{\delta pole}}} - 1 \qquad (4.10)$$

Considering two different air gaps δ_0, δ_1 such as, the corresponding attractive forces stay identical:

$$F_{\delta_1} = F_{\delta_0} \tag{4.11}$$

Then:

$$k1_e = (1 + k0_e) \cdot \frac{\delta_1}{\delta_0} - 1 \tag{4.12}$$

Figure 13 represents the correspondence between the different coefficients of the inductor MMF.

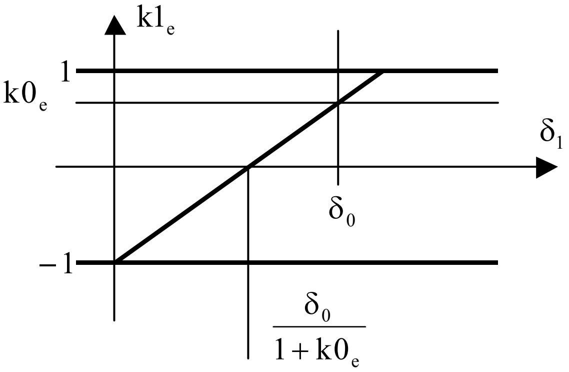


Fig. 13 Factor Ke as a function of the air gap.

Figure 13 indicates the interest to design the attractive force without inductor current as closed as possible to the nominal attractive force.

For the Swissmetro, the followings results presented in Figure 14 are obtained. They indicate that for the nominal air gap and its specified variation of 20±2 [mm], the variation of Ke will be inside 12.5 [%] of the permanent magnet MMF. The chosen permanent magnet corresponds to NdFeB with a remanent flux density of 1.23 [T]. For one pole, a permanent magnet MMF of 18.7 [kA] is achieved.

If the air gap decreases below 18 [mm], it appears that for an air gap of about 14 [mm], an emergency current should be injected to decrease the attractive force. Consequently, the rotor pole inductor winding should be able to produce a MMF of about 20 [%] of the permanent magnet MMF. This leads to an inductor winding MMF (one pole) of 3.74 [kA].

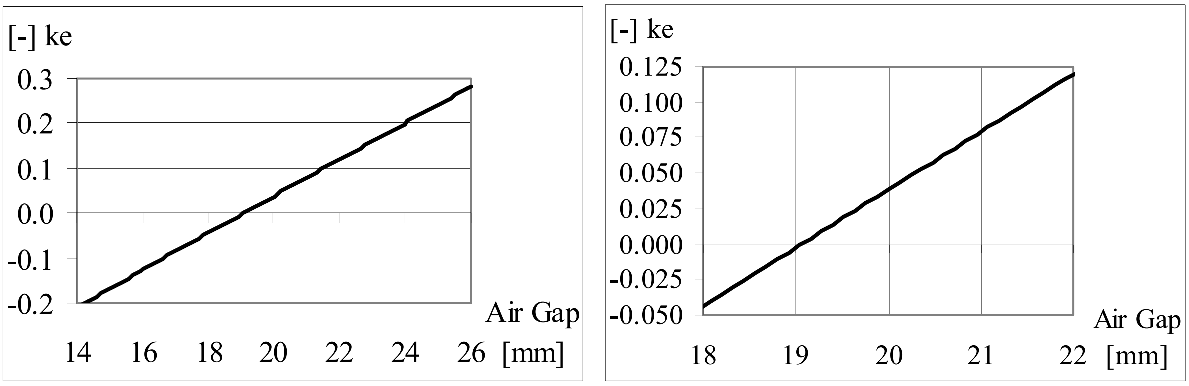


Fig. 14 Factor Ke as a function of the air gap; for a constant attractive nominal force.

4.3.2 Power

As the main attractive force component is produced by the permanent magnet, the inductor winding produces essentially the additional force to control the air gap. A current density of 4 [A/mm2] is imposed. Assuming the extreme case of 30 [%] of continuous use of the rotor inductor, the corresponding power is equal to 402 [W]. For the complete vehicle, the power will be of 106.3 [kW].

4.3.3 Finite Element Method Results

Finite element method is used to confirm the previous mentioned results. Figure 15 shows the flux distribution, produced by the permanent magnets only, in two consecutive inductors. As expected, the flux density in the air gap is low. A clear influence of the stator teeth on the flux density in the air gap is seen. The Levitation force under one rotor pole has a DC and an AC component.

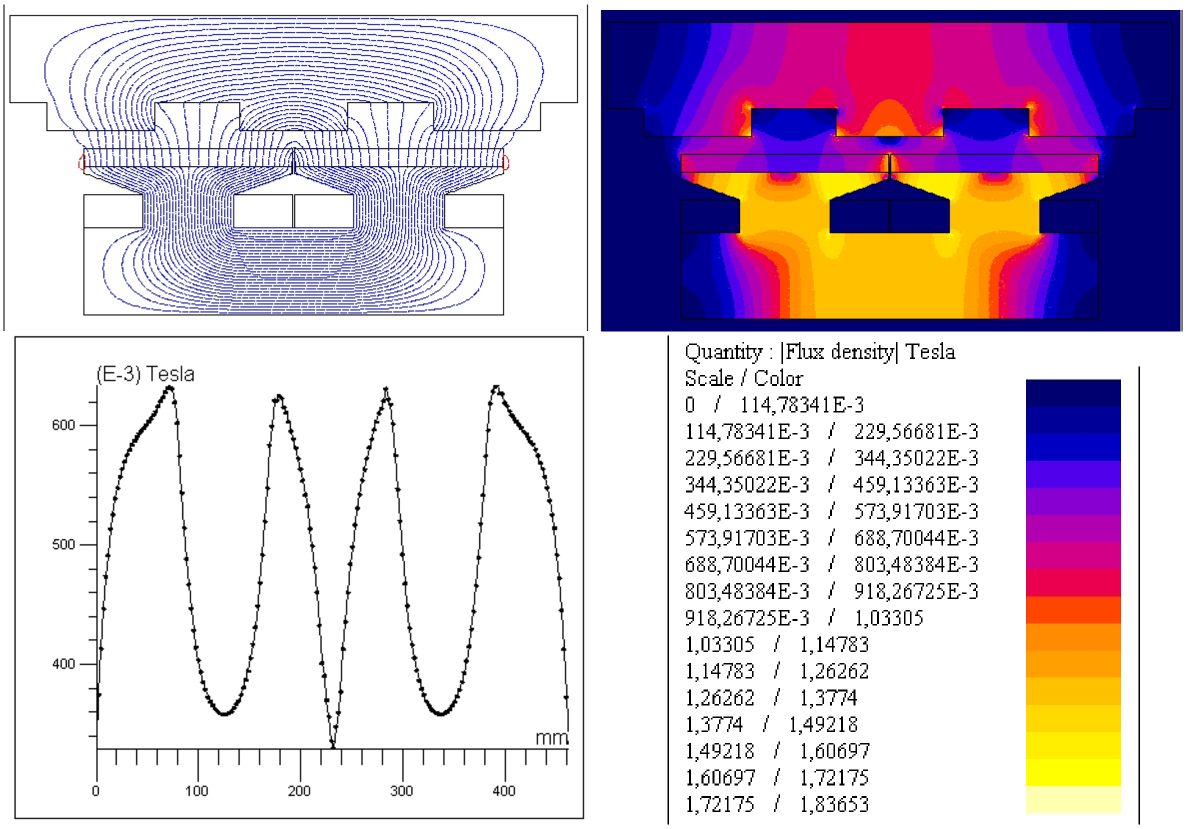


Fig. 15 FEM results: flux density in two consecutive rotor poles, due to the permanent magnet. Flux density in the air gap. Magnitude of the flux density line4s in the air gap.

5 GUIDANCE PRE-DESIGN

Table 2 of Specifications indicates that the force to produce for the guidance is of 38 [%] of the levitation force. Consequently, the design of the guidance is not decisive. A similar solution than the one for the levitation can be considered. All previous results can be considered for the guidance.

6 CONTROL STRATEGY

The control strategy of the motor and the control of the levitation inductors are based on the control of the stator current, its direct and transverse components, influencing the phase shift with the phase back EMF, the current electrical frequency and the current in the rotor inductors. As the current in the rotor inductor modifies the resulting rotor MMF, thus the phase back EMF Ui, then the control strategy should combine both the propulsion and the levitation. Figure 16 gives the background strategy of the influence of the different physical values on the control.

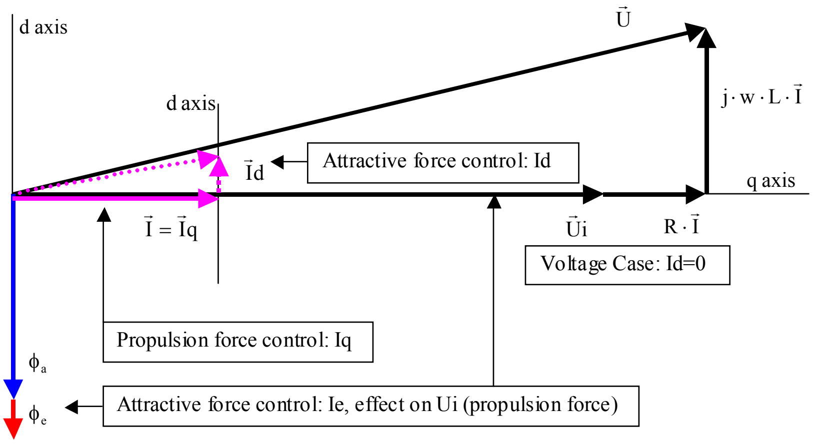


Fig. 16 Vector diagram of the voltages and flux.

7 INTEGRATION OF THE ELECTROMECHANICAL COMPONENTS

The combination of the propulsion and the levitation is, somehow, easier than the Variant A. The complete weight involved at the level of the vehicle for the electromechanical components is lighter (see Table 1).

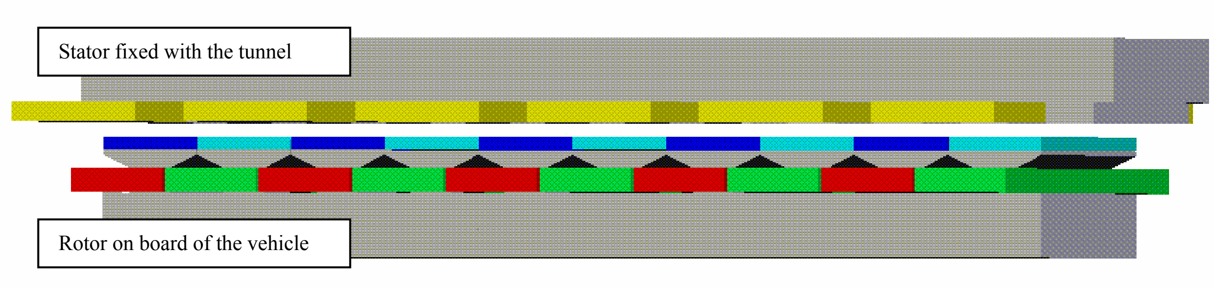


Fig. 17 Partial view of the stator and the rotor poles.

8 CONCLUSIONS

The presented paper is *a first order analysis* of the possible combination of the propulsion with the levitation and the guidance. The study of the Variant C is not mature enough to consider this solution, at this time, as a possible concept for Swissmetro, but is a challenging technical issue. The optimization of the concept requests a deeper technical investigation including an energy balance and an economical balance. The following first points can be considered.

- The combination of long stator and the choice of a classical stator winding, similar to industrial linear direct drives, request a deep investigation between the investment cost and the exploitation cost (cost of the energy), in order to determine the stator section length, seen by one inverter. This is a key point of the complete long stator concept.
- One possible way will be to combine short stators, fixed with the tunnel, and levitation and guidance. In that case the stator should be combined with the reactive rail of the levitation and the guidance for the parts of the track where there is no stator.
- A nominal air gap of 20 [mm] requests an important permanent magnet MMF to create the attractive force based only on the force produced bay the permanent magnet.
- For the specified air gap variation, the additional rotor winding has a relative limited MMF to produce.
- There is a direct interest that the tail and the nose comprise not only levitation and guidance inductors, but also section of the motor. This is new versus the actual Variants A and B of Swissmetro.
- The complete control comprises new challenging issues to solve.

9 SYMBOL LIST

A	surface	[m2]
C	coupling factor	[-]
F	force	[N]
Fa	reference force	[N]
k_a	inductor permeance factor	[-]
k_e	inductor MMF factor	[-]
Λ	permeance	[H]
Θ	MMF	[A]
μ_0	vacuum permeability	[Vs/Am]

a	permanent magnet
b	rotor inductor winding
δ	air gap

10 SPECIFICATIONS

Swissmetro Variants		A	B	C
Performances				
Acceleration	[m/s^2]	1.3	1.3	1.3
Speed	[m/s]	139	139	139
Vehicle				
Total mass	[ton]	80	80	80
Total length	[m]	80	80	80
Nb. of cells	[-]	4	4	4
Nose length	[m]	15	15	15
Tail length	[m]	15	15	15
Cell length	[m]	12.5	12.5	12.5
Nb. of passengers	[-]	200	200	200
Propulsion				
Air gap	[m]	0.02	0.02	0.02
Total mechanical power	[MW]	6	0.75	0.75
Nb. of motors per cell	[-]	-	2	2
Max. total propulsion force	[kN]	104	104	104
Design speed	[m/s]	57.7	57.7	57.7
Nb. of sections per cell	[-]	2	2	2
Rotor section length	[m]	9.3	3.413	5.082
Pole pitch	[m]	0.324	0.231	0.231
Nb. of poles per section	[-]	-	14	22
Levitation				
Air gap	[m]	0.02	0.02	0.02
Nb. of poles per section	[-]	-	14	22
Nb. of inductors per cell	[-]	4	4	44
Force per inductor	[kN]	33	33	2.97
Power loss (mean value)	[kW]	3.3	3.3	0.4
Mass of one inductor	[kg]	171	171	56
Guidance				
Air gap	[m]	0.02	0.02	0.02
Nb. of poles per section	[-]	-	-	70
Nb. of inductors per cell	[-]	4	4	140
Force per inductor	[kN]	12.5	12.5	<2.97
Power loss (mean value)	[kW]	2.25	2.25	<0.4
Mass of one inductor	[kg]	171	90	<56
Transfer of energy	[kW]	500	7000	500
Air gap	[m]	0.02	0.02	140
Linear Transformer		yes	no	yes
Mechanical contacts		no	yes	no
Primary length	[m]	1000	-	1000
Secondary length	[m]	80	-	80
Efficiency	[%]	90	-	90
Secondary weight	[kg]	1500	-	1500

Variant A. short stators fixed with the tunnel
Variant B: stators on board of the vehicle
Variant C: long stator fixed with the tunnel, combined with the levitation

Table 1 Swissmetro - Variant specifications

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