

Test Results From a High Power Linear Alternator Test Rig

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Abstract

Stirling cycle power conversion is an enabling technology that provides high thermodynamic efficiency but also presents unique challenges with regard to electrical power generation, management, and distribution. The High Power Linear Alternator Test Rig (HPLATR) located at the NASA Glenn Research Center (GRC) in Cleveland, Ohio is a demonstration test bed that simulates electrical power generation from a Stirling engine driven alternator. It implements the high power electronics necessary to provide a well regulated DC user load bus. These power electronics use a novel design solution that includes active rectification and power factor control, active ripple suppression, along with a unique building block approach that permits the use of high voltage or high current alternator designs. This report describes the HPLATR, the test program, and the operational results.

Nomenclature

| | |
|-----|----------------------|
| MPa | megapascal |
| Hz | hertz |
| VAC | volts AC |
| VDC | volts DC |
| kWe | kilowatts (electric) |

I. Introduction

As a step toward the development of a Stirling power convertor for use in a lunar Fission Surface Power (FSP) system, a pair of commercially available pressure wave generators was pneumatically connected with a pair of pressure wave alternators to create a High Power Linear Alternator Test Rig (HPLATR). The HPLATR is intended to simulate the coupling between the displacer piston and the power piston/linear alternator in a free piston Stirling engine. It was used to map and verify high power Stirling linear alternator performance and to develop a power management and distribution (PMAD) system.

II. High Power Linear Alternator Test Rig Description

A. Stirling Simulator

It was necessary to provide AC power to the PMAD that was analogous in character to a Stirling engine. The AC power level also had to be relevant to planned FSP power systems. Since there are no available Stirling engines available at that power level, a simulated system was fabricated. Two commercially available Pressure Wave Generators (PWGs) were procured from Clever Fellows Innovation Consortium (CFIC), of Troy, New York. Each PWG unit consists of two CFIC STAR linear motors that are mounted in a dual opposed configuration for balanced operation. The CFIC PWG was originally designed to provide pressure waves for acoustic pulse tube cryocoolers. The PWG has no wearing parts or lubrication needs, which means long-life and no scheduled maintenance. A second PWG unit was plumbed to the first PWR to create a common closed pneumatic space between them. One of the PWG units is powered with a variable frequency ac power supply power supply. This pair creates a pressure wave driving the second PWG which acts as a pair of linear alternators in an opposed configuration. The net effect is similar to the way a Stirling convertor displacer piston creates a pressure wave to drive its power piston. A photograph of the PWG units as configured in the HPLATR test facility is shown in Figure 1. The nominal operating conditions of the PWG are given in Table 1.



Figure 1.—Compressor alternator pairs as installed.

TABLE 1.—PWG NOMINAL OPERATING CONDITIONS

| | |
|-----------------------------|---------|
| Charge gas | Helium |
| Charge pressure | 4.0 MPa |
| Nominal operating frequency | 90 Hz |
| Mover amplitude | 13 mm |
| Nominal voltage | 330 VAC |
| Nominal motor input power | 10 kWe |

B. Stirling PMAD

A Stirling based power system has several unique characteristics compared to systems based on high speed turbo-alternators (Refs. 1 to 3) or DC sources such as solar cells or fuel cells. The power output of the source is single phase AC. Because the instantaneous power goes through zero twice every cycle some energy storage is required to supply continuous power to the loads. Also, the output frequency of the Stirling alternator is a relatively low frequency, on the order of 50 to 100 Hz, so the use of line frequency power transformers to boost the voltage for long distance power transmission can be heavy. Therefore, the alternator output has a relatively high voltage. The power electronics must work directly from this voltage, but must also provide a lower DC bus voltage output. Additionally, the alternator has a relatively high internal inductance, which requires reactive compensation to deliver the power to the load, and the power must be drawn nearly in phase with the internal voltage to allow the Stirling engine to operate efficiently.

Classically, power conditioning for a Stirling linear alternator used a passive system consisting of a full bridge rectifier and an output filter (Ref. 4). A parasitic load across the output bus provided voltage regulation and control of the Stirling engine stroke. However it could not perform the voltage regulation and stroke control functions independently from the other. Due to the high internal inductance of the linear alternator, a series tuning capacitor was used between the alternator and the rectifier. This compensated for the inductive impedance or else the inductive impedance was too great to extract much useful power out of the alternator. By adjusting the capacitor to be in resonance with the inductance, the output power was reasonably sinusoidal and in phase with the alternator motion. Both conditions were necessary for optimum operation of the Stirling engine. Increasing the alternator inductance and the impedance of the series capacitor improved how sinusoidal the waveform shape was, improving the Stirling engine operation. The drawback with this approach was that the capacitor became quite large, and the power losses in the inductor and capacitor decreased the overall efficiency.

Using an active rectifier with active Power Factor Correction (PFC) eliminates the large tuning capacitor while maintaining optimum power factor on the alternator, and has low current harmonics with minimum distortion. Additionally, the regulation of the output bus voltage can be performed independently of the control of the Stirling engine stroke.

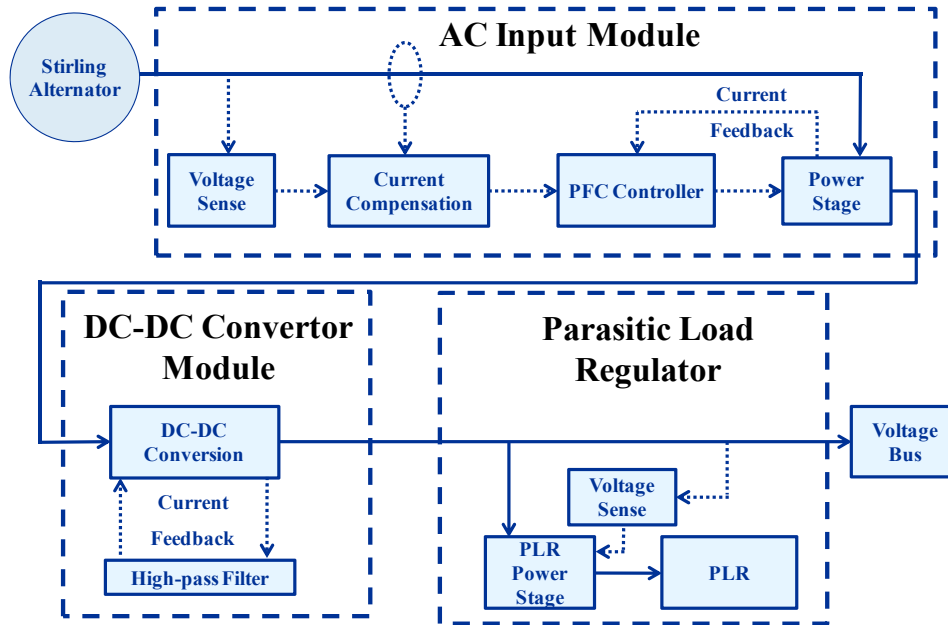


Figure 2.—HPLATR functional schematic.

The resulting linear alternator power conditioning system consists of three major elements. The functions of these elements are to rectify and filter the power output, provide constant engine loading, electrically isolate the load, convert to the desired bus voltage, and regulate the output bus voltage. These elements are the AC input module, a DC-DC converter module and a parasitic load regulator. A functional schematic of the overall HPLATR Stirling PMAD is shown in Figure 2.

The linear alternator of the Stirling engine produces a relatively low, 50 to 100 Hz, single phase AC output. The first element of the power conditioning system, the AC input module, is an active rectifier which performs the power factor control (PFC) required to absorb the input power at the correct phase angle. The circuit, shown in Figure 3, consists of a full bridge converter using PWM controlled FETs to modulate the input current. The operation is similar to a full bridge circuit used as a DC-AC inverter, but operating in a manner such that the power flow is from the AC input to the DC output. The module essentially generates an AC voltage at its input, where the alternator is connected, and the input current is consumed as a result of the difference between the alternator voltage and the voltage generated by the inverter. The control circuits act to consume current in phase with the voltage, and the input power to the inverter is converted to a DC voltage at the output of the AC input module. A capacitor and inductor are placed on the AC input to filter out the high frequency (50 kHz) modulation frequency. This minimizes the EMI induced in the AC power line.

The PFC circuit output is a DC voltage, but it is higher than desired for a user bus voltage, and also has a ripple component as a result of the single phase AC power input. The second element of the power conversion system is a DC-DC converter to reduce the PFC output voltage to the desired user bus voltage, and attenuate the voltage ripple. This stage is also required to provide isolation between the alternator bus and the user bus so that system grounding can be controlled independently between the power source and the user load bus. The circuit, shown in Figure 4, uses a full bridge inverter transformer coupled to a full bridge output rectifier. The inverter bridge uses high frequency conversion to minimize mass. This control method allows the frequency converter to operate at a nearly constant duty cycle (90 ± 10 percent) which allows close control of the rectifier reverse voltage transients.

The third element required is a parasitic load controller that is used to absorb the excess energy from the Stirling alternator that is not required by the user loads. By dissipating the excess energy the parasitic load controller regulates the bus voltage, and indirectly, the voltages within the AC input and the DC-DC converter stages. The circuit parasitic load controller, shown in Figure 5, uses PWM control of FET switches to modulate the power dissipated by the resistors.

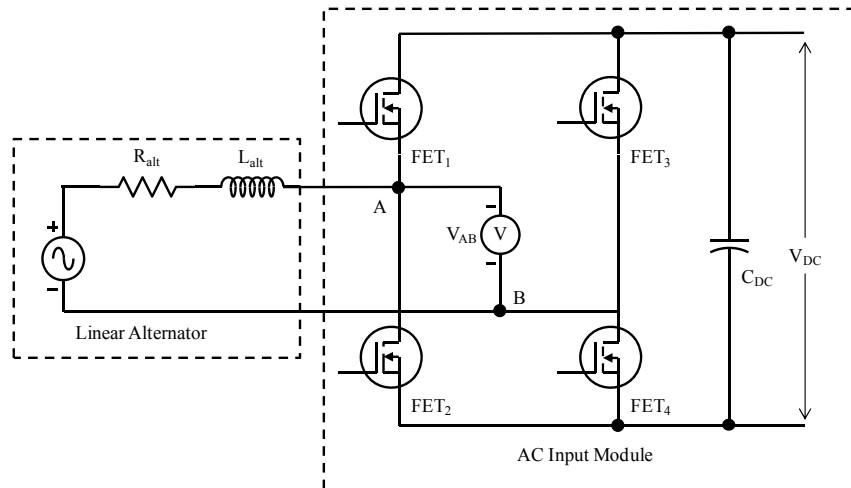


Figure 3.—AC input module schematic (Ref. 1).

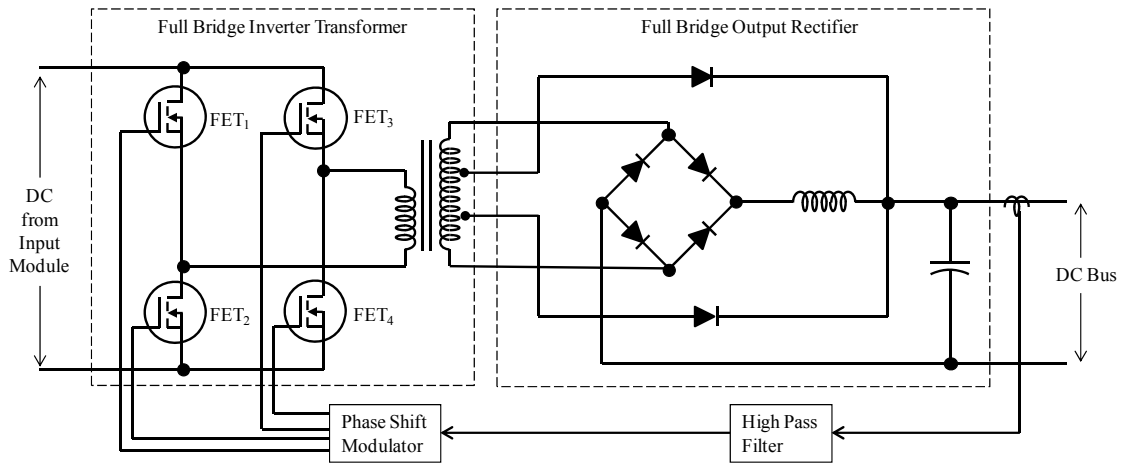


Figure 4.—DC-DC convertor schematic.

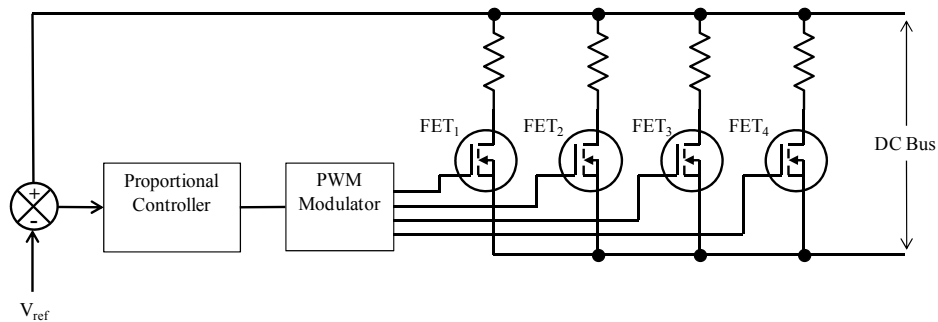


Figure 5.—Parasitic load controller schematic.

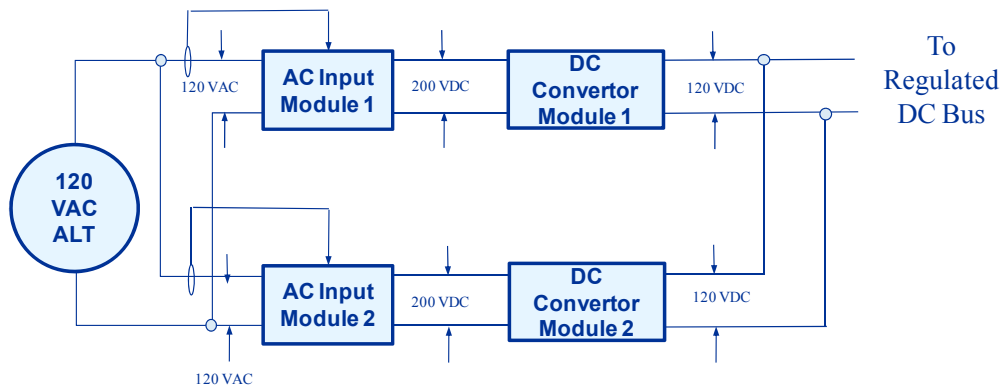


Figure 6.—Parallel connected power stage/DC-link for higher current handling capability.

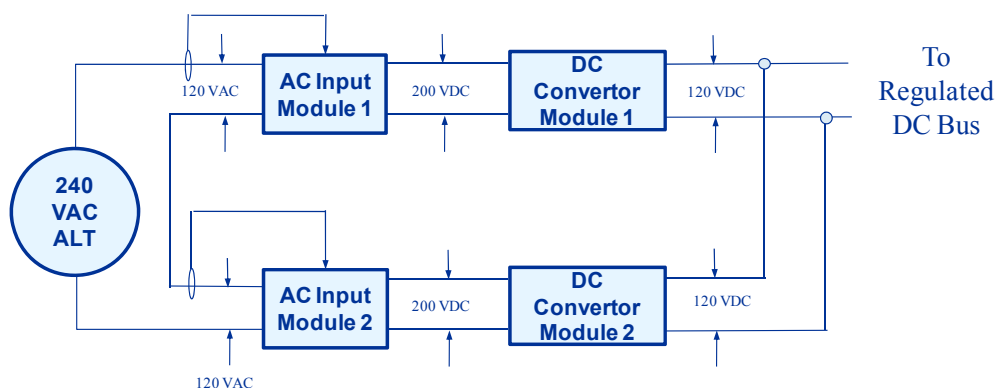


Figure 7.—Series connected power stage/DC-link for higher voltage handling capability.

C. Series/Parallel Module Connections

The AC input modules are always paired with one DC-DC converter module, and the DC-DC converter modules always have their outputs connected in parallel. Since the DC-DC converter modules provide isolation, the AC input modules may be connected in parallel to increase the current capability, as shown in Figure 6, or in series to increase their voltage capability as shown in Figure 7. The AC input modules always operate with independent controls, sensing the module input voltage and current, and the DC-DC converter modules also operate with independent controls, sensing their output current. The only common controls on any of these modules are the power commands to the AC modules used to control the engine stroke.

Since the control systems for these series and parallel modules are independent, the connections are simple and robust. Alternatively, individual current control could be used, but some balancing network would have to be employed, with its additional control loop stability concerns. By using a common control signal the single feedback path assures the switching will command the correct input current. An unbalance in the series or parallel connected stages will show up as a slightly different output power from each stage, but the unbalance is only a few percent even without any attempt to trim the circuits to balance them. Although differences in the modules result in some unbalance in the power they absorb, there is no interaction between modules, and therefore no control signal compensation required.

D. Stirling and PMAD Control System

The control strategies for the converter modules are a function of the use of the series and parallel connections. Each of the AC input modules, DC-DC converter modules, and the parasitic load controller has its own function, and the control functions are set up to allow these separate functions, and minimize interactions with the other modules.

The controls on the AC input modules perform two functions: The first is to consume current in phase with the alternator internal voltage source; the 2nd is to vary the amount of power it consumes to control the stroke of the linear alternator. The DC-DC converter controls are designed to convert the nominal 200 VDC input voltage to 120 V, and to attenuate the ripple voltage on the input. The parasitic load controller is designed to shunt excess power to the parasitic load elements in order to regulate the bus voltage to 120 VDC as the power input from the Stirling engines and the user loads vary.

Separating the control functions between AC input module, the DC-DC converter modules, and the PLR controller, allows parallel and series modules connections without changing the interaction between the modules. The AC input module outputs a nominal 200 V, with several percent ripple in the voltage due to the low frequency single phase input. But the AC input module does not regulate this voltage; it just pumps energy into its output filter in response to the power level command. A reference voltage, which will be nearly in phase with the internal alternator EMF is generated based on the alternator terminal voltage, with a compensation for the voltage drop across the internal inductance of the alternator. The power level command is developed from a measurement of the engine/alternator stroke, and the control loop increases the power command if the stroke exceeds its set point. The power level command is generated by a common controller, and must be isolated for each of the modules to maintain independence of the modules.

Since the DC-DC converter module does not have a voltage regulation loop, it operates at an almost constant conversion ratio, but modulated ± 10 percent to attenuate the ripple voltage at its input. The ripple is attenuated by controlling to a constant output current, but the DC component of the current feedback signal is removed by a high pass filter and the primary ripple current at twice the input frequency is the only active component in the control loop. With this control scenario, the DC-DC converter does not have a voltage regulation or power set point or any other external command input; it merely pumps whatever power is available from the AC input module to the output bus, and removes most of the AC ripple.

The voltage regulation is performed by the PLR controller stage connected in parallel with the power output bus. Since the DC-DC converter stage(s) are pumping current into the PLR controller stage, largely independent of the actual voltage at the bus, interactions are minimized.

III. Testing

The optimum Stirling engine operating frequency was determined by operating the engine at a constant drive motor voltage and then sweeping the drive frequency until a maximum alternator piston stroke was determined. For these tests the frequency was on the order of 90 Hz. Once this frequency was established, the amount of power produced by the linear alternator was varied by manually changing the drive motor voltage and commanding the desired current drawn by the AC power stage.

A. DC Bus Voltage Control With Switched User Loads

The first test, performed with the AC input modules in the parallel configuration, demonstrated the capability of the parasitic load to successfully regulate the DC user bus. The system was placed at a constant AC power output so that the corresponding total DC bus power was also constant. A series of five load combinations were then applied in increasing and decreasing fashion. The DC bus voltage and current were measured along with the user load current. The resulting DC bus and user load power was calculated. The timeline of the test showing user loads, DC bus power, current and voltage are shown in Figure 8. During the testing, the DC bus was deliberately “overloaded” by adding excess user load. This caused a DC bus voltage drop. The user load current increased in relative proportion to maintain a constant power level. These results are more clearly shown in Figure 9. The alternator voltage and stroke remained unaffected thus demonstrating the ability of the PMAD DC bus to provide protection to the linear alternator from adverse loading conditions.

B. DC Bus Current With and Without Ripple DC-DC Link Ripple Suppression

The next test examined the effectiveness of the DC-DC link high-pass filter current feedback in suppressing DC Bus current ripple. The HPLATR was operated at a constant power level to obtain time traces of DC link input voltage and DC bus current with the active ripple suppression operational (Fig. 10). The current feedback loop was then disabled and the same data was taken (Fig. 11). The difference in the magnitude in DC bus current traces between the two charts graphically illustrates the effectiveness of this method.

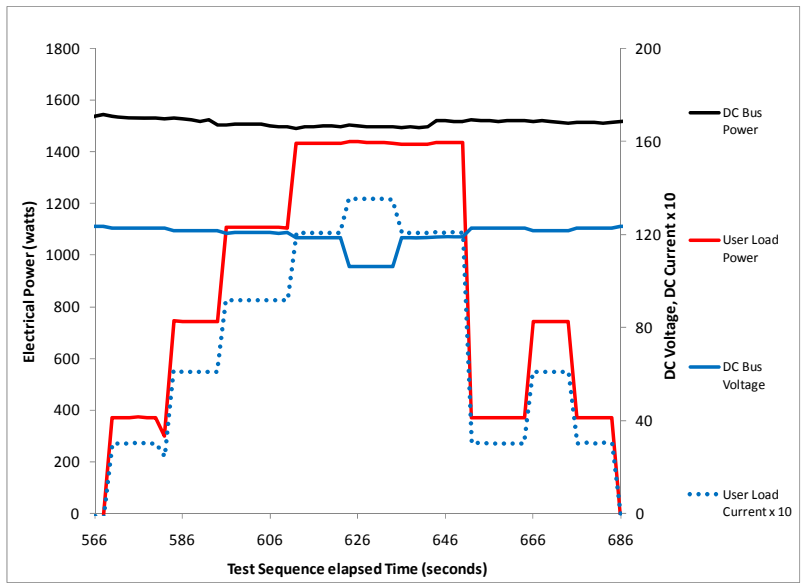


Figure 8.—User load test.

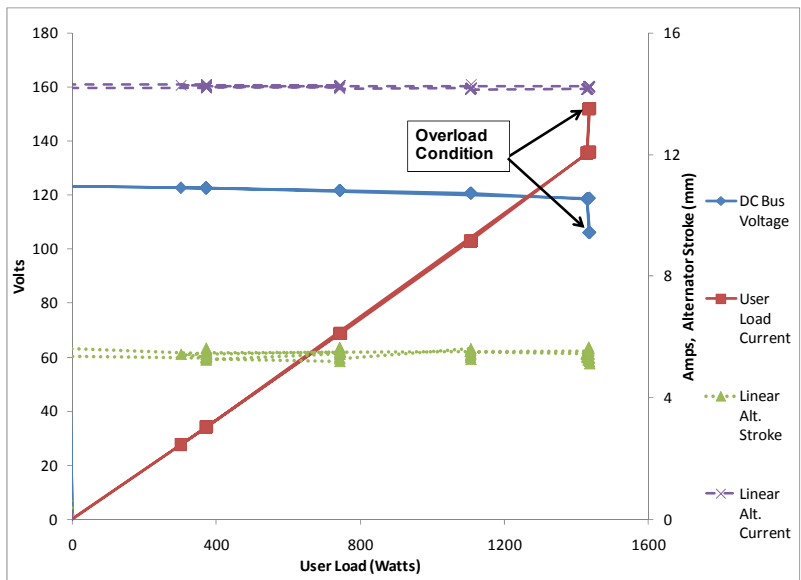


Figure 9.—User load current and voltage characteristics.

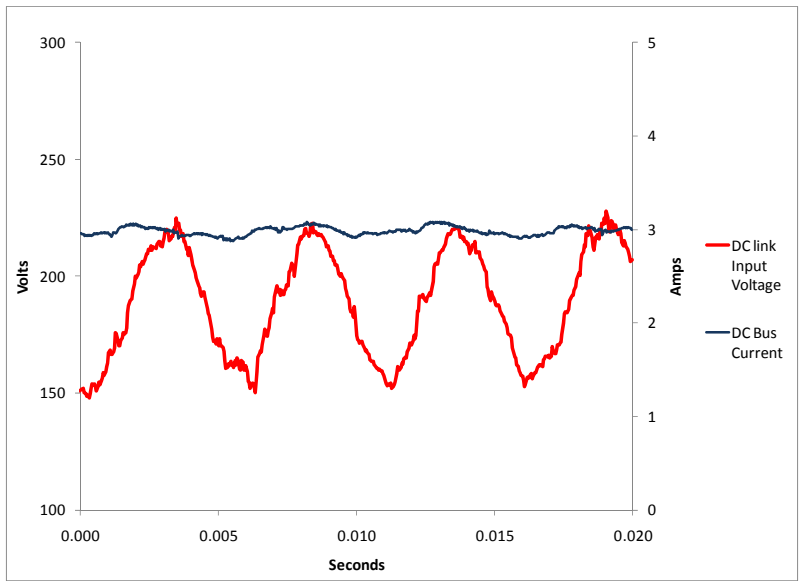


Figure 10.—DC bus current with DC-DC link active suppression.

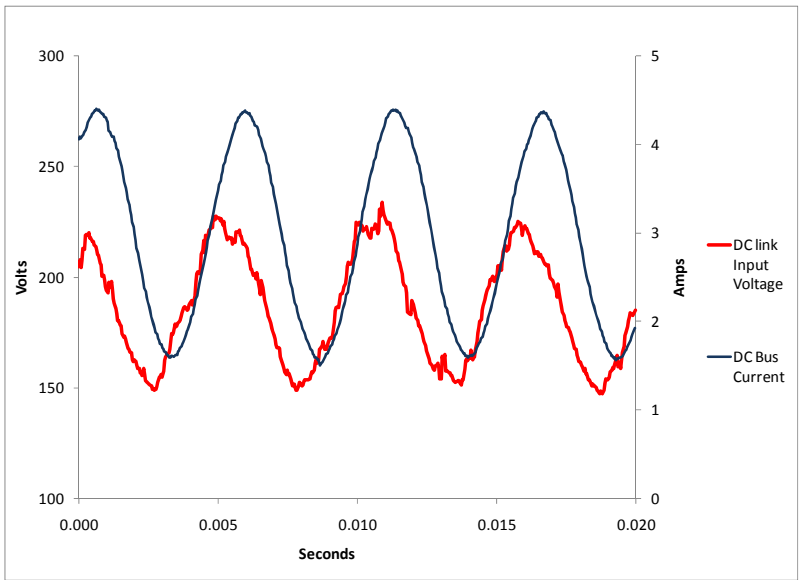


Figure 11.—DC bus current without DC-DC link active suppression.

C. Parallel and Series Module Configuration Tests

The final series of tests demonstrated the ability to connect the power modules in parallel or series depending on whether current or voltage handling capability is to be optimized. One of the measures that determine how well this works is the ability for the power modules to handle the power loads equally, and how well the DC user bus voltage is regulated regardless of how they are connected. This was first done with the power modules hooked in parallel. The resulting power sharing between the modules and DC bus voltage versus the alternator output power is shown in Figure 12. DC bus regulation was maintained for all realistic alternator power output levels (greater than 50 W) with the DC modules showing good power sharing between them.

The modules were then connected in series. The test was rerun at the same alternator output levels. Good DC bus regulation was maintained at all realistic alternator power output levels and the DC modules showing good power sharing between them. This is graphically shown in Figure 13.

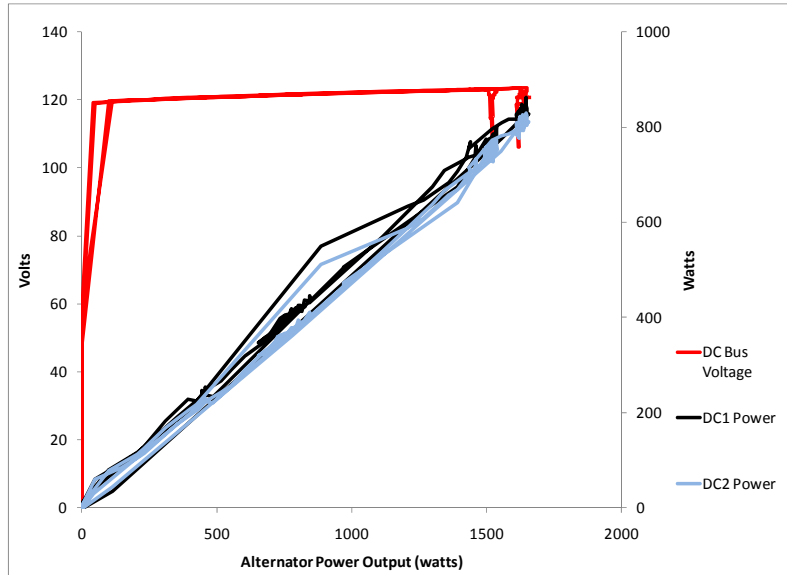


Figure 12.—Parallel connected power modules.

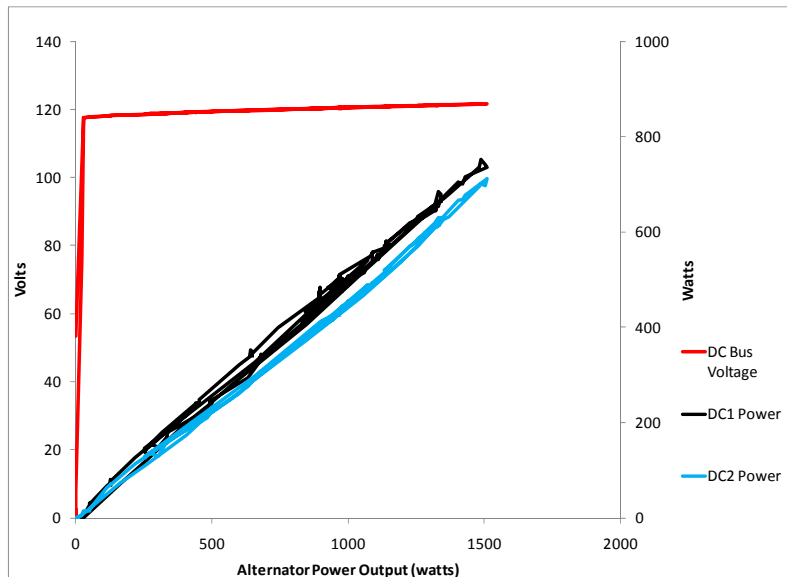


Figure 13.—Series connected power modules.

IV. Conclusions

The innovative use of independent controls to divide the functions of rectification, DC bus ripple suppression, and DC voltage control on a linear alternator representative of a Stirling engine was successfully demonstrated.

The DC bus parasitic load control maintained correct voltage regulation throughout a wide range of user loading conditions. The only exception to this came from a deliberate bus overload. This overload did not affect the total electrical load and AC voltage on the linear alternator due to the operation of the AC input module.

The DC-DC link current feedback loop using a high pass filter provided excellent DC bus current ripple suppression and provided electrical isolation from the linear alternator. Finally, by demonstrating successful power sharing of the AC input modules and corresponding DC-DC this method of PMAD control allows flexibility to configure the system for either high current or high voltage alternator designs.

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