LIMITATIONS ON THE MINIMUM CHARGING TIME FOR THE FIELD COIL OF AIR CORE COMPENSATED PULSED ALTERNATORS [FOR EM LAUNCHER APPLICATIONS]

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LIMITATIONS ON THE MINIMUM CHARGING TIME FOR THE FIELD COIL OF AIR CORE COMPENSATED PULSED ALTERNATORS

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Abstract: Air core compensated pulsed alternators (compulsators) are being developed for a variety of field-based applications in relation with electromagnetic launchers. Since these applications are essentially field portable, minimizing system mass is of great importance. Also it is desirable to use a room temperature field coil since carrying cryogens, such as liquid nitrogen or liquid helium on board a vehicle, has logistic problems. These requirements have led to the use of a self-excitation scheme using a room temperature field coil. In order to increase the field coil charging efficiency it is necessary to accomplish the charging in as short a time as possible. Quite often the parameters of the armature winding are not matched to afford a fast charging scheme. A separate exciter winding is therefore used, which has parameters matched to that of the field coil to minimize the charging time.

When the charge time of the field coil is decreased below a certain limit it is necessary to account for the coupling of various structural conductive paths of the machine with the field coil. This is important especially for two-pole machines and of less importance as the number of poles increases. The current induced in these closed conducting paths delay the establishment of the excitation field near the armature/exciter winding. Most of the problems associated with the structural conductors can be overcome by using a resistive material. However, the compensation (shield/winding) must be made with a conductive material. The compensating component can be designed to minimize the delay in establishing the field. But due to its primary function, the shield or compensating winding will impose a limit on the minimum charging time.

This paper discusses the eddy currents induced in the shield of the passive compulsator and the circulating currents induced in the compensating winding of a selective passive compulsator during the charge up of the field coil.

Introduction

The charging efficiency of any inductor such as the field coil of a compulsator is given by:

\[ \eta = \frac{-\frac{R_f}{2}i_f^2}{\int_0^1 i_f R_f dt + \frac{L_f}{2}i_f^2} \]

Where

- \( L_f \) = inductance of the field coil
- \( R_f \) = resistance of the field coil
- \( I_p \) = peak current in the field coil
- \( t_p \) = time to reach peak current

The energy stored in the field coil is independent of the time it takes to reach the peak current. However, the losses are directly related to the time of charging. It is therefore imperative to reduce the charging time to maximize the efficiency. Besides efficiency there are other considerations (such as temperature rise in the field coil conductors and the availability of adequate energy), which also require minimizing the charging time.

Neglecting any shielding effects, the excitation current in the field coil of a self-excited air-core compulsator can be written approximately as:

\[ i_f(t) = L_p \alpha i_f(t) \]

where

\[ \alpha = \frac{K - R_f}{L_f} \]

\[ I_o = \text{initial seed current} \]

\[ K = \text{proportionality constant relating rectifier voltage to field current} \]

The losses in the field coil while charging can be written as:

\[ W_{\text{loss}} = \frac{L_f}{2\alpha} \left( \frac{i_f^2 - I_o^2}{2} \right) + \frac{R_f}{2\alpha} I_o^2 \]

And correspondingly the efficiency of charging is given by:

\[ \eta_{\text{charg}} = \left( 1 - \frac{R_f}{K} \right) \]

Equations (1) and (2) indicate that to maximize efficiency, \( K \) i.e. rectifier voltage per unit field current, must be maximized. The peak exciter winding voltage must be selected as high as the insulation and rectifier system will permit and the required amp-turns in the field coil must be provided using the minimum number of turns, within the limits of the rectifier current rating. All of this results in a shorter field coil charging time.

In order to support the field coil, against charging and discharge related forces, a robust structure is required around it. Aluminum is the preferred material for the support structure because of its low density. If this support structure forms a continuous loop within or outside the field coil, then it is...
magnetically well coupled with the field coil. When the field coil is charged opposing currents flow in the structure. This slows down the increase in the magnetic field strength near the armature winding. It is then necessary to hold the current steady in the field coil while the eddy currents in the structure decay. This effect is stronger for faster charging rates. The result is that the losses in the field coil increase to a value far greater than that obtained from equation 1, thus offsetting the advantages of fast charging. There are several ways to overcome this problem. One of which is to break up the conductive path so it does not form a continuous loop around the field coil. Another method is to use structural material which is resistive, such as titanium or stainless steel, which allows the eddy currents to decay faster.

In some designs of the selective passive compulsator, breaking up the structural conductive paths on the same side of the field coil as the armature winding has its disadvantages. This disadvantage stems from the main discharge related forces, which now act on the field coil directly instead of the structure. The magnitude of the discharge related forces acting on the field coil can be controlled by closing the structural conductive paths and selecting the proper material or a combination of materials. The structure must be such that its circuit time constant \( \frac{L}{R} \) is much smaller than the charging time of the field coil and quite large compared to the discharge pulse width. In most cases, power requirements limit the charging time of the field coil to at least 10 times the discharge pulse width. The requirement on the time constant of the structure can therefore be satisfied.

The Passively Compensated Compulsator

Figure 1 shows the cross section of a typical passively compensated air-core compulsator. The shield in this machine provides the armature with eddy current compensation, thus, lowering the machine internal inductance and enabling it to deliver high power pulses to low-impedance loads. Several factors govern the selection of the shield material and thickness. The material is normally a good electrical conductor such as aluminum or copper, so that the depth of diffusion at the fundamental frequency is small. This assures a low armature inductance. The thickness is selected such that the shield is at least as thick as the steady state depth of penetration of the fundamental frequency. Other factors (such as mechanical hoop stress during discharge or thermal stresses) may also determine the thickness. But normally these stresses can be overcome by backing the conductive shield with a sleeve of lower electrical conductivity, which provides the requisite support or acts as a thermal sink.

Another factor governing the shield thickness is the transient current in the field coil. This transient is invariably obtained during the discharge of the compulsator due to the diffusion of the armature wave (which is stationary with respect to the shield) and to a lesser extent, also due to the diffusion of the fundamental and double frequency armature waves. Figure 2 shows the transient current in the field coil at various shield thicknesses. The example shown in this figure is the air-core, passive compulsator being developed for the small caliber EM gun system. This transient needs to be maintained within a certain limit deemed safe for the corresponding circuit components.

![Figure 2. Comparison of field current transients at various shield thickness](image_url)

The shield thickness, as can be seen, is driven by quite a few factors besides the charging requirements. This imposes a limit on the charging rate of the field coil. Figures 3a and 3b shows the charging of the field coil for two values of shield thicknesses. Also shown on the same figures is the curve for the current in the shield and the curve for ideal charging, i.e. neglecting the interaction with the shield. An interesting point to note is that the time to reach peak current is about the same in all three cases, which implies that the losses in the field coil during this period, until peak current, are also the same. This is because the currents in the shield lower the inductance of the field coil and the generated voltage in the exciter winding to the same extent, thus maintaining the factor \( \alpha \) in equation 1 approximately the same. The main differences in the two cases for the same charging rate is that the holding time of the current at peak value is longer for the case with the thicker shield. This holding time is approximately given by equation 3.
\[ t_{sh} = \frac{12\mu_{0}r_{s}}{p\pi} \]

\( \sigma \) = electrical conductivity of the shield  
\( r \) = average radius of the shield  
\( t_{sh} \) = thickness of the shield  
\( p \) = number of pole pairs in the machine

The losses in the field coil during the holding time are proportional to the thickness of the shield.

Figure 4 shows the efficiency for charging of the field coil at different rates. The machine considered is the same one as that in figures 2 and 3. Two shield thicknesses have been considered, i.e. 12.7 mm and 6.35 mm. Figure 5 shows the curves for the total losses while charging. These losses are normalized with respect to the ideal charging losses.

**Figure 3a.** Field coil charging-shield thickness 12.7 mm

**Figure 3b.** Field coil charging 6.35 mm shield

**Figure 4.** Efficiency for different field coil charging rates

**Figure 5.** Charging losses normalized to ideal charging losses

**The Selective Passive Compulsator**

In those applications where a specific current pulse shape is required, the selective passive compulsator is utilized. For example, a flat topped current pulse is required for the 9 MJ railgun demonstrator to limit the peak acceleration on the projectile to an acceptable value. The selective passive compulsator is characterized by a varying armature inductance. The variation is at twice the electrical frequency of the machine. The varying armature inductance is obtained by replacing the shield of the passive machine by a compensating winding. This compensating winding is short circuited without any external impedance. The conductors of this winding have a common magnetic axis.
There are two ways in which this winding can be built. One way is to connect all the loops of the winding in series and then short circuit the two ends. This scheme is convenient from the standpoint of charging the field coil because the short circuit can be accomplished through a switch. This switch can then be open during the field-coil charging and closed just prior to discharge. The charging can then be accomplished at a very high rate and efficiency. The problem, however, with this winding scheme is that during discharge some of the compensating conductors undergo a high loading in a direction which puts the epoxy bond under tension [1]. An alternate winding scheme is therefore required in most cases.

The second method of building the compensating winding, is to short circuit the individual loops on themselves. This reduces the tension on the epoxy bond. It is now inconvenient to switch each of these individual loops and the loops could remain under short circuit even during field-coil charging. The issues discussed under the passive compulsator also apply in the case of the selective passive machine. In some cases however, the axis of the compensating winding is sufficiently displaced from the axis of the field winding to significantly reduce the coupling. In this situation the currents induced in the compensating conductors are small and of less consequence. If the coupling is high when the axis of the compensating and field winding are aligned, a switch may be used in each loop.

**Conclusions**

Reducing the charging time of the field coil greatly enhances the efficiency. In some cases the rate of charging may be the determining factor on whether the field coil is room temperature or cryogenic and whether it needs active cooling. There is however an optimum charging rate. Increasing the charging rate beyond this limit does not result in proportional benefits. This is due primarily to the compensating component being coupled to the field coil and to a lesser extent due to the coupling of the structure with the field coil.

In the case of the passive compulsator, the limit to the charging rate is well defined. In the case of the selective passive machine, switches may be used in the compensating circuit to decouple it from the field coil while charging.

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