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The 2kW Mini-BRU Electrical Controls Concept and Transient Performance

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Abstract

The proposed Jupiter Icy Moon Orbiter, JIMO, mission selected a Brayton power conversion system as its electrical power generator. Although the JIMO mission power conversion system was expected to produce in the order of 100 kW, an available 2 kW Brayton system was used to develop control system strategies for the JIMO mission. This report describes the shunt loading voltage/speed regulation control concept developed for the 2 kW system, and the transient performance of controls. The 2 kW alternator is a permanent magnet alternator as proposed for the JIMO mission, and operates at a similar speed and internal impedance, allowing it to be used as an accurate model for performance of the larger system. The JIMO mission was cancelled in September 2005.

Introduction

The Glenn Research Center has been involved in the development of Brayton cycle power conversion systems since the 1960s. A number of control systems have been developed over the years as the program has evolved. As the JIMO mission requirements were identified the regulation limits and transient response of the power distribution system became important parameters in the design of the spacecraft. In order to demonstrate the performance capabilities of a proposed Brayton power conversion system and controls, a voltage/speed regulation concept was developed for the 2kW system, and tested to verify its performance. The performance data was then used to produce a draft power quality specification for the mission.

The 2 kW Mini-BRU hardware available consists of a complete hot loop consisting of flight quality hardware with an electrically heated heat source simulator and an external chiller simulating the heat rejection radiator, operating in a vacuum environment, and an identical alternator powered by an air turbine. The air turbine-powered alternator was used for the development and performance testing of this control concept, while the hot loop system was used with a similar control system for thermodynamic performance testing. The parameters of the 2kW alternator closely model the parameters of the proposed 100 kW alternators of the JIMO system. Both included permanent magnet alternators exhibiting similar operating speed, scaled impedance, and scaled inertia parameters.

Recent Control System Development for the 2 kW Mini-BRU

The current controls concept, known herein as BRU-J, is the third generation of controls for the Mini-BRU since the JIMO project was initiated in fiscal year 2003. The first generation, referred to as the "120 Vdc BRU," was developed to provide a DC power output bus at 120 Vdc. The concept used a 3 phase rectifier directly off the alternator output, producing 95 to 120 Vdc. The high efficiency Series Connected Boost Regulator (SCBR, ref. 1) was used to provide a well regulated 120 Vdc bus for the user loads and the parasitic load. The parasitic load was controlled to provide constant alternator speed, with an overvoltage limit to reduce speed under light load conditions. This system was developed using an air powered Alternator Test Unit (ATU) in a laboratory environment and then operated with a complete flight-qualified hot loop Brayton turbine alternator compressor assembly. The hot loop testing was documented in NASA/TM—2003–211999 (ref. 2).

The second generation of controls, referred to as the HV BRU, was based on the first generation, but modified to provide an AC power bus to the user load intended to interface with an ion engine. The HV BRU concept used a similar rectifier and parasitic load on the rectified output of the machine, with identical alternator speed and overvoltage limit controls as the 120 Vdc BRU, although the SCBR was not used as there was no need for accurately regulated voltage input to the parasitic load. The ac output of the alternator was used as the user power output. The high voltage required for the ion engine, ~1100 Vdc, was obtained using a transformer to step up the voltage. The transformer had three 3-phase secondaries, providing rectified outputs of approximately 600, 400, and 200 Vdc. The three rectified outputs were connected in series, with a regulator on the output of the 200 V segment, to provide a regulated 1100 Vdc to the ion engine. This system was also operated with the hot loop Brayton engine after development on the ATU, and was used in an integrated test providing the beam power for an operating ion thruster. These operations demonstrated several concepts:

- Supplying direct ac power to a load
- Use of a moderately high frequency, 866 Hz, and therefore light weight transformer to obtain the required high voltage without the complexity of dc-dc converters
- Using a series connection of low voltage rectifier stages to obtain a high voltage without the use of very high voltage components
- Regulation of the high voltage output by controlling only one element of the series connected rectifiers
- Operation with an actual ion engine

The tests also demonstrated the system stability and robustness during ion engine recycle events, as documented in NASA/TM—2004–212960 (ref. 3).

The third generation of controls, BRU-J, is being developed as an upgrade to the second generation system to recognize the need for higher power quality and to test redundant/fault tolerant control techniques. The major changes are an improved ac waveform through higher order rectification, more accurate bus voltage regulation and increased parallel modularity in the controls for fault tolerance.

BRU-J Description

A block diagram of the BRU-J control concept and test bed is shown in figure 1.

A description of the blocks is as follows:

Alternator

The alternator was a 52000 rpm 2 kW nominal unit. The nominal output voltage is 55 V rms L-L, 866 Hz. The impedance is 260 μ Henries L-N, which is 1.5 Ω reactance at the operating frequency. The winding resistance is 160 mΩ L-N, or ~10 percent of the machine inductive reactance. This impedance is approximately 1/3 per unit, or a short circuit current of 3 per unit. The nominal load impedance is 4 Ω L-N. The inertia is such that the unit accelerates approximately 100 percent per second at rated torque.

Although the frequency and voltage are only about 1/2 and 1/5 the initial JIMO baseline, the impedance and per unit impedance remained close to the JIMO parameters at the end of the project. The JIMO inertia, per unit, is expected to be greater due to the larger machine rating. A higher inertia is expected to have no effect on the transient data shown herein except for figures 8 and 9, where the speed changes would be expected to occur more slowly.

Boom Cable

The cable in the lab that emulates the initial JIMO boom cable concept is approximately 50 ft of 10–4 rubber jacketed cable. The parameters have not been measured since it appears as additional alternator impedance and is swamped by the magnitude of the alternator reactance.

Bus

The distribution bus was essentially a point on a terminal strip.

Power Distribution

The power distribution consisted of a single 3 phase contactor feeding a load, in addition to the feed to the Parasitic Load.

The load switching contained a high speed switch developed to disconnect the ion thruster during our integrated testing. It was a FET-based switch which switches on in a couple microseconds, and off in about 20 μs (due to charging of a snubber). The high speed switch was used for all load transients experienced in this study.

Loads

The loads used for testing consisted of a 12-pulse transformer rectifier set feeding resistive loads. The load value was varied in steps up to about 1500 W, or 3/4 rated load. The current transient into the load, including the transformer rectifier, usually showed no significant transient due to core saturation. There is no filter after the rectifier, except as noted for specific tests shown in figures 4 and 5, so there was no filter charging transient.

Parasitic Load

The parasitic or shunt load and its controls were the dominant factor in the response of the system. The control system parameters were effective in the frequency range from steady state up through several kilohertz. Load transients may have contained transition times in the microsecond range, and these transients were controlled by the capacitance on the output of the PLR rectifier.

The cabling for the PLR consisted of several feet of twisted wire and interconnect impedances and transformer leakage reactance's were judged representative of a full scale system. Voltage transients in this frequency range were not apparent in the data.

The block diagram shows a 24 pulse rectifier for the PLR. In actuality the BRU-J system used two 12 pulse rectifiers, phase shifted 15° to give a 24 pulse effect. Each 12 pulse rectifier in turn consisted of two 6 pulse rectifier sets paralleled thru interphase reactors. While the full scale system would use multiple transformer rectifier sets for redundancy, the response of the BRU-J system should be representative.

The block diagram shows a filter of 120 μFs. On a load dump the excess energy has to charge this capacitor up to raise the line voltage. The 120 μF capacitor would slow the charge rate to about 0.1 percent overshoot per microsecond for a 100 percent load dump. This is a major factor in how fast the control loop needs to respond. The value of this capacitor could be increased to reduce the rate of overshoot, but the data in this document and the JIMO mission voltage specification were developed based on this value. In the BRU-J configuration the 120 μF capacitor is distributed as 12 separate 10 μF capacitors, one for each of the 12 segments of the PLR, identical to the current concept for the full scale system.

The power switch was an FET operating in a PWM mode. Although there was a slight filter used for EMI it was ineffective in the frequency range of the control loop. 12 individual switches were used for the 12 segments of the BRU-J implementation.

The PLR itself would be sized to load the machine 100 percent, plus additional margin to overload the machine for shutdown and failure scenarios. The 4 Ω (equivalent) load was capable of nearly

80 percent overload, somewhat greater than required, but it was easily implemented as 12 to 50 Ω resistors and not important to the dynamic response during load transients.

The 12 phase modulator is an area where modeling this control system as a linear lumped single PLR element might not be sufficiently accurate for some analyses. The BRU-J test model had 6 separate modulation signals, each controlling 2 elements. Each of these elements is powered from a 12 pulse rectifier output, but the second rectifier's phase is shifted 15° to maintain balanced 24 pulse loading. The 6 signals are time sequenced such that the 6 signals, each at a 1733 Hz (twice alternator frequency) rate, essentially appear as a 10 KHz (actually 10.4 KHz) modulation rate. The segmenting and modulation scheme implemented are representative of what might be expected to be used in the JIMO mission.

Control Loop

Voltage sensing: The voltage sensing consisted of squaring each phase of the alternator output and adding the instantaneous value of the squares. The result was a dc level and an unfiltered output which contained (assuming a balanced system) no components below approximately 10 KHz, the 6th harmonic, and no time delay. It was effectively the rms value of the total three phase waveform, without the need for filtering at the fundamental frequency. The measurement did not implement the square root function on a true rms measurement, but over the voltage narrow range of the regulation band the lack of the square root function only appeared as a gain change, not as a significant non-linearity.

Voltage regulator: The regulation loop compared the measured output to the setpoint, and integrated the error, a simple integral control loop. However, current feedforward from sensing the load current was added to the integrator output. The gain of the feedforward loop is important in how much control effect the integral loop has to exert, but not critical to the system stability. For these tests the gain was intentionally reduced approximately 10 percent to generate an easily viewable error at the integrator output to check the system response.

BRU-J Performance

The focus of this report is a series of load step transient tests that were performed on the BRU-J test bed. The test conditions and an explanation of steady state system responses are as follows:

The alternator controls were configured to operate in a constant voltage (all data except fig. 9) or constant speed mode. Within the load capacity of the system, in steady state operation, the voltage or speed regulation was pretty much within the "noise" in the system, on the order of 0.1 percent. Thermal- or time-induced drifts were not studied, and as these would generally be eliminated by commands from the spacecraft computer, will not be reported further herein.

The air turbine power BRU was operating at nominally 1200 to 1500 W and the load step was from 0 to 1000 W user load, or 1000 to 0 W user load. The user load was a transformer rectifier set connected to a resistive load, representative of the expected JIMO loads. JIMO loads will typically also contain some filter capacitance, but these data, except for figures 4 and 5, are without any capacitance to allow clear identification of the load transient.

The user load was configured as a 12 pulse rectifier, and the parasitic load was operated in a 24 pulse configuration. Therefore the power factor at the alternator terminals changed as a function of the loading, from 0.995 at no user load to 0.98 with 1 kW user load. Since the waveforms were not pure sinusoids, the power factor was defined as the watts divided by the volt-amps.

The reduction in power factor due to the user load caused the steady state alternator speed to increase approximately 2 percent to provide a constant voltage, or alternatively the alternator voltage decreases approximately 2.5 percent if the system was operating in the constant speed mode. These effects are not visible in the data showing millisecond time spans, but are shown in figures 8 and 9. All data shown in this document was taken in the constant voltage mode except for the data in figure 9.

The load switching was performed with a solid state switch that switched all three phases simultaneously. The switch turned on in a few microseconds, and turned off in approximately 20 μsec due to snubber capacitance.

Figures 2 and 3 show the instantaneous output voltage transient for a load step and load removal, respectively. All three phase voltages were shown, and the instantaneous current was in one phase.

The most obvious effect of the load switching was the change in the voltage waveform since the PLR was based on a 24 pulse rectifier and the load was a 12 pulse system. Neither the load step nor removal caused a significant notch in the output voltage waveform. Figures 4 and 5 showed the effect of using a capacitive input filter on the output of the rectifier. The effect of the load changes on the voltage regulation loop is shown in figures 6 and 7.

The filter for transients in figures 4 and 5 consisted of a series inductor of 40 μH and 1 μF for figure 4 (20 μF for figure 5) across the load resistance of 250 Ω. In terms of impedance at the ripple frequency of 10 KHz (12 times the 866 Hz fundamental), the inductive reactance was 24 Ω, the reactance of the 1 μF capacitor was 15 Ω. The load current showed a 150 percent inrush spike for the filter with the small capacitance, and approximately 3 per unit rated-current (2 kW base) with the large capacitance. Although the bus voltage showed significant notches due to these inrushes, the system recovered in a couple of cycles. The load current is shown as the instantaneous Phase A current in figure 4, but as a voltage representing the rectified sum of all three currents in figure 5.

The response of the voltage regulator to the resistive load transients is shown in figures 6 and 7. The data is plotted as the direct scope readings of signals in the regulator, and require some explanation. The "Sum of Phase Voltages Squared" is essentially a root mean square (rms) signal except that the square root function has not been performed. For small signal changes as shown in the data, this results in an expanded scale so that an apparent 10 percent change is really only a 5 percent change in the rms voltage. Also, there is essentially no filtering in the calculation so high frequency data is not filtered out. The "Sum of Phase Currents" is similarly the signal voltage from the three-phase rectification of current transformers on the load current. This signal is used for the feed forward compensation in the regulator. The "Integrator Error" trace is the output of the integral stage of the control loop, and is shown to illustrate the duration of the transient more clearly than trying to interpret small changes in the output voltage signal.

The final two traces show the longer term response to load transients in the constant voltage and constant rpm modes. In figure 8 the alternator speed varied approximately 2 percent in response to the load changes. The cause of the change is the reduced power factor of the 12 pulse load compared to the power factor of the 24 pulse PLR. In order to maintain output voltage with the reduced power factor, the voltage regulator decreased the total load on the machine, allowing the alternator speed, and therefore internal alternator voltage, to increase. Figure 9 shows the corresponding response in the constant rpm mode. The initial transient response is identical between these modes since high speed inner voltage loop dominates the initial response.

Conclusions

A 2 kW Brayton cycle alternator was constructed as a prototype development test bed for the proposed JIMO mission. The alternator characteristics were similar enough to the expected JIMO machine characteristics that performance of the 2 kW test bed could have been representative of actual JIMO performance. Load transient data taken on this test bed, used to specify the draft JIMO Power Quality Specification, showed significantly faster response than typical motor generator sets using field control and source throttling.

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2. Hervol, D., Mason, L., and Birchenough, A., Glenn Research Center, Cleveland, OH, “Experimental Results From a 2 kW Brayton Power Conversion Unit,” NASA/TM—2003-211999, January 2003.
3. Hervol, D., Mason, L., Birchenough, A., and Pinero, L., “Experimental Investigations From the Operation of a 2 kW Brayton Power Conversion Unit and a Xenon Ion Thruster,” NASA/TM—2004-212960, February 2004.

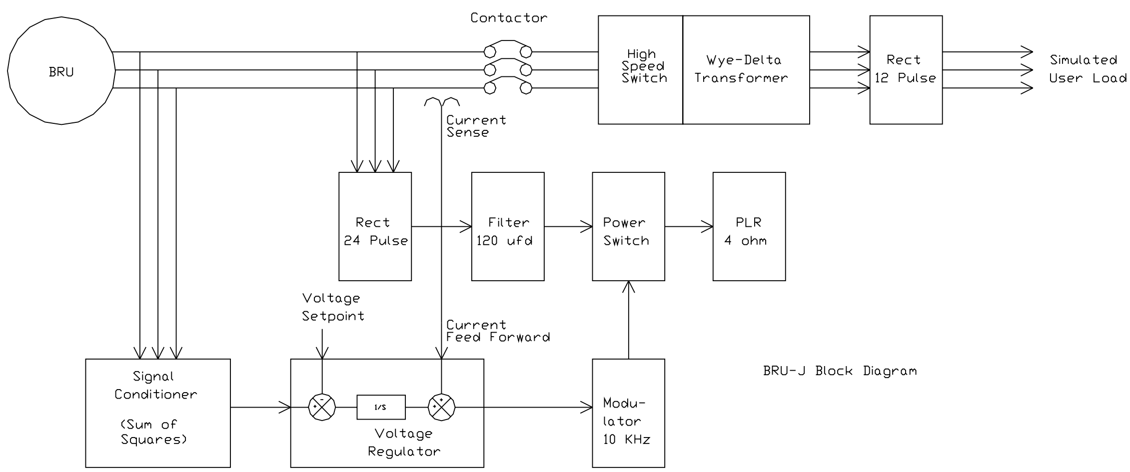

Figure 1.—BRU-J 2 kW block diagram.

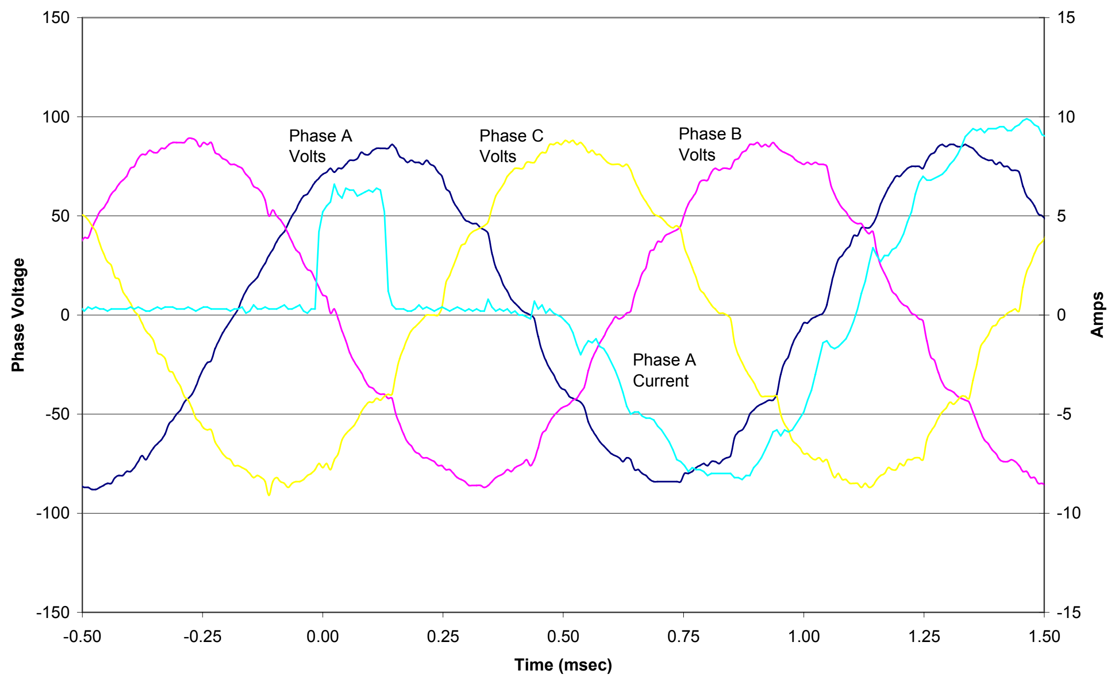

Figure 2.—Load step.

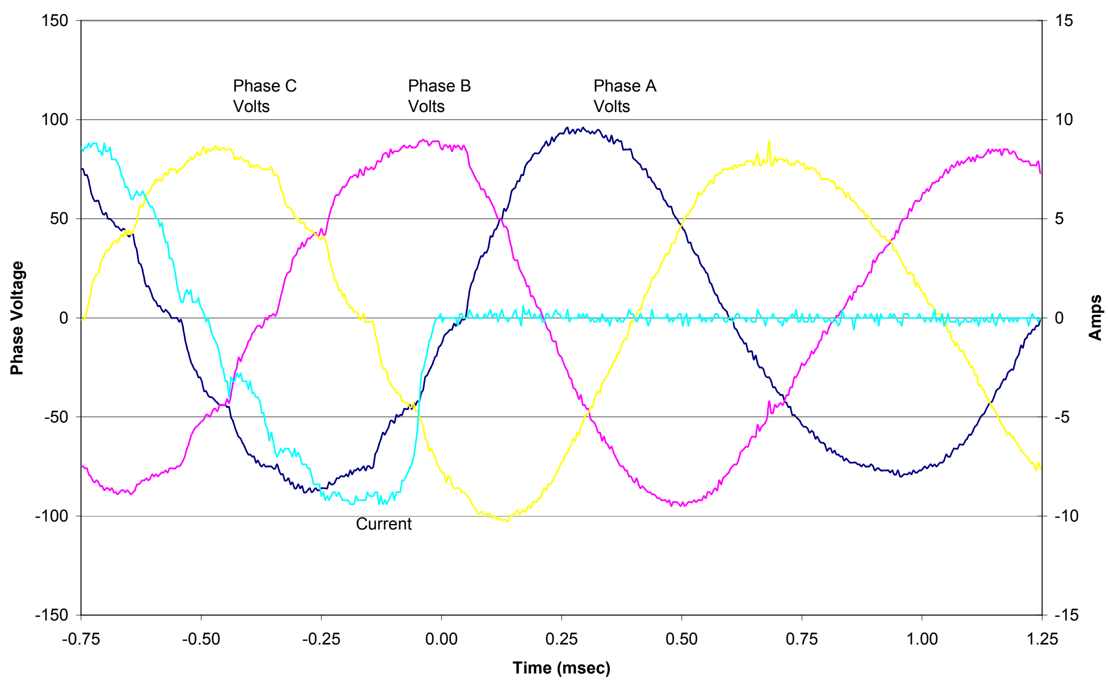

Figure 3.—Load removal.

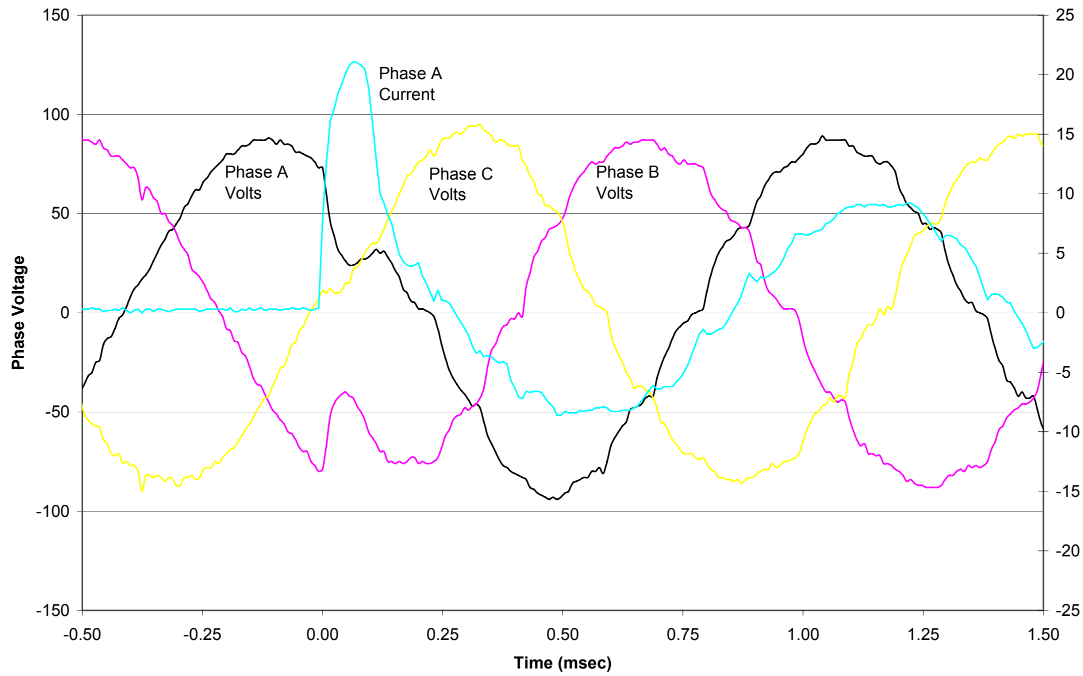

Figure 4.—Load step (with 1 µF capacitance).

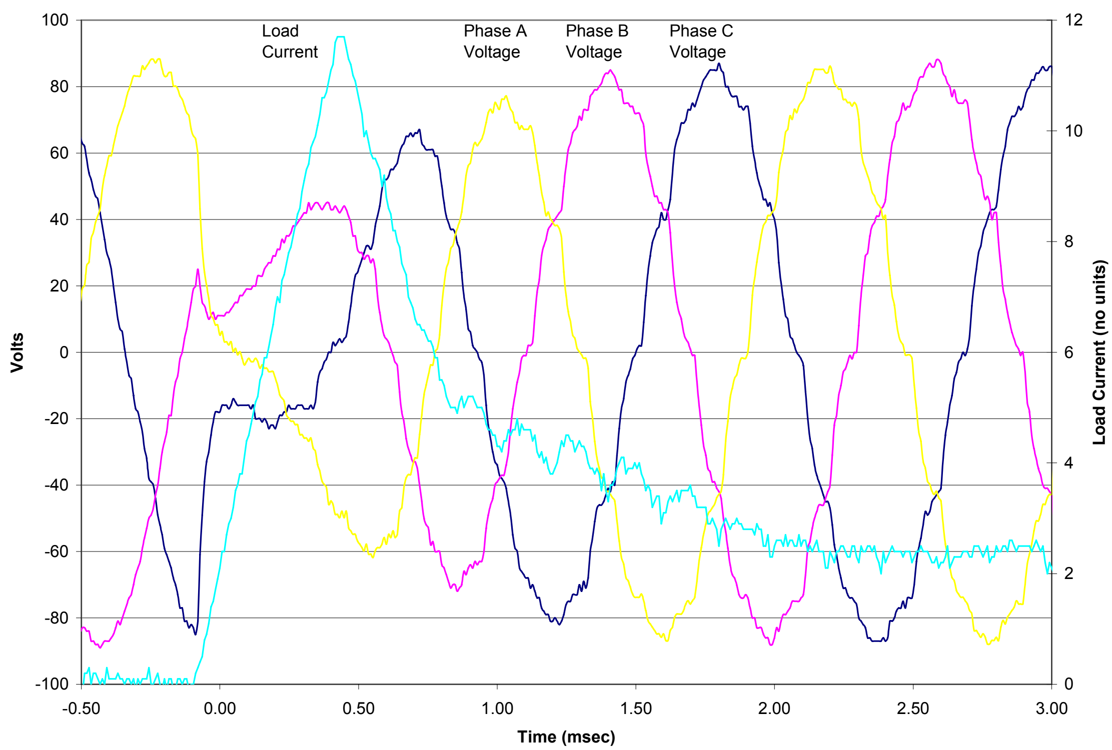

Figure 5.—Load step (with 20 µF capacitance).

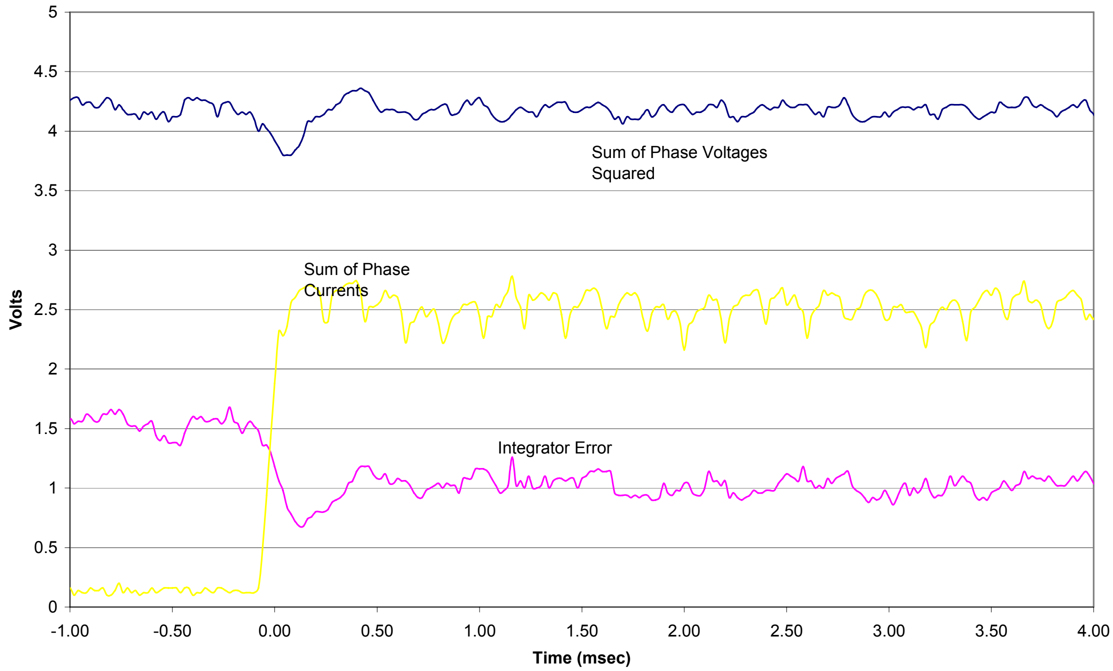

Figure 6.—Load step.

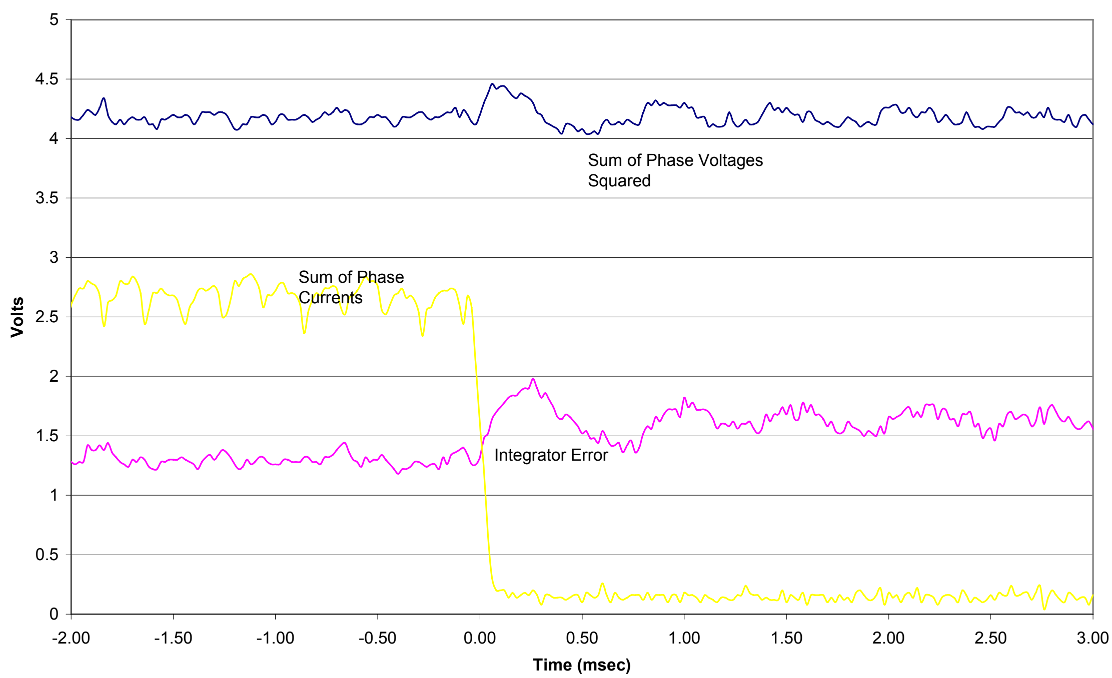

Figure 7.—Load removal.

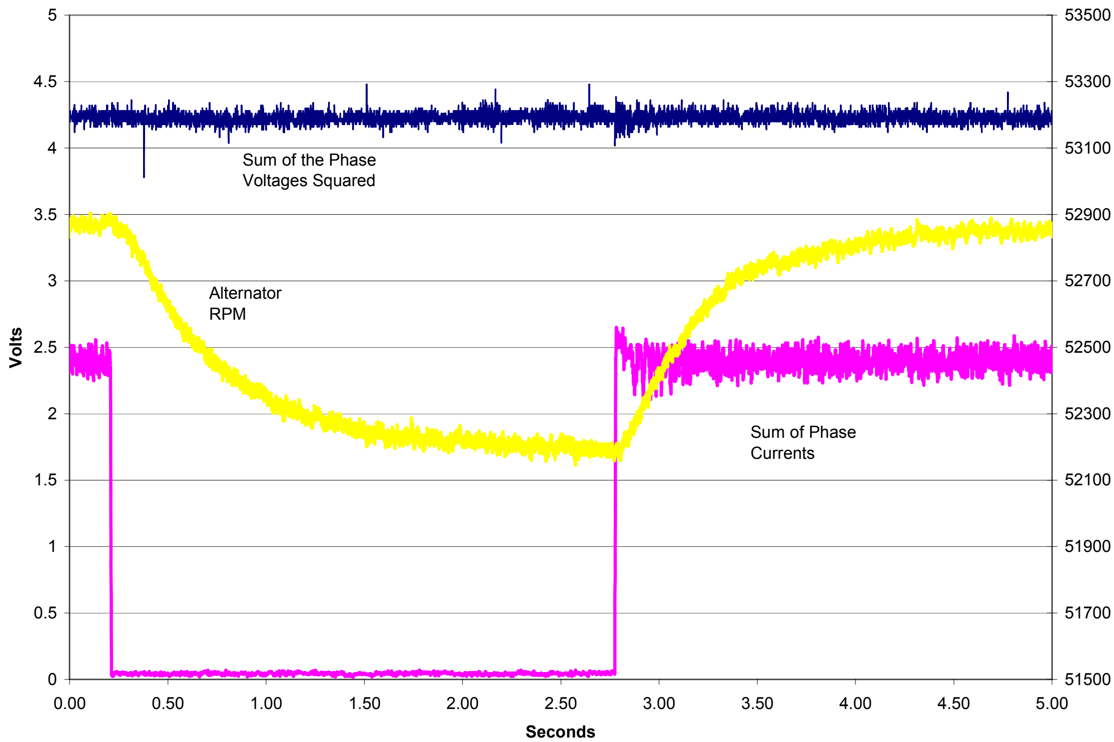

Figure 8.—Constant voltage mode.

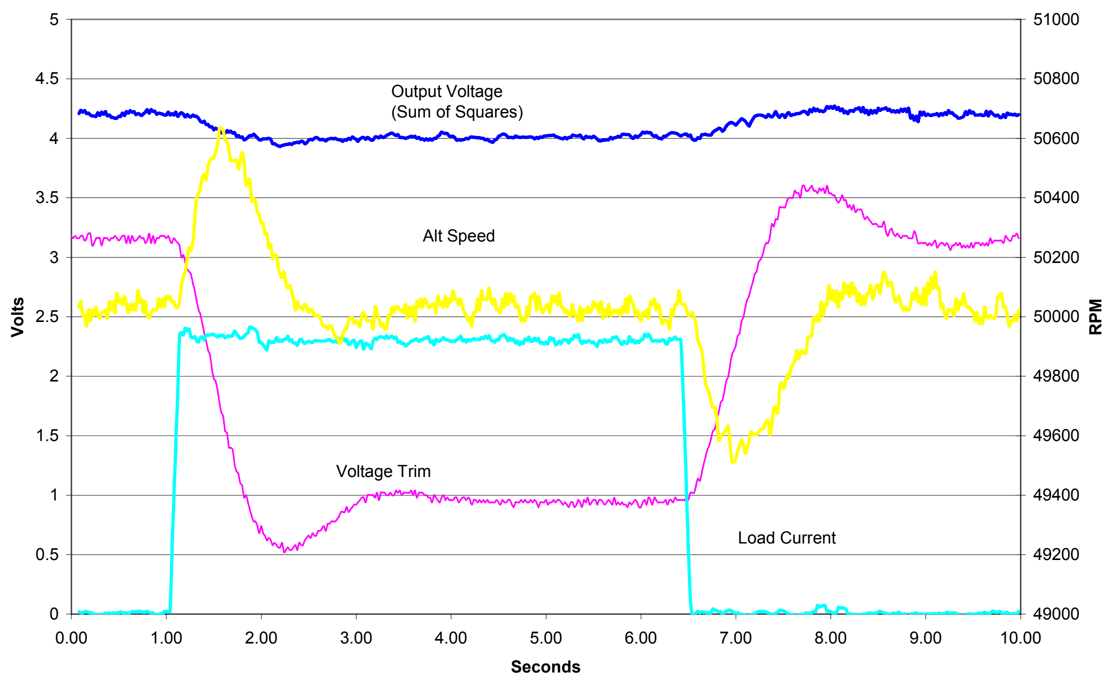

Figure 9.—Constant rpm mode.

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