ADVANCED COMPULSATOR DESIGN

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Abstract: Compulsator is a name defining a large family of high energy pulsed power rotating machinery[1]. The compensated pulsed alternators cover an extensive range of currents, voltages, pulse shapes, and also frequency in the case of multi-pulse generators. The compulsator embodies the single element philosophy combining in one element the energy storage, electromechanical energy conversion, and the power conditioning. However, inside the machine such functions are done in a "staged" manner. Two examples are given in this paper, in order to illustrate such a philosophy of design: the flat pulse air-core compulsator, and the high voltage two stage uncompensated machine (uncompulsator) capable of reaching voltages above 100-kV level.

Introduction

High energy, pulsed power supplies are increasingly required in different applications such as space launching, electromagnetic countermeasure systems, and industry. The one-element power supply must combine the energy storage, conversion and pulse shaping in a single generator. In two previous papers [2,3] the methods to shape the time profile of the output current for a given external impedance were related to the variation in time of both, the induced electromotive force and the internal impedance of the compulsator itself. Functionally there are two general methods of pulse shaping: topological distributions of the active conductors in the machine and dynamic interactions between active conductors and between windings and shields. The second method is actually a second stage of the process, in which the fixed distributions of active and passive conductors interact during the discharge, achieving compensation and flux compression in selected areas, leaving the flux unchanged in the rest of the machine, such areas changing in time as the machine turns.

Such an approach is illustrated in the first design case. In the second example a part of the generator armature winding is short circuited, thus creating a sudden increase in excitation as a reaction, and consequently a high voltage induced in the rest of the armature winding.

The Flat Pulse Compulsator

The flat pulse compulsator which is being designed for Task C of the armor antiarmor program is an air-cored machine. The cross section of this machine is shown in Figure 1. The machine generates a flat-topped current pulse when connected to a railgun (8 m long). The machine has two poles and is comprised of the excitation field coil, a six conductor per pole, lap wound armature winding, the compensating winding which is also lap wound and has 26 conductors per pole. The compensating winding is shorted on itself. The compensating winding with its ability to provide selective dynamic flux compression is the component which enables the machine to generate a flat-topped current pulse.

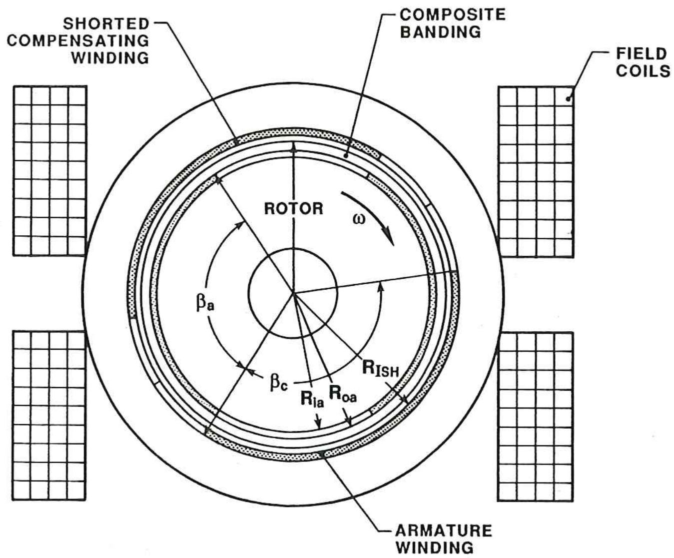

Figure 1. Flat pulse compulsator using selective passive compensation

A problem associated with this particular configuration is that certain sections of the compensating winding experience a radially inward force. It is difficult to support the compensating winding under the radially inward load without compromising machine performance. This problem is better understood by considering Figures 2 and 3. Figure 2 shows the current in the armature winding and compensating winding as a function of time. It is to be noted that the support structure of the field coil is made of aluminum which is a good conductor. The support structure also serves to exclude the discharge fields

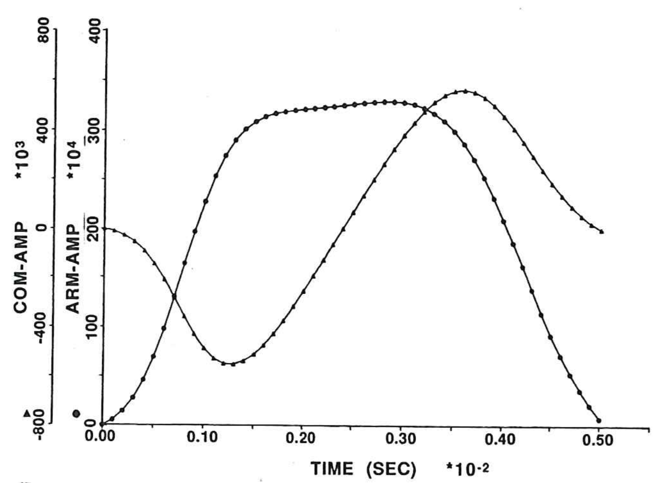

Figure 2. Current in the armature and compensating winding as a function of time

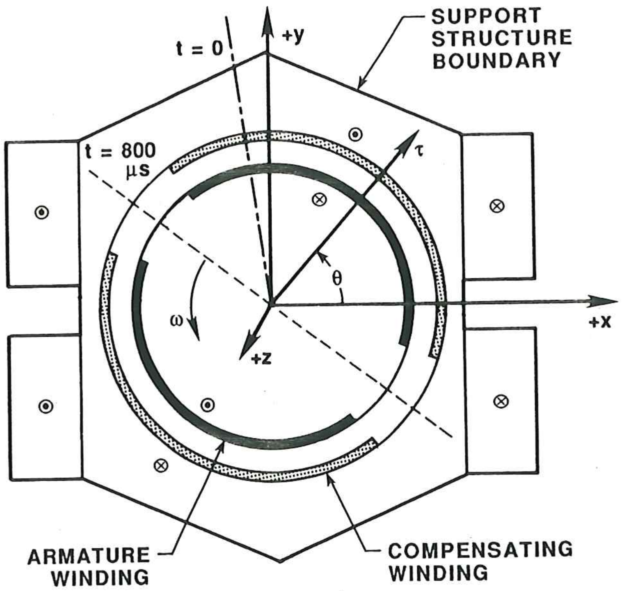

Figure 3. Rotor position at 800 μs

from the region of the field coil. This second function of the support structure also implies that there is a significant tangential component of the discharge magnetic fields between the compensating winding and the support structure. This is the source of a radially inward force on the compensating winding. Figure 3 shows the rotor position at 800 μs from the initiation of discharge. At this instant the armature is in the minimum inductance position. The magnetic field between the armature and compensating winding has a tangential component which is higher than the tangential component between the compensating winding and support structure, therefore the radial force on the compensating winding is entirely outward. Figure 4 shows the rotor position at 1.5 ms from the initiation of discharge. In this position the field below the compensating winding over the sector of the pole spacer of the armature winding is predominantly radial. The field outside the compensating winding is still tangential and therefore this sector sees a radially inward force. Figure 5 shows the force distribution as a function of angular location.

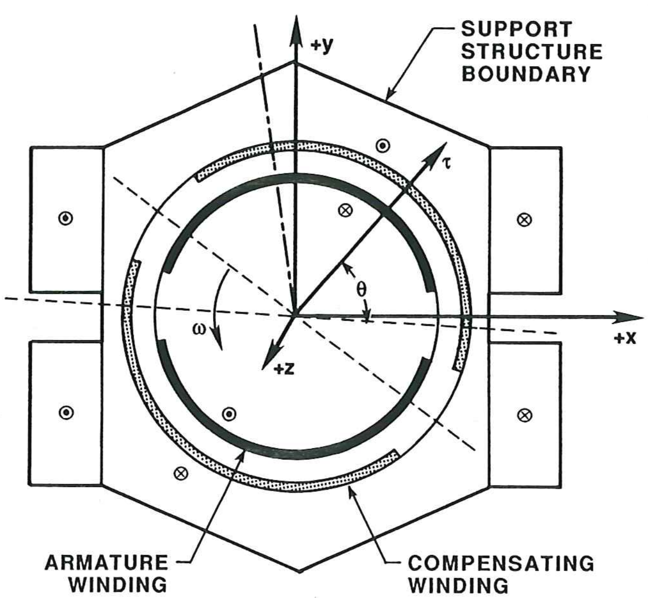

Figure 4. Rotor position at 1.5 ms

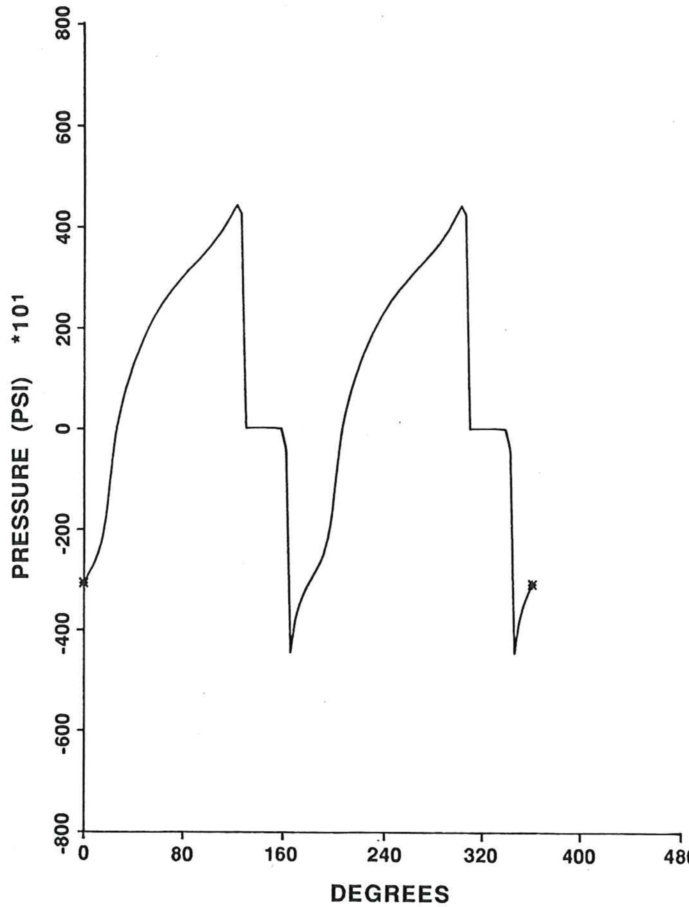

Figure 5. Radial force distribution on compensating winding at 1.5 ms

There are two methods of overcoming this problem, one mechanical and the second electrical in nature. The first method is to use an external rotor configuration shown in Figure 6. This configuration places the banding on the armature winding radially outward. The compensating winding can now be banded with high strength composite material to protect it from the radially outward electromagnetic forces, thus maintaining the coupling between the armature and compensating winding the same as in the case of the internal rotor machine.

The second solution is to make the compensating winding out of shorted single turns rather than a lap wound continuous wire. This configuration removes the constraint that the same compensating current must pass through each turn of the compensating winding. The current on each of these turns now follows a different profile with time thus introducing several degrees of freedom.

Figure 7 shows the current in the armature winding and also the current in the various shorted compensating conductors. The current in the compen-

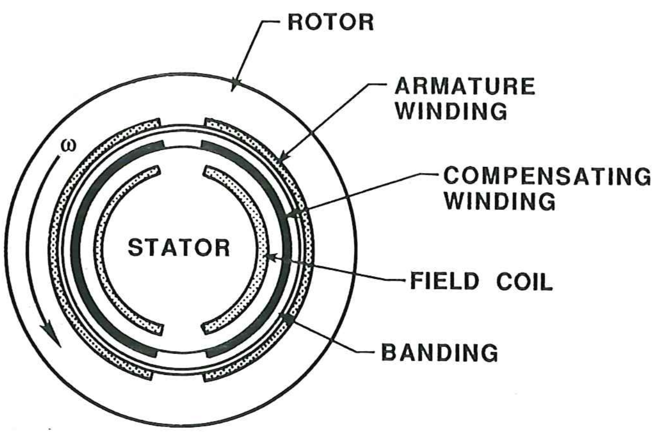

Figure 6. External rotor machine

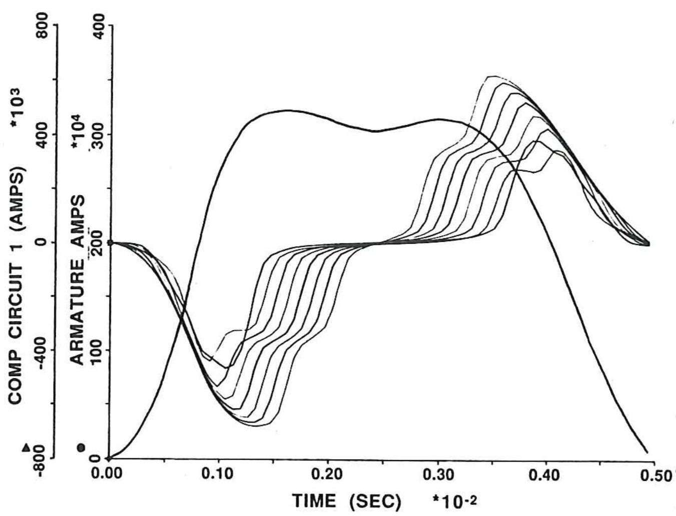

Figure 7. Current in the armature winding and various compensating conductors

sating turns closest to the pole spacer have the shortest pulse width and this pulse width increases for conductors further away from the poles spacer. This variation in pulse width is in accordance to the variation of the mutual coupling of the compensating turns with the armature windings. Since the pulse width of the compensating currents closest to pole spacer is reduced, the current in these conductors is significantly lower when the pole spacer of the armature winding is aligned with them thus reducing the radially inward forces. Figure 8 shows the radial force distribution in the compensating winding using shorted single turns for the rotor position shown in Figure 4.

High Voltage Generator

The high voltage generator, schematically represented in Figure 9, is technically the electromagnetic dual of a compulsator. Unlike the compulsator, which uses an active or passive compensating winding, this machine has a laminated structure and avoids any means

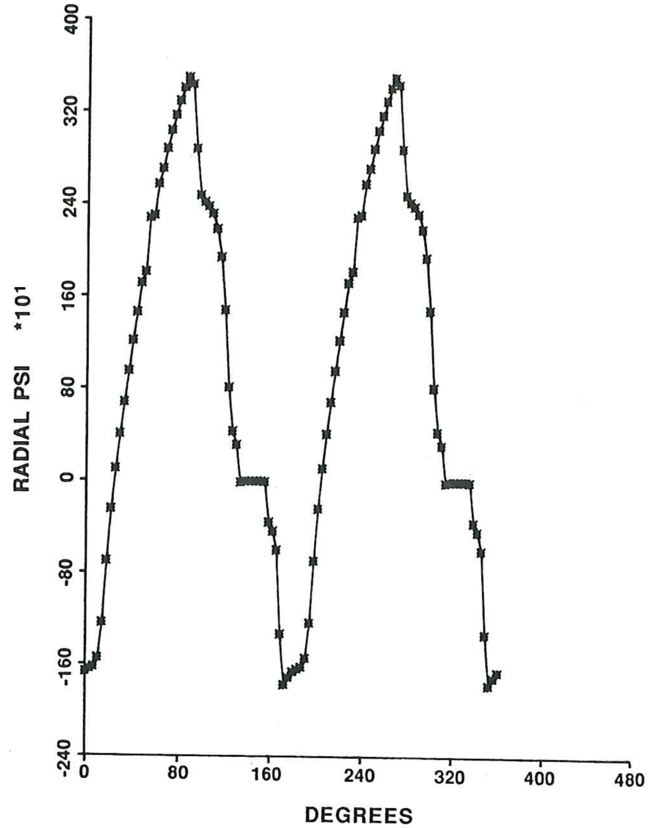

Figure 8. Radial force distribution

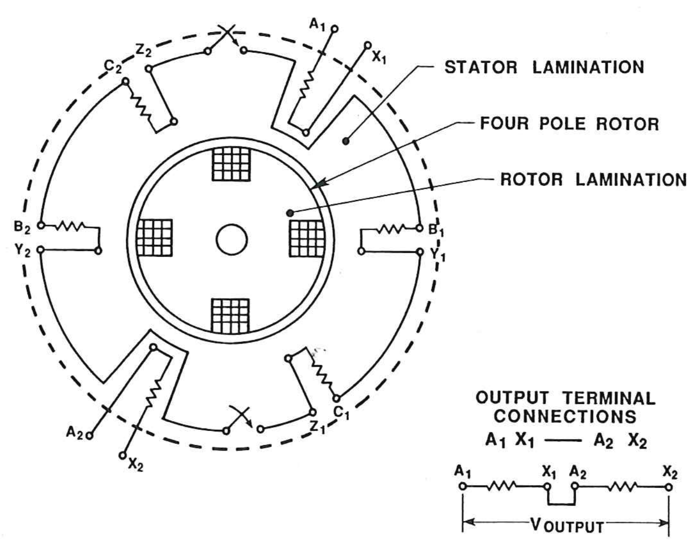

Figure 9. Schematic of the high voltage generator

of shielding, using finely laminated ferromagnetic materials or making use of high strength, high stiffness, low density composite materials such as epoxy impregnated graphite, glass, or boron fibers.

The operation is based on the "constant flux linkage principle" for short circuits in synchronous machines. The magnetic flux is trapped and the magnetic linkage of each winding must remain constant at the level it had at the instant of short circuit. If, however, only two phases (out of three) are short circuited, the third phase will produce a large voltage many times its rated voltage.

The two short-circuited phases form a winding whose axis is perpendicular to the axis of the third (output) phase (Figure 10). When the switch S is closed, the two phases, B and C, are short circuited and the event is similar to the sudden short circuit of a conventional synchronous machine. The fluxes, currents, and electromotive forces add vectorially for the two phases. Their resulting phasor makes an angle of 90° with the corresponding one for phase A (fig. 11a).

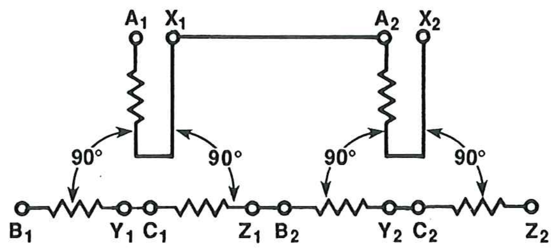

Figure 10. Disposition of the phase windings (electric angle)

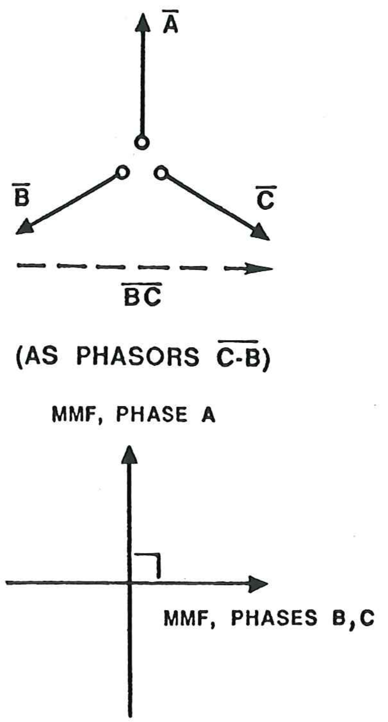

Figure 11a and 11b. Phasorial relationships between phase windings

The short circuit of phases B and C in series can be considered as a single phase in the direction of the resultant phasor (fig. 11b). If the short circuit occurs in the moment in which no flux of excitation is linking the shorted armature windings--we have the first characteristic position; if it occurs in the moment in which the maximum excitation flux links the shorted armature windings--we have the second characteristic position. The excitation (secondary) flux, Φ_2 can be divided into useful flux (ϕ_{2u}) and leakage flux ($\phi_{2\sigma}$). Assuming for simplicity that the primary and the secondary number of turns are equal--i.e., the respective primary and secondary useful inductances are equal, $L_{u1} = L_{u2} = L_u$. Then,

$$\Phi_2 = \Phi_{2u} + \Phi_{2\sigma} = (L_u + L_{2\sigma})i_{ex} = L_u(1 + \sigma_2)i_{ex} \quad (1)$$

After the rotor has turned with an angle α, after a time interval:

$$t = \alpha/\omega$$

The equations for the flux linking the primary and secondary windings become:

$$L_{1\sigma}i_1 + L_u(i_1 + i_2\sin\alpha) = 0$$

$$L_{2\sigma}i_2 + L_u(i_1 \sin\alpha + i_2) = L_u(1 + \sigma_2)i_{ex} \quad (2)$$

where

i_1, i_2 = the instantaneous values for currents in the stator and rotor, respectively

$L_1\sigma$, $L_2\sigma$ and L_u = the leakage inductances for primary, secondary, and respectively for the common flux

σ_1, σ_2 = leakage coefficients

Using relation (1) we arrive at much simpler equations

$$(1 + \sigma_1)i_1 + i_2 \sin\alpha = 0$$
$$(1 + \sigma_2)i_2 + i_1 \sin\alpha = (1 + \sigma_2)i_{ex}$$

$$i_2 = \frac{1 - \dfrac{\cos\alpha}{(1 + \sigma_1)(1 + \sigma_2)}}{1 - \dfrac{\cos^2\alpha}{(1 + \sigma_1)(1 + \sigma_2)}} i_{ex}$$

$$i_1 = \frac{1}{1 + \sigma_1}\left[1 - \frac{1 - \dfrac{\cos\alpha}{(1 + \sigma_1)(1 + \sigma_2)}}{1 - \dfrac{\cos^2\alpha}{(1 + \sigma_1)(1 + \sigma_2)}}\cos\alpha\right] i_{ex}$$

The values become critical for $\cos\alpha = -1$, 180° after the short circuit. These values are

$$\underline{i_2 cr} = \frac{2 - \sigma_1 - \sigma_2}{\sigma_1 + \sigma_2} i_{ex} \cong 2\frac{i_{ex}}{\sigma_1 + \sigma_2}$$

$$\underline{i_1 cr} = \frac{2}{1 + \sigma_1} \cdot \frac{i_{ex}}{\sigma_1 + \sigma_2} \approx i_2 cr$$

The resultant flux in the critical moment is produced by the excitation, on the rotor and for $\cos\alpha = -1$ (α = 180°).

$$\phi_r = L_u i_{ex}\left[\frac{2}{\sigma_1 + \sigma_2} - 1 - \frac{1}{1 + \sigma_1}\,\frac{2}{(\sigma_1 + \sigma_2)}\right]$$

$$= L_u\left(\frac{\sigma_1 - \sigma_2 + \sigma_1\sigma_2}{\sigma_1 + \sigma_2 + \sigma_1\sigma_2}\right) i_{ex}$$

$$\Phi_r \approx 0 \text{ (after 180°)}$$

The physical picture corresponding to the flux and current relations obtained above is:

1. For the first characteristic position--the armature is without current and links no flux. The resultant flux produced is half of the non-load flux, the other half is produced by the excitation in conjunction with the armature winding, along the airgap such that two halves compensate in the armature and add in the excitation member (in our case rotor).

2. For the second characteristic position, the armature is at full current and links maximum flux, the two windings trying to maintain the flux constant. Since after 180° (half period) the two fluxes have opposite directions they tend to compensate each other. The resulting flux is almost zero, so the two windings must produce the whole no-load flux along the airgap path.

The second stage of the system involves producing the high voltage in the third phase winding AA'. As shown in figures 10 and 11, the two short circuited phases form a winding whose axis is perpendicular to the axis of the high voltage winding AA', and, consequently they cannot induce the high voltage, being magnetically independent (decoupled). Only the current in the excitation winding (which is on the rotor in our case) can induce the high voltage. The rotor excitation current attains its maximum value after 90° in the first characteristic position and after 180° in the second characteristic position. The maximum instantaneous emf in phase AA' will be reached in these particular moments [90°(I)] and [180°(II)] and their values are:

$$V_{f,zero,\ell} = \frac{\sqrt{2}V}{\sigma} \tag{3}$$

for zero flux linkage at the moment of the short circuit and

$$V_{f,max,\ell} = \left(\frac{2}{\sigma} - 1\right)\sqrt{2}V \tag{4}$$

for the maximum initial flux linkage where

V_f = voltage, maximum value induced in the output phase,

V = steady-state, root mean square (rms) value of the phase voltage of the machine, and

$\sigma = \frac{\Phi_\sigma}{\Phi_\sigma - \Phi_u}$ = ratio between the leakage flux (slot, end turns, etc.) and the total flux (leakage and useful).

Table 1 shows the characteristics for a design of such a high voltage, uncompensated pulsed generator.

Table 1. Air core high voltage pulsed generator (uncompensated)

Parameters	Units	Value
Rotor diameter	m	0.254 (10 in.)
Rotor length	m	0.1524 (6 in.)
Rotor speed	rpm	33,000
Peripheral velocity	m/s	439
Number of poles	---	2
Frequency	Hz	550
Voltage (steady state, maximum value)	kV	10
Voltage output (reduced excitation)	kV	118
Voltage output (full excitation)	kV	145
Voltage multiplication factor	---	14.5 (max. 15.6)
Leakage coefficient	---	0.12 (12%)
Moment of inertia	js^2	0.249
Energy stored at peak velocity	MJ	1.49

Acknowledgements

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