DIRECT MODELING METHODS FOR AIR-CORED PULSED ALTERNATORS *

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Abstract

A railgun launcher requires very high-current pulsed power over the period of a few milliseconds. For laboratory systems, capacitor banks have traditionally been used to provide this energy, but field applications require a system with significantly higher energy storage density. Rotating machines that store the energy in the form of rotational kinetic energy and can quickly convert it to high-current electrical energy have been designed and built. These low-impedance multi-phase, multi-pole synchronous generators are referred to as pulsed alternators. The AC output of the pulsed alternator is rectified to provide DC to power the railgun, and the design of the rectifier set and control circuitry is very dependent on the alternator characteristics. To facilitate the design and evaluation of the overall pulsed power system, a modeling tool which accurately represents the performance of the pulsed alternator while allowing easy changes to the external circuitry and controls is needed.

This paper describes a manner in which these pulsed alternators can be accurately modeled. The validity of the model is established by comparing it to experimental data gathered from the "Subscale" alternator built by the Center for Electromechanics at The University of Texas under the Focused Technology Program (FTP).

I. BACKGROUND

In the simplest terms, a pulsed alternator is a synchronous generator that has been adapted for low-impedance pulsed duty. The most common configuration consists of a rotating drum structure carrying a field winding within a stationary drum structure carrying the armature windings. Current is fed to this winding through a set of brushes and slip rings on the shaft. The armature windings are arrayed evenly along the circumference of the stator and usually consist of several separate phases.

The high current and low internal impedance requirements for the pulsed alternator usually preclude the use of magnetic materials within the magnetic circuit. Typical iron-core machines have a peak magnetic flux density of approximately 1.5 T before the iron saturates, whereas the high currents in the pulsed alternator will generate flux densities in excess of 3 T at the stator. The absence of a well-defined magnetic circuit means that the magnetic field will interact with structures other than the windings; thus, any conducting materials near the windings will support induced currents whose effects must be included in the model.

Pulsed alternators are operated in a "self-excited" mode. A small seed current is injected into the field winding and the voltage that is developed at the armature windings is rectified and applied back to the field winding, forming a positive feedback circuit. The field current increases exponentially until a switch is closed that allows current to flow in the load.

II. THEORY

A synchronous generator is a set of inductor circuits on the rotor that are linked to another set of inductances on the stator by a mutual inductance that varies with rotor mechanical angle. When a load is applied to the secondary winding and current begins to flow, energy is then converted from the stored rotational kinetic energy of the spinning rotor into electrical energy delivered to the load. A torque is generated, due to the interaction between the magnetic fields and currents of the armature windings and the field windings, that causes the rotor to slow down or speed up depending on the polarity of the torque. The contribution to the total torque on the rotor from a single armature phase can be expressed [1] as

$$T = I_{arm} I_{field} \frac{dM}{d\theta} \tag{1}$$

where T is the torque, I_{arm} is the current flowing in the armature pole, I_{field} is the current flowing in the field winding, M is the mutual inductance between them, and θ is the mechanical angle of the rotor. The total torque on the rotor is the sum of all of the individual torques generated by each armature phase plus torque contributions from any structures with which the magnetic

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field interacts. The relationship between the angular position and the torque of the flywheel is governed by the moment of inertia of the flywheel, as in

$$T = J\frac{d^2\theta}{dt^2} \quad (2)$$

where J is the moment of inertia.

An important aspect of the modeling is to accurately represent the effects of conducting support or shielding structures within the stator and/or rotor on the overall performance of the pulsed alternator; the structures of interest here are modeled as a thin cylindrical conducting shell or a collection of such shells. A cylindrical conducting shell in a rotating machine can be modeled as a pair of coupled inductance-resistance equivalent circuits that are in electrical space-phase quadrature with one another; this model integrates seamlessly with the representations adopted for the rotor and stator physical windings.

The shell self-inductance is calculated from the ratio of the linked flux and the assumed sinusoidal winding current. The mutual inductance between the shell and the other windings is determined by relying on the fact that the coupling coefficient, k, is only dependent on the ratio of the winding radii and the number of poles. The effective resistance of the equivalent winding is determined by calculating the power dissipated in the shell resistivity and then again using the current to determine the lumped resistance. The details of the model development can be found in an earlier paper by Crawford et al. [2].

The equivalent self-inductance of a thin conducting shell is given as

$$L_{shell} = \frac{\mu_0 l\pi}{2} \quad (3)$$

which is independent of the radius of the shell and the number of electrical pole pairs in the machine. The mutual inductance between the shell and a winding can be calculated if the coupling coefficient is known. It has been shown [3] that for nested cylindrical windings, the coupling coefficient, k, is given by

$$k = \left(\frac{R_{inner}}{R_{outer}}\right)^N \quad (4)$$

where R_{inner} is the mean radius of the inner winding, R_{outer} is the mean radius of the outer winding, and N is the number of pole pairs. Using this relation and the definition for k,

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (5)$$

the mutual inductance is given by

$$M = \left(\frac{R_{shell}}{R_{winding}}\right)^N \sqrt{\frac{\mu_0 l\pi}{2} L_{winding}} \quad (6)$$

Finally, the equivalent resistance for the shell needs to be determined. If we assume that the current is flowing uniformly through the radial thickness ΔR_s, and the shell material has the resistivity ρ, the resistance of the equivalent winding representing the shell is given by

$$R_{shell} = \frac{\rho l\pi N^2}{4\Delta R_s} \quad (7)$$

The equivalent winding is modeled as two separate inductor/resistor loops, referred to as the direct and quadrature windings. When modeled in the circuit, the two windings have zero mutual inductance between them, and only the direct winding has a mutual inductance with the field winding on the rotating structure. There is a 90-degree electrical phase shift in the mutual inductance between the direct and quadrature windings with windings on the other side of the rotating structure.

In some cases, a compensating winding is built into the rotor to reduce the transient impedance of the alternator. This compensation can take the form of a shorted winding located in quadrature with the field winding and can be modeled in the same manner as the quadrature part of the conducting structure model. This configuration is normally referred to as a "compensated pulsed alternator," or the familiar "compulsator."

III. MODEL DESCRIPTION

The primary purpose of developing a new pulsed alternator model is to be able to easily change the circuit configuration of the entire system without rewriting basic equations for each change. Commercially available circuit solvers are quite good at allowing rapid changes in circuit topology by simply redrawing the schematic or changing an input file. By developing only the components that are unique to the pulsed alternator system and then integrating those components with the standard circuit components into a circuit that represents the overall pulsed alternator system, a very flexible overall model has been developed using two circuit solvers: SABER™ from Synopsis Inc. and PSPICE™ from Cadence Design Systems Inc.

SABER™ is a simulation package that contains a powerful model description language (MAST™) that makes the implementation of the custom components very easy. SABER™ can work in any energy domain (including thermal or mechanical), and it can handle coupling between these domains. This feature makes it simple to implement the mechanical components without resorting to translating between electrical and mechanical quantities. Implementation of the pulsed alternator system model required the development of an angularly-varying mutual inductance element and a mechanical flywheel model; all other required elements were included within the standard simulation package.

PSPICE™ is a widely used electronic circuit simulation package. Although it was originally designed for integrated circuit simulation, PSPICE can be configured to simulate power circuits accurately. Mechanical and other non-electrical dynamic systems need to be converted into their electrical equivalents so that their effects can be included within the general system simulation. Because PSPICE does not support a generalized system modeling language, an equivalent circuit emulation of the angularly-varying mutual inductance is required. The details of this are found in the Appendix.

The basic form of the pulsed alternator model is shown in Fig. 1. The windings on the rotor and the stator are modeled as an inductor with an equivalent series resistance that is connected either as closed loop (in the case of compensating windings or equivalent structure windings) or to the outside circuit (the field and armature windings). These loops have a static mutual inductance between inductors on the same structure (either the rotor or stator). An angular dependent mutual inductance, $M(\theta)$, component is required for each combination of a rotor winding and a stator winding. The $M(\theta)$ component requires the maximum mutual inductance between the windings as well as an offset angle. In addition to providing the coupling between the rotor and the stator, the $M(\theta)$ component also provides the value of the angular rate of change of the mutual inductance for use in calculating the torque. The flywheel component provides the angle θ, to the $M(\theta)$ component and varies that angle at a rate dependent on the torque and the moment of inertia, J. Other flywheel parameters are the initial angular velocity and initial angular position.

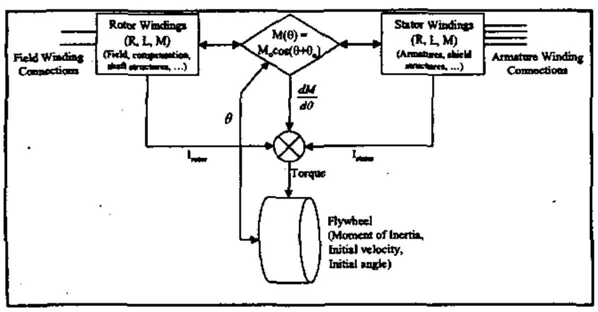

Figure 1. Block diagram layout of pulsed alternator model.

The validity of these models has been benchmarked against experimental results from the pulsed alternator called "Subscale" that has been designed and built by the Center for Electromechanics (CEM) at The University of Texas under an Army Research Laboratory (ARL) Focused Technology Program (FTP) [4]. For simplicity, this pulsed alternator will be referred to as SSFTP.

IV. RESULTS

The SSFTP system was built with two diode-based half-wave rectifiers. During field winding self-excitation, both rectifiers are used in a full-wave configuration. During the output discharge, one of these rectifiers provides the DC pulse to the load. The SSFTP was tested into a dummy load and these shots will be used as the benchmark data for the simulation.

The results from the benchmark simulation are shown in Fig. 2. Initially, a charged capacitor in the field initiation module is discharged into the field winding at time zero (the left extent of the field current plot in Fig. 2). The self-excitation process increases the current in the field winding until a predetermined level is reached. When the appropriate armature phase is then reached, a switch to the load is closed, and the load current begins to flow. The current flowing in the armature windings generates armature reaction current in the field winding that is seen clearly in the field current plot in the figure. The load current is the sum of the armature currents and matches the measured waveform quite well for the first six to eight cycles. The simulation waits a given amount of time and then reopens the switch to the load. In the experiment, an explosive opening switch was triggered that commutated the current into a parallel resistor. The disagreement at the end of the load current pulse is due to the time it takes for the explosive switch to finally open completely. Similarly, an explosive opening switch in the field circuit is triggered to dump the remaining current into a resistive load; this process was not modeled, which explains the difference in the traces at the end of the field current plot.

V. CONCLUSIONS

A simple method of modeling pulsed alternators has been developed and successfully benchmarked against experimental data. By developing only the specific components unique to the pulsed alternator and integrating those with existing circuit components, the overall system development time is reduced, and the flexibility of the model is improved. To accurately predict the performance from an air-core machine, it is necessary to include coupling to conductive structures. Structures that are conducting shells such as metallic shafts and shields can be modeled as a pair of coupled inductor-resistor circuits in space-phase quadrature. The inclusion of these effects is necessary to accurately predict the performance of this class of machine.

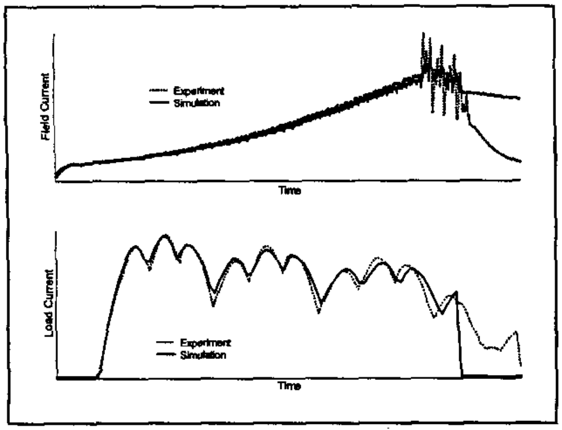

Figure 2. Results from the simulation comparing the field current (top) and the load current (bottom) for shot SC398 on the SSFTP system. Note that the time scales on the two plots are different.

VI. REFERENCES

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APPENDIX

The standard PSPICE mutual inductance element does not allow for a variable mutual inductance (or coupling). An equivalent circuit using standard PSPICE elements that emulates a variable mutual coupling is derived below.

The voltage equation for the *k*-th inductor in a set of mutually coupled inductors can be written as

$$v_k = L_k \frac{di_k}{dt} + \sum_{j \neq k} \frac{d}{dt}\left(M_j I_j\right) \qquad (8)$$

where it is assumed that any of the mutual inductances, M_j, can be time-varying. If we write this equation in integral form and solve for i_k, we have

$$i_k = \frac{1}{L_k}\int v_k dt - \sum_{j \neq k} \frac{M_j}{L_k} i_j \qquad (9)$$

The current i_k is simply the current through the self-inductance L_k combined with the weighted sum of all the currents in the mutually coupled inductors. A PSPICE representation of this is simply an inductor connected in parallel with a set of dependent current sources.

Figure 3 shows the field circuit portion of the PSPICE schematic for a three-phase pulsed alternator; the three dual input-dependent current sources represent the coupling of the field winding to the three armature phase windings. The "current meter" provides a measure of the field winding current for use as an input to the dependent sources used for modeling coupling in other windings.

The PSPICE voltage-controlled current source ("G" element) provides the functionality of a dual input-controlled source when the following arrangement of Fig. 4 is used.

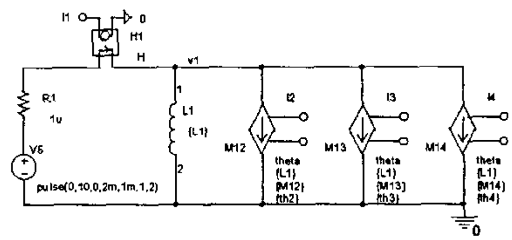

Figure 3. PSPICE equivalent circuit for rotor winding coupled to three-phase armature winding.

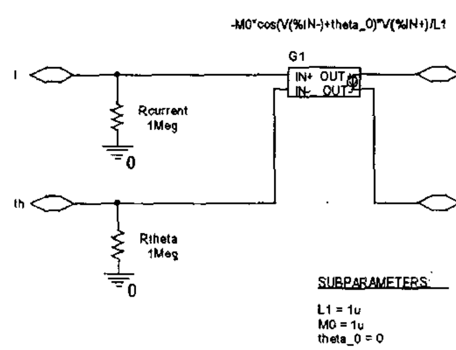

Figure 4. PSPICE sub-circuit for the dual input current source representing angular-dependent mutual coupling.