Optimization of Speed-Up Network Component Values for the 30 Ω Resistively Terminated Prototype Kicker Magnet

M. J. Barnes, G. D. Wait,
TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

Abstract

Kicker magnets are required for all ring-to-ring transfers in the 5 rings of the proposed KAON factory synchrotron. The kick must rise from 1% to 99% of full strength during the time interval of gaps created in the beam (80 ns to 160 ns) so that the beam can be extracted with minimum losses. In order to achieve the specified rise-time and 'flatness' for the kick it is necessary to utilize speed-up networks, comprising a capacitor and a resistor, in the electrical circuit. Speed-up networks may be connected electrically on both the input and output of the kicker magnet. In addition it is advantageous to connect a 'speed-up' network on the input of the resistive terminator(s). A sequence which may minimize the number of mathematical simulations required to optimize the values of the 8 possible speed-up components is presented. PE2D has been utilized to determine inductance and capacitance values for the resistive terminator; this data has been used in PSpice transient analyses. Results of the PE2D predictions are also presented. The research has culminated in a predicted kick rise time (1% to 99%) of less than 50 ns for a TRIUMF 10 cell prototype kicker magnet. The proposed improvements are currently being implemented on our prototype kicker system.

I. Introduction

The magnetic field rise time of a transmission kicker magnet results from a superposition of the the rise time of the pulse from the pulse generator and the propagation time of the pulse through the magnet (fill time) [1]. Many of the kicker magnets for the proposed KAON factory synchrotron require 1% to 99% kick rise/fall times of less than 82ns [2,3].

In order to compensate for unavoidable impedance mismatches it is necessary to include several 'speed-up' networks in the design of the pulse generator. In the case of a kicker magnet which is terminated in a short-circuit on its output, for example the booster extraction kicker magnet for the KAON factory [1], only one or two speed-up networks are required [4].

The collector injection kicker magnet for the KAON factory requires both a 1% to 99% rise and fall time of 82ns [2]. In order to achieve both the specified rise and fall time, a kicker magnet which is terminated resistively may require four speed-up networks, which results in eight components whose values are to be optimized. A methodology has been developed which permits optimum values to be determined for these eight components, with a minimum number of mathematical simulations.

As part of the KAON Factory project definition study a prototype transmission line type kicker magnet has been built at TRIUMF [2]. This kicker magnet is based on the design of those of CERN PS division [3,5]. The prototype kicker is a 10 cell magnet with a design value of 30 Ω for the characteristic impedance [1]. The prototype magnet has been simulated for the PSpice studies reported in this paper.

II. Equivalent Circuit

Fig. 1 shows a block diagram of the equivalent circuit for the kicker magnet and pulse generator; connections, cable plugs and sockets, as well as losses in the ferrite and mutual coupling between adjacent cells of the kicker magnet

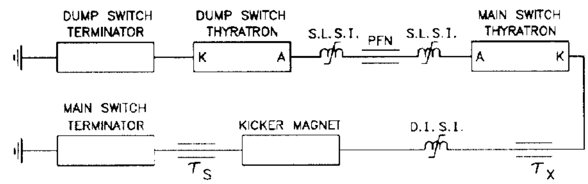

Figure 1: Block diagram of pulse generator and magnet

are simulated [6] but not shown in Fig. 1. The equivalent circuit of the main switch and dump switch thyratron allows for both anode and cathode displacement current [1,7]. The D.I.S.I. (Displacement Current Saturating Inductor) shown in Fig. 1 reduces the magnitude of prepulse cathode displacement current which flows through the kicker magnet to an acceptable level [1], therefore significantly decreasing the 1% to 99% field rise-time in the kicker magnet [1,8]

As mentioned above four speed-up networks are required in order to achieve the specified rise and fall times for the collector injection kicker magnet. Speed-up networks connected on the output and input of the kicker magnet mainly effect the leading and trailing edge, respectively, of the kick [9].

During the post-pulse period the D.I.S.I. is unsaturated (relatively high impedance); in order to obtain a satisfactory post-pulse kick, any reflections from the nonideal main-switch resistive terminator must be suppressed. Hence it is advantageous to connect a speed-up network on the input to the kicker magnet, between the magnet and the D.I.S.I. In addition, connecting the speed-up network between the magnet and the D.I.S.I. helps to suppress impedance resonances which the beam might otherwise 'see' [10].

In order to be able to select optimum component values for the speed-up networks, Figures of Merit (FOM) are calculated for the kick [11]. The integral with respect to time of the deviation of the kick from the ideal levels (0% and 100% of full kick strength) and outside of specified levels (±1% deviation of full kick strength from the ideal levels) is used to determine two FOM's for each of the prepulse, 'flat-top' and post-pulse periods: these FOM's also take into consideration the predicted and specified rise-times.

The resulting complex equivalent circuit has been analysed in the time domain by utilizing the transient analysis capabilities of PSpice [12]. The Analogue Behavioral Modelling capability of PSpice has been utilized to calculate the time integral of the deviation of the predicted kick from the ideal and specified levels. The powerful Goal Function capabilities of the Probe [12] post-processor are then utilized to determine the FOM's. The Goal Function capability of Probe has been used in conjunction with the Parametric Analysis capability of PSpice to rapidly determine the value of a component which results in a minimum FOM.

III. Proposed Design Methodology

The D.I.S.I. may significantly effect the optimum values of the speed-up network components connected on the input to the kicker magnet, hence it is necessary to simulate the D.I.S.I. throughout the optimization process. The following design methodology has been developed for identifying

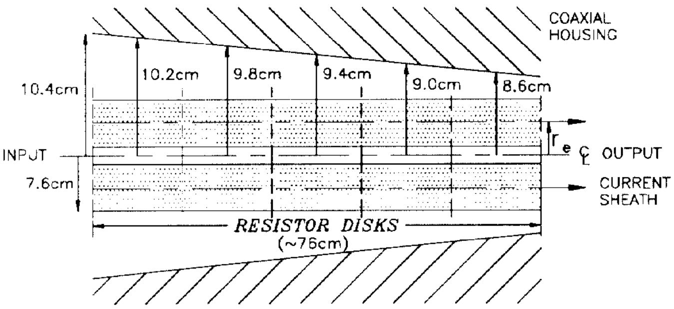

Figure 2: CERN PS Division Resistive Terminator

'optimum' values for speed-up network components, for a resistively terminated kicker magnet, with a minimum number of mathematical simulations [9]:

1. Simulate the main switch and dump switch resistive terminator as being ideal. The ideal main-switch resistive terminator must be simulated as being directly connected on the output of ideal transmission line τ_S (Fig. 1). Simulate a speed-up network on the output of the kicker magnet only:
   • this speed-up network is modelled as having a resistor whose value is equal to the characteristic impedance of the Pulse Forming Network (PFN). The value of the speed-up capacitor is swept through a range of values to identify an optimum;
   • subsequently simulate this speed-up network as having a capacitor whose value is equal to the optimum value identified above. The value of the speed-up resistor is swept through a range of values to identify an optimum value.
2. A speed-up network with optimized values for the capacitor and resistor is simulated on the output of the kicker magnet. A speed-up network is simulated on the input of the magnet too:
   • this input speed-up network is modelled as having a resistor whose value is equal to the characteristic impedance of the PFN. The value of the speed-up capacitor is swept through a range of values to identify an optimum;
   • subsequently simulate the input speed-up network as having a capacitor whose value is equal to the optimum value identified above. The value of the speed-up resistor is swept through a range of values to identify an optimum.
3. A realistic mathematical model of the main-switch resistive terminator is simulated, and speed-up networks with optimized values for the capacitor and resistor, as identified above, are simulated on both the output and input of the kicker magnet. A 'speed-up' network is simulated on the input of the main-switch resistive terminator:
   • the 'speed-up' network on the input to the main-switch terminator is modelled as having a resistor whose value is equal to the characteristic impedance of the PFN. The value of the capacitor is swept through a range of values to identify an optimum.
   • the 'speed-up' network on the input to the main-switch terminator is modelled as having a capacitor whose value is equal to the optimum value identified above. The value of the 'speed-up' resistor is swept through a range of values to identify an optimum.

A S.L.S.I. (Switching Loss Saturating Inductor) may be connected adjacent to the anode of the main switch thyratrons [1,7]. The S.L.S.I. has several beneficial effects such as reducing switching-losses in the thyratron, improving current rise-time, and reducing the effect of anode displacement current [1,7]. If a S.L.S.I. is to be incorporated, experience has shown that the S.L.S.I. should be simulated prior to optimizing the values of the components associated with the 'speed-up' network connected in parallel with the dump-switch resistive terminator. This 'speed-up' network mainly compensates for the tail which the S.L.S.I. may otherwise introduce: as the S.L.S.I. comes out of saturation magnetically stored energy is released into the system. When optimizing these component values, the optimum values for the other three speed-up networks, as identified above, are modelled.

Experience has shown that it is not necessary to re-optimize the values of the speed-up capacitors after the resistor values have been optimized.

The predicted results for the kick are relatively insensitive to the exact value of the parasitic inductance associated with the speed-up networks.

IV. Resistive Terminator

The inner diameter (D) of the coaxial housing of the CERN resistive terminator is tapered (see Fig. 2). This design permits the resistive terminator to withstand the pulse voltage while minimizing the parasitic inductance of the terminator. PE2D [13] has been utilized to calculate the inductance of the CERN PS Division resistive terminator [9]. Since PE2D is a two dimensional electromagnetic analysis package, it cannot simulate a tapered terminator. Hence the PE2D analysis is repeated for several diameters, between the minimum and maximum inner diameters, of the tapered housing.

The overall inductance per metre length (L_{pm}) of the resistive terminator is calculated by using the stored energy/unit length (integral B.H/2 ds), as determined using PE2D. The effective radius (r_e) of current flow in the resistor disks is calculated from this inductance:

$$r_e = \left(\frac{D}{2 \times e^{\left(\frac{L_{pm}}{2 \times 10^{-7}}\right)}} \right) \quad (1)$$

Analysis of the results of PE2D simulations, for a given driving frequency, shows that r_e is independent of the inner diameter of the coaxial housing. Thus, for a given driving frequency and resistivity of resistor disks, the PE2D analysis need only be carried out for one diameter of a tapered housing: from a knowledge of r_e the inductance per metre length can then be calculated for any inner diameter along the length of the tapered housing.

The inside diameter of the resistor disks is 34.2mm. Approximately 30 disks, with a resistance of 1Ω each, may be used for a 30Ω terminator. For a disk of resistivity $0.68\Omega \cdot m$ (as per the CERN PS Division resistive terminator) the effective radius of the current sheath is approximately 6.1cm, and only increases by about 1% as frequency is increased from 1MHz to 60MHz. At 60MHz the current density in the disk increases linearly, by about 16%, from the inside to the outside diameter of the resistor disks. As a result of proximity effect image current flows on the inside diameter of the coaxial housing. Assuming a dissipation of 60W per resistor disk, cooling of $0.02\text{W}\cdot K^{-1}\cdot\text{cm}^{-2}$ on all surfaces of a disk, thermal conductivity of the resistor material of $0.0334\text{W}\cdot K^{-1}\cdot\text{cm}^{-2}$ [14], and a disk thickness of 25.4mm, the maximum predicted temperature, which is $10°$K above bulk fluid temperature, occurs at a radius of 45mm and halfway through the thickness of the disk [15]. For a disk of resistivity $0.34\Omega \cdot m$ the effective radius of the current sheath increases by about 4% as frequency is increased from 1MHz to 60MHz.

The capacitance per metre length of a coaxial structure is given by:

$$C = \left(\frac{2 \times \pi \times \epsilon_0 \times \epsilon_r}{Ln\left(\frac{D}{2 \times r_e}\right)} \right) \quad (2)$$

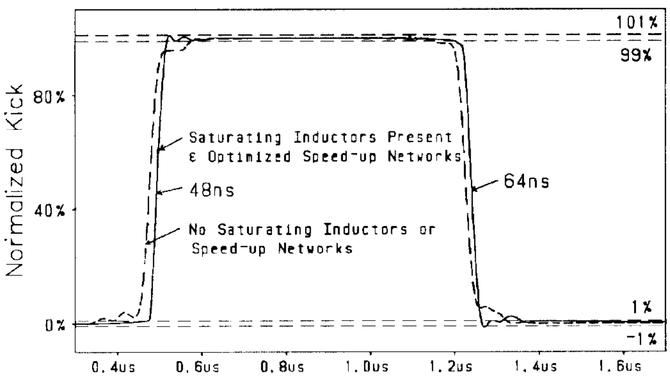

Figure 3: Predicted normalized kick for the 10 cell prototype kicker magnet

In order to calculate capacitance per metre, for use in PSpice simulations, ϵ_r for the resistor disks has been assumed to be unity.

The resistive terminator is simulated, in the PSpice analyses, as five equal length sections connected in series [9] (see Fig. 2).

V. General Results

The presence of resistors in the speed-up networks, connected on the input and output of the kicker magnet, do not have a significant effect upon the predicted field in the flat-top or post-pulse period. However the presence of a resistor, whose value is equal to the characteristic impedance of the PFN, in the speed-up network on the input to the kicker magnet, damps some of the impedance resonances which the beam may 'see' [10]. The resistor associated with the 'speed-up' network, connected on the input of the main-switch resistive terminator, does help to damp oscillations during the flat-top and post-pulse period.

A 'speed-up' network on the input of the resistive terminator is effective at dealing with the non-ideal characteristics of the terminator. In addition the 'speed-up' network can be optimized to permit the use of a cylindrical housing, rather than the tapered coaxial housing associated with the CERN PS division resistive terminator; the diameter of the housing would be as per the input of the tapered housing, so as to maintain voltage withstand. With a suitably optimized 'speed-up' network, a cylindrical coaxial housing results in virtually identical FOM's as a tapered housing.

Fig. 3 shows two predicted time-responses for the 30Ω prototype kicker magnet connected in a representative electric circuit. The 'dashed' pulse in Fig. 3 is predicted when there are no D.I.S.I., S.L.S.I. or speed-up networks. The 'continuous' pulse in Fig. 3 is the prediction obtained when the D.I.S.I. and S.L.S.I. inductors, and the optimized speed-up network values are utilized: the predicted rise-time (1% to 99%) is less than 50ns, as opposed to 164ns without saturating inductors or speed-up networks.

VI. Conclusion

A sequence which may minimize the number of mathematical simulations required to optimize the values of the speed-up network components has been developed. Initially the main-switch and dump-switch resistive terminators are modelled as being ideal and the speed-up networks on the output and input of the magnet are optimized, respectively. It is necessary to simulate the D.I.S.I. while optimizing these speed-up networks. Subsequently a realistic main-switch resistive terminator is simulated and the 'speed-up' network on the input to the main-switch terminator is optimized independent of the other speed-up networks. In order to properly optimize values of the resistor and capacitor associated with the 'speed-up' network connected on the input to the dump-switch resistive terminator it is necessary to simulate the S.L.S.I.'s.

PE2D has been utilized to determine inductance and capacitance data for the resistive terminators. A 'speed-up' network on the input of each resistive terminator is effective at dealing with the terminators non-ideal characteristics. In addition the 'speed-up' network can be optimized to permit the tapered coaxial housing, associated with the CERN PS division resistive terminator, to be manufactured as a coaxial cylinder instead.

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