PRINCIPLES AND THEORY OF RESONANCE POWER SUPPLIES

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Abstract

The resonance power supply is widely used and proved to be an efficient method to supply accelerator magnets. The literature describes several power supply circuits but no comprehensive theory of operation is presented. This paper presents a mathematical method which describes the operation of the resonance power supply and it can be used for accurate design of components.

1. INTRODUCTION

The resonance power supply is being used for accelerator magnet excitation in the last two decades.The first application was in the Princeton Pennsylvania Accelerator [1]. In 1978 Praeg and McGhee [2] reported the utilization of series resonant network to generate biased sine wave excitation current for the Argonne National Laboratory Synchrotron. Subsequently Praeg and colleagues presented several papers discussing the dual frequency resonance power supply with flat top and flat bottom [3,4]. Karady et al [5,6] presented a design method for a 10 kA, 10 kV resonance power supply in which they proposed component realization and system optimization. In the literature transient simulation techniques (SPICE, MICROCAP etc.) are used to analyze the operation of resonance power supplies. These techniques simulate the operation correctly but do not describe the phenomena. A mathematical analysis is required to obtain better understanding of the system operation.

The resonance power supply operation consists of distinct periods and each period represents a state of the system. The cyclic operation of the power supply can be described by the transition from one state to the other. Each period can be described by a set of state equations. The state space method simplifies the computation and provides insight into the physical phenomena.

The purpose of this paper is to apply the state space method for the analyses of resonant power supply operation.

2. METHOD OF ANALYSIS

a. System definition

The resonance power supply circuit diagram and the required current wave shape are shown in Figure 1. It can be seen that the system operation is divided into four states: injection, acceleration, flat top and reset.

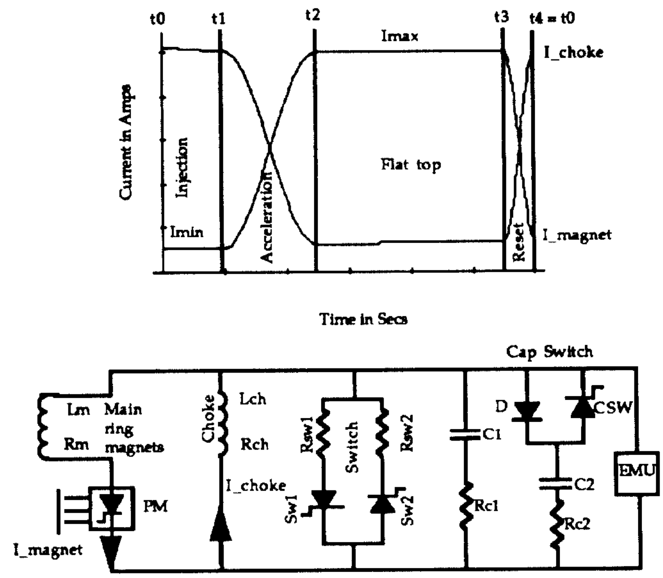

Figure 1. Required Current shape and Circuit diagram.

b. Concept of the analysis

The circuit diagram for each state was identified and the state space equations were derived. In steady state sequential operation the states follow each other. Therefore the initial conditions for a state are the final conditions of the previous state. This procedure results in a set of simultaneous differential equations. The solution of these equations using the state space method describes the system operation. The state equations were also solved using the Laplace Transform method. The solutions obtained by the state space method were verified by the Laplace Transform method using the MATHEMATICA package for computation.

c. List of symbols

Lm, Rm Magnet inductance and resistance respectively.
Lch, Rch Choke inductance and resistance respectively.
C1, Rc1 Capacitor Bank 1 and bus bar resistance respectively.
C2, Rc2 Capacitor Bank 2 and bus bar resistance respectively.

3. OPERATION ANALYSIS

a. Injection

The system equivalent circuit for the injection period is shown in Figure 2.

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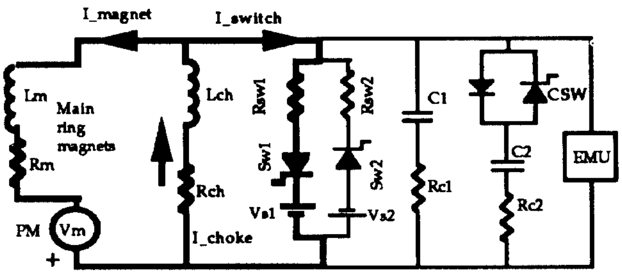

Figure 2. Current path during injection period

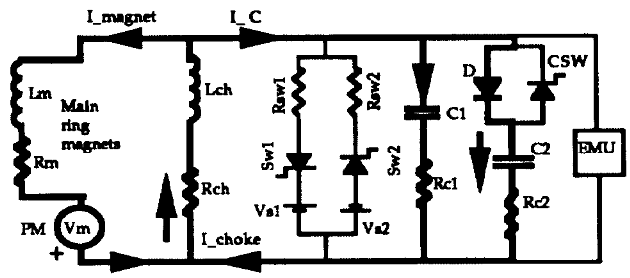

Figure 3. Current path during acceleration.

The state space equations for this circuit are :

$$\frac{\partial i_{ch}}{\partial t} = -\alpha \; i_{ch} - \frac{(V_{s1} + i_m R_{SW1})}{L_{ch}} \qquad 1$$

$$V_m = i_m R - V_{s1} - i_{ch} R_{SW1} \qquad 2$$

where,

$$\alpha = \frac{(R_{ch} + R_{sw1})}{L_{ch}}, \quad R = R_{ch} + R_{sw1} \qquad 3$$

The solution of these equations results in the equation,

$$i_{ch}(t) = i_{cho}\, e^{-\alpha t} + \left(\frac{I_{mo} R_{sw1}}{R} - \frac{V_{s1}}{R}\right)(1 - e^{-\alpha t}) \qquad 4$$

The equations 1 and 2 in state space form are,

$$\begin{bmatrix} i_{ch}(t) \\ \frac{di_{ch}}{dt} \\ i_m(t) \\ \frac{di_m}{dt} \end{bmatrix} = \begin{bmatrix} a1 & 0 & a2 & 0 \\ b1 & 0 & b2 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Icho \\ i_{ch}(t0) \\ Imo \\ i_m(t0) \end{bmatrix} + \begin{bmatrix} a3 \\ b3 \\ 0 \\ 0 \end{bmatrix} \qquad 5$$

The final value of the choke and magnet current for the injection period are the initial values for the acceleration period.

b. Acceleration

The acceleration period starts with the opening of the GTO switch SW1 and the closing of the capacitor bank switch CSW. The switches insert the capacitor banks in the circuit. The current paths are shown in Figure 3.

The differential equations representing the accelerating period are given by,

$$\frac{\partial^2 i_{ch}}{\partial t^2} = -a \frac{\partial i_{ch}}{\partial t} - \frac{i_{ch}}{CL_{ch}} + \frac{1}{L_{ch}}\left(R_c \frac{\partial i_m}{\partial t} + \frac{i_m}{C}\right) \qquad 6$$

$$\frac{\partial^2 i_m}{\partial t^2} = -b \frac{\partial i_m}{\partial t} - \frac{i_m}{CL_m} + \frac{1}{L_m}\left(R_c \frac{\partial i_{ch}}{\partial t} + \frac{i_{ch}}{C}\right) \qquad 7$$

where,

$$a = \frac{R_c + R_{ch}}{L_{ch}}, \quad b = \frac{R_c + R_m}{L_m} \qquad 8$$

The solution of the circuit equations is obtained from the state representation,

$$\begin{bmatrix} \dot{x}1 \\ \dot{x}2 \\ \dot{x}3 \\ \dot{x}4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a1 & a2 & a3 & a4 \\ 0 & 0 & 0 & 1 \\ b1 & b2 & b3 & b4 \end{bmatrix} \begin{bmatrix} x1 \\ x2 \\ x3 \\ x4 \end{bmatrix} \qquad 9$$

The final values obtained from equation 9, are used as initial values for the next state.

c. Flat Top

The flat top state is initiated by the closing of SW2, which short circuits the capacitor bank. The current path is similar to that shown in Figure 2, except that, the current direction is reversed and SW2 is operating instead of SW1. The state space equations for this period are similar to that of the injection period.

The final values of the flat top period are used as initial values for the next state.

d. Reset

The reset period is initiated by the opening of SW2, which inserts the capacitor bank in the circuit. The current path is similar to that shown in Figure 3, but now only capacitor bank C1 is in the circuit.

The state space equations are similar to the equations obtained for the acceleration period.

The final values obtained are used as initial values for the next injection state of the next cycle.

4. SOLUTION STRATEGY

The input data required for the solution of the state space equations are : a) The starting time and ending time for each state, b) The system parameters(resistance, inductance, capacitance values), c) The constraints on the magnet current. For example the magnet current has to be kept constant during the flat top and the maximum and minimum values of the magnet current for any cycle are fixed.

The analysis uses two variables Icho and Imo which are the initial choke and magnet currents. The state space representation of different periods in terms of these variables are formulated. The system behavior is studied with respect to variations in Icho and Imo and other parameters.

5. LOSS ANALYSIS

The application of the developed method is demonstrated by the calculation of energy losses in a resonant power supply system described in detail by Karady et al [5]. The analysis starts with computation of voltage required in series with the magnet during injection and flat top periods. These voltages are highly regulated ramps to keep the magnet current constant. The state space equations were solved using the described method using the MATRIXX Math Program.

Typical results are shown in Figure 4, which presents the capacitor bank current during the acceleration and reset period. Figure 5 shows the load on the system as a function of time. It can be seen that the majority of the losses occur during the flat top period. Also the calculation indicates that the current at the end of the reset is less than the initial current required for the injection period. Therefore the system requires additional energy injection.

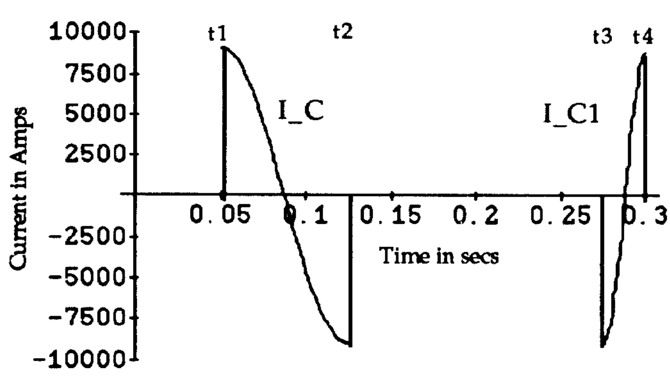

Figure 4. Capacitor bank current in Acceleration and Reset.

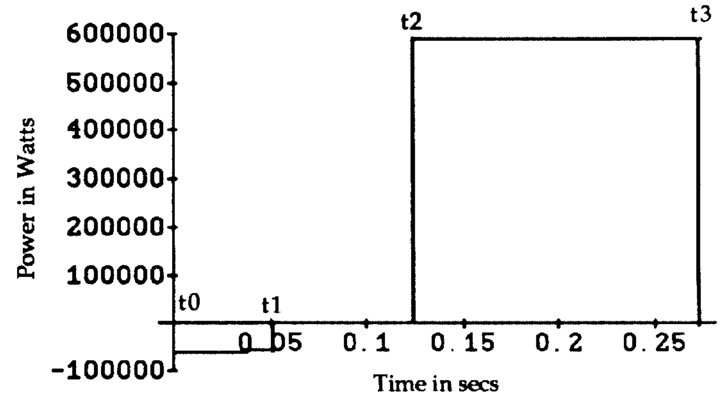

Figure 5. Load on the system as a function of time.

6. CONCLUSION

The results of the presented analysis can be summarized in the following points;

1. This paper introduces the state space method for the analysis of resonant power supply operation.
2. The state space method reduces simultaneous differential equations to a set of linear equation, which reduces computational complexity.
3. This method can be used an an effective design tool for physical realization of resonance power supplies.
4. The advantages of the method were demonstrated using a practical example.

7. REFERENCES

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