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DISCRETE PRECISION BEAM SWITCHING IN LINEAR INDUCTION ACCELERATORS THROUGH HARMONICS CONTROL

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Summary

Continued development in inertial fusion reactor research identifies the potential of providing beam of heavy ions associated with long pulse duration, low level of kinetic energy and multi-killoamperes current. This paper presents continuation of work for the ultimate goal of precision design in the spark gap switching mechanism for the linear induction accelerators including the core type as well as the line type. The pulse switching involves the utilization of the saturable - resistor with hard ferromagnetic material core, where sudden changes in its ohmic value can provide precise automatic switching synchronized with that of the charging beam. Calculations centered on establishing remarkable switching sequence spectrum with respect to the fundamental frequency as well as for a discrete sequence of harmonics contained in the saturable-resistor exciting current. Discrete time switchings are characterized in the form of discrete pulses with continuous ascending sharp increase in amplitude and controlled reduction in time duration.

Properties of Hard Magnetic Core Reactor(1,2,3)

Closed core reactor with hard ferromagnetic core is known as the saturable resistor. It has the following properties:

a. The ohmic values, namely the impedance reactance and resistance will rise sharply beyond the level of the AC pick-up current, attaining their peak followed by a rapid decline in the saturation regime to almost zero values, as shown in Fig. 1.

b. The resistive component is hysteresis in nature and hence is a linear function of frequency.

c. The reactor power factor is almost constant.

d. The normal magnetization curve is a displaced mode where the magnetic induction B starts its rise when the field H is larger than the coercive force H_c, as shown in Fig. 2

e. Absolute values for the impedance, reactance and resistance could be reduced substantially by the superposition of DC field.

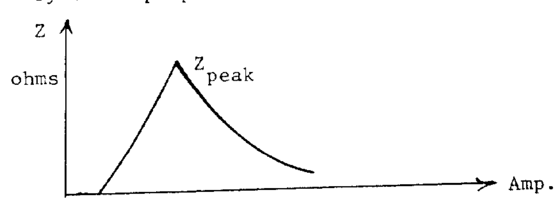

Fig. 1

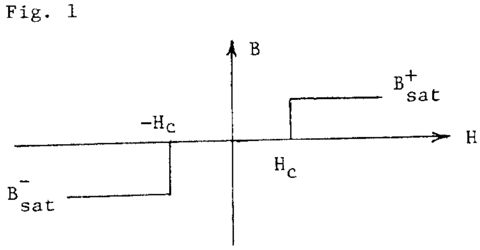

Fig. 2

Solution of the Induced Electric Field(2,3,5-6)

From previous work carried out by this author, solution of the induced electric field produced by a sinusoidal applied magnetic field of the form $h(t) = H_m \sin \omega t$ is rewritten below,

$$E = \sqrt{B_o}\left[\frac{(k_2 \sin\omega t - \frac{1}{2}k_1 \cos 2\omega t + \frac{1}{2}k_1 - k_3)}{\left[\omega t\left(\frac{k_1}{2\omega} - \frac{k_3}{\omega}\right) - \left(\frac{k_1}{4\omega}\sin 2\omega t + \frac{k_2}{\omega}\cos\omega t\right)\right]^{\frac{1}{2}}}\right] \tag{1}$$

where

$$k_1 = k H_m^2, \qquad k_2 = n H_m - k H_c H_m$$

$$k_3 = - n H_c, \qquad k = \frac{m\ell}{N} \tag{2}$$

H_c = coercive force in At/m

n, m are constants for the electrical conductivity σ,

$$\sigma = 1/mh + n \tag{3}$$

$h = H_m \sin \omega t$

ℓ = length of the magnetic path

N = reactor number of turns

From previous experimental work conducted on a three phase saturable-resistor with ALNICO 5-7 core, the following waveforms for the E field were obtained before and after saturation as shown in Fig. 3a,b.

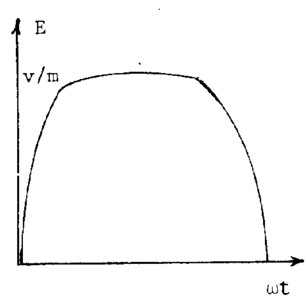

Fig. 3a
Pre-saturation State.

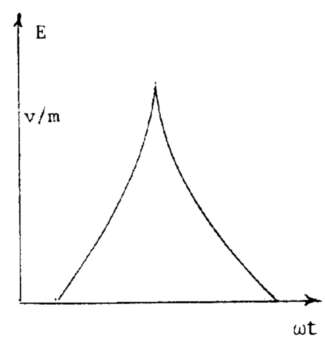

Fig. 3.b
Post-saturation State

From Fig. 3a, the conclusion that can be drawn is that for an external magnetic excitation sinusoidal in form will induce a set of odd rectangular pulses for the electric field in the region below saturation and a similar set of odd triangular pulse for the region within and beyond saturation as in Fig. 3b.

To express the induced electric field in the pre-saturation regime in the form of sinusoids, Fourier expansion has been obtained for e_p:

$$e_p = \sum_{n=1}^{\infty} b_n \sin n\omega t \tag{4}$$

$$b_{np} = \frac{1}{\pi}\int_{\omega t_c}^{\pi-\omega t_c} A \sin n\omega t \, dt$$

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$$= \frac{-2A}{n\pi} \cos n\omega t_c \quad (5)$$

$$\therefore \quad e_p = \sum_{n-1}^{\infty} \frac{-2A}{n\pi} \cos n\omega t_c \sin n\omega t \quad (6)$$

where

A = amplitude of e_p in the rectangular pulse

t_c = commencing time of magnetization within the hard ferromagnetic core.

e_p = pre-magnetization induced field.

Turning to the post-saturation regime where the induced electric field waveform is triangular pulse and designated as e_s,

$$e_{s_1} = \frac{A\omega t}{\pi/2-2\omega t_c} + \frac{A\omega t_c}{2\omega t_c-\pi/2} \quad (7)$$

for $(\omega t_c) \leq \omega t \leq (\frac{\pi}{2} - \omega t_c)$

$$e_{s_2} = \frac{-2A}{\pi} \omega t + (2A - \frac{2A\omega t_c}{\pi}) \quad (8)$$

for $(\frac{\pi}{2} - \omega t_c) \leq \omega t \leq (\pi - \omega t_c)$

$$b_{nse} = \frac{1}{\pi}\left[\int_{\omega t_c}^{\frac{\pi}{2}-\omega t_c} e_{s_1} \sin n\omega t\, dt + \int_{\frac{\pi}{2}-\omega t_c}^{\pi-\omega t_c} e_{s_2} \sin n\omega t\, dt \right]$$

$$b_{nse} = \frac{1}{\pi}\left[\cos \omega t_c \left\{ \frac{A}{n^2(\frac{\pi}{2} - 2\omega t_c} + n\omega t_c + \frac{A\omega t_c}{n\pi(2\omega t_c - \frac{\pi}{2})} - \frac{2A}{n^2\pi} \right\} - (\sin \omega t_c) \frac{A\omega t_c}{n\pi(2\omega t_c - \frac{\pi}{2})} + \sin n\omega t_c \left\{ 1 + \frac{n\pi}{2} - n\omega t_c - \frac{2A}{n^2\pi}(1 - \frac{n\pi}{2} + \omega t_c - n\omega t_c) \right\} \right] \quad (9)$$

$$e_s = \sum_{n=1}^{\infty} \frac{\sin n\omega t}{\pi} \left[\cos \omega t_c \left\{ \frac{A}{n^2(\frac{\pi}{2} - 2\omega t_c)} + n\omega t_c + \frac{A\omega t_c}{n\pi(2\omega t_c - \frac{\pi}{2}} - \frac{2A}{n^2\pi} \right\} - (\sin\omega t_c) \frac{A\omega t_c}{n\pi(2\omega t_c - \frac{\pi}{2})} + \sin n\omega t_c \left\{ 1 + \frac{n\pi}{2} - n\omega t_c - \frac{2A}{n^2\pi} (1 - \frac{n\pi}{2} + \omega t_c - n\omega t_c) \right\} \right] \quad (10)$$

Eqs. 6 and 10 refer to the set of harmonics contained within the induced electric field in the pre and post saturation regimes.

However the generated surface impedance will account to only the fundamental components of the applied h field and that from the induced. Therefore to account for other harmonics contained in the induced (e) field, a similar waveform for the (h) field must be applied to generate an (n) spectrum of surface impedances

$$\therefore \quad h_p = \sum_{n=1}^{\infty} b_{nph} \sin n\omega t$$

$$(\omega t_c) \leq \omega t \leq \pi - \omega t_c \quad (11)$$

h_p is a set of rectangular pulses

and

$$h_s = \sum_{n=1}^{\infty} b_{nsh} \sin n\omega t \quad (12)$$

h_s is a set of triangular pulses

h_p, h_s = applied magnetic field for the pre and post saturation of the saturable resistor.

Spectrum of Surface Impedances(3-7)

In the pre-saturation regime, let Z_{sp} be the generated surface impedance which can be expressed:

$$Z_{sp} = \frac{e_p(t)}{h_p(t)} = \sum_{n=0}^{\infty} \frac{-\frac{2A}{n\pi} \cos n\, t_c \sin n\omega_e t}{b_{nph} \sin n\omega_h t} \quad (13)$$

And the post-saturation surface impedance designated as Z_{ss} could be expressed as,

$$Z_{ss} = \sum_{n=0}^{\infty} \frac{b_{nse} \sin n\omega_e t}{b_{nsh} \sin n\omega_h t} \quad (14)$$

b_{nse} is expressed in equation 9

Criteria expressed in equations 13 and 14 refer to the surge impedance the saturable resistor can offer in the pre and post period of saturation. ω_e and ω_h, each represents the angular frequency for the induced electric field and the exciting applied magnetic field respectively.

For prompt switching on the spark gap network of the particle accelerator, regarding the charging beam, complete synchronization between ω_e and ω_h must be ensured. Z_{sp} is the harmonic impedance for switch opening and Z_{ss} is the harmonic impedance for switch closing.

Accelerators Equations (4-7)

1. Core Linear Induction Accelerator:

$$\rho_{total} = \rho_{core} + \rho_{sat,\ p.s.}$$

$$\rho_{sat-p} = \frac{A}{L} \mathrm{Re}(Z_{sp}) \quad (15)$$

$$\rho_{sat-s} = \frac{A}{L} \mathrm{Re}(Z_{ss})$$

$$i_c = \frac{\pi d^2}{4\rho_{tot.}} \quad \sqrt{ba} + b$$

and that

$$\rho_{sat_p} \gg \rho_{sat-s}$$

where

A = accelerator core cross-section.

b,a = inner and outer diameter of accelerator core.

ρ is the resistivity

2. Line Conical Accelerator

Z_o = accelerator characteristic impedance
= $120\ \ell_n \,\mathrm{ctn}\ \theta/2$

θ = angular inclination of the cone.
For perfect switching of the charging beam, prompt matching between Z_o and the switching impedance offered by the saturable resistor through the control network must be set. This could imply a variable conical angle θ.

$$\therefore \quad Z_o = Z_{sp} \quad \text{switch opening} \qquad = Z_{ss} \quad \text{switching closing} \tag{16}$$

3. Line Cylindrical Accelerator

$$Z_o = 60 \ \ell_n \frac{c}{b} = 60 \ \ell_n \frac{b}{a} \tag{17}$$

$= Z_{sp}$ switch opening

$= Z_{ss}$ switching closing

where a, b, c = geometircal dimensions of the accelerator

4. Electron Auto-Accelerator

$$Z_o = V_a/i_c - i_b = 60 \ \ell_n \frac{a}{b} \tag{18}$$

where

i_c, i_b = charging current and accelerating current respectively

V_a = accelerating voltage

Also for prompt switching on and off complete synchronization and matching must be secured between Z_o and Z_{sp} (switching off) and Z_{ss} (switching on).

$$\therefore \quad V_a = (i_c - i_b) Z_{sp},\ Z_{ss} \tag{19}$$

Conclusions (4-7)

1. Longer pulse duration for the accelerating beam could be feasibly ensured through the insertion of a saturable resistor in the control network of the particle accelerator.

2. Pulse duration in the order of μsec. could be expected for the accelerating beam since the saturable - resistor has a time constant in the order of 13 msec. and front time rise in the order of 4 msec.

3. Prompt and discrete switching of the charging beam could be ensured at a set of distinct periods generated by perfect synchronization between the applied magnetic field waveform and that of the induced electric field.

4. Switching on of the powering beam is expected to occur when the exciting magnetic field waveform is triangular and off for a corresponding rectangular wave.

5. Synchronized switching could be produced at discrete moments corresponding to every harmonic contained in the exciting (magnetic) and induced (electric) fields.

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