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Description of the Prometheus Program Alternator/Thruster Integration Laboratory (ATIL)

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I. Abstract

The Project Prometheus Alternator Electric Thruster Integration Laboratory's (ATIL) primary two objectives are to obtain test data to influence the power conversion and electric propulsion systems design, and to assist in developing the primary power quality specifications prior to system Preliminary Design Review (PDR). ATIL is being developed in stages or configurations of increasing fidelity and complexity in order to support the various phases of the Prometheus program. ATIL provides a timely insight of the electrical interactions between a representative Permanent Magnet Generator, its associated control schemes, realistic electric system loads, and an operating electric propulsion thruster. The ATIL main elements are an electrically driven 100 kWe Alternator Test Unit (ATU), an alternator controller using parasitic loads, and a thruster Power Processing Unit (PPU) breadboard. This paper describes the ATIL components, its development approach, preliminary integration test results, and current status.

II. Introduction

The NASA Vision for Space Exploration includes the development of innovative technologies, knowledge and infrastructure both to explore the solar system for scientific purposes and to support human exploration. As part of NASA's Space Exploration Program, Project Prometheus was created to develop technology and conduct studies in the areas of nuclear power and electric propulsion for the peaceful exploration of the solar system. It is anticipated that nuclear electric power (NEP) will provide the opportunity for much greater energy availability for spacecraft propulsion and electrical power for payload and communications. An integrated Prometheus Project team consisting of JPL, the supporting NASA Centers, the Department of Energy's Naval Reactors Prime Contractor Team (NRPCT), and Northrop Grumman Space Technology (NGST) were co-designing the Prometheus 1 Deep Space Vehicle (spacecraft module and reactor module).

NASA Glenn has extensive experience with Dynamic Power Systems and Electric Thrusters dating back to the 1960s. NASA GRC developed the NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) primary propulsion ion thruster: the first ion thruster flown on a deep space science mission (Deep Space 1). GRC has also successfully demonstrated operation of a 2 kW Brayton Rotating Unit, associated power control and distribution, with an Engineering Model (EM) of the NSTAR gridded ion thruster (ref. 1).

Glenn Research Center is playing a major role in the development of the dynamic power conversion, power management and distribution, heat rejection and electric propulsion for Project Prometheus. In order to support the NASA Glenn Prometheus Project role, a flexible experimental facility to study end-to-end EP electrical power system is under development. The Alternator Thruster Integration Laboratory (ATIL) includes a representative alternator and associated controller, power distribution hardware, and a representative Power Processing Unit (PPU) and electric thruster. In addition, GRC is responsible for the development (and validation by test) of analytical models for performance and lifetime prediction of the power conversion, management, and distribution system. The two primary objectives of the laboratory are to obtain test data to influence the power conversion and electric propulsion design and to assist in developing the primary power quality specifications (ref. 2) prior to system Preliminary Design Review (PDR). ATIL provides a timely insight of the electrical interactions between a representative Permanent Magnet Generator, its associated control schemes, realistic electric system loads, and an operating electric propulsion thruster.

III. Test Facility Description

The Alternator Electric Thruster Integration Laboratory (ATIL) is being developed in stages or configurations of increasing fidelity and complexity in order to support the various phases of the Prometheus program. A block diagram of the ATIL final configuration is shown in figure 1 and figure 2 shows a picture of the ATIL facility at NASA GRC. The ATIL main elements include an electrically driven 100 kWe Alternator Test Unit (ATU), an alternator controller using parasitic loads, AC power distribution hardware, and a thruster Power Processing Unit (PPU) simulator. These elements have been developed using breadboard type hardware and/or simulated components. The ATIL initial configuration under development uses readily available off-the-shelf components. During the initial stage of ATIL a commercial AC power supply will be used to verify proper operation of the power distribution hardware, the alternator controller hardware, load simulators, and the facility control and data acquisition system. The power supply is capable of providing 90 KVA of three-phase AC power at variable frequencies up to 2000 Hz and output voltage up to 528 VAC line to line. External circuitry has been added to the power supply to simulate the output impedance of a representative PMG. The power supply will be replaced by the Alternator Test Unit in early 2006.

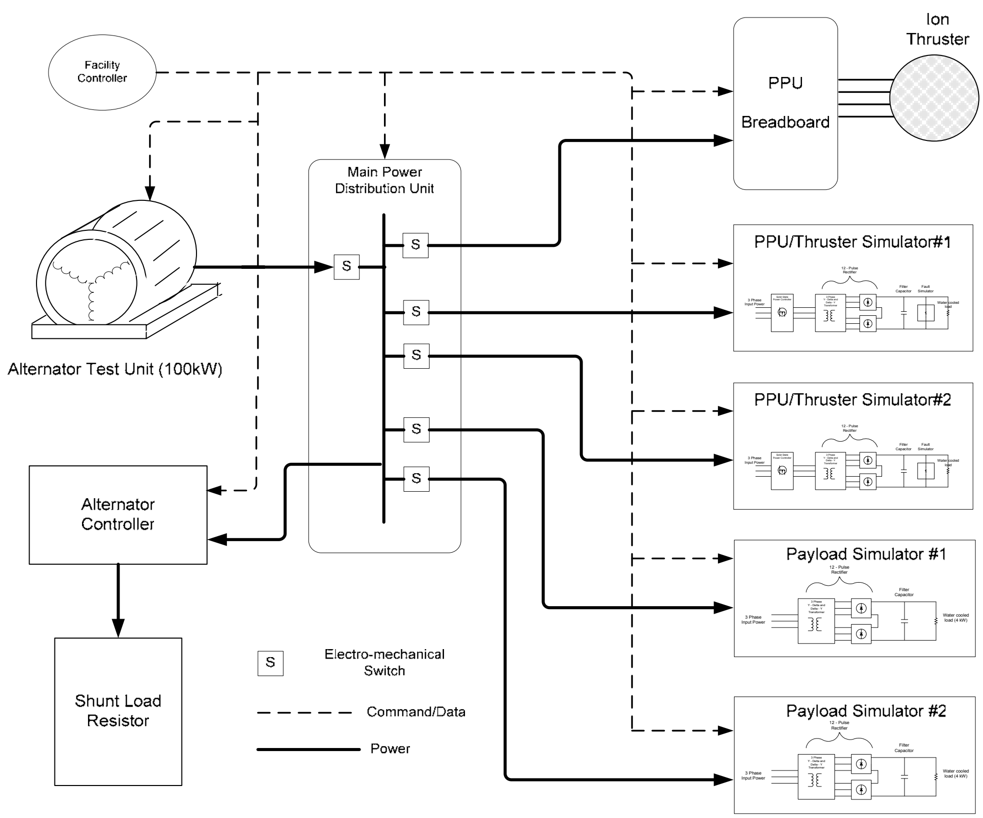

Figure 1.—ATIL Block Diagram.

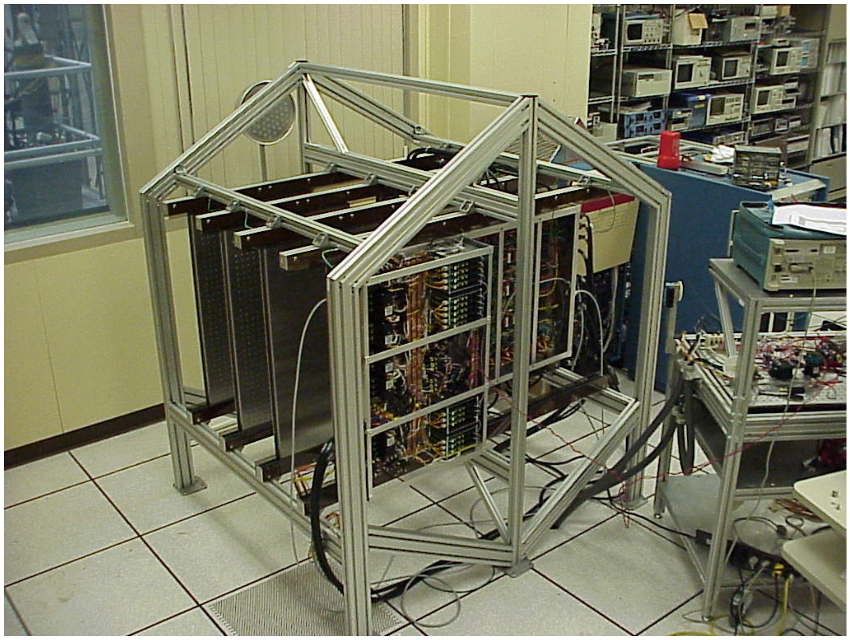

Figure 2.—ATIL Facility at NASA Glenn Research Center.

A. Alternator Test Unit

The Alternator Test Unit (ATU) is an electrically driven Permanent Magnet Generator that is being developed by Hamilton/Sundstrand for NASA. The output of the ATU is a sinusoidal 2250 Hz waveform rated at 100 kWe, 440 V line to line. The ATU requires three-phase 480 Vac, 60 Hz input power. The prime mover for the generator is a permanent magnet (Samarium Cobalt) 2-pole motor driven by a variable voltage and frequency inverter. The motor drive is capable of simulating Brayton Engine speed/torque characteristics in the generating mode, and can simulate the bearing drag and turbine compressor windage losses to simulate the motor starting mode. These simulation parameters can be modified by programming the motor controller algorithms. The ATU is also capable of operating in both torque and speed control modes. The motor will deliver 130 kW at 45,000-rpm continuously to the PMG. A cut-out diagram of the ATU is shown in figure 3.

An oil lubrication and cooling system is included in the ATU assembly. Oil jets are used to lubricate and cool each bearing and to cool the ends turns of the motor and alternator. Additionally, oil passages are used to cool the rotor and stator. The oil system is cooled using a heat exchanger attached to a facility water cooling system. The facility water loop also provides motor drive electronics cooling.

The alternator is a Permanent Magnet Generator (PMG), six pole, oil cooled, rated for a 100 kW output at 440 V AC line to line, three-phase at a nominal power factor of 0.85. The frequency is 2250 Hz. The PMG rotor uses common Samarium Cobalt magnets in a Halbach array (ref. 3). The alternator design is representative of the Prometheus flight concept with similar power ratings (100 kW), similar rotor and stator construction, inertia and impedance, and similar operating rpm and frequency. The prime mover motor and PMG are in line coupled with a stiff spline coupling.

The prime mover, the PMG, the lubrication system, the system controller and motor drive electronics, and the input power conditioning hardware are all enclosed in a stand alone sound insulating cart. The ATU is being constructed to be used in a laboratory environment and is mounted on casters for ease of operation and handling. The control of the ATU is through a remotely located computer interface. The ATU system provides fault detection and management capability to protect against injury to a user or damage to the ATU itself.

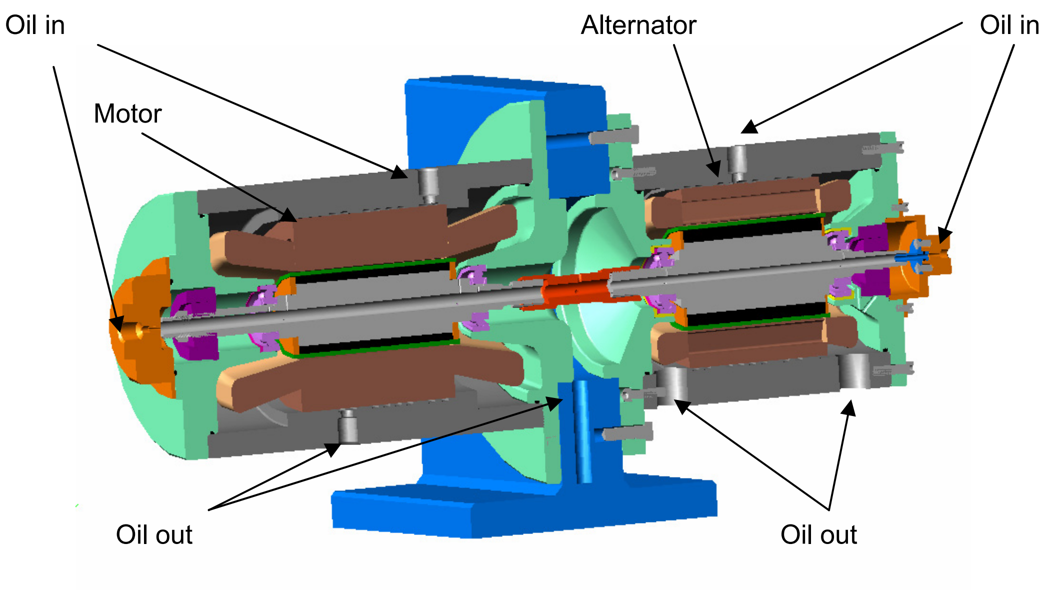

Figure 3.—Alternator Test Unit.

B. Alternator Controller and Shunt Load Resistor (SLR)

The alternator control function is based on applying a shunt or parasitic load to the alternator output in order to maintain a total load to the machine as required causing the machine to operate at the desired output voltage and/or speed. The alternator controller consists of two main circuits, the power circuits including the parasitic load elements, and the sensing circuits and feedback control loops sending the control signals to the power circuits.

Figure 4 contains a functional block diagram of the alternator controller. The power circuit uses a Wye-Delta transformer in combination with direct rectification of the power bus to effect a 12 pulse rectification of the bus power. The parasitic load resistor is connected across the rectified output, in series with a PWM FET switch, through an EMI filter to reduce noise radiated off the parasitic load. In the actual implementation two such resistor/EMI filter/PWM switch segments are connected in series to reduce the voltage requirement of the PWM switch. Additionally, there are 12 such circuits, each having a separate transformer-rectifier-parasitic load and PWM switch, in parallel to share the power and provide redundancy. The PWM switches are controlled by six-phase staggered signals to reduce waveform distortion.

The sensing and control circuits use a three-phase true root mean square voltage sensing, alternator speed sensing, and load current sensing as inputs. The basic control loop compares the sensed bus voltage to a reference, and uses a proportional plus integral control function to generate a command to the PWM modulator. Feed forward compensation for load current sensing is used to speed up the loop response. Additionally, alternator speed is sensed, and the error from the desired speed is used as a trim signal to change the voltage command slightly to run in a constant speed mode if desired. The PWM modulator generates 6 different PWM signals, equal width but phase shifted equally over a half the period of the alternator frequency to reduce waveform distortion by providing a more steady loading of the alternator.

C. Main Power Distribution Unit (MPDU)

The Main Power Distribution Unit contains the electrical switches and associated electronics to manage and distribute power from the generating power source to the user's loads and to the alternator controller. The unit's design accommodates dual power feeds to the main payloads and/or critical electrical loads. Figure 5 contains a functional block diagram of the MPDU and figure 6 shows a picture of this unit.

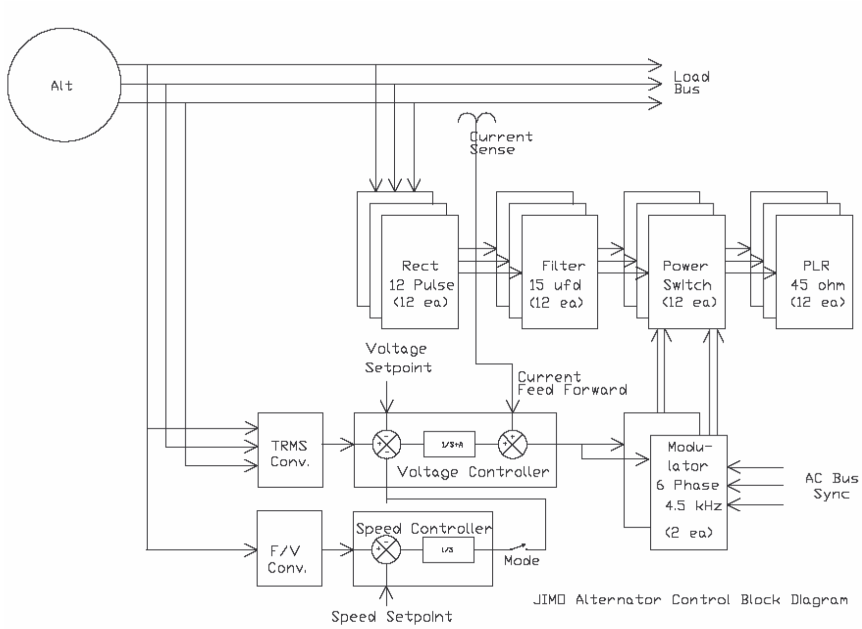

Figure 4.—ATIL Alternator Controller Block Diagram.

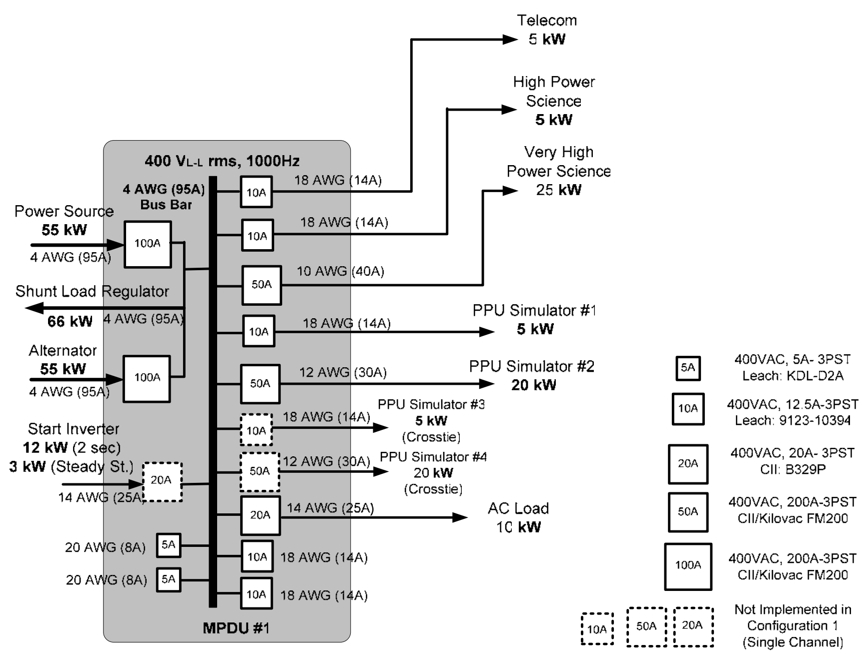

Figure 5.—ATIL Main Power Distribution Unit Block Diagram.

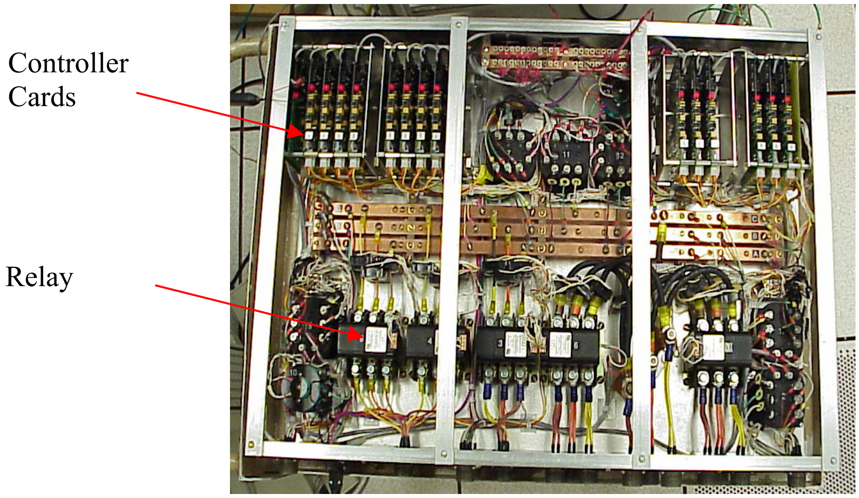

Figure 6.—Main Power Distribution Unit.

The MPDU is sized to distribute 100 kW of three-phase AC power at 440 V line to line (rms), 2250 Hz. The electrical switches are 3-pole single throw electromechanical relays that are de-rated to operate at 440 V line to line (rms) at a frequency of 2250 Hz. It should be noted that these relays are intended to be used with 400 Hz power distribution systems and manufacturers do not provide de-rating data on frequency. One secondary objective of the ATIL project is to validate the operation of these commercial off the shelf (COTS) relays in a mid-frequency (1500 to 2250 Hz) power system application. There are four types of relays in the MPDU with current ratings of 100A, 20A, 10A, and 5A. Each of the MPDU relays has an associated custom built micro-controller circuit card assembly (CCA) that provides digital and analog data handling and control. The CCA controller is an industry standard 8051 micro-controller and contains the logic to implement current and voltage sensing as well as analog circuitry for ON/OFF control and over-current protection. The over-current protection strategy is as follows: Instantaneous trip for currents 2 p.u. and above; and I (ref. 2) T (integrator) for currents higher than 1 p.u. but lower than 2 p.u. Both the over-current trip set-point (1 p.u. value) and instantaneous trip set-point (2 p.u. value) for each MPDU relay is adjustable. This feature will provide the flexibility to use the MPDU relays to feed and protect loads that require currents that are lower than the relay's nominal rating. A second type of CCA provides a single point data communication port between the MPDU and the main facility controller as well as senses the bus frequency and measure four temperature channels. The MPDU is air cooled and all its components are mounted on a common aluminum base plate.

D. System Loads

Project Prometheus was created to develop technology and conduct advanced studies in the areas of nuclear power and electric propulsion. A major challenge and principal area of technology development is the study of the interactions between the power generating source and large system loads like the electric propulsion thrusters and the high power scientific instruments. The ATIL project addresses these areas with the use of a combination of realistic electrical loads like the PPU/EP thruster breadboard and simulated loads. Figure 7 shows a functional block diagram of the PPU transformer-rectifier Load Simulator. These high power loads are powered directly from the main distributions bus with a 440 V line to line (rms) three-phase, 2250 Hz waveform. In order to process AC power, these loads will implement a three-phase Transformer-Rectifier that will change the AC voltage to the required voltage level and will then use a rectifier and filter to provide DC to the load. The rectifiers will be implemented as 12 pulse transformer rectifiers. The advantage of 12 pulse over 6 pulse rectifiers is a reduced bus voltage ripple, high power factor, and reduced harmonics in the AC bus. For loads that require multiple secondary

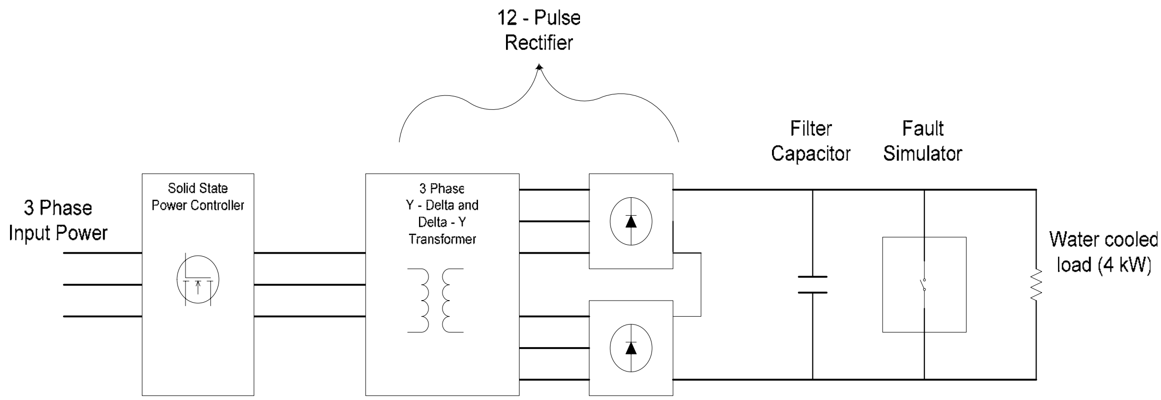

Figure 7.—PPU Load Simulator Block Diagram.

windings to achieve high voltages, such as the Power Processing Units for electric propulsion, the 12 pulse transformer rectifier can be implemented by connecting some of the secondary windings in wye configuration, and the other secondary windings in delta configuration. This will provide the 30 degrees phase shift that is necessary for the 12 pulse rectification. This required phase shifting can also be implemented by means of a "Star Transformer". A "Star Transformer" is a three phase transformer that contains additional windings that provide series voltages that are out of phase with the phase (or line to line) voltages to produce a phase-angle-regulating transformer. The required phase shift is then proportional to the magnitude of the added series voltages from the additional windings.

In the Prometheus ATIL, it is important to represent the electrical behavior (rectification, power factor, harmonics, etc.) of high power transformer rectifier loads such as the PPU Simulator, High Power Science and Telecommunications. Therefore, each of these loads will be implemented with its own Transformer Rectifier Unit at the required power level and a resistive load bank. However, the output voltages for the transformer rectifier units in ATIL, may be different form the voltages that the actual loads will require. For practical purposes, the output voltage of the transformer rectifier units will be selected at a voltage value that is suitable and compatible with the Power Systems Facility resistive load bank equipment. In addition to the TRF, the PPU Simulator incorporates a solid state power controller and a fault simulator to represent the actual thruster recycles. These load simulators are modular and based on a 4 kW block or module.

E. Facility Data Acquisition and Control (FDAC)

The main functions of the Facility Data Acquisition and Control (FDAC) system are the collection of performance data from the various elements of the ATIL, execution of control algorithms, and derivation of the necessary control signals. Figure 8 shows a block diagram of the FDAC. The FDAC system consists of a commercial off-the-shelf computer and associated peripherals (e.g., Controller Area Network (CAN) Card, LonWorks Card, and USB-IEEE-488 Adapter/Expander) to meet software and control requirements of the ATIL.

The power control algorithms include: system initialization and start-up, operator command execution, system fault protection, and system shut-down. The ATIL performance data will be collected approximately every half a second to one second. As portrayed in figure 8, the FDAC system collects data from and issues commands to the various elements of the ATIL via various data bus interfaces. The MPDU and the Alternator Controller telemetry is via a CAN data bus (refs. 4 and 5) interface programmed to communicate at 500 kbps, although it is capable of communicating at 1 Mbps at a 40 meters. Within the MPDU, digital and analog data handling and control between the single-point data communication CCA port and the relay CCAs is accomplished with a System Management Bus (refs. 6 and 7) (SMBus), which is I (ref. 2) C compatible, running at 100 kbps. The ATU will communicate with

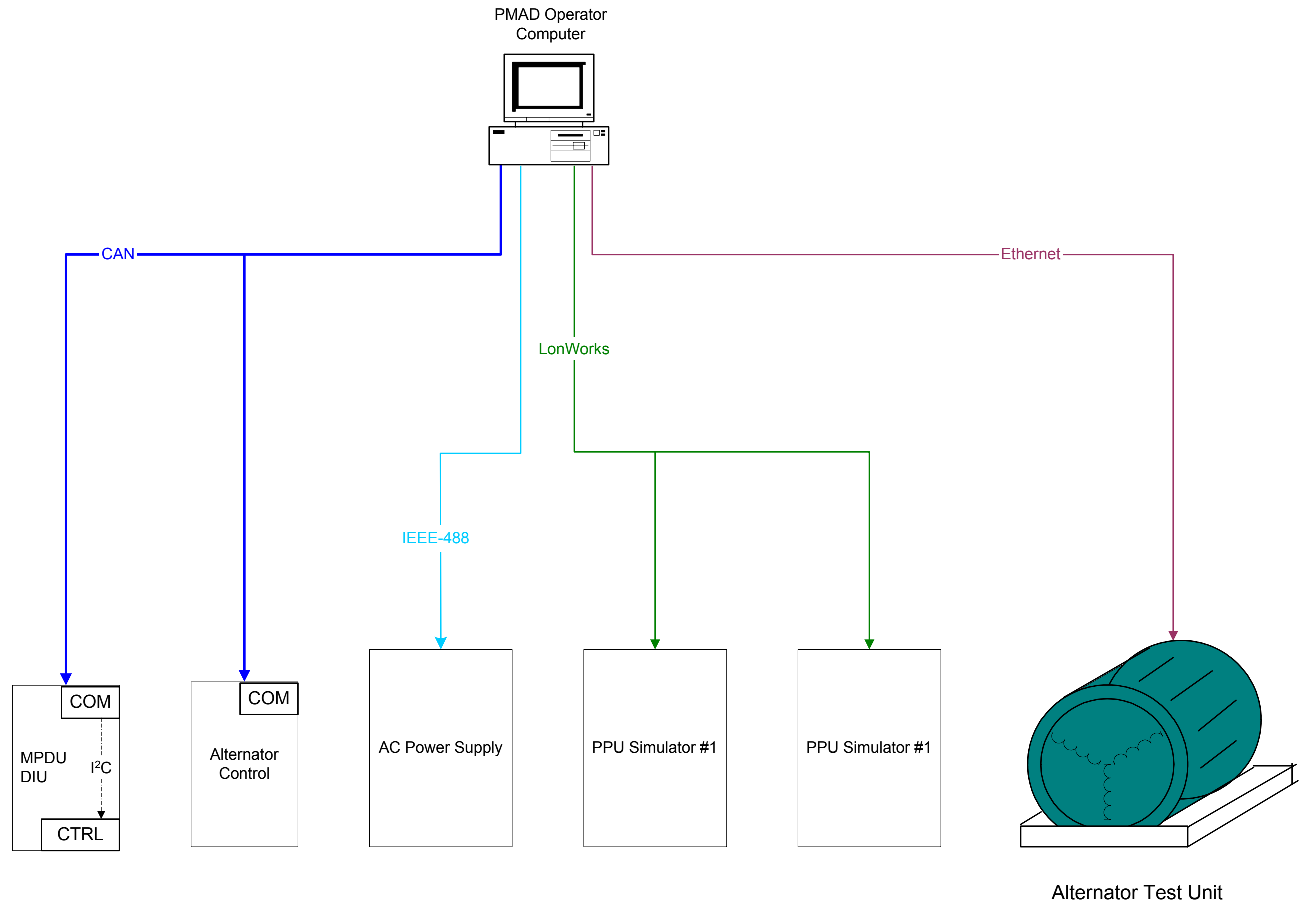

Figure 8.—Control and Data Acquisition System Block Diagram.

the FDAC via an Ethernet data bus and communication with the PPU Load Simulators, the Safety System, and the 28 V housekeeping Supply is through a LonWorks data interface. Communication with the AC Power Supply is accomplished via an IEEE-488 bus.

IV. Testing

A series of tests will be conducted to verify end to end operation in the ATIL facility. Initially individual component performance verification testing will be conducted to characterize each major element of ATIL but the emphasis in this test facility will be the interactions between elements and system level performance. The series of tests include testing for normal operation and abnormal or out limits conditions, particularly the transients associated with the thruster operation, and the effect of transient conditions on the alternator, including the inductance of the long power cable between the alternator and the MPDU (see fig. 1). Tests will be conducted specifically to anchor the development of Power Quality Specifications. Among these tests are: steady state operation at various power levels, load transients, system start up, fault transients and recovery, waveform distortion and conducted EMI.

A. Preliminary Test Results

Figure 9 shows initial integration test results of the 90 KVA three-phase power supply with the Main Power Distribution Unit (MPDU) and the 12 pulse transformer rectifier loads. Three air core inductors were connected in series with each phase of the power supply to emulate the electrical source impedance

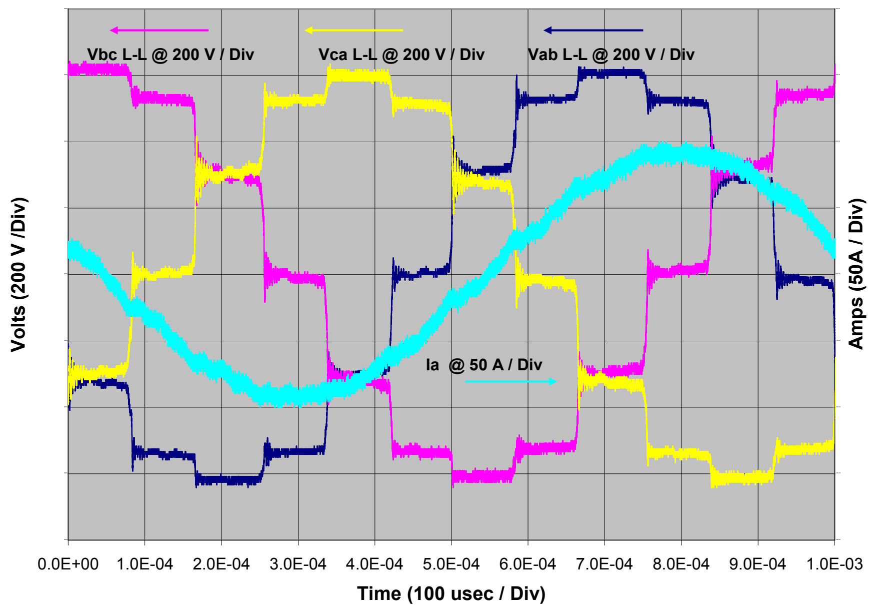

Figure 9.—Line to Line Voltages and Phase A Current in the MPDU Main Distribution Bus with 48 kW on 12 Pulse Transformer Rectifier Loads (200 V/Div and 50 A/Div).

of the ATU. This test was run with a line to line (rms) source voltage of 440 Vac, at a frequency of 1000 Hz, with a total transformer rectifier load of 48 kW. The voltage waveforms were taken at the MPDU Distribution Bus and they show the characteristic 12 step sine wave form produced by the transformer rectifier loads. The Phase A current shows a smooth sine wave shape due to the combination of the series air core inductance and the inductance of the long cable that connects the power source to the MPDU (see fig. 1). The inductance of this air core is 130 micro-henries and the cable inductance measured from the air core to the MPDU Input terminals is 10 micro-henries.

V. Conclusion

Project Prometheus was created to develop technology and conduct studies in the areas of nuclear power and electric propulsion in order to develop a nuclear powered spacecraft. The Alternator Thruster Integration Laboratory (ATIL) provides the Prometheus project a unique and flexible experimental facility to study end-to-end electrical power system, including a representative alternator and associated controller, and an Electric Propulsion Power Processing Unit. ATIL provides risk reduction and benefits to the project design effort prior to PDR (data available in 2006). ATIL provides experimental data to anchor the development of primary power quality specification. A major challenge and principal area of technology development is the study of the interactions between the power generating source and large system loads like the electric propulsion thrusters and the high power scientific instruments. The ATIL project addresses these areas with the use of a combination of realistic electrical loads like the PPU/EP thruster breadboard and simulated loads. ATIL's initial capability end to end (source to loads) system integration and tests is scheduled to begin in June 2005.

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