Modeling Magnetic Pulse Compressors*

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Abstract

In this paper, we consider the problem of modeling the dynamic performance of high-average-power, high-repetition-rate magnetic pulse compressors. We are particularly concerned with developing system models suitable for studying output pulse stability in high repetition rate applications. To this end, we present a magnetic switch model suitable for system studies and discuss a modeling tool we are developing to perform these studies. We conclude with some preliminary results of our efforts to simulate the MAG1D compressor performance.

I. INTRODUCTION

Magnetic pulse compressor systems find application as drivers of linear induction accelerators that require high average power and operate at high repetition rates. An important issue in such applications is the stability of the output pulse of the compressors. In particular, the proper operation of an accelerator places stringent constraints on the pulse timing and amplitude variations during a burst of pulses [1].

The basic network configuration underlying most compressor designs is the series Melville line [2] shown in Fig. 1. While the topology of the network is relatively simple, precise analysis and design can be a difficult task because of the highly nonlinear, dynamic characteristics of the saturable inductors or magnetic switches. Moreover, pulse-to-pulse stability depends upon a complicated interaction of many dynamic factors in the compressor. The predominant factors include the energy reflections caused by mismatches between the compressor stages as well as input voltage variations and core reset point variations during the burst.

At Lawrence Livermore National Laboratory, we have been attempting to address stability issues for the MAG1D magnetic pulse compressor by way of mathematical analysis, numerical simulation, and actual experiments. The MAG1D is a three stage magnetic pulse compressor designed to deliver a nominal output voltage of 100kV with pulse width of 70nS. (The ETA-II accelerator at Livermore employs three MAG1D's to drive its 60 accelerator cells and one to drive its injector.) Our recent experimental effort in characterizing the MAG1D is summarized in [3].

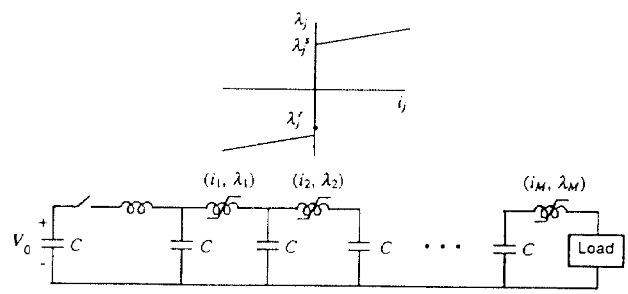

Fig. 1. An M-stage Melville line with ideal magnetic switch λ-i characteristic.

In this paper, we address the problem of modeling the dynamic performance of magnetic pulse compressors for the purpose of studying system stability. First, we present a sensitivity analysis showing the effect of input voltage regulation and magnetic switch reset variation on pulse timing stability. Next, we present a model for magnetic switches that we are using in system studies. We then discuss a general system modeling tool incorporating this model that we are using to model magnetic compressors. Finally, we summarize some preliminary results of our study of the MAG1D.

II. THE STABILITY PROBLEM

The exact nature of the stability problem is suggested by a sensitivity analysis of an ideal Melville line. Consider the M stage ideal Melville line shown in Fig. 1. Let λ_j^r be the flux reset state of switch j and let t_j denote the time at which the switch saturates. Define the arrival time of the output pulse as the time at which switch M saturates. It can then be shown that the relative variation in output pulse arrival time is well-approximated in terms of the relative variation in input voltage V_0 and the relative variation in the reset points of the magnetic switches by

$$\frac{\delta t_M}{t_M} = -\frac{1}{2}\frac{\delta V_0}{V_0} + \sum_{j=1}^{M} S_j \frac{\delta \psi_j}{\psi_j} \qquad (1)$$

where

$$S_j = (t_j - t_{j-1})/2t_M \qquad (2)$$

and

$$\psi_j = \lambda_j^s - \lambda_j^r \qquad (3)$$

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By design, the sequence $\{t_j - t_{j-1}\}$ is a strictly monotone decreasing sequence, so $S_1 > S_2 > ... > S_M$. The timing stability of the output pulse is, therefore, more sensitive to the reset variation of the earlier stages than the later stages.

While this analysis provides some insight into the problem, the behavior of actual magnetic components in a compressor deviates significantly from the idealized λ-i relation used to derive (1). Therefore, to study the effects of input voltage regulation and magnetic core reset state in an actual pulse compressor system, we require a good simulation model of the system.

III. MAGNETIC COMPONENT MODEL

The most critical elements to the construction of an overall system model are the magnetic components. These are also the most difficult to model. We present here a simple model that we have found useful for system studies.

Consider a toroidal magnetic core of cross-sectional area A with N windings. We assume that the B and H fields in the core have only azimuthal components. Furthermore, we assume that these fields can be adequately represented by their average values across the core. In the case when this assumption does not hold, it is a trivial matter to extend the results given below to a core that has been zoned into a number of concentric annuli. Let H denote the average magnetic field and M the average magnetization in the magnetic material ($B = \mu_0(H+M)$). By Faraday's law, the voltage across winding j is

$$v_j - n_j\dot{\phi}_j = 0 \qquad (4)$$

The flux ϕ_j satisfies

$$\phi_j - \mu_0(A_jH + K_sAM) = 0 \qquad (5)$$

where K_s is the core stacking factor and A_j is the area enclosed by the winding. Finally, neglecting displacement currents, we obtain from Ampere's law

$$Hl - \sum_{j=1}^{N} n_j\, i_j = 0 \qquad (6)$$

where l is the mean magnetic path length.

It remains to specify the mathematical model relating H and M (or B) in the magnetic core material. Many magnetic material models have been proposed over the last four decades (see, for example, the survey in [4]). Recently, we have devised a new model that is conceptually simple and that shows some promise for use in system studies. We merely sketch here the salient features of the model. The actual mathematical details and proofs will be the subject of a future paper.

Our model of the magnetic material consists of a set of two simultaneous differential-algebraic equations:

$$\dot{H}_a - \dot{H} + g(M,\dot{M})(H_a - H + w(M,\dot{M})) + \dot{M}\frac{\partial w(M,\dot{M})}{\partial M} = 0 \qquad (7)$$

$$M - F(H_a) = 0 \qquad (8)$$

Each function in (7) and (8) has a simple physical interpretation. First, the function F defines the anhysteretic curve of the magnetic material and must possess the property that

$$\lim_{H\to\pm\infty} F(H) = \pm M_s \qquad (9)$$

where M_s is the saturation magnetization. Equation (7) insures that the trajectories approach the major loop defined by

$$H = F^{-1}(M) + w(M,\dot{M}) \qquad (10)$$

for constant $|dM/dt|$. The function g determines the path that minor loops take, whereas the function w provides the rate-dependent loop widening and accounts for hysteretic loss in the magnetic material.

In order to apply (7) and (8), we must specify the functions F, w, and g. A simple choice is

$$F(H) = \frac{M_sH}{\alpha + |H|} \qquad \alpha > 0 \qquad (11)$$

$$g(M,\dot{M}) = \gamma|\dot{M}| \qquad \gamma > 0 \qquad (12)$$

$$w(M,\dot{M}) = H_c\mathrm{sgn}(\dot{M}) + k\dot{M} \qquad (13)$$

In this case, the material properties are completely specified via (11)-(13) in terms of the five parameters M_s, α, γ, H_c and k. The parameter α governs the squareness of the M-H loop. The loop can be made arbitrarily square by making α sufficiently small. In (13), H_c is the dc coercive magnetic field and k determines the loop widening and, consequently, the hysteretic loss. Other functions can be used to provide a better fit to experimental data, but this will generally require that additional parameters be identified from experimental data. There is, therefore, a trade between the fidelity of the model and its facility of use.

IV. SYSTEM MODELING FRAMEWORK

We have implemented the model described above in a new network and system simulation code that is currently under development at LLNL. The code is intended to be a basis for a suite of tools being devised for pulsed power systems analysis and design optimization. At present the code possesses a collection of basic circuit component models and a free-format input language for describing the system to be simulated. It employs a sparse tableau formulation [5] of the network equations. In this formulation, the system model takes the form of a system of simultaneous differential-algebraic equations

$$\begin{aligned} \mathbf{f}(\mathbf{x}(t), \dot{\mathbf{x}}(t), t) = 0 \quad t \geq t_0 \\ \mathbf{x}(t_0) = \mathbf{x}_0 \end{aligned} \qquad (14)$$

The vector function **f** includes the topological constraints of the system (Kirchhoff's current and voltage laws) and the element constitutive equations. A magnetic switch or saturable reactor element consist of one or more windings and a magnetic core. The element constitutive equations that enter the tableau equations are (4)-(6) for the windings and (7)-(8) for the magnetic core. The vector **x** consists of element currents and voltages, node voltages and any other variables in the element constitutive relations (e.g., H and M for magnetic components). A stiffly stable, adaptive step-size, adaptive order solver permits the simulation of highly nonlinear and stiff dynamical systems, such as magnetically switched circuits. It also exploits the sparsity of the tableau matrix (Jacobian) of (14).

The use of a general circuit code permits changes in system topology to be made quite easily. This is an important consideration in the design of reset or bias circuits for the magnetic components. Special purpose codes written to solve the system of differential equations for a fixed topology do not enjoy this advantage.

V. MAG1D STUDIES

We have developed an end-to-end simulation model of the MAG1D compressor in our High Average Power Test Stand (HAPTS). Figure 2 depicts a simplified circuit diagram of the HAPTS system, and reference [3] gives a description of its operation.

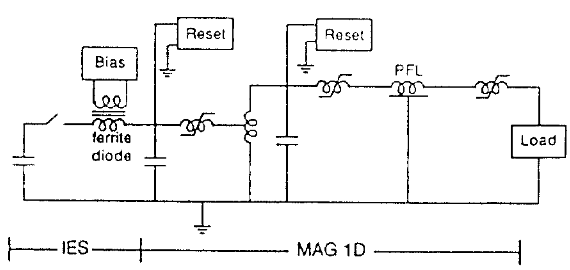

Fig. 2. Simplified circuit diagram of the MAG1D magnetic pulse compressor.

Our system model includes the nonlinear dynamics of the each of the three magnetic switches, the step-up transformer and the intermediate energy storage (IES) ferrite diode. Figure 3 shows the simulated response of the output voltage of the compressor. For comparison purposes, the actual experimentally measured output voltage is shown in Fig. 4. The qualitative agreement is good.

Presently, we are using our model to study the pulse-to-pulse stability of the system. In particular, we are analyzing the sensitivity of output pulse timing and amplitude to variations in input voltage, magnetic switch reset points and IES ferrite diode bias point. We are also presently making measurements on HAPTS that will enable us to refine and validate our model. The next step will be the design of new reset circuits that insure stable performance at high repetition rates. The results of these analyses are forthcoming.

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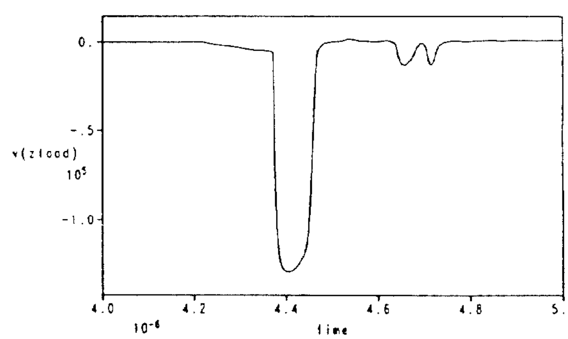
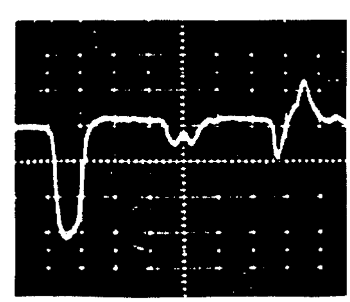


Fig. 3. Simulated output voltage waveform for the MAG1D –28kV input, 128kV peak output.



100nS/div

Fig. 4. Measured output voltage waveform for the MAG1D – 28kV input, 126kV peak output.