OPTIMIZATION OF RESONANT POWER SUPPLY CIRCUIT

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Abstract

A Resonant Power Supply has been proposed to power Rapid Cycling Accelerator magnets. The Resonant Power Supply circuits were studied extensively [1,2], but were not optimized. Most designs assume equal choke and magnet inductance, however, the variation of inductance affects both performance and cost of the system. This paper optimizes the Resonant Power Supply Circuit by selecting the most feasible choke inductance. For this optimization, a computer model and an approximate design method were developed. The effect of choke inductance on the components rating and cost was determined. It was found that the increase of choke inductance reduces the maximum and increases the minimum choke current, which leads to a significant increase of system losses. The maximum voltage is independent of the choke inductance. The described change of choke current reduces the current of the By-pass Thyristor Switch and the Capacitor Bank Switch, which results in cost reduction. The increase of choke inductance reduces the size of capacitor banks. The loss increase requires larger Make-up Power Supply and AC supply systems. It also increases the operation costs. The system cost function has a minimum, when the choke inductance is about 1.5-2 times larger than the magnet one. The application of the result will lead to a more economical and efficient Resonant Power Supply.

Introduction

The Resonant Power Supply is economical and efficient to supply a Rapid Cycling Accelerator magnet system. The system concept was presented by Praeg [1]. An engineering design and system description was published by Karady at all [2]. The system design is based on the magnet data, which is the result of careful computer studies. The choke inductances in the previous studies were selected equal to the magnet inductance. This determines the currents and voltages of all other components, which defines the components rating. However, recent studies indicated that the selection of choke inductance is critical and its value has a significant effect on the system operation parameters and economics.

The objective of this paper is the optimization of the Resonant Power Supply circuit and the determination of the most feasible choke inductance value.

Computer Model for Operation Analyses

The resonant power supply one line diagram is shown in Figure 1. The required magnet current wave is shown in Figure 3 a.

The equivalent circuit for each component and a model circuit, shown in Figure 2, were developed [2]. The operation of the circuit was studied by a transient network analysis code . The choke, magnet current, and voltage have been calculated for different choke and magnet inductance ratios.

Figure 3 shows that the maximum voltage is independent of the choke inductance. But the maximum choke current decreases and the minimum choke current increases by increasing the choke inductance. The difference between the magnet and choke current, which is the Thyristor Switch and Capacitor Bank current, decreases with the choke inductance.

The circuit operation can be studied by an approximate analytical method, that neglects the resistances and assumes that the sum of the energy stored in the magnet and choke is constant during the flat-top and injection periods. The comparison of the approximate calculation with the results of computer analyses shows that the approximate calculation is sufficiently accurate for the system design. Even the losses and the required make-up energy can be estimated by calculating the integral of the I^2R function at the end of the analyses.

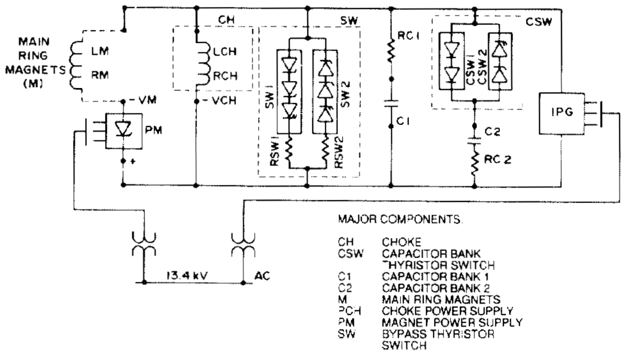


Figure 1. Resonant Power Supply One Line Diagram.

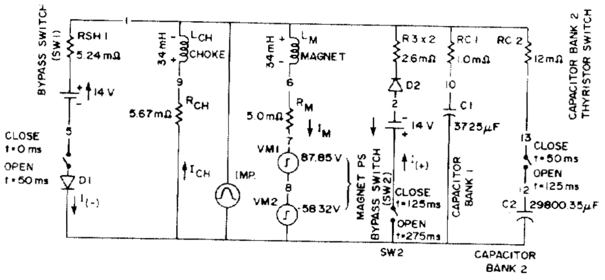
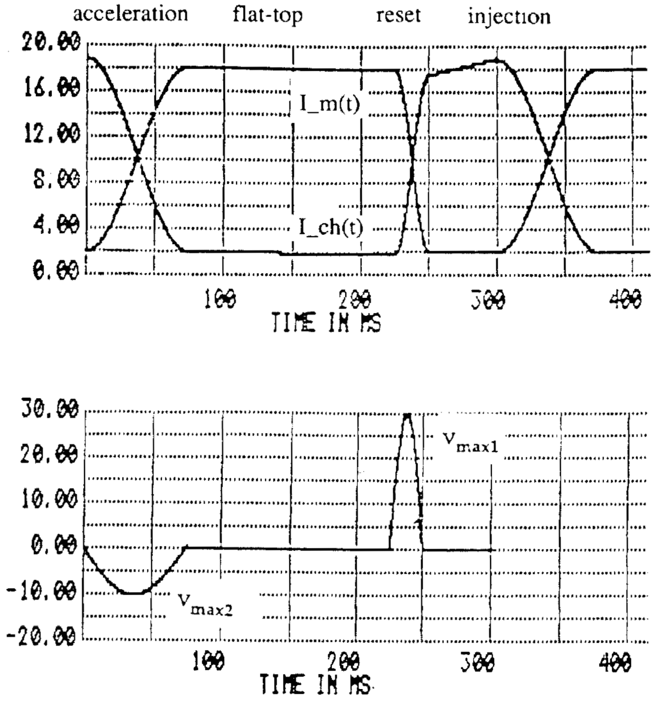


Figure 2. Equivalent Circuit For Computer Modeling.



a. Choke and Choke and Magnet inductance are equal.

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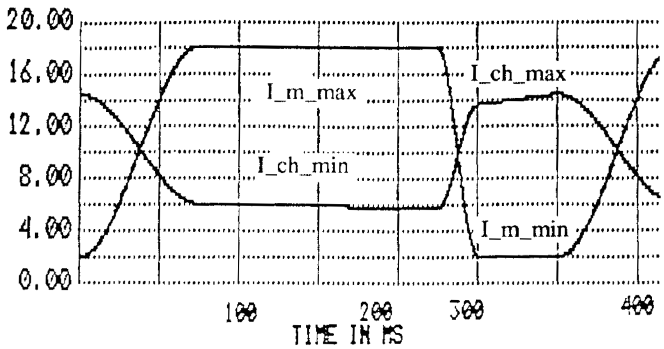
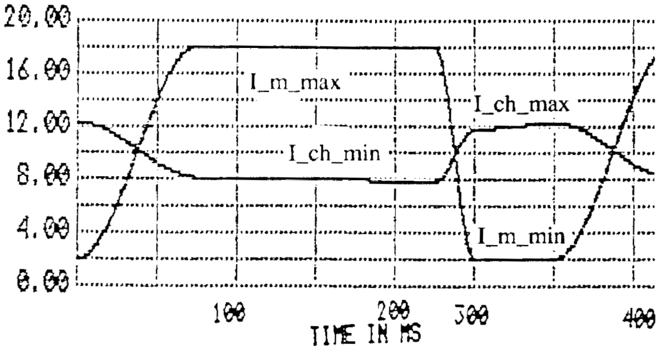


b. Choke inductance is twice the magnet inductance.



c. Choke inductance is four times the magnet inductance.

Figure 3. System Voltage, Magnet and Choke Current.

Approximate Analyses

The sum of the energy stored in the magnet and choke is constant and remains the same during flat top and injection.

The energy balance equation is :

$$(\mathrm{I\_m\_max})^2 \cdot \mathrm{L\_m} + (\mathrm{I\_ch\_min})^2 \cdot \mathrm{L\_ch} = (\mathrm{I\_m\_min})^2 \cdot \mathrm{L\_m} + (\mathrm{I\_ch\_max})^2 \cdot \mathrm{L\_ch} \qquad (1)$$

The definitions of the currents are shown in Figure 3. From equation 1 the choke current values are calculated,

$$\mathrm{I\_ch\_max} = \mathrm{I\_m\_max} \cdot (k+1)/2k + \mathrm{I\_m\_min} \cdot (k-1)/2k \qquad (2)$$
$$\mathrm{I\_ch\_min} = \mathrm{I\_m\_max} \cdot (k-1)/2k + \mathrm{I\_m\_min} \cdot (k+1)/2k \qquad (3)$$

$$k = \mathrm{L\_ch} / \mathrm{L\_m} \qquad L = \frac{\mathrm{L\_ch} * \mathrm{L\_m}}{\mathrm{L\_ch} + \mathrm{L\_m}} \qquad (4)$$

The variation of the choke current as a function of choke inductance is shown in Figure 4.

The change of choke inductance affect the rating of Capacitor Bank 1 and 2. The required capacitance can be calculated from the resonance frequency equation if L_m and L_ch are connected in parallel. The required capacitance is :

$$C = (1/\omega^2 \cdot L) \cdot (1+k)/k \qquad (5)$$

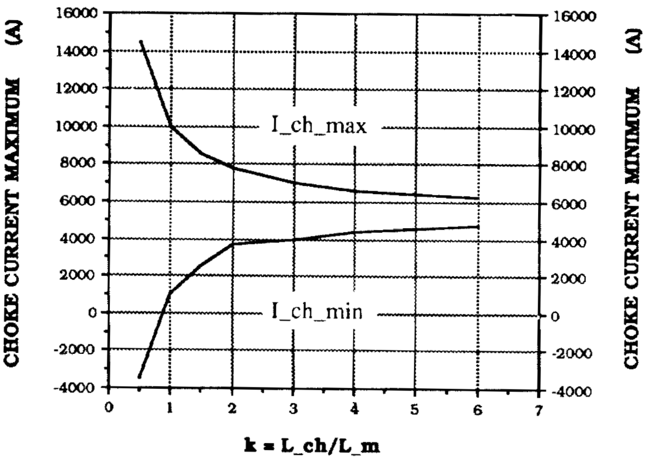


Figure 4. Maximum and Minimum. Choke Current.

Figure 5 shows that the percentage capacitance variation is significant. If the choke inductance is five times the magnet inductance, the capacitor banks rating can be reduced by 40 %.

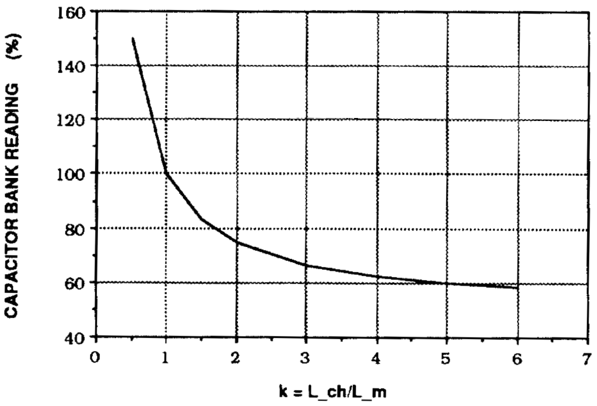


Figure 5. Change of Capacitor Bank Rating.

The thyristor switch current is the difference of the magnet and choke current. Its value can be expressed as :

$$\mathrm{I\_sw\_max} = (\mathrm{I\_m\_max} - \mathrm{I\_m\_min}) \cdot (1+k)/2k \qquad (6)$$

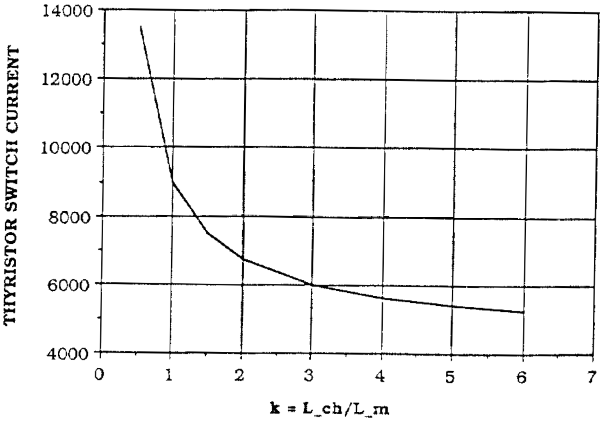


Figure 6. Thyristor switch current.

A similar equation can be derived for Capacitor Bank 2 Thyristor Switch. The equation shows that both currents are reduced by the increase of choke inductance.

For the system loss calculation, the choke current as a function of the time is determined.The magnet losses are not affected by the choke inductance. The currents during the injection and flat-top periods are constant and their values are shown in Figure 3. The currents during acceleration and reset are described by a sine function. The choke current during acceleration is :

$$I\_cha(t) = 0.5\,[(I\_ch\_max + I\_ch\_min) + (I\_ch\_max - I\_ch\_min) \cdot \sin \omega t] \qquad (7)$$

The choke current during reset is:

$$I\_chr(t) = 0.5\,[(I\_ch\_max + I\_ch\_min) + (I\_ch\_max - I\_ch\_min) \cdot \sin(\omega(t-Tf))] \qquad (8)$$

The total current is:

$$I\_ch(t) = \mathrm{if}(t<Ta, Icha(t), \mathrm{if}(t<Tf, I\_ch\_min, \mathrm{if}(t<T_R, Ichr(t), I\_ch\_max) \qquad (9)$$

Where: Ti, Ta, Tf, Tr marks the end of acceleration, flat-top and reset respectively.

The choke loss is:

$$Loss\_ch = R\_ch \cdot \int_0^T [I\_ch(t)]^2\,dt \qquad (10)$$

Where: T is the repetition time

$R\_ch = R\_cho \cdot k$ is the choke resistance

It is assumed that the L_ch/R_ch is constant, therefore the choke resistance is proportional with the k factor.

The losses in the thyristor, capacitor bank and ac system were also calculated. The variation of the total losses as a function of choke inductance is shown in Figure 7. The figure shows that the system loss increases significantly with the increase of choke resistance. This is an important finding because the system loss determines the operation cost and affects the Make-up Power Supply and AC system rating.

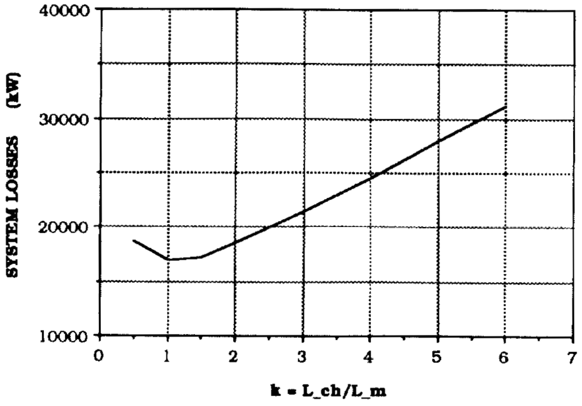


Figure 7. Choke Loss versus Choke Inductance.

The system cost was calculated using manufacturers' quotations. The analysis of the data obtained is summarized in Table 1.

The variation of total cost is shown in Figure 8. It can be seen that the total cost function has a minimum at around k = 1.4 - 1.8. The function changes rapidly, which suggests that the choke inductance should be between 1 - 2 times the magnet inductance.

Table 1. Choke inductance effect on the major cost components.

Cost Component	Effect of Choke Inductance on Component Cost Increase.
Magnet	none
Magnet P. S.	none
Choke	small cost increase
Make- up P. S.	significant cost increase
Capacitor Bank	substantial cost reduction
Thyristor Switch	substantial cost reduction
Capacitor bank Switch	small cost reduction
AC system	significant cost increase
Total hardware	moderate cost decrease
Operation cost	significant cost increase.

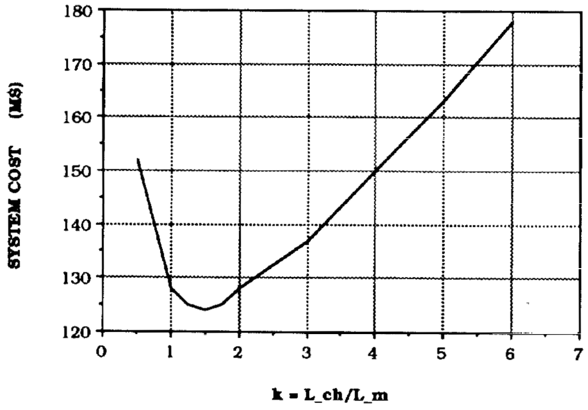


Figure 8. System Cost versus Choke Inductance.

Discussion.

The results indicate that the hardware cost decreases but the operation cost increases with the choke inductance, which explains the cost function minimum.

The hardware cost decreases at the beginning because of the reduction of component current. However, the later increase of Make-up Power Supply and AC system costs compensates for this reduction.

The increase of operation cost is due to rapid increase of the choke loss. During the short injection period the choke current reduced, but during the long flat-top period the choke current is increases with the increase of choke inductance. This in term increases the choke loss.

Conclusion.

- The system cost is significantly affected by the variation of choke inductance.
- The cost function has a definite minimum between k=1 and k=2
- The most feasible choke inductance is around 1.5 times the magnet inductance.
- The use of the optimal choke inductance results in a more economical and efficient Power Supply.

References.

[1] W. F. Praeg, "Dual Frequency Ring Magnet Power Supply with Flat-Bottom," IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, Aug. 1983.

[2] G. Karady, H.A. Thiessen, E.J. Schneider, "Resonant Power Supplies for a Rapid-Cycling Accelerator", IEEE Trans. on Nuclear Science, Oct. 1988, Vol 35, No. 5, pp 1992-1098.