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Comparison between Asynchronous and Synchronous Linear Motors as to Thermal Behavior

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ABSTRACT

A linear motor has a lot of advantages in comparison with conventional feed mechanisms: high transitional speed, acceleration, high control performance and good positioning at high speed. Through the omission of a power transfer element, the linear motor shows no wear and no backlash, has a long lifetime and is easy to assemble. Recently, the two types of linear motors, asynchronous and synchronous linear motors, are often applied to machine tools as a fast feed mechanism. In this paper, a comparison between the two types of linear motors as to power loss and thermal behavior is made. The heat sources of the linear motor - the electrical power loss in the motor and the frictional heat on the linear guidance - are measured and compared. Also, the temperature on the linear motor and machine structure is measured and presented.

Keywords: Linear motor, machine tool, feed mechanism, power loss, thermal behavior, linear guidance

1. Introduction

A linear motor, which has the primary and the secondary part as fundamental element, is an unwounded form of a rotary motor. The primary part is correspondent to the stator and the secondary part to the rotor of a rotary motor. When the linear motor is used as a feed mechanism for the machine tools, a power or motion transfer element such as ball screw or rack-pinion system is not necessary. Because the linear motor moves directly through the induction force, it has a high linear velocity and an acceleration. Through the reduction of the inertia moment of the power transfer element, the linear motor has a good positioning accuracy. Therefore, the linear motor is suitable for the high speed and precision machine tools as a feed mechanism [1]. On the other side, the linear motor has a lower efficiency and greater power loss compared to a rotary motor. The higher power loss leads to the overheating of the linear motor itself and the thermal deformation of the neighboring machine structure during operation. For this reason, the linear motor in a machine tool is usually equipped with an effective cooling system [2].

In order to apply the linear motor to the machine tools, it is important to analyze and to improve the thermal behavior. Like a rotary motor, a linear motor is classified into asynchronous and synchronous linear motors according to the driving principle. The two types of the linear motor show different electrical and mechanical characteristics. In this paper, the thermal characteristics of the asynchronous and synchronous linear motors are compared. For a direct technical comparison, we investigated the two linear motors with the identical size and manufacturer. In section 2, construction, advantages and disadvantages of both motors are introduced. In section 3, the heat sources of the two types of linear motors are experimentally analyzed and compared. In section 4, the measured temperatures of the asynchronous and synchronous linear motors at the nominal current are presented.

2. Construction and Technical Comparison between Asynchronous and Synchronous Linear Motors

Fig. 1 shows the construction of asynchronous and synchronous linear motors. The construction of the primary part of the two motors is identical. The three phase windings are imbedded in the primary part, through which the current flows. The secondary part of the asynchronous and the synchronous linear motors are different. With the asynchronous linear motor, the secondary part is magnetized through the inductive current in the short circuit cage. Unlike the asynchronous motor, the secondary part of the synchronous motor is permanent magnets. Generally, the primary part moves with the machine table linearly on the fixed secondary part as a feed mechanism in the machine tool [3].

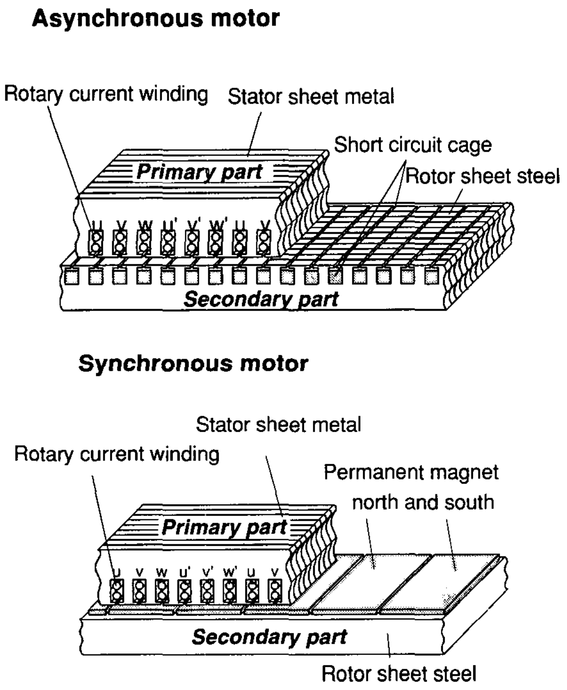


Fig. 1 Construction of asynchronous and synchronous linear motors

In Table 1, advantages and disadvantages of the asynchronous and synchronous linear motors are summarized. With the asynchronous linear motor, the magnetic attraction between the primary and the secondary part is not active without the driving current, which makes the assemblage easier. An important disadvantage of the asynchronous linear motor is greater power loss in the secondary part during the magnetization. Therefore, a water-cooling for the secondary part is necessary to apply the asynchronous linear motor to the machine tools. The asynchronous linear motor has a smaller continuous force than the synchronous motor with the same size.

The synchronous linear motor has a greater continuous force and higher efficiency compared to the asynchronous motor, since it has no power loss in the secondary part. Because of the permanent magnets of the secondary part, the synchronous motor is difficult in assembling and chip removal during the metal cutting. The system price of the synchronous linear motor is more expensive because of the permanent magnets in the secondary part [4].

Table 1 Advantages and disadvantages of asynchronous and synchronous linear motors

Asynchronous linear motor	**Synchronous linear motor**
⬆ No magnetic force without current ⇨better assembling ⬇ Smaller air gap between the primary and the secondary part⇨difficulty in adjusting ⬇ More power loss in the secondary part ⬇ The secondary part requires water cooling ⬇ Smaller continuous force	⬆ Greater continuous force ⬆ No power loss in the secondary part ⇨ higher efficiency ⬆ Larger air gap between the primary and the secondary part ⬇ The secondary part has a permanent magnet ⇨ difficulty with assembling and chip removal ⬇ Expensive, especially with long path

3. The used Linear Motors and Experimental Set-up

In Table 2, the technical data of the used two types of linear motors are presented [5]. The size and mass of the primary part of the used asynchronous and synchronous linear motor are identical. With water-cooling, the continuous force of the asynchronous linear motor reaches at 1800 N with the continuous velocity of 60 m/min. On the other hand, the continuous force of the synchronous linear motor is 3200 N with the continuous velocity of 90 m/min with water-cooling. Even with the same size, the force constant, force per unit current, of the synchronous linear motor, is twice as much as that of the asynchronous linear motor. The power loss in the primary part of the two linear motors is the same with 2600 W at the nominal current. The power loss in the secondary part of the two types of the linear motors is different, so that the power loss of the asynchronous motor reaches 1300 W and the synchronous motor 20 W. The magnetic attraction between the primary und secondary part of the asynchronous motor is present only during operation, while it always exists in the synchronous linear motor. Generally, the magnetic attraction is 5 - 10 times greater than the induction force. The magnetic attraction of the asynchronous motor in this research is 11800 N and that of the synchronous motor 14600 N.

Table 2 Technical data of asynchronous and synchronous linear motors (* with water cooling)

Technical data	**Unit**	**Asyn. motor**	**Syn. motor**
Continuos force*	N	1800	3200
Maximal force	N	5000	7000
Magnetic attraction	N	11800	14600
Continuous velocity	m/min	60	90
Maximal velocity	m/min	120	170
Nominal current	A	25	22.6
Maximal current	A	70	57
Force constant	N/A	72	141
Mass of primary part	kg	30	30
Mass of secondary part	kg/m	40	33
Power loss in the primary part (at nominal current)	W	2600	2600
Power loss in the secondary part (at nominal current)	W	1300	20
Air gap between primary and secondary part	mm	0.6	1.5

With the asynchronous linear motor introduced above, the experimental setup is presented in Fig. 2. Because the two motors have the same size, the synchronous linear motor can be constructed without any change of the machine bed and the machine table of the asynchronous linear motor. At the assembling for linear motors, the air gap between the primary and the secondary part of the two motors is different. The air gap of the asynchronous linear motor must be constructed as small as possible to reduce the power loss during the induction process. But the minimal air gap is limited because of the bending deformation of the magnetic attraction between the primary and the secondary part. With synchronous linear motors, the heat generation during the induction process is small. Therefore, it is possible for synchronous linear motors to have a greater air gap in comparison to asynchronous linear motors. For this reason, the asynchronous linear motor in this research has an air gap of 0.6 mm and the synchronous linear motor one of 1.5 mm [5].

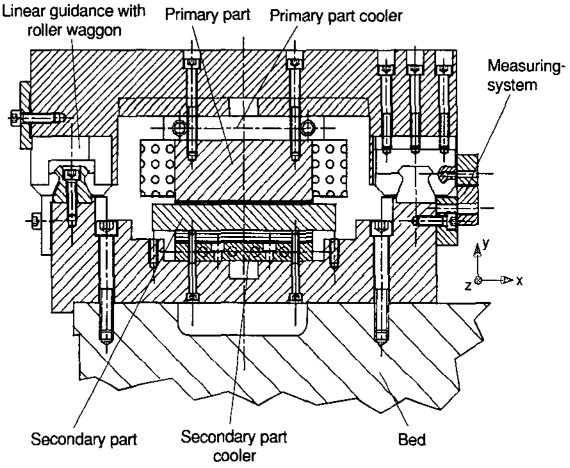


Fig. 2 Experimental set-up with the asynchronous linear motor

The machine table is connected to the primary part through bolt joints and moves to the z-direction due to the induction force in working. The secondary part is fixed on the machine bed. For the cooling of the primary part and the machine table, a water cooler is installed between the machine table and the primary part. Likewise, another water cooler is also installed between the secondary part and the machine bed. Both coolers are connected to the cooling unit, and the cooling water inlet temperature and the flow rate can be controlled. To take the great magnetic attraction and the high feed rate, a rolling linear guidance is used. To measure the position, an optical measuring system – LC 181 manufactured by Heidenhein [6], and to control the linear motor, a digital numerical control system – DDS 2.1 SERCOS interface manufactured by Indramat, are used [7,9].

4. Heat Sources of the Linear Motor

When the linear motor is applied to machine tools, there are two heat sources: electrical power loss (P_{Elect}) in the motor and mechanical frictional loss (P_{frict}) on the linear guidance. The electrical power loss is divided into Ohmic resistance loss (P_{Ohm}) in the windings and iron loss (P_{Pe}) in the sheet metal. The iron loss is the sum of hysteresis loss (P_H) and eddy current loss (P_W) [8]. Fig. 3 shows the heat sources of the asynchronous linear motor. For the synchronous linear motor, the power loss in the secondary part is negligible. These electrical power loss and frictional loss cause temperature rise in the linear motor and thermal deformation of machine structure. In this part, power loss in the linear motor and frictional loss on the linear guidance of the asynchronous and the synchronous linear motors are measured and compared.

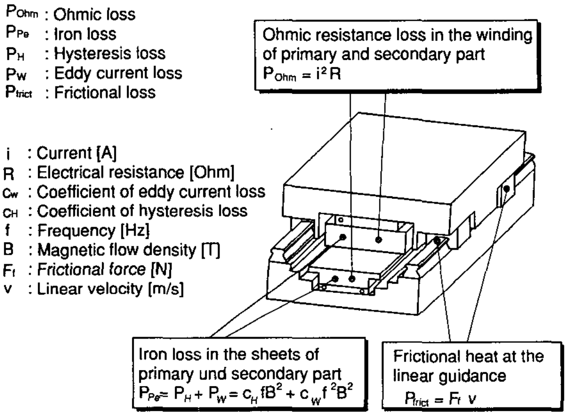


Fig. 3 Heat sources of the asynchronous linear motor

4.1 Power loss in the linear motor

As with other electrical machines, electrical power loss occurs in linear motors during operation. In this research, the electrical power loss was measured in two ways. The first method is a direct measurement of the power loss by a power meter. The second method is an indirect measurement through electric resistance and current in the winding. Because the iron loss in the sheet metal is small and negligible, the power loss of the linear motor can be precisely measured through measurement of the electrical resistance and the current. According to the technical data of the manufacturer and the result of the measurement, the Ohmic resistance loss is the greatest and reaches at 99.8 % of the total power loss [5]. This is an unique electrical characteristic of the linear motor. The power loss is directly dependent on the current, and the induction force of the linear motor is proportional to the current:

$$F = k_k \cdot I \qquad (1)$$

In equation (1), F is induction force, k_k force constant and I current. With equation (1), the Ohmic resistance loss in the windings may be noted as follows:

$$P_{Ohm} = I^2\ R = \left(\frac{F}{k_k}\right)^2 \cdot R = C \cdot F^2 \qquad (2)$$

$$C = \frac{R}{k_k^{\ 2}} \qquad (3)$$

In equation (2) and (3), R is electrical resistance of windings and C constant. The power loss of the linear motors is measured and presented in Fig. 4.

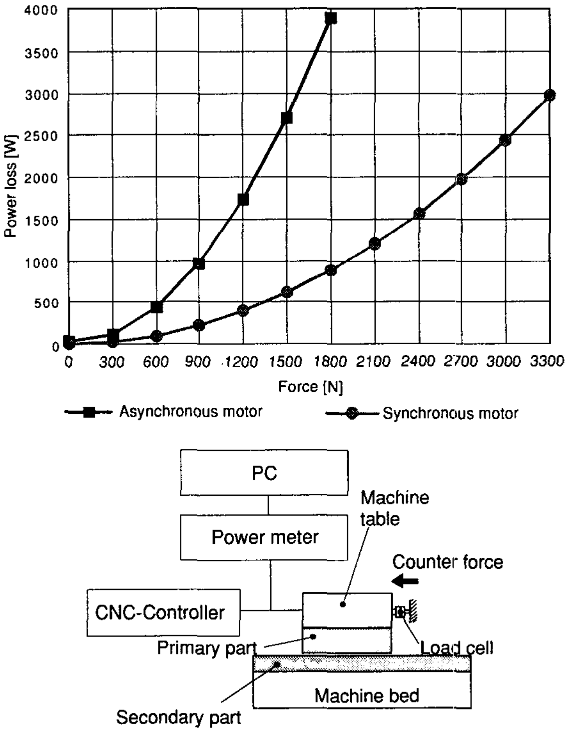


Fig. 4 Electrical power loss of linear motor in dependence on the force

For a direct comparison, the two linear motors are loaded by a counter force through a load cell. The counter force is applied up to the limit of the continuous force of each motor. As equation (2) and Fig. 4 show, the power loss of the both motors is proportional to the square of the force. In comparison with the synchronous linear motors, the asynchronous linear motor has a greater power loss at the same force. The reason for the different power loss lies in the secondary part. The asynchronous linear motor produces the Ohmic loss in the winding of the secondary part during the magnetization, while the magnetization process of the secondary part is not necessary for the synchronous linear motor because of the permanent magnets.

4.2 Power loss on the linear guidance

Mechanical heat source is the frictional loss on the linear guidance during linear motion, as the linear motor is applied to the machine tools. The total friction on the linear guidance results from rolling and sliding friction in ball contact, friction in the turning zone and friction through smearing substance and through sealing. The frictional force is dependent on normal load, preload, linear velocity, smearing substance, temperature, assembling precision and the sealing. It can be calculated with the following equation [10]:

$$F_f = \mu \cdot F_N + f_d \tag{4}$$

In equation (4) the symbols stand for:

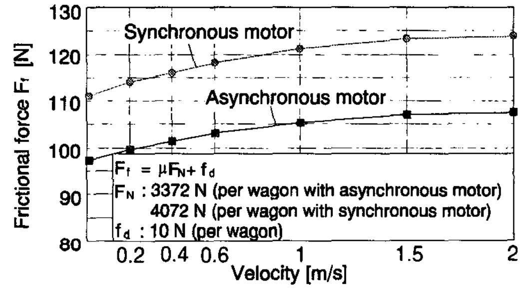
F_f	frictional force
μ	frictional coefficient
F_N	normal force
f_d	resistance force through scraper and sealing

The friction behavior of different profile rolling bearings in dependence on the load and the speed was examined through Ispaylar [12]. The frictional coefficients decrease with increasing load of profile rolling bearings, while the speed doesn't have any dominating influence on the friction coefficients. The scraper as well as the sealing which protect the rolling wagon from penetrating of dirt exerts an essential influence on the total friction. According to Ispaylar, the friction through the scraper is up to 50 % of the total friction.

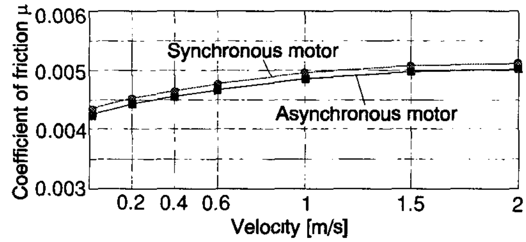
With a linear motor, the normal force (F_N) is a sum of the magnetic attraction (F_m) between the primary and secondary part and the own weight (F_w) of the moving machine components, and is calculated as follows:

$$F_N = F_m + F_w \tag{5}$$

With the use of linear motors into machine tools, the magnetic attraction is usually greater than the own weight of the moving components. The magnetic attraction of the asynchronous linear motor is 11800 N and the synchronous linear motor 14600 N (see table 2). In this research, the mass of the moving components composed of the machine table, the primary part, the primary part cooler and four rolling wagons is 172 kg. This corresponds to a weight force of 1687 N.



(a) Frictional force with four rolling wagons



(b) Coefficient of friction in dependance on the verlocity of linear motor

* 4 Rolling wagons (RUE 35 DHL)
- Scraper at linear guidance
- Grease lubrication

Fig. 5 Frictional force and coefficient on the linear guidance in dependence on the velocity of the linear motor

According to equation (5), the total normal force (F_N) is 13487 N (3372 N per wagon) with the asynchronous motor and 16287 N (4072 N per wagon) with the synchronous motor. For the asynchronous and synchronous linear motor the frictional force and coefficient are calculated according to equation (4) and compared in Fig. 5 with respect to the speed.

The rolling profile bearings are lubricated with grease. The sealing resistance force of 10 N per wagon is measured and the frictional coefficients with respect to the speed are examined by the manufacturer [11]. The frictional coefficients lie in between 0.0045 and 0.0052. The frictional forces of the two motors increase with the speed. Because of the higher magnetic attraction, the synchronous linear motor shows a greater frictional force. With the frictional force F_f and the linear velocity v, the frictional heat can be calculated as follows:

$$P_{frict}=F_f \cdot v \tag{6}$$

The frictional heat with respect to the speed is presented in Fig. 6. With the increase of the speed, the frictional heat increases. Because of the greater magnetic attraction, the synchronous linear motor shows a higher frictional heat at the same velocity.

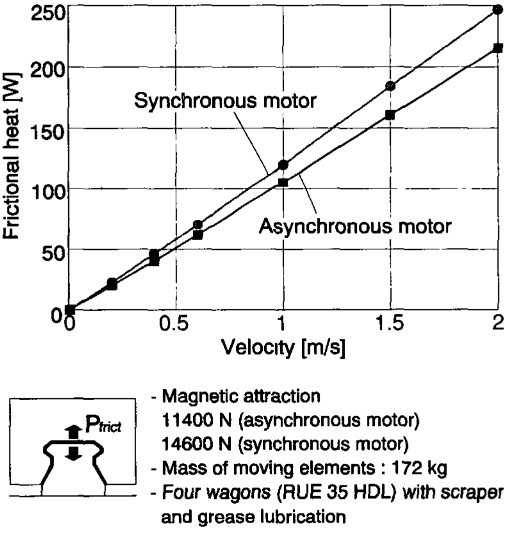


Fig. 6 Frictional heat on the linear guidance in dependence on the velocity of the linear motor

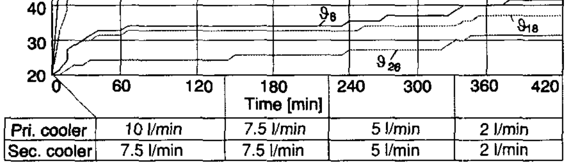
These frictional losses only appear, when the linear motor moves. With the stoppage of the linear motor or in the case of the load by a counter force in a low linear speed, the frictional losses can be neglected. As Fig. 6 presents, the linear profile rolling system doesn't show any considerable frictional losses in comparison with the electrical power loss mentioned above because of the low frictional coefficient. The main heat source, when a linear motor is applied to machine tools, is the electrical power loss in the motor.

5. Temperature Measurement

Temperatures at the experimental set-up including linear motors are measured and the results of the two linear motors are compared. For a temperature sensor, metal resistance thermometers of platinum (PT100) are used, which shows almost linear temperature - resistance characteristics between –220 °C and 750 °C and has a tolerance of ±0.3 °C [13]. (6)

For a better heat transfer between the thermal sensors and the machine structure, conducting paste is used. The measured temperatures are saved in a PC through a parallel interface.

The measured temperature with the asynchronous linear motor is presented in Fig. 7. The motor was loaded by a counter force of 1800 N. By this counter force of 1800 N, the nominal power loss of 3900 W is produced in the linear motor (2600 W in the primary and 1300 W in the secondary part). The two water coolers for the cooling of the primary part and the secondary part were installed and the water flow rate was varied between 2 - 10 l/min.



Pri. cooler	10 l/min	7.5 l/min	5 l/min	2 l/min
Sec. cooler	7.5 l/min	7.5 l/min	5 l/min	2 l/min

Fig. 7 Measured temperature with the asynchronous linear motor

The temperature at the primary part side (ϑ_{Pri}) is 105 °C, at the secondary part (ϑ_{Sec}) 46 °C and on the machine table (ϑ_{26}) 24.7 °C, while the water volume in the primary part cooler flows 10 l/min and in the secondary part cooler 7.5 l/min with a water inlet temperature of 19 °C. At the same cooling condition the temperature at the inside of the machine table (ϑ_8) reaches about 35 °C and at the inside of the machine bed (ϑ_{18}) 33 °C. The temperatures increase with the decrease of the water flow.

Fig. 8 shows measured temperature on the experimental set-up with the synchronous linear motor loaded by 3200 N. The corresponding power loss in the primary part is 2600 W and the power loss in the secondary is negligible. The primary part is cooled with a water cooler, which has a flow rate of 10 l/min and a water inlet temperature of 19 °C. The secondary part has no water cooler. The temperature at the primary part side (ϑ_1) reaches 105 °C as with the asynchronous linear motor. The secondary part (ϑ_2) is also warmed by the heat transferred from the primary part and the temperature is 26.7 °C. The temperature at the machine table (ϑ_3) is 24.7 °C and at the machine bed (ϑ_4) 24.3 °C.

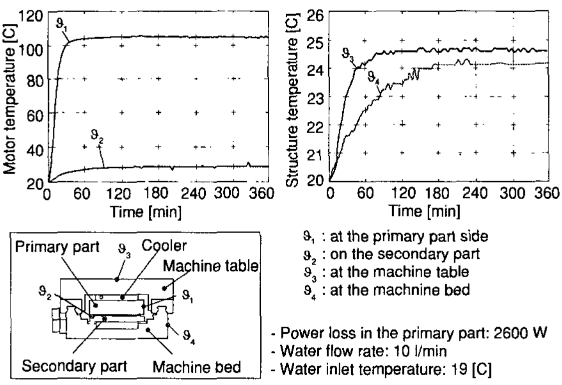


Fig. 8 Measured temperature with the synchronous linear motor

The temperature difference at the secondary part of the two linear motors can be explained as follows: The secondary part of the asynchronous linear motor has a heat source in itself, while the secondary part of the synchronous linear motor is warmed by the heat transferred from the primary part through the air gap. Therefore, the secondary part of the synchronous linear motor is less warmed than that of the asynchronous linear motor.

Fig. 9 shows different loading cases for the secondary part. For the asynchronous linear motor, critical loading case is the loading by a counter force in stoppage, because the power loss occurs only in the limited length, where the primary part covers. On the other hand, during linear motion the power loss is distributed on the whole length of the secondary part. For the synchronous linear motor, the maximum heat transferred from the primary part is considered as a critical case [14,15], while the own power loss is neglected. This thermal critical case of the secondary part must be considered for the application of the linear motor to the machine tools.

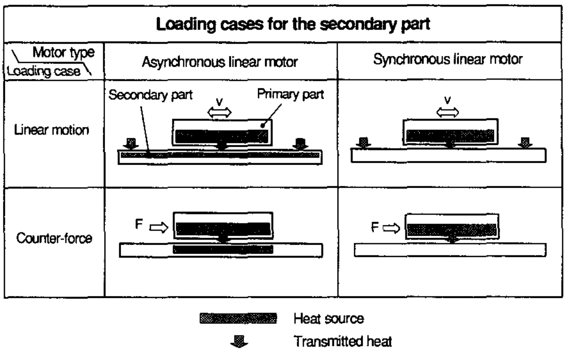


Fig. 9 Different loading cases for the secondary part

6. Conclusions

In this paper, the two types of linear motors, an asynchronous and a synchronous linear motor, which have an identical size manufactured by the same manufacturer, are investigated und compared in viewpoint of thermal behavior.

The electrical power loss of the both motors is proportional to the square of the induction force. The main heat source of the linear motor is the Ohmic resistance loss in the windings. With the same induction force, the synchronous linear motor has smaller electrical power loss, because the magnetization for the secondary part is not necessary. The frictional loss on the linear guidance is negligible in comparison with the electrical power loss in the motor. At the nominal power loss, the temperature at the primary part side of the two linear motors is similar and reaches at 105 °C with the water-cooling. The temperature behavior of the secondary part of the two motors is different: the secondary part of the asynchronous linear motor has a higher temperature even with water cooling than the secondary part of the synchronous linear motor without water cooling. From the viewpoint of thermal behavior, the synchronous linear motor is better than the asynchronous linear motor. In order to improve the thermal behavior, it is recommendable to change the linear motor and cooler construction.

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