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A study of the Power Consumption of German Maglev Passenger Vehicles

(EDS and EMS)

SUMMARY

The sample revenue vehicle designs of the two German Maglev groups have been analysed and the complex power requirement at trackside substations has been calculated.

The two systems are the Electromagnetic system (EMS) with either linear induction motor (LIM) or long stator motor propulsion, and the Electrodynamic System (EDS) with linear synchronous motor (LSM) propulsion.

The operational conditions considered were 400 and 500 km/h velocities either at a steady-state cruise or with a grade or headwind additional loading.

It is found that the LSM of the EDS is the most suitable form of propulsion for these operating conditions, the long stator motor for the EMS having reasonable characteristics at 400 km/h, but becoming degraded at 500 km/h, and the LIMs studied being unsuited to 500 km/h, and not very good even at 400 km/h.

These results highlight the need in a system comparison to not merely compare specific power or lift to drag ratio, which denote the active power supplied to a vehicle, but to compare complex power at wayside substations to indicate the overall efficiencies and power factors of the competing system.

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A Study of the Power Consumption of German Passenger Vehicles (EDS and EMS)

1. Background and reason for study

The two German Maglev groups have prepared sample designs for passenger and goods carrying vehicles. However, although vehicle details are relatively easy to find in the literature, vehicle performance, and general operating power consumption data are not so forthcoming.

A recent publication (1) quotes figures of power consumption for the comparative German designs which are misleading, because, as the author correctly states, the EDS (Electrodynamic system) and EMS (Electromagnetic system) long and short stator cannot be directly compared.

Of particular damage to the EDS design is the section 4-2 in the Table which compares power supply requirements of the substations, in real power rating.

(a)	EMS short stator	5MW/vehicle at 400 km/h D.C. substation every 12 km, 4 kV distributio
(b)	EMS long stator	4.7 MW/vehicle at 400 km/h Substations every 12 km, with pulse inverters and isolators feeding a travelling field machine. Frequency 0-200 Hz.
(c)	EDS long stator	12.5 MW/vehicle at 500 km/h Substations every 15 km, with pulse inverters and isolators feeding a travelling field machine. Frequency 0-50 Hz.

A literal conclusion from these figures could be that the EDS is particularly wasteful in real power consumption, needing two and a half times as much real power as the other two systems. This is not a valid conclusion and the following major differences in design should be observed:

(a) The cruise speeds are different
(b) The vehicle weights are different
(c) The passenger capacities are different
(d) The EDS system has railway bogies
(e) Overall power factor - efficiency product is not included (i.e. no indication of system total MVA requirement)

Some comparisons can be made for speed extrapolations from the base designs. The "Konstanz 1977 Statusseminar VI"(2) gives sufficient detail for the active power requirements to be estimated, but there is little clear information on power factor and efficiency of the short and long stator motor EMS designs.

Vehicle weight differences in the designs will effect the specific power of the levitation system (kW/tonne). In particular, the choice of railway type bogies on the EDS vehicle for low speed guidance and support must impose a greater weight penalty than, for example, the Canadian Maglev Revenue Vehicle wheel sets. (The wheelset weight is only 4% of all-up weight in the CIGGT design).

Passenger capacity is the least important difference, with respect to power requirement, since the pay load is a small proportion of the vehicle total weight.

viz.	EMS short stator	240 passengers,	24t on 170t, 14.1%
	EMS long stator	240 passengers,	24t on 165t, 14.5%
	EDS " "	200 passengers,	20t on 130t, 15.4%

An increase of 40 passengers on the EDS system gives a weight increase of 4 tonnes, or 3%, so this would have about the same effect on propulsion power requirements, but the overall effect on specific energy consumption (kW-h/passenger-km) would be a reduction of about 15% (i.e. quite marked).

Because of the different characteristics of the three systems, they will be analysed individually.

2. Electrodynamic system (EDS) of Levitation.

2.1 Vehicle concept.

The vehicle is made up of two similar end sections. A five section train can be made by introducing three middle sections with their own lift, guidance and propulsion. Passenger seating is 100 per section.

The lift is provided by ten superconducting magnets, and the guidance and propulsion by fifteen magnets, per section.

The main vehicle characteristics are from Chapter P "Application Investigation and Project Design, Description and Explanation of the EDS Concept", by K. Mandt (2) and are reproduced in Table 1. Figure 1 shows a general section of the passenger vehicle

Vehicle length	56m	No. of levitation magnets	20
Length of one section	28m	Strength	616 kAT
No. of sections	2	Size (L×W)	1.5×0.3m
Speed	500 km/h	Mass	470 kg
No. of passengers	200	No. of propulsion magnets	30
Vehicle mass	135t	Strength	1.15MAT
Payload	20 t	Size (L×W)	1.12×0.7m
Vehicle height	4.2 m	Mass (of a 3 coil cryostat)	2.2 tonne
Vehicle width	3.5 m	Damper winding mass (3/cryostat)	280 kg
Rail gauge	1.435 m	Pole pitch	1.4m
Levitation gauge	2.7 m		
Levitation height	0.20 m		

Table 1 Characteristics of EDS Vehicle

Figure 2 shows the substation and armature winding of the linear synchronous motor (LSM) distribution network.

2.2 Drag figures at 500 km/h

From reference (2) the values of magnetic drag and aerodynamic drag at 140 m/s (500 km/h) are displayed graphically as 41.7 kN and 47.5 kN respectively. The steady state drag on the vehicle is therefore 89.2 kN or 12.5 MW.

Although the level of residual acceleration needed to overcome head-on gusting and gradients is not quoted for the EDS system, a figure of 0.013g will be taken, as this is used in the EMS studies.

Table 2 gives a breakdown of the steady state and effective power required for propulsion.

	Drag kN	Power MW	lift/drag	Specific power, kW/t
Magnetic drag	41.7	5.8	31.8	43.2
Aerodynamic drag	47.5	6.7	27.9	49.3
Total steady state drag	(89.2)	(12.5)	(14.9)	(92.5)
Residual acceleration	17.2	2.4	77.0	17.8
Effective total drag	106.4	14.9	12.4	110.3

Table 2. Power Breakdown for EDS (500 km/h)

2.3 Drag figures at 400 km/h

The aerodynamic drag at 400 km/h can be obtained by interpolation of graphical data (28 kN), or by observing that aerodrag is proportional to (velocity)^2, (3).

$$\text{Aerodrag @ 400 km/h} = \text{Aerodrag @ 500 km/h} \times \left(\frac{111}{140}\right)^2 = 29.9 \text{ kN}$$

Magnetic drag power from a graph is 4.9 MW, which corresponds to a drag force of 44.1 kN.

Table 3 gives a breakdown of the power requirements at 400 km/hr.

	Drag kN	Power MW	lift/drag	Specific power, kW/t
Magnetic drag	44.1	4.9	30.0	36.3
Aerodynamic drag	29.9	3.3	44.3	24.6
Total steady state drag	(74.0)	(8.2)	(17.9)	(60.9)
Residual acceleration	17.2	1.9	77.0	14.1
Effective total drag	91.2	10.1	14.5	75.0

Table 3 Power Breakdown for EDS (400 km/h)

2.4 Power Factor and Efficiency

The LSM is capable of operating at high power factor and efficiency. However the choice of power factor depends largely on the superconducting coil design, and the leakage inductance in the track winding. Similarly, the efficiency is determined by the transferred power required, and the track winding cross-section. Both parameters are obtained by a machine design which takes into account the energy used, and the capital costs of the system, and trades the two against each other.

2.4.1 Power factor and efficiency at 500 km/h

Albrecht gives a power-factor-efficiency product of 2/3,(4), for a 120 tonne two section vehicle, with 87 kN thrust at 500 km/h. The machine output power was 12 MW, and total input power 18 MVA.

The Statusseminar values differ only slightly, being presented as fractions of the number of sections in the train, and the track wound sectional area.

$$\text{Typically, they are} \quad \left.\begin{aligned} \eta &= 0.75 \\ \cos\theta &= 0.88 \end{aligned}\right\} \quad \text{product} = 0.66$$

So for a steady state, on the level cruise at 500 km/h, the machine input power is 16.7 MW, and total input power is 18.9 MVA.

For operation with full residual acceleration, the power factor and efficiency have to be re-evaluated. Since the motor thrust is proportional to armature current (and is also speed independent), and since the track losses are proportional to (armature current)^2, then

$$\text{Track losses for 106.4 kN thrust} = \text{losses for s.s. 89.2 kN thrust} \times \left(\frac{106.4}{89.2}\right)^2$$

$$= 4.2 \times 1.42 = 6.0 \text{ MW}$$

i.e. an input power of $14.9 + 6.0 = 20.9$ MW,
and an efficiency of $\dfrac{14.9}{20.9} = 0.71$.

For the LSM, if the airgap m.m.f. waves are in quadrature, the power factor can be expressed as a fun-tion of the efficiency and reactance-resistance ratio, X/R.

$$\cos\theta = \frac{1}{\left(1 + \frac{X^2}{R^2}(1-\eta)^2\right)^{\frac{1}{2}}}$$

$$\text{rearranging,} \quad \frac{X}{R} = \frac{\tan\theta}{1-\eta}$$

Using the steady state of $\eta = .75$ and $\cos\theta = .88$, $X/R = 2.16$. For residual acceleration operation, $\eta = 0.71$, so $\cos\theta = 0.85$, and total input power is $\dfrac{20.9}{0.85} = 24.6$ MVA.

2.4.2 Power factor and efficiency at 400 km/h.

As with the last section, losses can be established at the different thrust requirements, and the efficiency and machine active power input found. Using the reactance-resistance ratio the power factor can also be found. The losses at 400 km/h for steady state and accelerating duty are 2.9 MW and 4.4 MW, that is 68.8% and 105% of the loss for steady state duty at 500 km/h, respectively. The efficiencies are hence 0.74 and 0.70, giving power factors of 0.91 and 0.89. Total input complex powers become 12.2 and 16.3 MVA.

2.5 Other power requirements

On board power requirements are met by a gas turbine set. The gas turbine drives the Helium compressor and also a 400 Hz three phase generator. Power is distributed throughout the vehicle on a 380 V, 400 Hz line. Albrecht quotes a figure of I MW for vehicle on board power (4), and the statusseminar gives 300 kW required for the Helium compressor and 238 kW for other on board systems per section. These are hydraulic and pneumatic power, heating, ventilation for oil and gas heat exchangers, lighting, primary damping for list and guidance, and at low speeds, wheel synchronization.

2.6 Final figures for EDS

The power breakdown for the EDS long stator is summarised in Table 4.

	400 km/h	500 km/h
Magnetic drag MW	4.9	5.8
Aerodynamic drag MW	3.3	6.7
Steady state drag MW	8.2	12.5
Losses MW	2.9	4.2
Propulsive power, machine input (@ η), MW	11.1(.74)	16.7(.75)
" " total input (@ $\cos\theta$), MVA	12.2(.91)	18.9(.88)
Residual acceleration, MW	1.9	2.4
Total effective drag, MW	10.1	14.9
Losses MW	4.4	6.0
Propulsive power, machine input (@ η), MW	14.5(.70)	20.9(.71)
" " total input (@ $\cos\theta$), MVA	16.3(.89)	24.6(.85)

Table 4. Total Machine Input Active and Complex Power for Long Stator EDS.

Note that the residual acceleration chosen is in line with the EMS value, rather than any published EDS figure.

3. Common points for short and long stator EMS systems

3.1 Make-up of total power requirements

In establishing the total power used by a transportation system, the choice of specific power consumption in kWh/passenger-km only highlights the real power consumed. However the plant and power converters are all rated in terms of total power used, and with inductive magnetic energy transfer (linear induction motors) the power factor and efficiency can have an extreme effect on calculations based purely on real power transferred across the air gap. Energy drawn from a supply utility will also be costed to take into account the amount of reactive power used.

Generally, the total power flow is made up of the following parts:

(a) Aerodynamic drag power is proportional to the cube of velocity and the aerodynamic reference area for the vehicle.

(b) Magnetic drag power is proportional to $(\text{velocity})^{3/2}$ and is made up of both guidance and lift drag components. The exact value is highly dependent on gap size and magnet control and suspension strategy.

(c) Cooling drag power is required to overcome the inlet momentum drag associated with the cooling air for the on board power conditioning, magnets and motors.

(d) Residual acceleration power is the spare capacity for acceleration at cruise speed over inclines, headwinds, etc.

(e) Power losses within the on board systems.

(f) Acceleration power to reach cruise speed.

(g) Miscellaneous power demands.

(h) Distribution losses in trackside equipment downstream of the substation.

(i) Reactive power loading is the total amount of power flowing in quadrature to the active power, and is associated largely with the leakage inductance in the supply network and the linear induction motor.

(j) The steady state drag power is the sum of (a), (b) and (c).

(k) The effective power is the sum of (j) and (d).

(l) The picked uppower is the sum of (k) and (e).

(m) The installed propulsive power is the sum of (l) and (f).

(n) The total active load is the sum of (m), (g) and (h).

(o) The total power flow is the vector sum of (n) and (i).

3.2 Power mix for previous EMS designs

The literature is scarce of complete sets of figures for power mixes of EMS vehicles. The two exceptions are Hebst (5) and Winkle (6).

Interpolation of Hebst's diagram for power flow gives the following mix (based on magnitude of total active power load ≡ 100).

Total reactive power load	200
Total active power load	100
Installed propulsive power	85
Power pick up	67
Effective power	42
s.s. drag power	33

The effective power is broken down as

Aero drag	48%
Mag drag	20%
Cooling drag	11%
Residual acceleration	21%

These figures are based on a 720,000 lb (327t) vehicle with three cars and 300 passengers.

The overall power factor is $^1/\sqrt{5}$ (0.45), and the overall efficiency is

$$\eta = 1 - \frac{\text{losses}}{\text{active power}} = 1 - \frac{(\text{Power pick up - Effective power})}{\text{active power}} = 0.75$$

The figures are inconsistent within the paper, but using the quoted figure of 17.8 MW as the speed × total drag, total effective power (assumed to be at steady state, on the level).

Aerodrag	61%	10.9 MW
Mag drag	25%	4.5 MW
Cooling drag	14%	2.4 MW
		17.8 MW

i.e. the cooling drag is ∿ 20% the magnitude of the aerodynamic drag, and 54% the magnitude of the magnetic drag.

Winkle quotes the mix for the propulsion power as being (for a short stator EMS)

Aerodrag	45%
Mag drag	20%
Cooling drag	11%
Residual acceleration	24%

i.e. virtually identical with Hebst, even though the vehicle weight has now changed to 270 tonnes.

Winkle also quotes an aerodynamic coefficient $C_W F = 9.0\ m^2$, which corresponds to 68.2 kN or 7.6 MW at 400 km/h. His figures for traction resistance and mechanical propulsion power (128 kN and 14.2 MW) do not fit with the mix mentioned. 68.2 kN is 53.3% of 128 kN, so by changing the amount of residual acceleration, but keeping the ratios of magnetic and cooling drags to aerodrag the same, the mix would become

Aerodrag	53.3%	68.2 kN	7.6 MW
Mag drag	23.7%	30.3 kN	3.4 MW
Cooling drag	13.0%	16.7 kN	1.8 MW
Residual acceleration	10.0%	12.8 kN	1.4 MW
		128.0 kN	14.2 MW

Here the cooling drag is 24% the magnitude of the aerodynamic drag, and 55% the magnitude of the magnetic drag.

Winkle suggest values of power factor and efficiency for both the EMS designs. The total picked up active power for the EMS short stator is quoted as 25.6 MW, which suggests an efficiency of 0.555.

The long stator motor efficiency and power factor suggested by Winkle is 0.8 and 0.72 respectively. Comparing this apparent efficiency of 0.58 to the 0.3 of the short stator motor illustrates that for every kW of drag supplied by the propulsion, the terminal rating of the short stator machine would have to be roughly twice that of the long stator equivalent.

The characteristics of Hebst's and Winkle's vehicles are given in Table 5

Common details:	Vehicle length (train)	91m
	Length of end section	32m
	Length of middle section	27m
	No. of sections	3
	Speed	400 km/h
	No. of passengers	300

(continued over)

	Hebst	Winkle Short Stator	Winkle Long Stator
Maximum vehicle mass, t	327	270	205
Resulting payload, t	34	30	30
Tractive resistance @ V = 400 km/h, kN	160	128	63
Aerodynamic coefficient $C_W F$, m^2	12.9	9.0	6.3
Mechanical propulsion power @ V = 400 km/h, MW	17.8	14.2	7.0
$\cos\psi$	0.5	0.5	0.72
η	0.7	0.6	0.8
Picked up active power @ r = 400 km/h, MW	25.6	25.6	8.8

Table 5. Characteristics of 3 Car EMS Designs

3.3 Statusseminar EMS designs

Chapter D, "Design of EMS Vehicle and Guideway," by Weidinger of Transrapid-EMS (2) gives outline designs for both long and short stator propelled vehicles, with passenger and goods payloads.

The common characteristics are reproduced in Table 6, and sections of proposed Revenue Vehicles are shown in Figure 3.

Vehicle length (train)	64 m
Length of one section	32 m
No. of sections	2
Speed	400 km/h
No. of passengers	240
Payload	24 tonnes
Maximum vehicle width	4.2
Track gauge	3.0 m
Average acceleration	0.3 m/s^2
Average braking deceleration	0.75 m/s^2
Residual acceleration	0.013 g
Aerodynamic coefficient $C_W F$	4.75 m^2

Table 6. Common characteristics of 2 Car EMS Designs

It should be noted that a common aerodynamic coefficient is used for the long and short stator designs. The short stator vehicle has protruding brushgear, but this only affects the aerodynamic drag by 5% (200 kW).

Extension of the two designs to 500 km/h and 300 km/h operation was performed and the power division and weight breakdown were presented graphically. No estimates were given for the power factor or efficiency of the designs.

Figures 4 and 5 show the distribution systems used for the short and long stator propulsions. The main difference is the absence of mechanical pickup for the long stator design. A linear generator provides the power transfer to the on-board network. The difference of weight of only 5 tonnes between EMS vehicles despite the lack of massive on-board components for propulsion on the long stator vehicle is caused by a larger magnet weight decided by a lower working current density, and by an increased battery weight required to maintain slow speed running.

The short stator machine picks up power from a 4 kV d.c. rail, whereas the long stator machine has the 12 km distance between substations subdivided into about 8 subsections, through auxiliary thyristor switching and tapping, to carry the variable frequency line power.

4. EMS short stator system.

4.1 Drag figures at 400 km/h

The power division of a short stator EMS vehicle (total weight 170 tonnes) is given in Chapter D of the Statusseminar (2). Knowing the aerodynamic coefficient of 4.75 m^2 gives an aerodrag power of 4.0 MW, the steady state propulsion power (6.6 MW) can be split down into aerodrag and 2.6 MW of remaining power. Presumably the majority of the 2.6 MW is cooling drag, but the text does not specifically refer to it as such.

The power for lift and guidance comes to 0.5 MW or $\sim$ 3 kW/tonne vehicle weight. The lift specific power is $\sim$ 2 kW/t. Residual acceleration propulsion power is the power surplus needed for the extra acceleration over gradients, at cruise speed.

Table 7 gives a breakdown of the effective propulsion power required.

	Power, MW	Drag, kN	Lift/drag	Specific Power, kw/t
Lift / Guidance	0.5	4.5	370	2 / 1
On board systems	0.4	3.6	463	2
Aerodynamic drag	4.0	36.0	46	24
Remaining s.s. drag	2.6	23.4	71	15
Total s.s. drag	(7.5)	(67.5)	(25)	(44)
Residual acceleration	2.4	21.6	77	14
Effective total drag	9.9	89.1	19	58

Table 7. Power Breakdown for Short Stator EMS

4.2 Drag figures at 500 km/h

Weidinger only gives the 500 km/h values of steady state and maximum power with respect to the maximum power at 400 km/h.

The steady state figure is 14.5 MW, maximum figure 18.2 MW, interpolated from a graph.

Because of the increase in propulsive power required, two linear induction motors (LIM) per section are necessary, and this increases the all-up weight by 20% to 205 tonnes.

As a check on the graphical values, the 400 km/h values can be scaled approximately as follows.

(a)	Lift and guidance power	: scales as $(\text{velocity})^{3/2}$	, .5 × 1.42	.7 MW
(b)	On-board systems	: assume scales with vehicle weight	, .4 × 1.2	.5 MW
(c)	Aerodynamic drag	: scales as $(\text{velocity})^3$	, 4.0×1.42^2	8.1 MW
(d)	Remaining s.s. drag	: assume this is all cooling drag, and motors are doubled up	, 2.6 × 2	5.2 MW
Total steady state drag,		sum of (a) - (d)	,	14.5 MW
(e)	Residual acceleration.	: ($.013g$ m/s^2) scales with velocity and weight	2·4 × 1·26 × 1·2 ,	3.7 MW
Total effective drag				18.2 MW

4.3 Power Factor and Efficiency

The statusseminar makes no attempt to display the power factor or efficiency of the short stator machines. The product of the two, i.e. the ratio of active power output to total complex power input, is not likely to be high.

Winkle (6) quotes an efficiency of 0.6 and power factor of 0.5 (apparent efficiency = $\eta \cos\theta = 0.3$) and states that new calculations suggest efficiencies ~ 0.78 and power factors of $\sim .65$, which brings the apparent efficiency up to 0.51. It must be emphasized that these are calculations and do not represent measurements on constructed machines.

Since the apparent efficiency is not known with any certainty at 400 km/h, predictions for 500 km/h must be questionable. Although it might be argued that the "goodness" of the overall machine could be expected to increase, in fact the design calls for two motors per section, whose output rating will not change much from the 400 km/h motor. (18.2 MW at 500 km/h, 9.9 MW at 400 km/h). Therefore the estimates of input power will be made using the same power factor and efficiency used at 400 km/h.

4.4 Final Figures for short stator EMS

The total steady state and total effective drags are shown in Table 8. Note that the 500 km/h individual breakdown is from deduced values, and the total drag figures are interpolated from a graph in reference (2).

The machine total active power input and total complex power input are deduced from values of power factor and efficiency suggested by reference (6). They are shown in Table 9.

No attempt has been made here to estimate increased losses in current collection systems running at 500 km/h, if indeed this is possible for loads of $\sim$ 30 MW (see Section 6.1). An increased loss in the on-board power convertor which has a 4 kV D.C. input and output to the double-sided linear induction motors must also be expected, as well as in the 4 kV distribution system itself.

	400km/h	500km/h
Lift and guidance power	0.5	0.7
On-board systems	0.4	0.5
Aerodynamic drag	4.0	8.1
Remaining s.s. drag	2.6	5.2
Total s.s. drag	7.5	14.5
Residual acceleration	2.4	3.7
Effective drag total	9.9	18.2
Vehicle mass (tonnes)	170	205

Table 8. Power Breakdown Comparison for 400 and 500 km/h Short Stator EMS (Power in MW)

	400 km/h		500 km/h	
Total s.s. drag, MW	7.5		14.5	
Propulsive power, machine input (@ η),MW	12.5(.6)	9.6(.78)	24.2(.6)	18.6(.7
" " , total input (@ $\cos\theta$),MVA	25.0(.5)	14.8(.65)	48.4(.5)	28.6(.
including residual acceleration:				
Total effective drag, MW	9.9		18.2	
Propulsive power, machine input (@ η),MW	16.5(.6)	12.7(.78)	30.3(.6)	23.3(.7
" " , total input (@$\cos\theta$), MVA	33.0(.5)	19.5(.65)	60.7(.5)	35.9(.

Table 9. Total Machine Input Active and Complex Power for Short Stator EMS

Note: Losses in the d.c. line and pick-up system are not included.

5. EMS long stator system

5.1 Drag figures at 400 km/h

Some slight inconsistency exists in reference (2) on the values of drag forces on the long stator vehicle. Weidinger's Chapter D and Weh's Chapter G, "Investigation into EMS Long-stator Technology," values are given in Table 10

Weidinger		Weh	
Lift and guidance drag	0.2	Iron losses	0.5
On board systems	0.2	On board systems	0.35
Aerodynamic drag	4.0	Aerodynamic drag	4.35
Remaining s.s. drag	1.7	Winding loss	0.8
Steady state drag	6.1	Distribution loss	0.8
		Steady state drag	6.8

Table 10. Different Drag Powers (in MW) Associated with Long Stator EMS.

Weh's total for power output (Aerodynamic drag + on-board systems) is 4.7 MW; this could be the source of Leonhard's figure for power supply requirement.

It is difficult to know which figures to use, especially as the cooling drag is unknown. For continuity with section 4, Weidinger's figures will be used with the assumption that the distribution and winding losses are the main system losses.

In common with the short stator design, a residual acceleration of 0.013g requires a power of 2.4 MW.

Table 11 gives a breakdown of the effective propulsion power required.

	Power, MW	Drag, kN	Lift/drag	Specific Power, kW/
Lift and Guidance	0.2	1.8	899	1.2
On board systems	0.2	1.8	899	1.2
Aerodynamic drag	4.0	36.0	45	24.2
Remaining s.s. drag	1.7	15.3	106	10.3
Total s.s. drag	(6.1)	(54.9)	(29)	(36.9)
Residual acceleration	2.4	21.6	75	14.5
Effective total drag	8.5	76.5	21	51.4

Table 11. Power Breakdown for long stator EMS

5.2 Drag figures at 500 km/h

As with the figures for the short stator vehicle, steady state and maximum power with respect to the maximum power at 400 km/h are plotted in reference (2). In addition a numerical value of 11.5 MW is given in the text as the steady state 500 km/h power requirement. The graphical value for maximum power at 500 km/h is 14.8 MW. The vehicle weight is increased by 10%, to ∿ 180 tonnes for the speed increase.

Scaling the 400 km/h values approximately, results in a difference of 200 kW from the quoted 11.5 MW, s.s. power

(a) Lift and guidance	: Assume scales as (velocity)$^{3/2}$,	.2×1.42	0.3MW
(b) On board systems	: Assume scales with vehicle wt.,	.2×1.1	0.2MW
(c) Aerodynamic drag	: scales as (velocity)^3,	4.0×1.42^2	8.1MW
(d) Remaining s.s. drag	: assume all cooling, drag scales as (velocity)^2	1.7×1.59	2.7MW

(e) Remaining 500 km/h s.s. drag	0.2 MW
Total steady state drag, sum of (a) - (e)	11.5 MW
(f) Residual acceleration : scales with velocity and weight 2.4 × 1.26 × 1.1	3.3 MW
Total effective drag	14.8 MW

5.3 Power factor and Efficiency

As with the short stator designs, the statusseminar does not quantify the power factor or efficiency expected with the full size vehicle design. However, Weh's figures for 800 kW winding loss and 800 kW distribution loss indicate an efficiency of

$$\eta = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{1.6}{6.1+1.6} = .79.$$

For comparison, Winkle's figures are 0.8 for efficiency and 0.72 for power factor.

Assuming $\eta = .79$ and $\cos\theta = .72$, and using the power factor - efficiency relationships from section 2.3.2,

$$\cos\theta = \frac{1}{\left(1 + \frac{X^2}{R^2}(1-\eta)^2\right)^{\frac{1}{2}}} \quad , \quad \frac{X}{R} = \frac{\tan\theta}{(1-\eta)} = 4.59$$

The corresponding reactance-resistance ratio at 500 km/h is 5.78.

As in Section 2.4, the losses can be scaled by the ratio of drag forces, squared, to obtain loss at differing drag powers. The efficiency can be computed, and power factor obtained using one of the above formulae.

It should be noted that the equations used for power factor estimation are suitable for an air cored armature, as in the L.S.M. Inherent saturation and extra leakage in the EMS long stator armature implies that the resulting power factors will be lower than calculated, leading to an increased MVA requirement to that tabulated. Detailed design characteristics are not available, and so the estimates have been made on this basis.

5.4 Final Figures for long stator EMS

The total steady state and total effective drags are shown in Table 12. Note that the 500 km/h individual breakdown is from deduced values, and total drag figures are interpolated from a grasph in reference (2).

Total active and complex power inputs to the machine are shown in Table 13. The increased losses are scaled from a 1.6 MW loss on the steady state 400 km/h baseline. Power factor estimates are made which are on the conservative side since saturation and leakage effects are ignored.

	400km/h	500km/h
Lift and guidance power	0.2	0.3
On board systems	0.2	0.2
Aerodynamic drag	4.0	8.1
Remaining s.s. drag	1.7	2.9
Total s.s. drag	6.1	11.5
Residual acceleration	2.4	3.3
Effective drag total	8.5	14.8
Vehicle mass (tonnes)	165	180

Table 12. Power Breakdown Comparison for 400 and 500 km/h Long Stator EMS.
(Power in MW)

	400km/h	500km/h
Total s.s. drag, MW	6.1	11.5
Propulsive power, machine input (@ η), MW	7.7(.79)	15.1(.76)
" " , total input (@ $\cos\theta$), MVA	10.7(.72)	26.0(.58)
including residual acceleration:		
Total effective drag, MW	8.5	14.8
Propulsive power, machine input (@ η), MW	11.6(.73)	20.8(.71)
" " , total input (@ $\cos\theta$), MVA	18.4(.63)	40.8(.51)

Table 13. Total Machine Input Active and Complex Power for Long Stator EMS

6. Analysis of Final Figures

6.1 Common Points.

It must be emphasized that the values obtained are modified from the published speed extrapolations for short and long stator EMS designs by assumptions of efficiency and power factor. For the EDS system, however, the 400 km/h extrapolation is obtained by reworking the 500 km/h values, and this does not represent a re-optimised system.

Inclusion of a residual acceleration of 0.013g into EDS figures brings the accelerating mode of operation in line with that of the EMS studies.

The short stator EMS design has no estimate for the distribution loss in the 4 kV D.C. line, or current pickup loss or on board inverter loss. A typical line copper loss (equivalent to voltage regulation) might be 15%, which represents a 2.2 MW increase on just the 12.5 MW active power load drawn by a 400 km/h accelerating LIM. Overall power factor efficiency product of 0.51 for the short stator system is evaluated, although 0.3 represents a more probable figure.

Figures for the long stator EMS system must be regarded as tentative, since the only linear testing has been on the 100 m track at Kassel (Thyssen Henschel) and the 30 m track at Braunschweig, at low speed..

6.2 Active Power Requirements.

The figures generated in the previous sections are displayed as the active power requirements for each of the three Maglev systems in Figure 6. The total values are broken down into their constituent parts. Steady state (i.e. cruise) power is the sum of blocks 1-5 for the EMS and 1, 2 and 5 for EDS. Including a residual acceleration (block 6) incurs an additional loss (block 7), which added to the steady state value gives the total accelerating active power requirement shown at the top of each column.

It is immediately apparent that in terms of real power consumed the long stator EMS and the EDS are roughly equivalent, when loaded, at 500 km/h. The low efficiency short stator uses roughly 45%, the high efficiency short stator roughly 11%, more active power (ignoring d.c. line loss). Including a 15% line loss the figures are 70% and 31% respectively.

At 400 km/h, using the unoptimised EDS as a base of 100%, the equivalent long stator EMS figure is 80%, loaded, short stator EMS 114% and 88% (134% and 103% with 15% line loss).

Figure 7 expresses the active power requirement as a percentage of the steady state, 500 km/h EDS value of 16.7 MW.

6.3 Reactive Power Requirements.

Table 14 shows total active, reactive and complex power of the Maglev systems, for the four operating conditions. Figures which include an allowance for the EMS D.C. rail loss estimated at 15% complete the range of data.

Table 15 is a reworked version of Table 14, normalised by the 500 km/h steady state EDS values.

The most striking feature of Table 15 is the relative success of the EDS system in using only small amounts of reactive power to provide propulsion of the vehicle. As mentioned in Section 2.4 this is mainly because the superconducting magnets provide the majority of machine air gap field, and also because of the low per-unit reactance of the air-cored long stator winding. The figures for steady state 500 km/h operation of the long stator EMS machine are 21.2 MVAR, i.e. 241% that of the EDS design. Roughly the same figure is obtained for the high efficiency short stator EMS (247%), and inclusion of D.C. line brings the figure up to 291%. The low efficiency short stator EMS figures are 476% and 561% respectively.

Table 16 is Table 14 reworked, normalised by the 400 km/h steady state EDS values.

TABLE 14 Total Active, Reactive and Complex Power of Systems

EDS		MW	MVAR	MVA
	1	11.1	5.1	12.2
	2	14.5	7.4	16.3
	3	16.7	8.8	18.9
	4	20.9	13.0	24.6

EMS		MW	MVAR	MVA
LONG	1	7.7	7.4	10.7
STATOR	2	11.6	14.3	18.4
	3	15.1	21.2	26.0
	4	20.8	35.1	40.8

EMS		MW	MVAR	MVA
SHORT	1	9.6	11.2	14.8
STATOR	2	12.7	14.8	19.5
HIGH η	3	18.6	21.7	28.6
	4	23.3	27.3	35.9

EMS		MW	MVAR	MVA
SHORT	1	11.3	13.2	17.4
STATOR	2	14.9	17.4	22.9
HIGH η	3	21.9	25.6	33.7
+15% Loss	4	27.4	32.1	42.2

EMS		MW	MVAR	MVA
SHORT	1	12.5	21.7	25.0
STATOR	2	16.5	28.6	33.0
LOW η	3	24.2	41.9	48.4
	4	30.3	52.5	60.6

EMS		MW	MVAR	MVA
SHORT	1	14.7	25.5	29.4
STATOR	2	19.4	33.6	38.8
LOW η	3	28.5	49.4	57.0
+15% Loss	4	35.6	61.7	71.2

1 400 km/h steady state
2 400 km/h accelerating
3 500 km/h steady state
4 500 km/h accelerating

EDS		MW	MVAR	MVA
	1	66	58	65
	2	87	84	86
	3	100	100	100
	4	125	148	130

EMS		MW	MVAR	MVA
LONG	1	46	84	57
STATOR	2	69	163	97
	3	90	241	138
	4	125	399	216

EMS		MW	MVAR	MVA
SHORT	1	57	127	78
STATOR	2	76	168	103
HIGH η	3	110	247	151
	4	140	310	190

EMS		MW	MVAR	MVA
SHORT	1	68	150	92
STATOR	2	89	198	121
HIGH η	3	131	291	178
+ 15% loss	4	164	365	223

EMS		MW	MVAR	MVA
SHORT	1	75	247	132
STATOR	2	99	325	175
LOW η	3	145	476	256
	4	181	597	321

EMS		MW	MVAR	MVA
SHORT	1	88	290	156
STATOR	2	116	382	205
LOW η	3	171	561	302
+15%loss	4	213	701	377

1. 400 km/h steady state
2. " accelerating
3. 500 km/h steady state
4. " accelerating

Table 15. Total Active, Reactive and Complex Power of Systems as a Percentage of EDS 500 km/h steady state values.

EDS		MW	MVAR	MVA
	1	100	100	100
	2	131	145	134
	3	150	173	155
	4	188	255	202

EMS		MW	MVAR	MVA
LONG	1	69	145	88
STATOR	2	105	280	151
	3	136	416	213
	4	187	688	334

EMS		MW	MVAR	MVA
SHORT	1	86	220	121
STATOR	2	114	290	160
HIGH η	3	168	425	234
	4	210	535	294

EMS		MW	MVAR	MVA
SHORT	1	102	259	143
STATOR	2	134	341	188
HIGH η	3	197	502	276
+15% loss	4	247	629	346

EMS		MW	MVAR	MVA
SHORT	1	113	425	205
STATOR	2	149	561	270
LOW η	3	218	822	397
	4	273	1029	497

EMS		MW	MVAR	MVA
SHORT	1	132	500	241
STATOR	2	175	659	318
LOW η	3	257	969	467
+15% loss	4	321	1210	584

1. 400 km/h steady state
2. " accelerating
3. 500 km/h steady state
4. " accelerating

Table 16. Total Active, Reactive and Complex Power of Systems as a Percentage of EDS 400 km/h steady state values.

6.4 Complex Power Requirements

Figure 8 shows the total complex and active power requirements of the Maglev systems. The power factor of the systems is simply the abscissa to ordinate ratio for each of the operating conditions. Since it is the complex power value that must be designed for and for which system penalties will be incurred, the relative merits of the three systems is demonstrated by the size of the ordinate. Figure 9 displays just the total complex power requirements, in percentages of the 500 km/h steady state EDS, for the four operating conditions. The EMS long stator has 38% more, the high efficiency short stator 51% more than the EDS base, despite the rough equivalence of active power used. Including line loss the short stator value rises to a 78% increase. If the lower efficiency short stator EMS is considered, then the figures become increases of 156% and 202% on the EDS 100%.

7. Conclusions.

7.1 System Conclusions.

Because of the multiplicity of operating conditions, the systems' performance will be taken in turn, referenced to the values obtained for 400 km/h (Table 16) and 500 km/h (Table 15), EDS steady state service.

7.1.1. EMS Long Stator.

7.1.1.1. 400 km/h. Compares well with the EDS in terms of active power (69% EDS value) and complex power (88%). Uses, however, an extra 45% more reactive power. When loaded, the advantages are degraded, and needs an extra 51% more complex power compared to an EDS requirement of an extra 34%.

7.1.1.2. 500 km/h. Marginally better than one EDS in terms of active power (90%) but uses 141% more reactive power, resulting in an extra 38% total complex power needed for steady state. Grade operation requires an extra 116% more complex power, compared with an EDS 30% requirement.

7.1.1.3 Power Factor and Efficiency. At the 400 km/h operating condition, the apparent efficiency of the long stator motor is 0.57.

Operation at grade or at 500 km/h, steady state, and at grade, reduces this to 0.46, 0.44 and 0.36 (Table 17). As mentioned in previous sections, this means that an excessive amount of complex power is required for other than low speed cruise. Insufficient evidence exists to confirm these values which are computed predictions. Only very low speed testing on short linear tracks has been accomplished (Section 6.1).

EDS		η	$\cos\theta$	$\eta\cos\theta$
	1	0.74	0.91	0.67
	2	0.70	0.89	0.62
	3	0.75	0.88	0.66
	4	0.71	0.85	0.60

EMS		η	$\cos\theta$	$\eta\cos\theta$
LONG	1	0.79	0.72	0.57
STATOR	2	0.73	0.63	0.46
	3	0.76	0.58	0.44
	4	0.71	0.51	0.36

EMS SHORTSTATOR HIGHη	η	$\cos\theta$	$\eta\cos\theta$
	0.78	0.65	0.51

EMS SHORT STATOR LOW η	η	$\cos\theta$	$\eta\cos\theta$
	0.60	0.50	0.30

1. 400 km/h steady state
2. " accelerating
3. 500 km/h steady state
4. " accelerating.

Short stator values the same for all running conditions 1-4.

Table 17. Efficiency, Power Factor and Apparent Efficiency

7.1.2. EMS Short Stator

7.1.2.1 400 km/h. The high efficiency version compares well with the EDS in terms of active power, and including a line loss the values are virtually identical. However, uses 43% more complex power and 88% more (compared to 34% more) than the EDS, when loaded.

The low efficiency version is a lot worse; without including a line loss, the complex power used is twice that of the EDS; including a line loss, complex power is 141%.more than for steady state, and 218% more when loaded, (compared to 34% for the loaded EDS).

7.1.2.2 500 km/h. As might be expected, the operation of the linear induction motor at very high speed degrades its performance. The increases in complex power required at steady state operation for the high efficiency motor are 51%, and 78% including a line loss. Loading the vehicle results in 90% and 123% increases compared to 30% for the EDS.

A similar result for the low efficiency machine produces a requirement of 156% and 202% increases at steady state, with and without line loss, 221% and 277% compared to 30% for EDS when loaded.

7.1.2.3 Power Factor and Efficiency. As mentioned in Section 4.3, there is little performance data forthcoming about power factor and efficiency and their product for multi-megawatt motors. It was therefore decided to use the values of 0.6 and 0.78 for the low and high efficiency machines respectively, with power factors of 0.5 and 0.65, resulting in products of 0.30 and 0.51, and to assume that these values are load and speed invarient. In doing so it cannot be argued that particularly "bad" machines have been used in the analysis and comparisons.

7.1.3. EDS Power Factor and Efficiency. A previous section (2.4) has indicated that chosen power factor and efficiency values of the EDS are energy and capital trade-offs rather than being inherently limited. There is little change in apparent efficiency in going from 500 to 400km/h (0.67 to 0.66, steady state, 0.62 to 0.60 loaded).

7.2 Overall Conclusions.

This study has attempted to establish total power requirements for the three German Maglev vehicles operating under similar conditions. The comparisons cannot be strictly rigorous, since the EMS and EDS vehicles are primarily designed for different baseline operation. However, the spread of system total complex power, at the trackside substations, (Figs. 8,9), is indicative of the type of system performance that might be expected for identical service conditions.

Several conclusions can be drawn from the dat studied, namely

(1) The EDS has good system performance at 500 and 400 km/h in terms of energy conversion and power consumption.

(2) The short stator induction machines for the EMS are unsuitable for high speed (500 km/h) operation, and are not very suited to 400 km/h operation, because of the high reactive power consumption resulting in excessive overall power requirement. For example, at 500 km/h, compared to the EDS machine on cruise, the higher efficiency LIM studied required 1.8 times, and the lower efficiency LIM, 3.0 times as much total complex power. At 400 km/h, the figures are 1.4 and 2.4 times for the higher and lower efficiency LIMs studied, respectively.

(3) The long stator motor EMS appears to need marginally less power than the EDS at 400 km/h cruise (90% EDS value), but when loaded, or at the higher speed of 500 km/h, this slight advantage is lost; (loaded, 400 km/h, 1.13 times EDS value, 500 km/h, 1.4 times EDS value cruise, 1.7 times EDS, loaded).

An additional shortcoming is that the machine concept has only been tested at low speed, so high speed operating characteristics must be tentative.

(4) In assessing system performance, using the value of specific power (kW/tonne), lift to drag ratio or specific power consumption (Wh/passenger-km) only indicates active power supplied to make up thrust and (if included) losses in the system. Because of the low power factors in some of the systems, trackside and transmission components as well as Utility energy supply costing will be in terms of total complex power used by a system. The MVA as well as the MW requirements of a system must be obtained, related to a common guideway route and similar baseline specifications before a totally reasonable comparison can be made.

8. References

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E. Abel.
January 1978.
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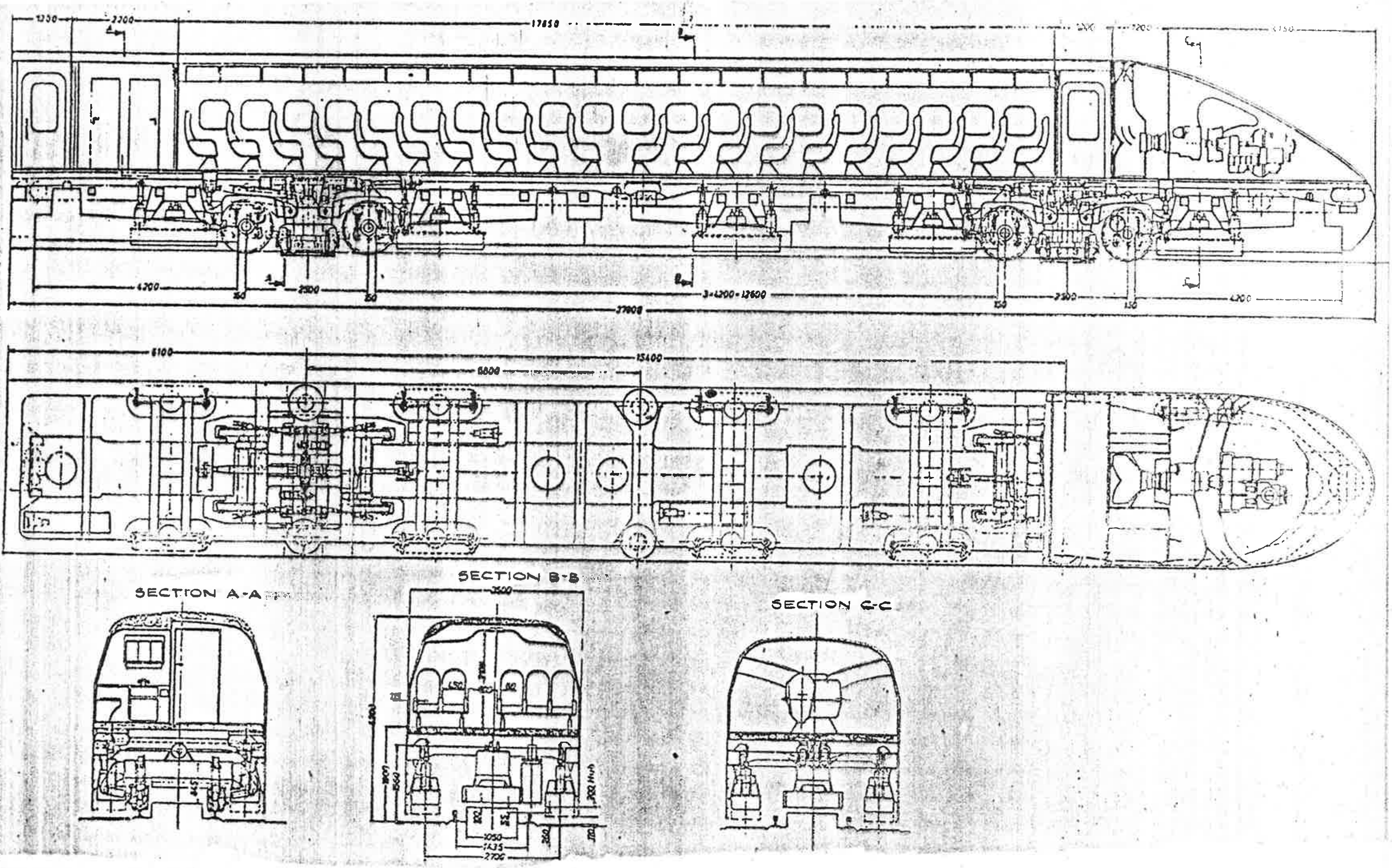

Fig.1 EDS Passenger vehicle AVE/P06

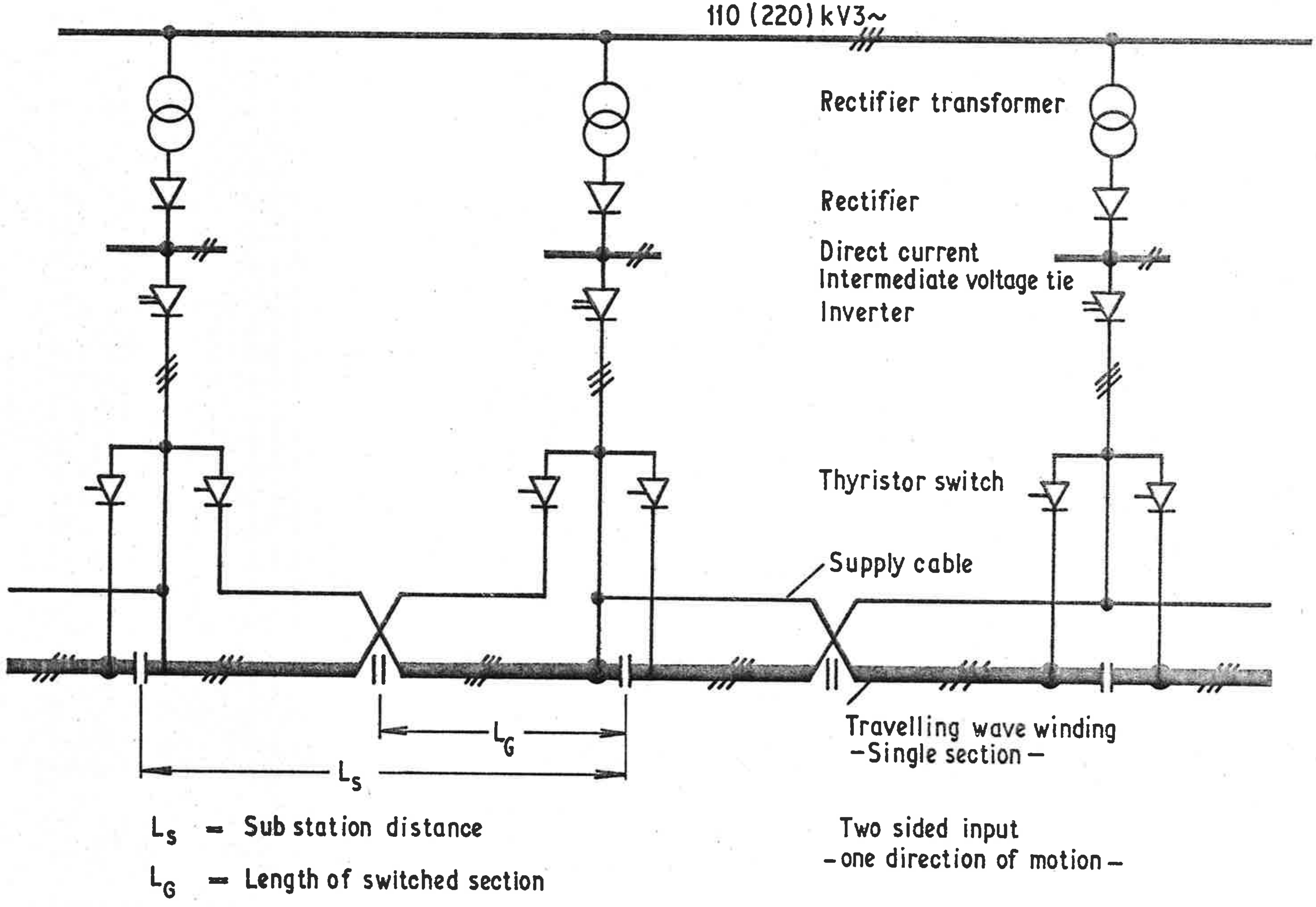

Fig.2. Distribution diagram for the EDS long stator motor propulsion.

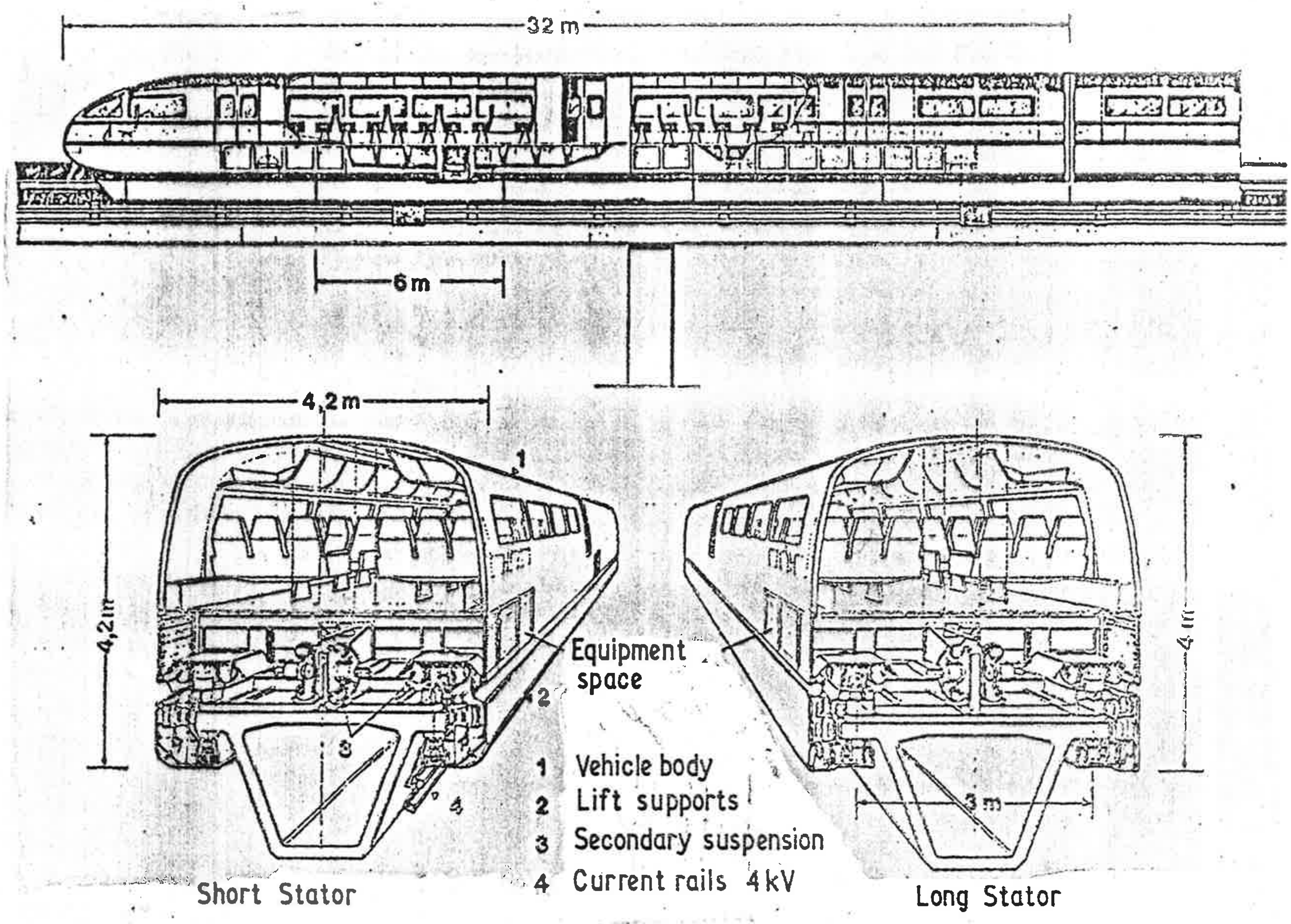

Fig. 3. EMS Passenger vehicle.

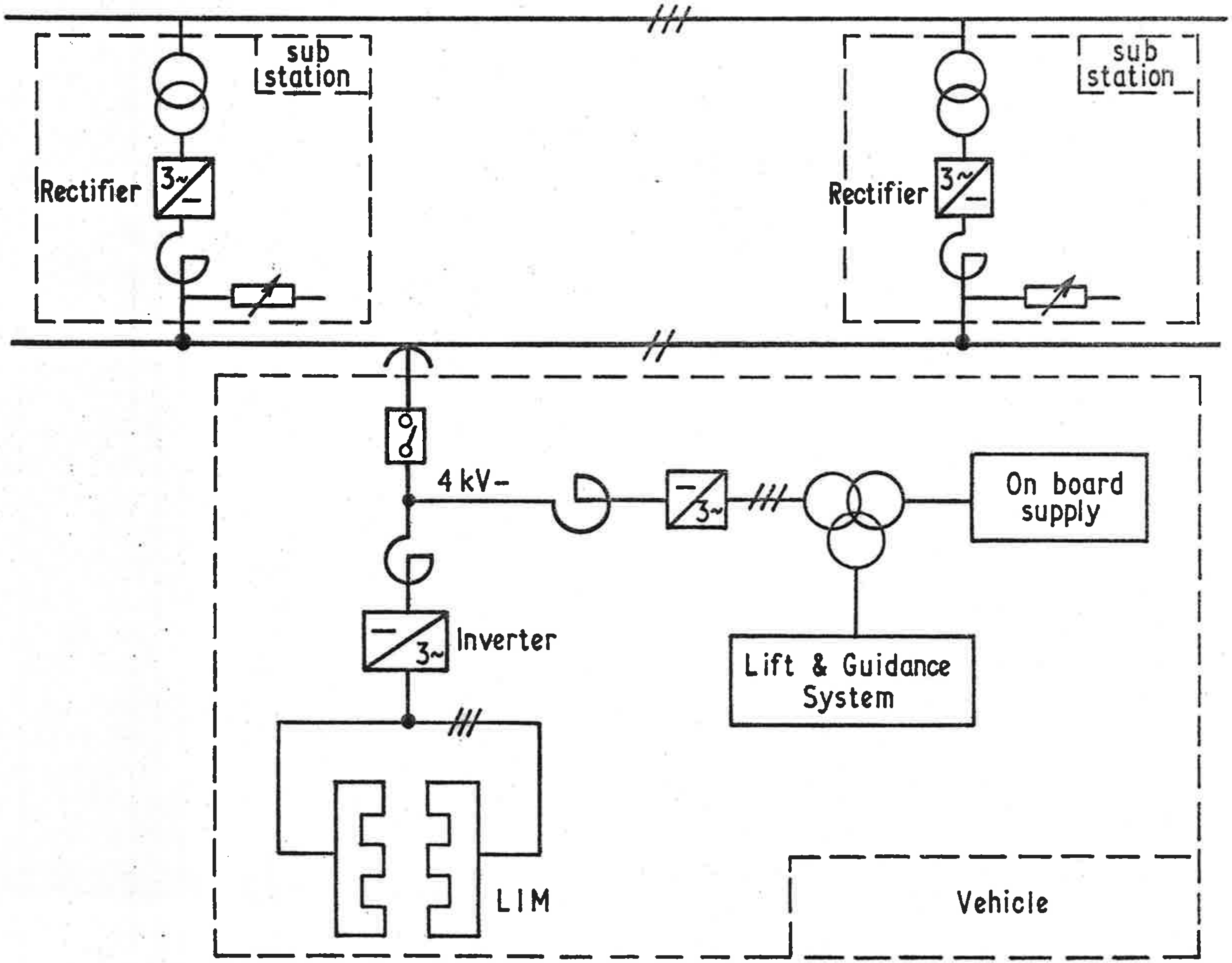

Fig.4. Distribution diagram for the EMS short stator motor propulsion.

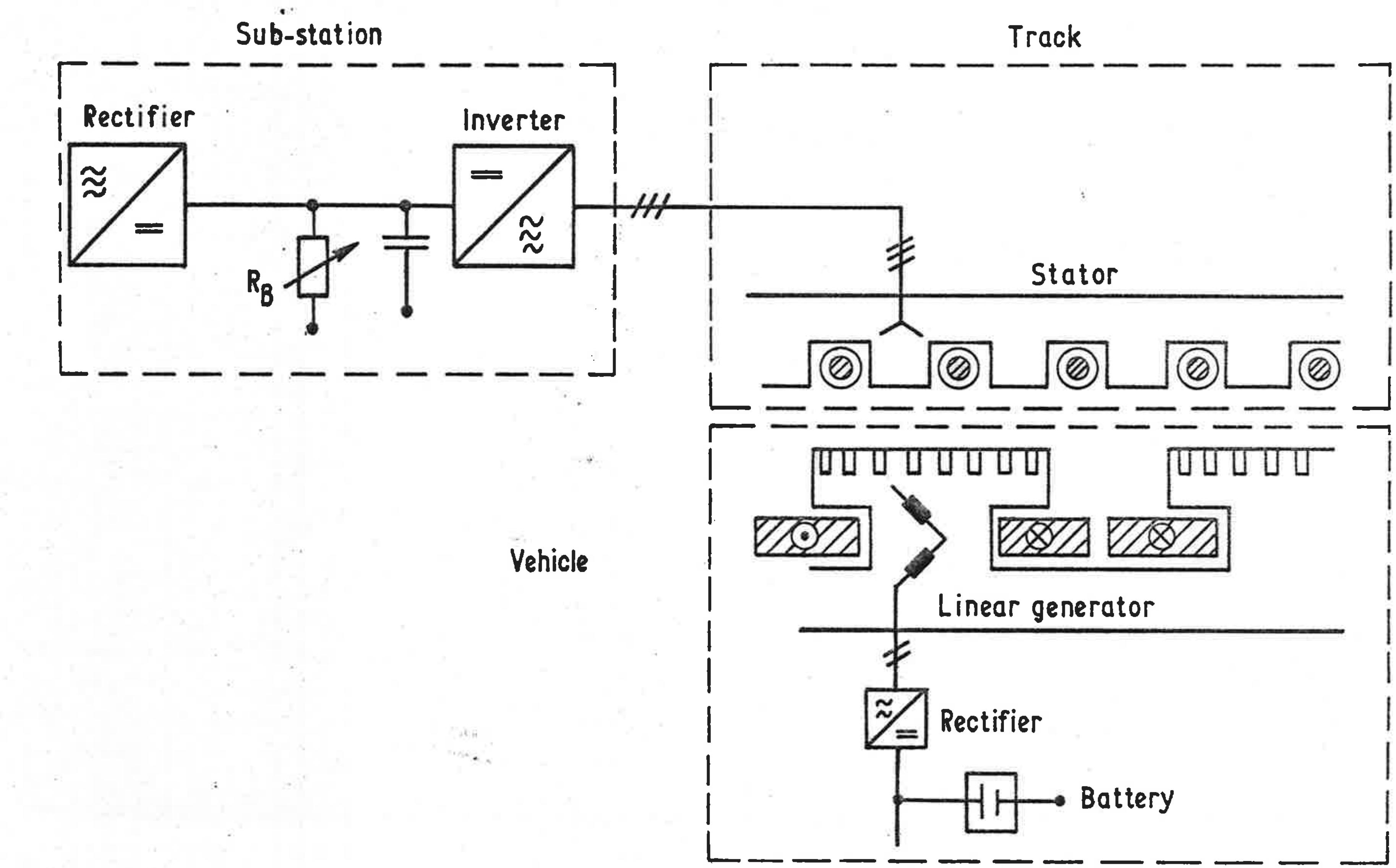

Fig. 5. Distribution diagram for the EMS long stator motor propulsion.

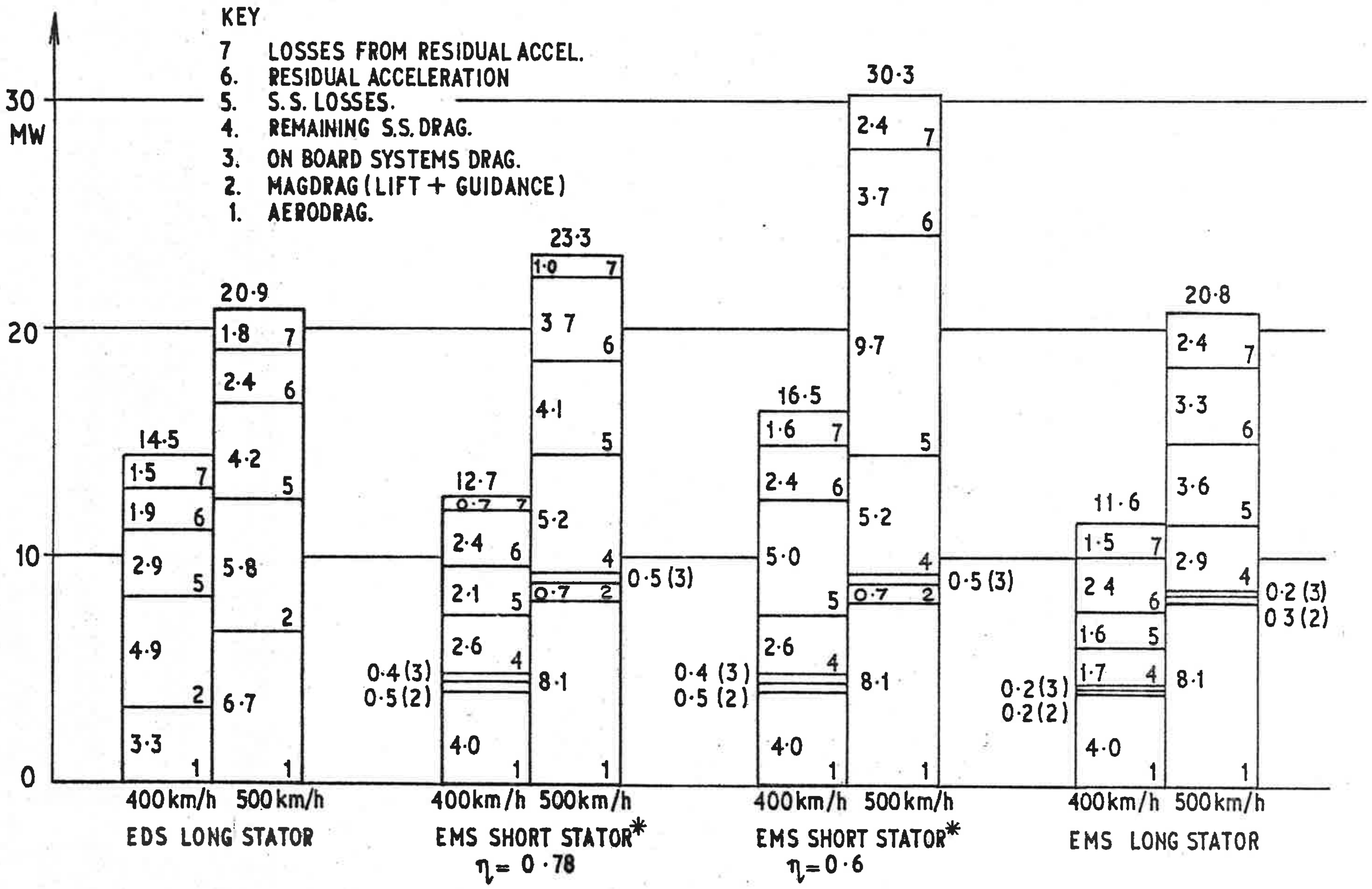

Fig. 6. **Total active power of systems (MW)** *NOTE. D.C. DISTRIBUTION & PICKUP LOSS NOT INCLUDED.

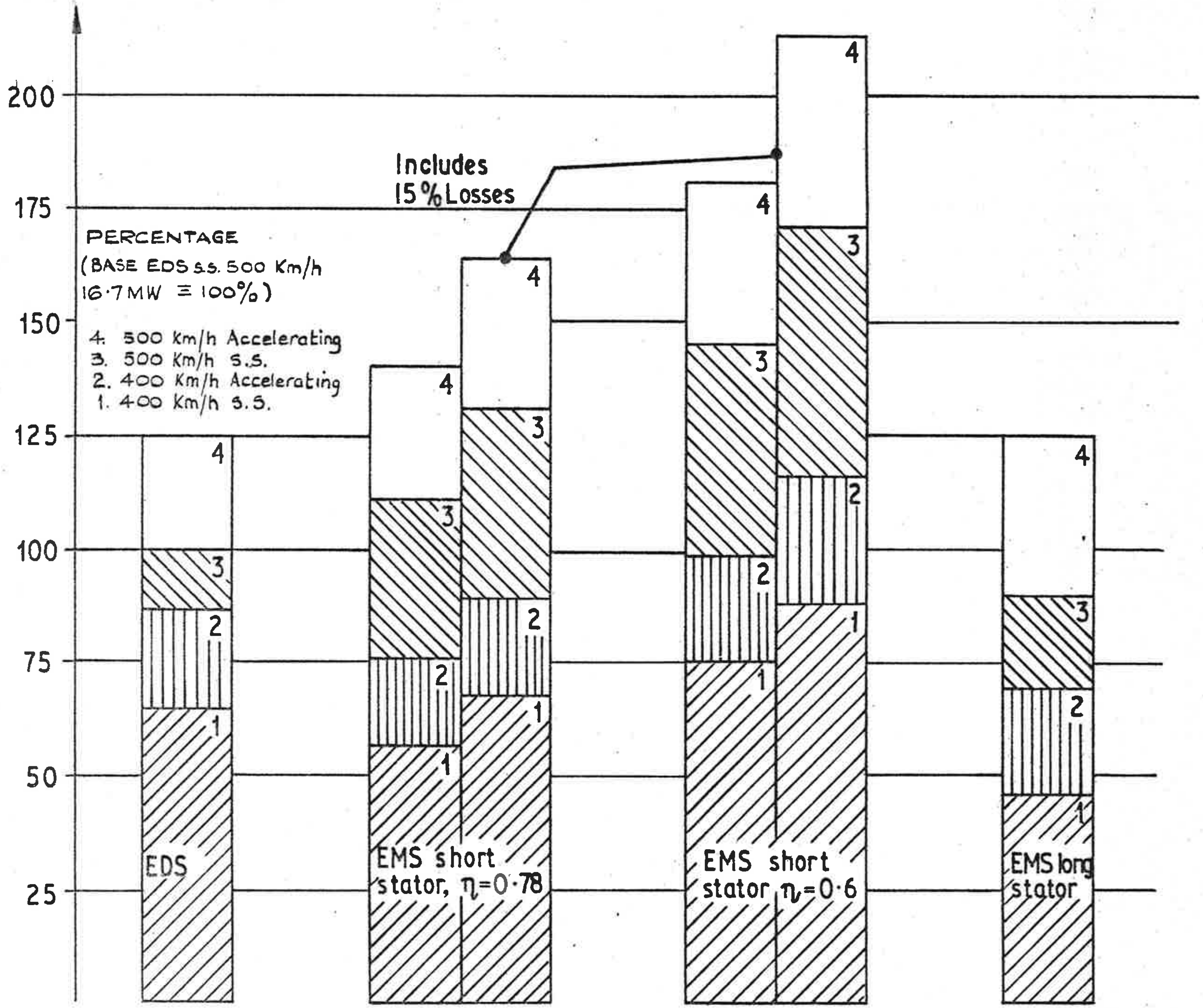

FIG. 7. Relative system active power requirements at 500 and 400 KM/H.

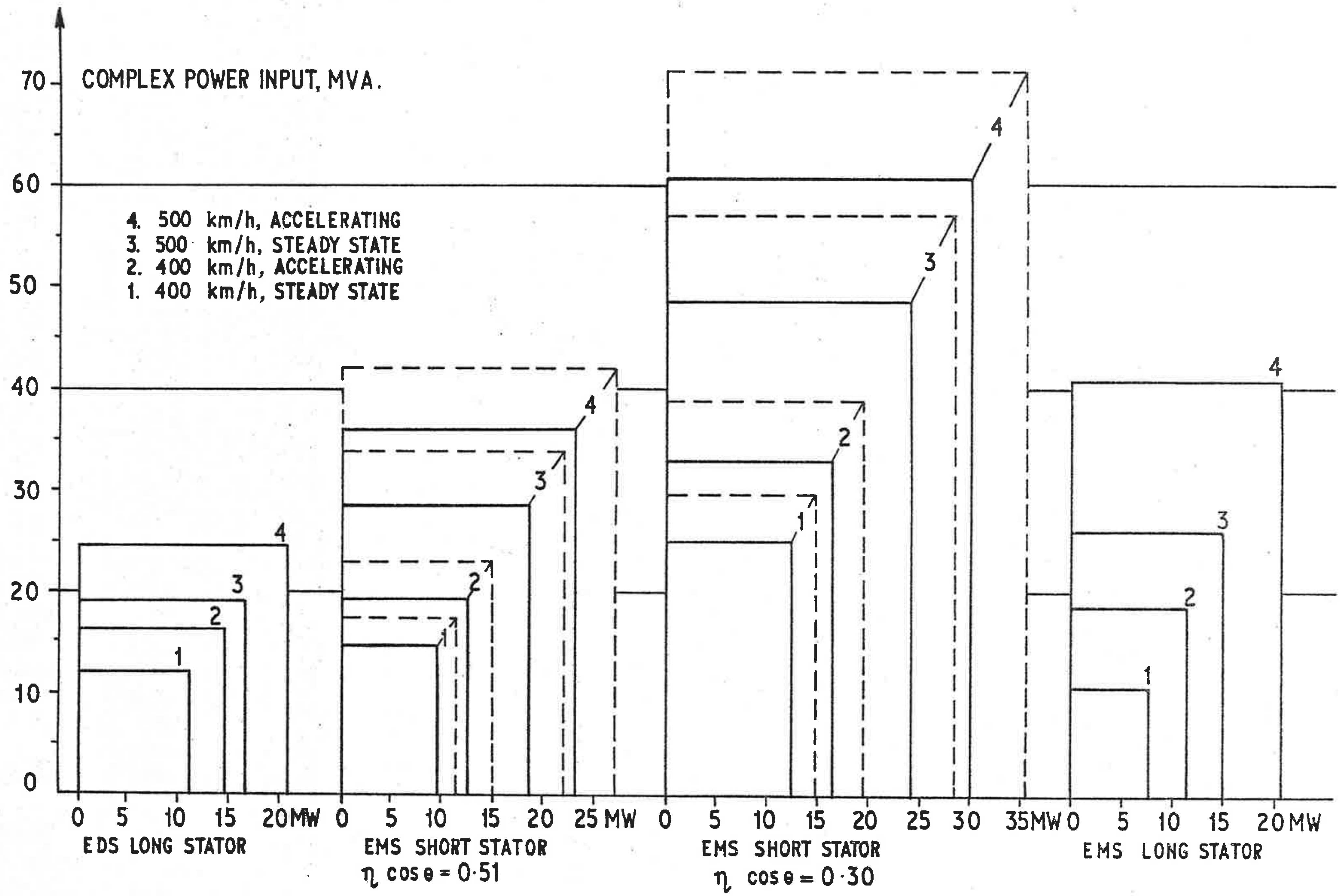

Fig. 8. Total complex and active power of systems. Note:- Short stator: Broken lines indicate an included 15 % distribution loss

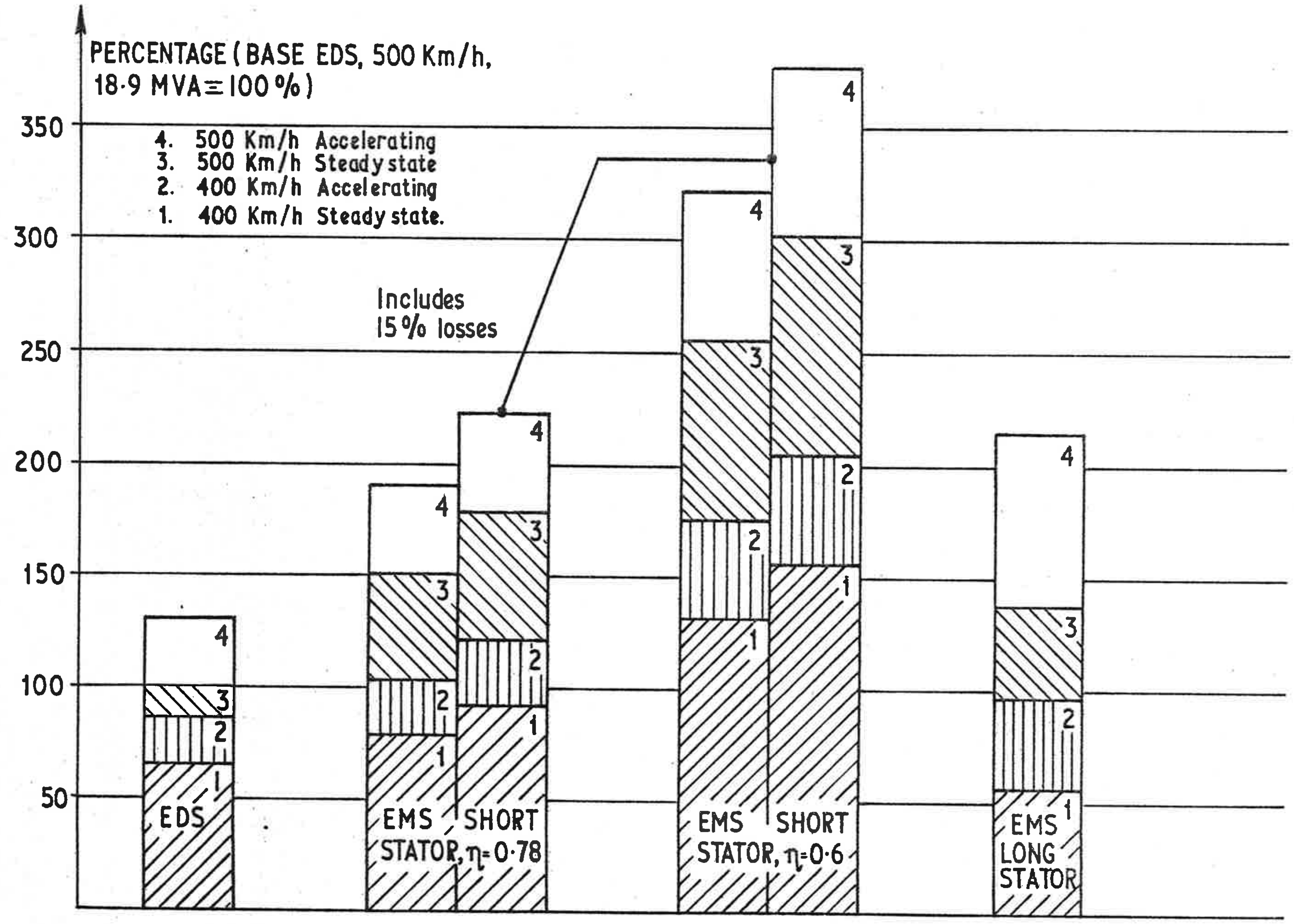

Fig. 9. Relative system total complex power requirements at 500 and 400 Km/h