

Modeling, Analysis, and Control Design for an Intermittent Megawatt Generator

B. P. Loop, M. Amrhein, S. D. Pekarek, A. Koenig,
B. Deken and E. A. Walters
P. C. Krause and Associates

L. Sorkin
Innovative Power Solutions

Copyright © 2008 SAE International

ABSTRACT

An Intermittent Megawatt Generator (IMG) has been designed by Innovative Power Solutions (IPS) to meet the needs of future directed energy loads on high-performance aircraft. These loads significantly impact the electrical, mechanical, and thermal performance of the generator, load, and aircraft. If representative simulation models of the generator and other important subsystems can be obtained, the impact on system performance can be analyzed and optimized before the generator is deployed. The objective of this work was to utilize various modeling techniques to obtain accurate electrical, thermal, and mechanical performance models of the IMG, and to apply these models to analyze dynamic response transients to sudden load changes as seen for directed energy loads. Additionally, the models have been used to optimize the IMG control to mitigate voltage transients during these load changes.

INTRODUCTION

Several models of the IMG were utilized to predict and evaluate the relevant aspects of its performance. First, a finite element (FE) model of the IMG was created to examine the electromagnetic behavior of the generator. A two-dimensional (2D) dynamic FE model was used to perform a transient analysis, to extract a lumped-parameter electrical model to support control optimization, and to extract power loss data for the thermal analysis. Second, a thermal equivalent circuit model of the IMG was developed to investigate heat flow and temperature distribution of the machine under quasi steady-state loading conditions (repetitive dynamic load pulses). This thermal model included approximations for the generator main body and end-winding region, as well as oil cooling in the armature and the rotor. Thus, temperature rating violations could be identified, and the amount of cooling power required during nominal operation could be determined. Finally, lumped parameter models of subsystems impacting the IMG performance (such as turbine engine and directed energy load) have been developed to study and optimize

the system impact of sudden load changes. Advanced control techniques (gain-scheduling, anticipatory, and field-squelch techniques) have been optimized to mitigate load turn-on and turn-off generator voltage transients under intermittent loading conditions including turbine-speed transients. The utilized optimization routine is based on genetic algorithms.

The purpose of the paper is a discussion about integration of different modeling techniques to analyze and optimize the generator performance. It should serve as an example for system-level modeling, analysis, and optimization in the early development cycle of the generator. The construction of and results obtained from the various models will be described, including per-unit analysis of the simulation of transient loads. In addition, the generator control optimization approaches and corresponding results will be discussed.

FINITE ELEMENT MODELING

Due to the excessive computational intensity of 3D FE analysis, a 2D model was used to establish the expected transient response of the machine in order to identify parameters values for a lumped parameter model.

To establish the FE model of the IMG, the stator dimensions, rotor dimensions, and stator winding pattern were obtained from IPS. Within the model, each conductor that is part of the stator coils is individually represented. No attempt was made to model the individual conductors of the rotor coils. Instead, these coils have been grouped to form a lumped representation.

The initial model consisted of the airgap, rotor, stator, individually modeled stator coils, and the grouped representations of the rotor coils. It is noted that a mesh is not required outside of the stator nor within the shaft of the rotor since it has been assumed that no flux is present in these regions. In addition, the error associated with the FE is proportional to the size of the elements that compose the mesh. Since the accuracy is

critical in the air gap, the elements of this region are relatively small.

The IEEE Standard 115A-1987, "IEEE Standard Procedure for Obtaining Synchronous Machine Parameters by Standstill Frequency Response Testing" (SSFR) was applied to the 2D FE model of the IMG to determine the qd model parameters. For the q-axis in the SSFR test, the rotor was positioned at $\theta_r = 0$ and the b- and c-phases were connected as shown in Figure 1. In the transient FE model, the frequency of the applied voltage was varied from 0.1 to 1000 Hz. To compute the respective impedance, the applied voltage was divided by the scaled phasor of the measured current. Specifically,

$$(1) \quad Z_q = \frac{2v_s}{3i_s}$$

represents the respective q-axis impedance.

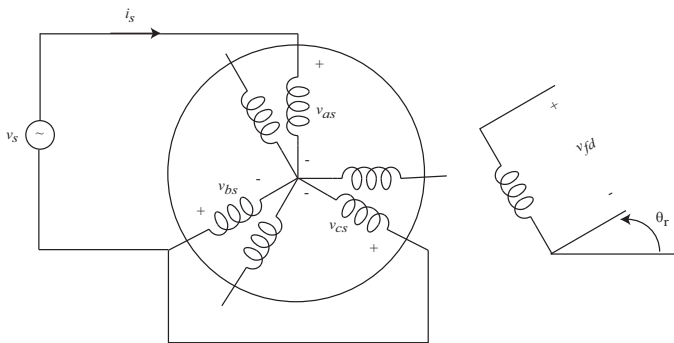


Figure 1. Generator configuration for Standstill Frequency Response Test.

One of the challenges is determining a value of the leakage inductances. Specifically, it is common practice to approximate the leakage as a percentage of the magnetizing quantity (i.e 10%). In this effort we attempted to extract a more-exact representation. To determine a value for the stator leakage inductance, a two-step experiment was developed. As a first step, the zero-sequence inductance was determined. By definition, the zero-sequence flux linkage is obtained by taking one-third the sum of the phase flux linkages

$$(2) \quad \lambda_{0s} = (\lambda_{as} + \lambda_{bs} + \lambda_{cs}) / 3.$$

Adding the phase flux linkages results in the expression

$$(3) \quad \lambda_{0s} = L_{ls} i_{0s}.$$

To determine the value of zero-sequence inductance, step changes in input voltage were applied to series-tied stator windings as shown in Figure 2. The input current was measured during the entire transient, providing an

expression for the derivative of the zero-sequence flux linkage. In particular,

$$(4) \quad d\lambda_{0s} / dt = v_{in} / 3 - r_s i_{in}.$$

The steady-state zero-sequence flux linkage was obtained by the numerical integration of (4). The ratio of the calculated λ_{0s} versus measured i_{0s} provides the zero-sequence inductance.

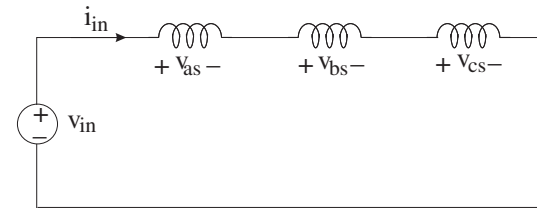


Figure 2. Generator configuration for leakage inductance test.

Using the transient model, the parameters of the q- and d-axis equivalent circuit of a synchronous machine were obtained. These parameters are discussed in [1]. Specifically, they are

- r_s , stator resistance
- L_{ls} , stator leakage inductance
- r_{fd} , field winding resistance
- L_{lfd} , field winding leakage inductance
- L_{md} , d-axis magnetizing inductance
- r_{kd} , d-axis damper winding resistance
- L_{lkd} , d-axis damper winding leakage inductance
- L_{mq} , q-axis magnetizing inductance
- r_{kq} , q-axis damper winding resistance
- L_{lkq} , q-axis damper winding leakage inductance

It should be noted that the rotor quantities are the so-called referred variables as described in [1].

For each frequency, the peak-to-peak voltage and current and phase delay were determined from the time-domain FE data. The voltage applied across the a- and b-phase terminals and the current flowing through the windings are depicted in Figure 3. The impedance at this frequency is then calculated as

$$(5) \quad Z = \left(\frac{v_{ab,pk}}{2i_{ab,pk}} \right) e^{j2\pi f \Delta t},$$

where f is the frequency of the applied voltage $v_{ab,pk}$, $i_{ab,pk}$, and Δt are as depicted in Figure 3.

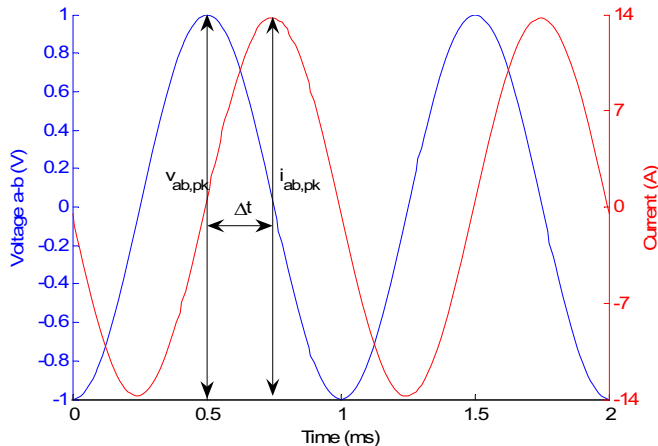


Figure 3. Obtaining impedance data from ac waveforms.

This impedance data was obtained at nine frequencies for both the q and d axes. Next, PCKA's Distributed Heterogeneous Optimization (DHO) software [2] was used in an attempt to find the circuit parameters listed above that replicate the impedance profile as accurately as possible. DHO is a genetic algorithm-based optimization code. The genetic algorithm evaluates the members of a population according to an objective function. In this case, the objective function was

$$(5) \quad f_{obj}(x) = \sum_{k=1}^9 \frac{|Z_{dk}^* - Z_{dk}(x)|}{|Z_{dk}^*|} + \sum_{k=1}^9 \frac{|Z_{qk}^* - Z_{qk}(x)|}{|Z_{qk}^*|},$$

where k is an index over the number of evaluated frequencies, Z_{dk}^* is the d -axis impedance obtained from the FE studies at frequency k (similarly for the q -axis), and $Z_{dk}(x)$ is the impedance evaluated using the parameters represented by the solution vector x . It should be noted that the stator resistance r_s was not included in this optimization study because it was not represented in the FE calculations. The value of the stator resistance was calculated using power loss data from IPS data. The results of this optimization study are depicted in Figure 4. Therein, it can be seen that the impedance profile is accurately approximated by the parameter values obtained.

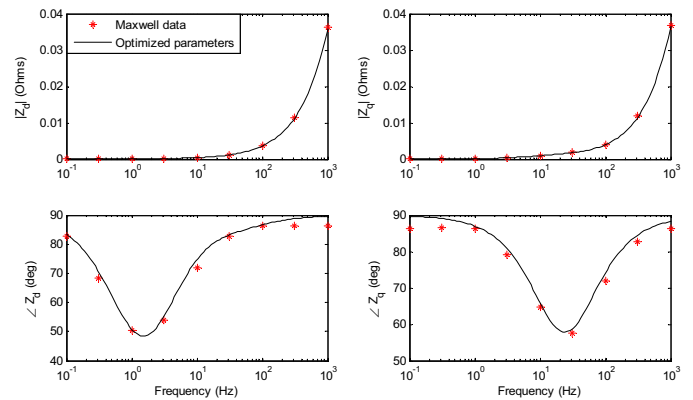


Figure 4. Finite element and optimized circuit parameter impedances.

PCKA's Graphical Automated State Model Generator (GASMG) [3] was used to create the generator model use for transient studies and to provide the currents used for FEA-based torque analysis and the lumped-parameter-based thermal modeling. The model consists of six mutually coupled inductors, feeder inductance, a twelve-pulse rectifier, a dc filter, rotor windings, and the field-squelch circuitry.

THERMAL MODEL

Another goal of this effort was to establish techniques to model the coupled electromagnetic/thermal dynamics of the IMG system. In the past, lumped parameter thermal networks have successfully approximated thermal machine behavior [4], [5]. These networks model the main machine components using thermal resistances, capacitances (for thermal energy storage), and heat sources. Conductive, convective, and radiated heat transfer can be considered by using appropriate equations for the lumped thermal resistances [6]. Influences in the thermal behavior such as air circulation between stator and rotor or the endspace are included with behavioral equations, which have been derived from measurement results [7]–[9]. Cooling effects (forced and natural) are similarly incorporated in thermal machine models. The obtained thermal network can be solved and analyzed with techniques from electric circuit theory.

Under this research it was determined that such an approach would provide the most effective design and analysis tool. Coupling of electromagnetic and thermal models was achieved by calculating the losses in the various machine parts from the electromagnetic solution and feeding them into the thermal model at the appropriated locations. Details of the thermal model are provided below.

THERMAL NETWORK MODEL BACKGROUND

The lumped parameter thermal network used in this effort is based on the modeling work described in [4], [6]. There, cylindrical shapes, such as stator and rotor cores and winding arrangements of electrical machines, are approximated by the lumped parameter thermal network shown in Figure 5. The thermal network distinguishes