EFFICIENCY AND CONDUCTOR HEATING IN A MULTISTAGE INDUCTION ACCELERATOR

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High velocities can be produced for macroscopic bodies by conductor acceleration in an electromagnetic accelerator: contact (rails) and contactless (induction) ones. Interest attaches to multistage induction accelerators whose coils are solenoids capable of accelerating relatively massive bodies with restricted currents and mechanical loads. There are no high-current sliding contacts, so an induction accelerator has a relatively high efficiency and long working life, and it enables one to accelerate a body made of ordinary conductors [1] or superconductors [2]. Calculations have been performed [3] on an electromagnetic accelerator in the form of a linear asynchronous motor having solenoidal windings supplied from a three-phase ac line, in which a body of mass 1 kg could be accelerated to 10 km/sec. However, this requires a three-phase current source with power of 100 GW. In [4], a model was devised for a multistage induction accelerator with coils fed from capacitor banks, and a physical model was tested.

Here we examine the electromagnetic processes, the energy relationships, and the conductor heating in a multistage accelerator having magnetically coupled coils supplied from capacitors, which serves to define the optimum parameters and the attainable velocities.

1. Electromagnetic-Accelerator Ideality Coefficient. Particular interest attaches to attaining the maximum efficiency, which is defined as the ratio of the increment in the kinetic energy W to the initial energy accumulated in the source W_0:

$$\eta = W/W_0, \tag{1}$$

and also to the maximal limiting velocity, which corresponds to melting due to the eddy currents. Such velocities can be attained if the method provides the maximum ratio of W at the end of the acceleration to the heat energy Q dissipated in the conductor, or in terms of accelerator segment, the ratio of the increments dW/dQ.

We consider the ideal case of acceleration by a planar magnetic wave acting on a thin sheet whose conductivity at normal temperature is σ_0. Variational methods show that the maximum dW/dQ occurs when the current density is uniformly distributed over the thickness of the sheet and is

$$\frac{dW}{dQ} = \frac{1}{2}\mu_0\Delta\sigma v\frac{1+H_1/H_0}{1-H_1/H_0}. \tag{2}$$

Here H_0 and H_1 are the field strengths ahead of and behind the sheet correspondingly, while v is the velocity of the sheet and σ the conductivity at that velocity.

The v dependence of dW/dQ confirms the empirical conclusion that electromagnetic acceleration is most effective in the final acceleration of a conductor previously accelerated in some other way. We integrate (2) with $H_1 = 0$ (maximum acceleration force) on the basis that $\sigma = \sigma_0/(1 + \beta q)$ (β is the thermal coefficient of the conductivity, with q the specific heat content), which gives

$$\frac{W}{Q} = \frac{1}{2}\beta v^2 [\exp(2\beta v/\Delta\sigma_0\mu_0) - 1]^{-1}. \tag{3}$$

We introduce dW/dQ together with W/Q as attained in this type of accelerator taken as the ratios to the corresponding quantities derived from (2) with $H_1 = 0$ and from (3):

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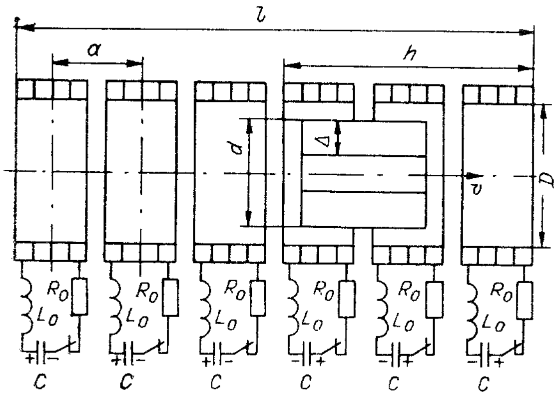

Fig. 1

$$\varkappa = \frac{2}{\mu_0 \sigma v \Delta} \frac{dW}{dQ}; \tag{4}$$

$$\mathrm{K} = \frac{2}{\beta v^2} [\exp(2\beta v/\sigma_0 \mu_0 \Delta) - 1] \frac{W}{Q}, \tag{5}$$

which are subsequently called the differential ideality coefficient in (4) and the integral one (5). $\varkappa$ and K have simple relations to the limiting velocity v_* corresponding to the conductor melting:

$$v_* \simeq \frac{\sigma_0 \mu_0 \Delta}{2\beta} \ln(1 + \beta q_* \mathrm{K}), \tag{6}$$

or if $\varkappa$ remains constant during the acceleration,

$$v_* \simeq \varkappa \frac{\sigma_0 \mu_0 \Delta}{2\beta} \ln(1 + \beta q_*) \tag{7}$$

(q_* is the heat content of the conductor on transition to the liquid state). Here (6) and (7) are exact if the current density is uniformly distributed over the cross section, or approximate if it is nonuniform. In any case, the conductor will melt at higher speeds as the ideality coefficient increases. For example, with a simple rails accelerator having rails with width b_1 separated by b_2 and working with a plate having its current density uniformly distributed over the cross section and without allowance for the heat production at the contacts, we have

$$\varkappa = \frac{\alpha}{\pi} \left[\ln \frac{1}{\alpha} + \frac{\alpha^2 - 1}{2\alpha^2} \ln(1 + \alpha^2) + \frac{2}{\alpha} \operatorname{arctg} \alpha \right] \quad (\alpha = b_1/b_2). \tag{8}$$

With α = 0.2-1.0, (8) gives $\varkappa$ = 0.2-0.5. For a coaxial rail accelerator with cylindrical outer and inner electrodes, the same assumptions give $\varkappa$ = 1.0. That coefficient is reduced by nonuniformity in the current distribution. For example, near-ideal acceleration occurs with a flat annular conductor in the field of an annular coil. Calculations have been made on the acceleration from the actual current density distribution [5], which give K = 0.5-0.6 even for fairly thin conductors ($\Delta = 10^{-3}$ m). An accelerator in the form of a linear asynchronous motor gives [3] K = 0.03-0.04.

2. Electromagnetic Processes in a Multistage Induction Accelerator. Figure 1 shows an accelerator with solenoids connected to capacitors. If the coils are closely spaced, the accelerator can be considered as a line with distributed parameters, whose components (LC circuit) are inductively coupled. We introduce the inductance per unit length L^0 and capacitance per unit length C^0 [4]: $C^0 = C/a$, $L^0 = (\pi\mu_0/4)(DN/a)^2$ (N is the number of turns on a coil). We consider a segment with length ℓ, in which the parameters of each of the stages containing an accelerating coil connected via a switch to a capacitor bank are the same. All the capacitors are charged to the same voltage U. General results are obtained with the [4] dimensionless parameters:

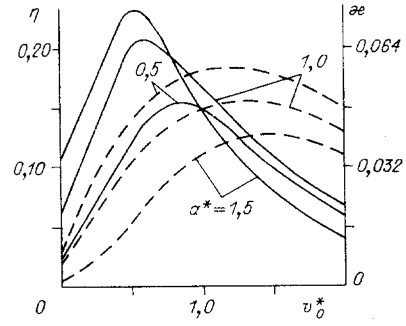

Fig. 2

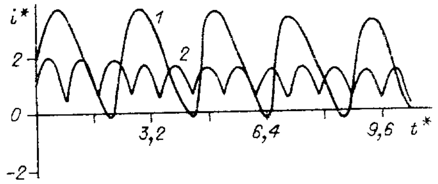

Fig. 3

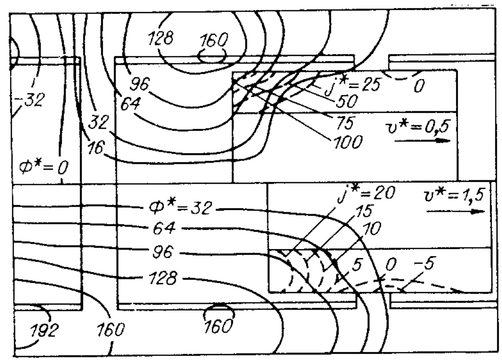

Fig. 4

$$l^* = l/D,\ a^* = a/D,\ h^* = h/D,\ d^* = d/D,\ R^* = R_0\sqrt{C^0/L^0},$$
$$L^* = L_0/L^0D,\ v^* = v\sqrt{L^0C^0},\ \sigma^* = \sigma D\sqrt{L^0/C^0},$$
$$\beta^* = \beta C^0U^2/2D^2,\ m^* = m/(DL^0(C^0U)^2),\ t^* = t/(D\sqrt{C^0L^0}),$$
$$i^* = (i/U)\sqrt{L^0/C^0},\ j^* = j(D^2/U)\sqrt{L^0/C^0},$$

in which R_0 and L_0 are the resistance and inductance in the connecting wires to the switch, while i and j are the current and current density. Figure 1 shows the other parameters. If no particular note is made, the calculations have been performed for $\ell^* = 24$, $R^* = 0.1$, $L^* = 0.3$, $\sigma^* = 5\cdot10^4$, $\beta^* = 0.1$, $m^* = 10$, $d^* = 0.95$, $\Delta/D = 0.75$ (Δ is the wall thickness of the conductor, which is a hollow metal cylinder). The analysis was based on a model containing integral equations [4]. The cross section of the conductor was split up into 6 × 6 = 36 working loops. The efficiency in an accelerator segment was given by (1) and the ideality coefficient by (4), where the differentials dW and dQ were replaced by the corresponding increments ΔW and ΔQ during the flight through the segment. We examined how the relative velocity in an accelerator segment v_0^* affected the efficiency and the ideality coefficient, as well as the length a^* of an individual stage, the conductor diameter d^*, and the length h^* of the accelerator part in which the capacitor banks are charged with the same polarity.

Figure 2 shows η and ϰ as functions of v_0^* and a^* for $h^* = 3$. The dependence of the efficiency on the entry velocity is qualitatively analogous to that derived in [6] for a single-stage accelerator. The maximum efficiency occurs for $v_0^* = 0.5$-1.0 and can exceed 0.2. The ideality coefficient as a function of v_0^* also has a maximum, but it is flatter and is attained at much higher velocities ($v_0^* = 1.2$-1.6). Figures 3 and 4 show the electromagnetic processes for these two states.

Figure 3 shows the time dependence of the total current in the conductor i^* for $v_0^* = 0.5$ and 1.5 (curves 1 and 2 correspondingly), while Fig. 4 shows the distributions for the magnetic flux $\Phi^* = \Phi/DU\sqrt{L^0C^0}$ and current density j^* over the conductor cross section corresponding to those velocities. At low velocities ($v_0^* < 0.5$), the current in the preceding coil has decreased substantially from the peak when the conductor enters the next coil. Shunting the capacitors with diodes to prevent charge reversal does not alter the electromagnetic processes appreciably. The current in the preceding coil decreases rapidly because

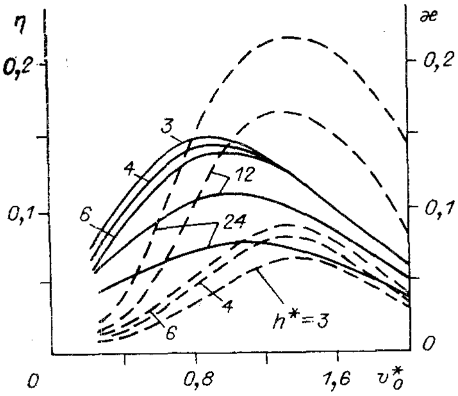

Fig. 5

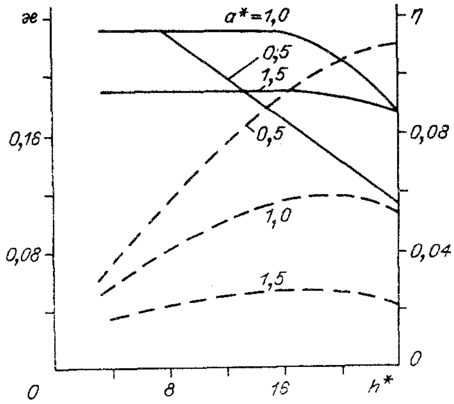

Fig. 6

of the emf induced in it by the rising current in the next coil. The coil in one stage is thus involved in producing the accelerating field at any instant (Fig. 4). The current in the conductor takes the form of short pulses, which results in a marked skin effect, with high current densities and rapid heating. On the other hand, the slight field penetration into the conductor results in a high efficiency. With $v_0^* = 1.2$-1.6, which correspond to the peak ideality coefficient, several coils participate simultaneously, which form a type of long solenoid, which as a result of the switching moves in synchronism with the conductor. The pulsating field acting on the conductor means that the current in it is unipolar and has a dc component, while the current density distribution over the wall approximates to uniform (Fig. 4), and the current density and heating rate are reduced. At higher entry velocities ($v_0^* > 1.6$), the ideality coefficient is reduced because of the considerable reduction in the kinetic energy increment, because the conductor enters the next coil before the current there attains the peak value. From (7) and Fig. 2, it follows that the conditions for maximum efficiency and maximum limiting velocity differ considerably. The highest limiting velocities may be attained with an efficiency about half the maximum possible.

We now consider how a^*, the stage length, affects the performance. With fixed L^0 and C^0, a shorter stage has less inductance and requires a lower capacitance, so the frequency of the discharge circuit is higher, so the maximum efficiency is attained at higher speeds, while the maximal efficiency is itself reduced because of the increase in the proportion of magnetic energy wasted in the inductances L_0 (Fig. 2). On the other hand, the ideality coefficient for an accelerator with short stages is much higher. As a^* falls from 1.0 to 0.5, the strong magnetic coupling between the coils results in the peak current in the conductor being roughly halved, so the heating is reduced considerably. At the same time, the accelerating force remains quite large, since in a short coil there is a predominant proportion for the forces acting axially on the conductor. A consequence of the reduction in current in the conductor for $a^* < 1$ and $v_0^* > 1$ is that the forces compressing the conductor are reduced.

We now examine how the performance is affected by alternating the capacitor connection polarities to the coils along the accelerator. With the coils connected with identical polarity, the amplitude of the total current in the conductor gradually decreases because the dc component decays (Fig. 3). Dividing the accelerator segment for example into two parts with differing capacitor polarities increases the current amplitude in the conductor by 15-20%, and the velocity increment in a segment is increased to 30-40%. However, the sharp change in current direction in the conductor results in a marked skin effect, and the heating rate is increased, while the ideality coefficient is reduced. Figure 5 shows the efficiency and ideality coefficient (solid and dashed lines, correspondingly) for a segment as a function of v_0^* and h^* with identical capacitor polarities. The curves have been derived for $a^* = 0.5$. As h^* increases from 3 to 24, $\varkappa$ increases by almost a factor four, while the efficiency is roughly halved. Figure 6 shows the maximum $\varkappa$ (dashed lines) and the efficiency then attained (solid lines) as functions of h^*. The type of curve is substantially dependent on a^*. In states giving the maximal ideality coefficient, $\eta = 0.06$-0.12. As a^* decreases from 1.0 to 0.5, $\varkappa$ almost doubles. The efficiency falls rapidly in an accelerator having short stage for $h^* > 8$-10.

The energy conversion efficiency is very much dependent on $d^* = d/D$, the diameter ratio for the conductor and accelerating coils. As d^* increases, so do the efficiency and ideality coefficient. Approximate relations are $\eta \sim (d^*)^{2.4-2.6}$, $\varkappa \sim (d^*)^{1.3-1.4}$.

These results imply that $\varkappa = 0.06$-0.20 for an induction accelerator in accordance with the parameters and conductor speed, but it always remains much less than one, since the current density is unevenly distributed over the conductor cross section. In states corresponding to the maximum efficiency, the current is very unevenly distributed along the conductor and in the thickness. In states with maximum ideality, the current density distribution over the thickness is close to uniform, but in that case the current is localized in the rear end (Fig. 4). As a consequence, the resistance in the current circuit is increased and so is the heating rate.

From (7) we estimate the velocities attainable for an aluminum conductor heated to its melting point for wall thickness $\Delta = 0.01$ m ($\sigma_0 = 3.8 \cdot 10^7$ $(\Omega \cdot m)^{-1}$, $\beta = 4.42 \cdot 10^{-6}$ kg/J, and $q_* = 1.02 \cdot 10^6$ J/kg). With maximum efficiency ($\varkappa = 0.06$-0.08), $v_* = 5$-7 km/sec. With maximum ideality ($\varkappa = 0.16$-0.20), $v_* = 14$-16 km/sec.

The ideality coefficient enables one to estimate the performance or the mode of operation as regards the attainable limiting velocity set by the melting. The highest efficiency is attained with a relative stage length $a^* = 1.0$-1.5, with the lengths of the parts having the same capacitor polarity $h^* \leq 3$-6, and relative conductor speed $v^* = 0.4$-0.8; the maximal limiting velocities set by the melting condition are attained with $a^* \leq 0.5$, $h^* > 10$, $v^* = 1.2$-1.6.

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