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# Simulation of Power Supply for Rapid Cycling Accelerator

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## Abstract

This paper presents a simulation of power supply for rapid cycling accelerator. Both the normal and fault condition operations are described.

## 1. Introduction

In rapid cycling accelerator, magnet circuit is designed into a resonant network because of two important considerations: the need to avoid drawing a large reactive power from the magnet a.c excitation source, and a uniform field intensity in each magnet(1). These requirements are satisfied by the method of connection which is based on the distributed resonance system proposed by M.G.White. The well-known White circuit (Fig.1) were consequently employed on Princeton Pennsylvania Accelerator, Electron Synchrotron NINA, KEK Proton Synchrotron Booster etc.. As for a.c excitation source, pulse method is generally chosen chiefly because of its operational flexibility and reliable performance. An energy storage choke is used to seperate a.c and d.c source and the resonant circuit also provides a path for circulating d.c current (but the path for d.c connection is omitted in Fig.1 for simplicity). Here we take the NINA resonant magnet network and power supply as example to carry out the simulation.

## 2. Normal Operation

(1). Parameters

The parameter of each element is shown in Fig.1.

The filter circuit has a resonant frequency $f_F$.

$$f_F = \frac{\omega_F}{2\pi} = \frac{1}{2\pi\sqrt{L_F C_F}} = 12.5Hz \quad ,$$

and the pulse circuit resonate at frequency of $f_P$.

$$f_P = \frac{\omega_P}{2\pi} = \frac{1}{2\pi\sqrt{L_P C_F}} = 150Hz.$$

Assume the resonant frequency of the magnet network is $f_a$, we have

$$f_a = \frac{\omega_a}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{L_M + L_{ch}}{L_M \cdot L_{ch} \cdot C_M}} = 50\text{Hz}.$$

The total resonant magnet network a.c power loss is $P_{a.c}$=950kW at maximum excitation.

(2). Operation and simulation results

The cyclic operation of the system can be divided into two periods: charging period and pulse period.

The normal operation is according to the following basic equations provided by J.A.Fox(1).

During the charging period

$$\left(\frac{\pi}{2\omega_p} \to \frac{2\pi}{\omega_a} - \frac{\pi}{2\omega_p}\right), \ i_p=0 \qquad (1.a)$$

$$i_F = \frac{V_s}{L_F\omega_F}\frac{\cos(\omega_F t - \pi(\omega_F/\omega_a))}{\sin\beta} \qquad (1.b)$$

$$V_F = V_s\left[1 + \frac{\sin(\omega_F - \pi(\omega_F/\omega_a))}{\sin\beta}\right] \qquad (1.c)$$

note: $V_S$=V'ch

During the pulse period $\left(-\frac{\pi}{2\omega_p} \to \frac{\pi}{2\omega_p}\right)$

$$i_p = \frac{V_s}{L_F\omega_F}\left[\cot\beta(1+\sin\omega_p t) + \frac{\omega_p}{\omega_F}\cos\omega_p t\right] \qquad \text{------(2.a)}$$

$$i_F = \frac{V_s}{L_F\omega_F}\left[\cot\beta - \frac{\omega_F}{\omega_p}\cos\omega_p t\right] \qquad (2.b)$$

$$V_F = V_s\left[(1-\sin\omega_p t) + \frac{\omega_F}{\omega_p}\cot\beta\cos\omega_p t\right] \qquad \text{------(2.c)}$$

where $\beta = \frac{\pi}{2}\left(\frac{2\omega_F}{\omega_a} - \frac{\omega_F}{\omega_p}\right)$

With simulation software PSpice53, each waveform of steady-state behavior of the system is obtained as shown in Fig.2.

From the results, we can see that in pulse period the energy-storage-choke primary voltage $V'_{ch}$ reaches the peak value $V_M/n$, and the energy storage-capacitor voltage $V_F$ is opposed by $V'_{ch}$, the capacitor $C_F$ is charged twice the V'ch voltage peak. The peak capacitor voltage of $2V'_{ch}$ is obtained by cyclic charging through filter choke $L_F$. The choice of $V_s=V'_{ch}$ makes it possible to discharge the capacitor voltage $V_F$ to zero and utilize the capacity $C_F$ economically.

Thus, the steady-state behavior of the pulse power supply can be described as follows. The rectifier set supplying the d.c voltage of $V_s=V'_{ch}$, charges the $C_F$ through filter choke $L_F$ to $2V_s$. The pulse thyristor is then triggered to discharge $C_F$ through the pulse choke $L_p$ and the energy storage choke, consequently the resulting half-cycle current $i_p$ occurs symmetrically around the positive peak of the choke primary voltage $V'_{ch}$. Following self extinction of the pulse thyristor at $i_p=0$, $C_F$ is charged once more and the process is repeated.

## 3. Fault operations

Under fault condition, such as parameter mismatch, considerable $V_s$ variation, and maloperation of pulse thyristor, the system operation will deviate from the normal operation, and result in large voltage or current swing. In serious case, the system operation will not be recovered.

(1). Parameter mismatch

According to the circuit behavior, the pulse power supply has to provide the pulse of energy, equal to the cyclic ac power loss of the the resonant magnet network. Fig.3 shows the resonant network (1mesh) and it's equivalent circuit. The balance between the average network a.c power loss $P_{a.c}$ and power provided by the pulse power supply can then be expressed as: $P_{a.c} = V_s \times i_{F(av)}$ (3.a)

where $P_{a.c} = \frac{\tilde{V}^2_{ch\cdot rms}}{R_e} \times 10$ (3.b)

and the average value of $i_F$ is provided by,

$$i_{F(av)} = \frac{V_s}{L_F\omega_F}\left(\frac{1}{2}\frac{\omega_a}{\omega_p}\cot\beta + \frac{1}{\pi}\frac{\omega_a}{\omega_F} - \frac{1}{\pi}\frac{\omega_a\omega_F}{\omega_p^2}\right) \quad \text{------- (4)}$$

According to circuit parameters, we get $i_{F(av)}=187A$ and $P_{a.c}=950kW$.

Accordingly, $R_e=2.164k\ \Omega$,

and the Q value is, $\omega_a R_e C_M=108$.

Now a circuit simulation at $R_e \neq 2.164k\Omega$ (Fig.4) shows that $V_F$, $i_F$ and $i_p$ have no change if compared with the normal operation in steady state. But we noted that the related phase changed and desired magnet current will not be reached.

(2). $V_s$ variation

a. Start-up fault operation

Owing to the high Q value of the magnet resonant network, a number of cycles elapse before the magnet current reaches the steady state corresponding to the initial $V_s$.

Fig.5 shows a large negative voltage swing on $C_F$ due to sudden starting by the initial value of $V_s$.

b. $V_s$ step reduction

Similar to the starting transient described above, the effect of an unrestrained reduction of $V_s$ is of great severity. The case of a step reduction of $V_s$ to half its original steady-state value is examined. Fig.6 shows the results.

(3). Maloperation caused by pulse thyristor

a. Failure of pulse valve to fire

$V_F$ is limited to a peak value of $V_F=2V_s$ according to eq(1) at normal operation. However, should the thyristor fail to fire during any one of the subsequent pulses, $V_s$ will rise to a maximum positive value of $2.64V_s$, and the pulse thyristor will be applied an overvoltage of $3.64V_s$. This process is simulated as shown in Fig.7.

b. Firing impulse $180^0$ out of phase

This occurs when firing impulse triggered the thyristor halfway through the charging cycle. As the simulation (by Micro-cap4) shows(Fig.8), an overswing occurs on $V_F$ and $i_p$ reaches a value of almost twice the normal amplitude.

The knowledge on either the normal operation or the fault condition behavior of the system will be valuable for us in designing control and protection system for this kind of power supply.

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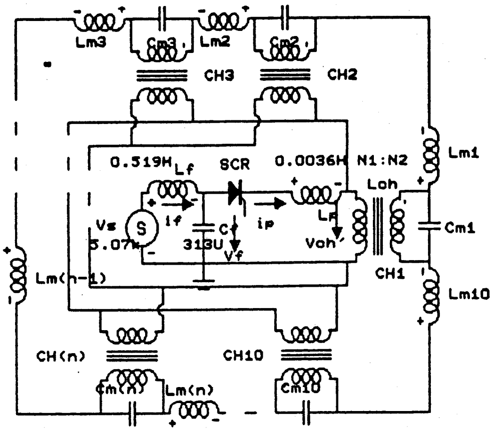
Reference. (1) Resonant magnet network and power supply for the 4GeV Electron Synchrotron NINA, J.A.Fox. Proc.I.E.E.Vol 112,No.6,June 1965.



Cm1=Cm2=Cm3=...=Cm(n)=...Cm10=CM=160.3UF
Lm1=Lm2=Lm3=...=Lm(n)=...Lm10=LM=0.0948H
Loh(secondary)=0.1896H, N1:N2=1:4

Fig.1 White circuit for resonant magnet network and pulse power supply

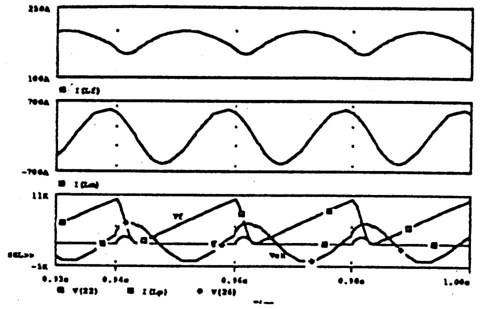


Fig.2 Steady state normal operation

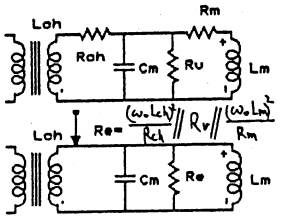


Fig.3 Equivalent circuit for 1 mesh

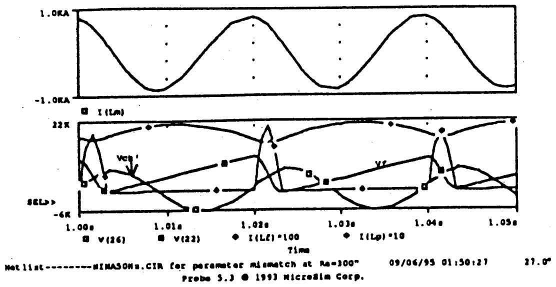


Fig.4 Parameter mismatch at $R_e=4k$

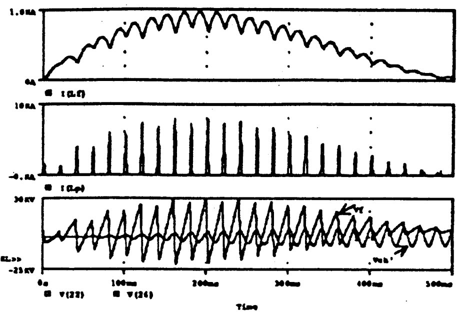


Fig.5 Start-up fault operation ($V_S$=5.07kV)

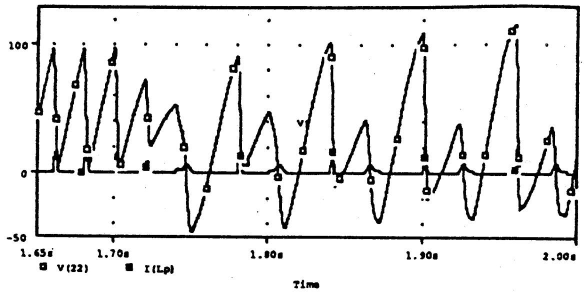


Fig.6 Behavior of step-reduction of $V_S$ ($V_S$=50.7V)

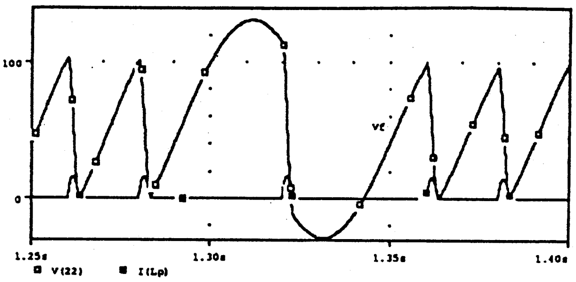


Fig.7 Thyristor firing failure ($V_S$=50.7V)

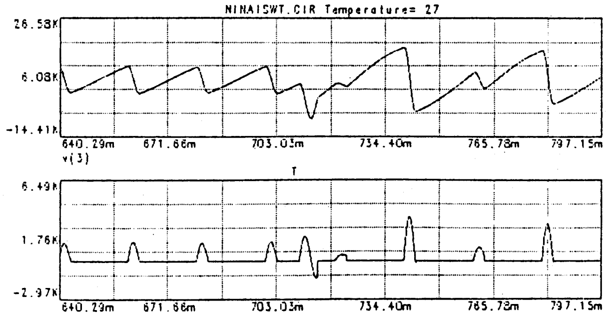


Fig.8 Halfway firing ($180^0$ out of phase) $V_S$=5.07k