INITIAL TEST RESULTS FOR THE FAN SHAFT DRIVEN GENERATOR

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Abstract

The Fan Shaft Driven Generator system has been studied as part of future More Electric Aircraft concept. The generator is mounted on the engine fan shaft in the tail cone and driven via a step-up gearbox. The power electronics unit is mounted on the fan case. It generates supplementary emergency power in an engine flame out condition as well as providing electrical power in normal engine operation. The requirement for wide operating speed range makes the design and control of the generator challenging. Prototype 150kW, 350Vdc Switched Reluctance generator systems were built and tested. Initial tests results confirmed the validity of the technology and stable operation both in steady and transient conditions.

1 Introduction

This paper describes the development and initial test results of the Fan Shaft Driven Generator (FSDG). The FSDG has been studied as part of the future More Electric Aircraft (MEA) [1-2], aiming to replace/supplement Ram Air Turbine in emergency conditions as well as provide additional electrical power during normal engine operating conditions. Fig. 1 shows the FSDG mounted in the tailcone on the fan-shaft of the engine via a step-up gearbox (G/B). A typical operating speed range of the fan-shaft, including the emergency windmilling operation, is approximately 14:1. The FSDG needs to operate over this wide speed range. Candidate technologies include Switched Reluctance (SR) [3-4] and Permanent Magnet (PM) [5-6] generators. Goodrich has been studying both technologies in collaboration with the Universities of Bristol and Glasgow [7-9]. A 150kW SR generator has been developed under the completed UK DTI-funded Fan Shaft Driven Generator and EU-funded Power Optimised Aircraft (POA) programme. Under POA, two similar generator control systems have been developed: the first for ASVR (Aircraft System Validation Rig) and the second for ESVR (Engine System Validation Rig). The ASVR water cooled power converter was built first. The lessons learnt while testing this converter were used in optimising the size, weight and reliability of its second iteration which is the fuel-cooled ESVR converter. An overview of the developments and initial test results are described in this paper.

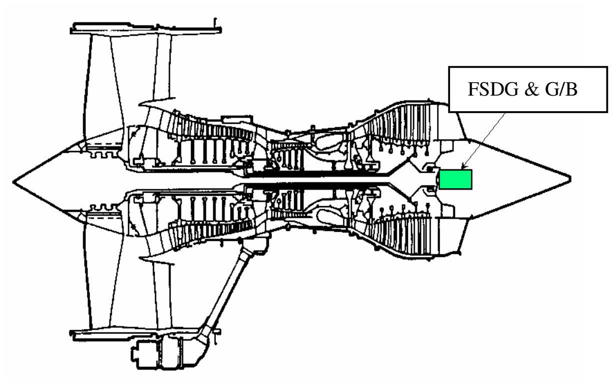

Fig. 1 Location of the FSDG

2 Requirements

The following requirements were generated within the POA programme:

- Generate power over the entire engine operating speed range in normal conditions (150kW, 350Vdc, fan shaft speed of >1,050rpm).
- Generate supplementary power in windmilling conditions (25kW, > 250rpm).

The bus voltage and output power were chosen partly due to the requirements and restrictions imposed by the engine and aircraft system rig tests. Those requirements may be changed for the future MEA. Ambient temperatures in the engine tailcone can be as high as 140°C during normal engine operation. It could exceed 300°C in a soakback condition after engine shut-down. The generator is cooled by the engine oil. The maximum oil inlet temperature is estimated at approximately 110°C. The power converter is located on the engine fancase where the maximum ambient is approximately 90°C. It is cooled by engine fuel, which has a maximum inlet temperature of 41°C.

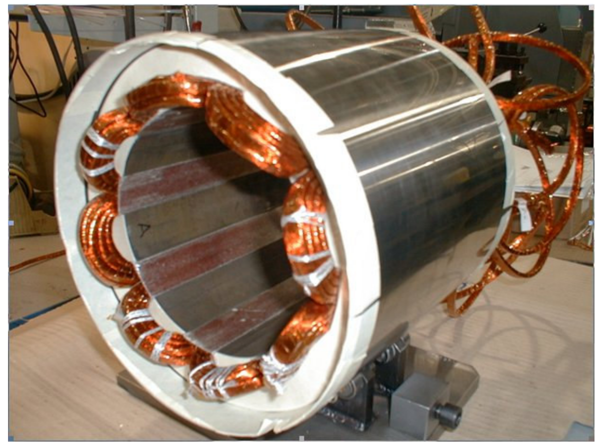

Fig. 2 Stator Assembly

Fig. 3 Rotor Assembly

3 System Configuration

3.1 SR Generator

The SR generator is a 4-ph 8/6-pole machine with stator OD of 236mm and stack length of 185mm. To maximise power density, cobalt iron laminations are used. To minimise high frequency losses, Litz wire is used for windings. A PM exciter rated at approximately 1kW is fitted on the shaft to provide the initial excitation of the main SR generator and the controller power. The PM exciter can also be used to detect rotor position. A resolver is also fitted for testing. Pictures of the stator and rotor assemblies are shown in Fig. 2 and Fig. 3 respectively. Total generator weight including the 4.5:1 step-up G/B is 105kg.

3.2 Power Electronics

Fig. 4 shows a diagram of the power converter. The main converter has a conventional SR circuit topology. The PM exciter is connected to the dc-link via the diode rectifier. It is also connected to a flyback dc/dc converter to supply dc power to the controller [10] (This circuitry was not implemented in the system used in the POA testing). Fig. 5 shows the internal view of the ESVR converter designed for the engine mount with dimensions of 650×750×270mm and the dry weight is 80kg. For comparison, the ASVR converter size is 800×600×1530mm with a weight of approximately 150kg (see Fig. 6). For both converters, the IGBT modules (1.2kV, 800A) were specially developed by Dynex Semiconductors.

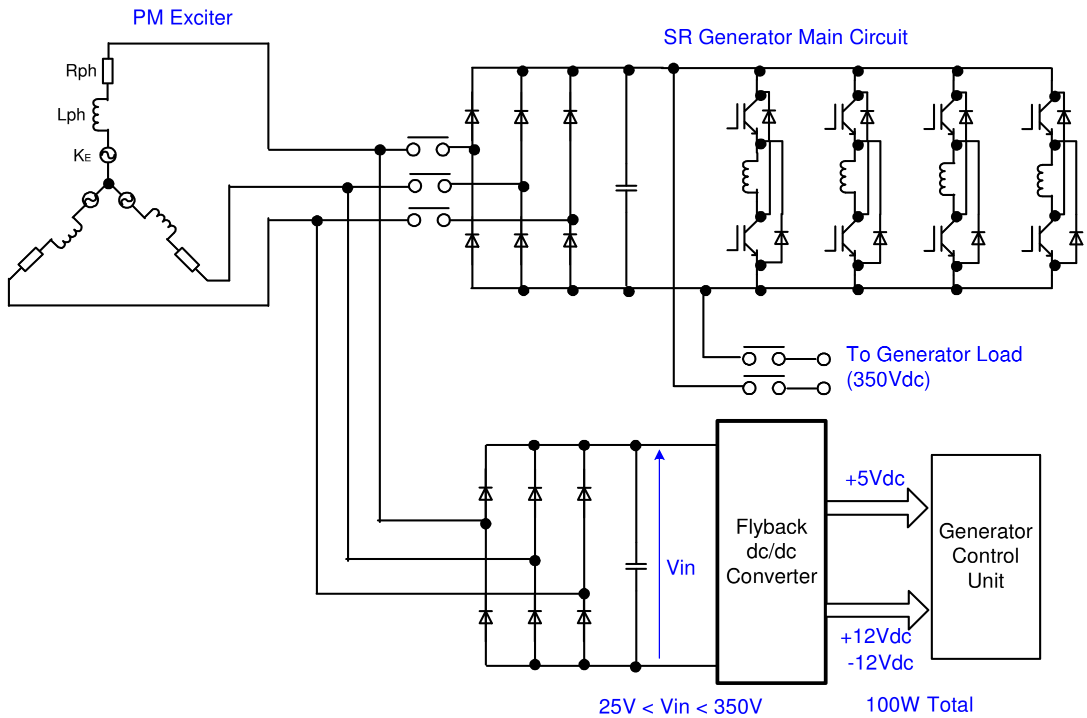

Fig. 4 Power Converter Diagram

The IGBT modules are mounted on one side of the fuel cooled heatsink and the dc-link capacitors (metallised plastic film) are mounted on a plate above close to the IGBT module to minimise power circuit inductance. A module consists of one IGBT and a diode, which are not connected internally, and electrical terminals are arranged so that the bus-bar construction can be optimised. Maximum switching frequency is limited to about 10kHz. The gate drive has integrated protection functions including Desat detection. The digital controller consists of TMS3206713 DSP and Xilinx Spartan IIE FPGA. The controller has CAN-bus and RS-485 interfaces so that internal parameters can be monitored and changed during operation. The RS485 link was attached to a PC running a Visual Basic application which displays all the relevant parameters in a user-friendly graphical format. During system operation, the user can also modify essential parameters such as phase current switching angles, PI controller gains, maximum PWM frequency, etc (Fig. 7 and Fig. 8).

4 Thermal Design

4.1 Generator

The generator has two separate cooling oil channels for the stator and rotor. The stator cooling oil is fed through the middle section of the housing into the oil jacket between the housing and core pack. The stator oil flows through grooves in the jacket removing heat from the back iron. At the ends of core pack the oil is sprayed onto the end windings before being scavenged through the bottom of the stator. The rotor cooling oil is tapped from the central oil tube which runs through the hollow shaft of the generator to the engine shaft. The oil flows through the grooves between the shaft and rotor core pack.

Fig. 9 and Fig. 10 show finite element thermal analysis results for the stator and rotor respectively. Maximum local temperatures of 185°C and 310°C are predicted in the stator and rotor respectively.

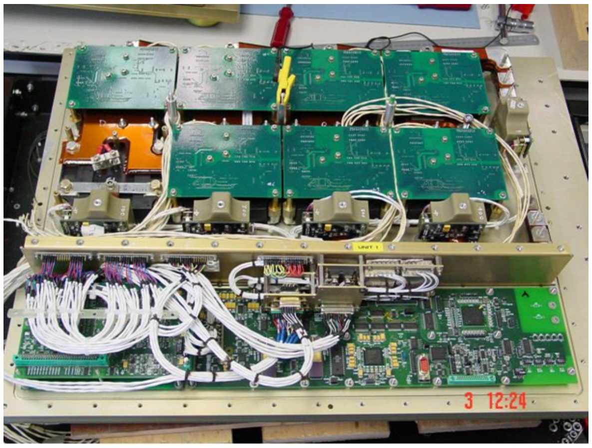

Fig. 5 Internal View of ESVR Power Electronics

Fig. 6 Internal View of the ASVR Power Electronics

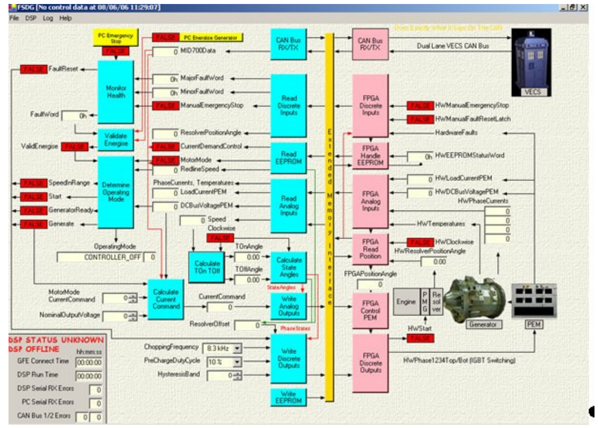

Fig. 7 Main Window of the Visual Basic Interface

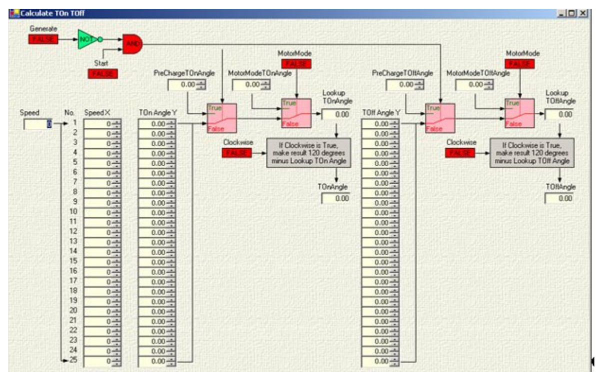

Fig. 8 Control Parameter Setting Window

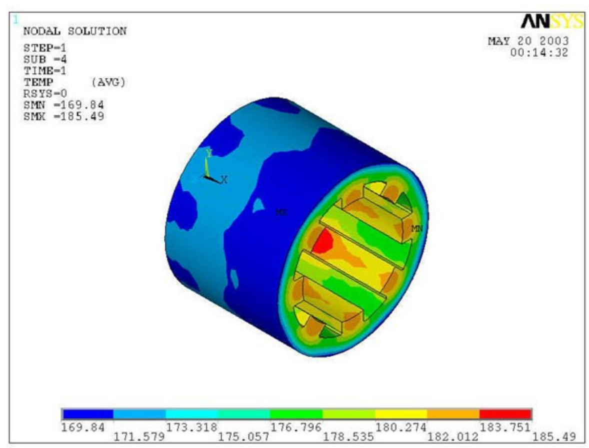

Fig. 9 Stator Thermal Analysis

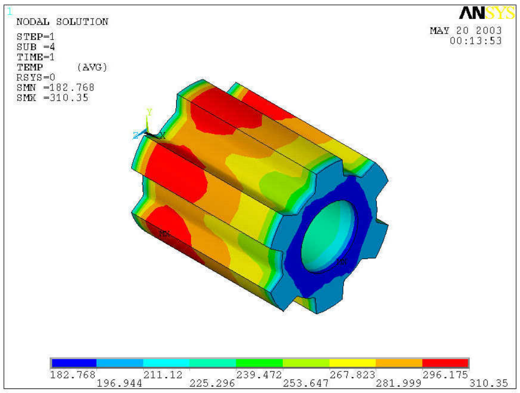

Fig. 10 Rotor Thermal Analysis

Although not shown here, maximum temperature of the windings was predicted to be less than the temperature limit of the insulation material.

4.2 Power Electronics

A fuel flow channel is machined on the heat sink directly underneath the IGBT modules (see Fig. 11). Temperature rise and fuel flow characteristics were simulated by finite element analysis. Fig. 12 shows a result of the analysis showing the worst case junction temperature of 105°C. Fig. 13 shows measured and simulated results of the fuel pressure versus flow characteristics. The measured and simulated results match well, confirming the validity of the analysis.

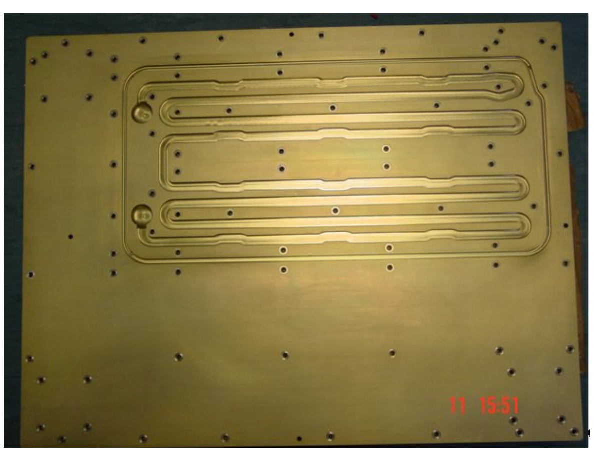

Fig. 11 Cooling Fuel Channel

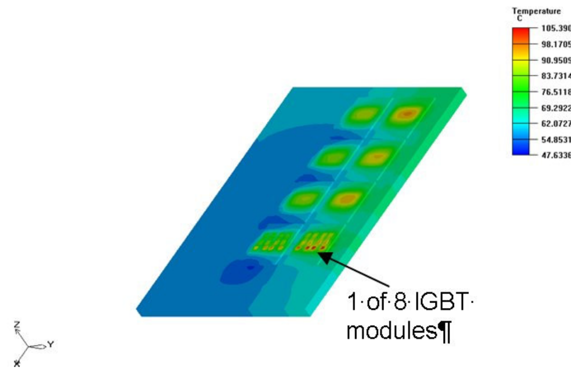

Fig. 12 Heat sink and IGBT Thermal Analysis

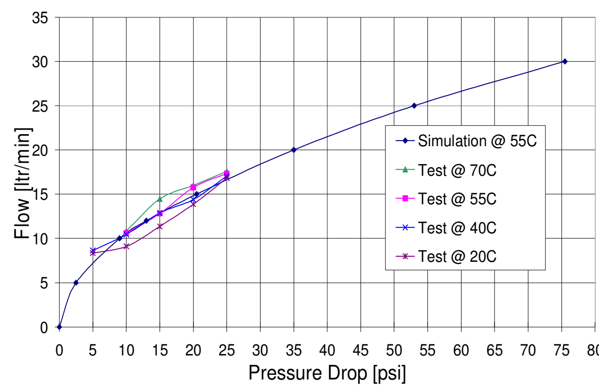

Fig. 13 Fuel Pressure vs. Flow

5 Test Results

5.1 Static Tests

Measured magnetisation curves (solid), which represent electromagnetic characteristics of the SR machine, are shown in Fig. 14 together with finite element calculated curves (dotted). The curves match reasonably well, confirming the design and the manufacturing standards.

Fig. 15 shows measured and calculated static torque curves for constant phase currents up to 600A at step intervals of 100A. Green lines are measured and blue lines are calculated by electromagnetic finite element analysis using Maxwell's stress method. Also shown as dotted lines are the calculated values from the rate of change of coenergy using finite element calculated magnetization curves (up to 400A).

The calculated results overestimate the static torque near the aligned position where magnetic saturation effects are significant.

5.2 Generating Tests

Fig. 16 shows the phase current when the system is operated at a generator speed of 10,000rpm, generating 105kW DC load. The phase current is regulated at approximately 400A in the single-pulse mode under this condition. The output power was limited to 105kW during the testing due to the capability of the load bank.

The DC output voltage of the power converter is controlled by a simple software-implemented PI controller described in the time and Z domains by the equations below where "err" is the difference between the reference voltage and the measured voltage.

Fig. 17 shows the response of the ASVR system to a small load step change from 10kW to 20kW at 5,480rpm. The ASVR transient length is relatively long due to the slow sampling time of the DSP-implemented PI controller (T_s=20ms).

$$y(t_{N+1}) = K_P \cdot err(t_N) + K_I \cdot T_S \cdot \sum_{i=0}^{N} err(i) \quad (1)$$

$$F(z) = K_P + \frac{K_I}{1 - z^{-1}} \quad (2)$$

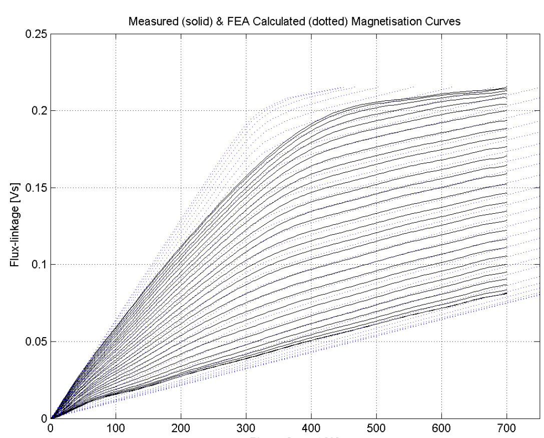

Fig. 14 Measured (solid) and FEA Calculated (dotted) Magnetisation Curves

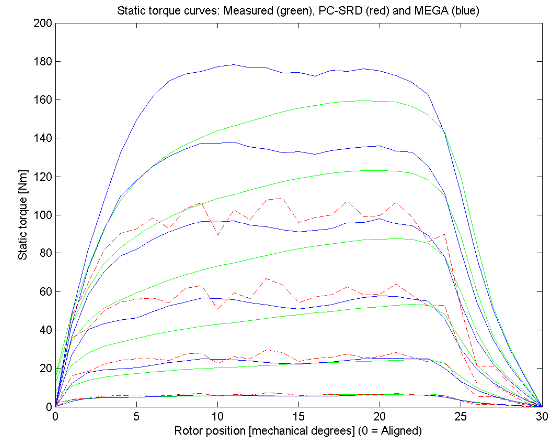

Fig. 15 Static Torque Curves (Green: Measured, Blue: Maxwell's stress method, Dotted: Rate of change of coenergy)

Based on the preliminary results of ASVR testing, the decision was taken to implement a much faster PI control loop for the ESVR controller. A fast PI controller with adjustable sampling time has been implemented in the Spartan IIE FPGA available on the ESVR controller card. Initial tests show that best transient performance is achieved with sampling periods of around 0.3ms. Under such conditions, both the transient response time and the steady-state stability of the system are improved compared to ASVR although the ESVR DC-link smoothing capacitor is almost ten times smaller than the ASVR capacitor (2.8mF versus 26.4mF). However, further reducing the sampling rate does not lead to additional improvements in the system response because T_s becomes comparable to the PWM frequency of the phase control loops.

5.2 Efficiency

Fig. 18 shows the efficiency of the power electronics module. Solid lines show predicted values from simulation when the system is generating at rated values. Square dots are calculated efficiencies from the measured waveforms. Due to the test limitations output power was set at 25, 60, 90 and 105kW for generator speeds of 2500, 5480, 8400 and

10000rpm respectively. Maximum efficiency of over 97% was confirmed.

Generator efficiency was estimated from cooling oil flow and temperature rise data. The power extracted by cooling oil Q can be calculated by the following equation:

$$Q = mC_p \Delta T \qquad \text{[kW]} \qquad (3)$$

where m is the mass flow of the oil in [kg/sec], C_p is the specific heat of the oil in [kWsec/kgK] and ΔT is the difference in temperature between inlet and outlet oil in [K]. An oil density of 860 [kg/m^3] and $C_p = 2.09$ were assumed in the calculation. This method would overestimate the generator efficiency as it neglects the heat rejection through conduction and radiation. However, it would still be expected to provide reasonable predictions.

Fig. 19 summarises the overall system efficiencies. Maximum system efficiency of over 90% was estimated.

5 Summary

The development of the FSDG system for the future MEA was discussed. Promising initial test results were shown. System integration and characterisation are on-going at Goodrich and the speed and load are gradually being increased towards the rated values. POA on-engine testing is planned for 2006.

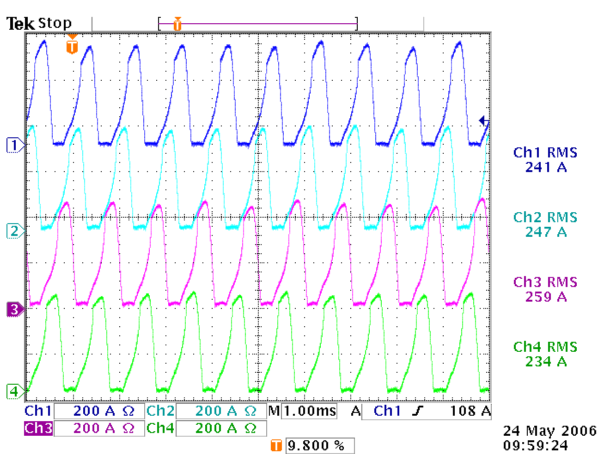

Fig. 16 Measured Phase Currents (10,000rpm, 105kW)

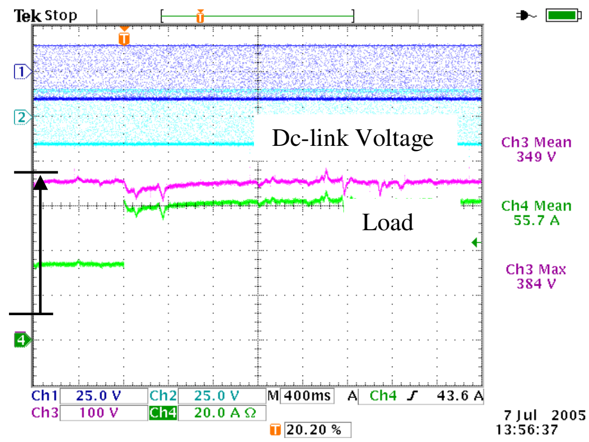

Fig. 17 Response to a Load Step Change (5,480rpm, 10-20kW)

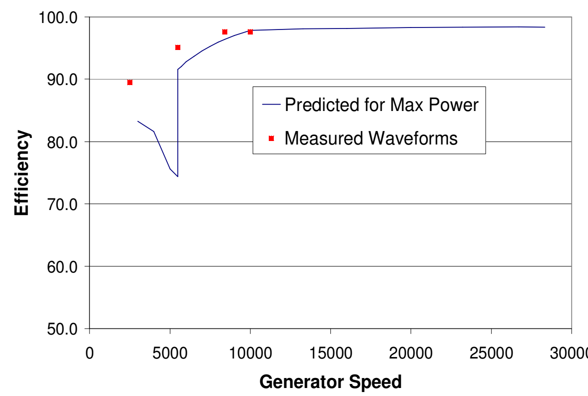

Fig. 18 Efficiency of Power Electronics

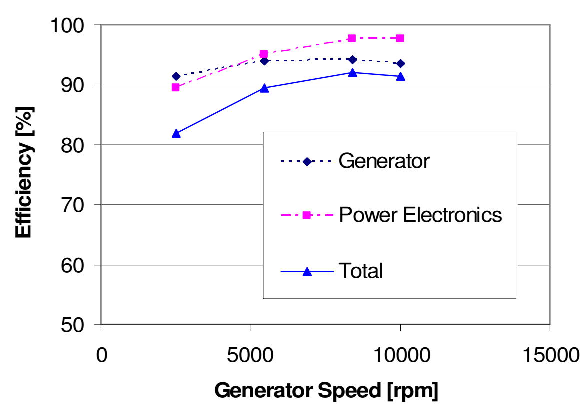

Fig. 19 System Efficiencies

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