EWB Warwick wind turbine alternator and electrical system test report

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Introduction

In order to ensure that the Wind turbine built by EWB Warwick was safe to be installed on the Warwick University campus, a test was commissioned by Warwick University Estates. This test was carried out at The University of Nottingham by Nicholas Shattock. This report documents the test and has specific recommendations for the installation of the turbine and electrical system.

The turbine built by EWB Warwick was based on a design by Hugh Piggott and the construction was facilitated by V3 Power, a DIY renewable energy co-operative. The turbine was built with 3.6m diameter blades and had a rated output of 1kW at 10m/s wind speed. This turbine was connected to a Mastervolt WindMaster 500 grid tie inverter, with the possibility of adding a second inverter to realise the full output power of the turbine.

In order to protect the turbine from over-spin, a dump load controller, LDR 96-15, was used to divert any excess energy to a power resistor when the turbine was operating near its maximum speed. This was needed to restrict the maximum rotation speed of the turbine in the case of disconnection from the grid, either by a fault in the connection or a fault with the inverter. Without this controller the turbine would continue to spin up until the lift from the blades caused the turbine to stall, at a much higher RPM than the turbine should operate at. The dump load controller also enables the turbine to furl out of the wind more easily in winds that may otherwise damage the turbine, due to the increased torque on the blades when operating producing a greater furling force.

One method of adjusting the output power for a given wind speed is to alter the distance between the two magnet disks. This was not adjusted during the testing, but the result would be an increased voltage, and therefore power, for a given RPM. The current turbine had a spacing of approximately 3mm between the stator and each disk (21mm total distance between the two disks). As the strength of the magnetic flux density is a square law, reducing this distance by a small amount would have a large effect on the power produced by the turbine. The disadvantage with reducing the magnet disk spacing is that during operation there is a greater chance that the vibrations from the turbine may cause the magnet disk to rub against the stator, or that foreign objects may become trapped in the air gap, causing damage to the stator or rotor disks.

Background

The test rig at the University of Nottingham comprises of a 150kW DC motor and a Control Techniques Mentor DC drive. It is designed for testing a wide range of motors and generators and is capable of driving a machine under torque control, speed control or both. To measure the power output from the turbine, and the power going to the grid, two Voltech PM3000As were used. These power analyzers are able to measure current, RMS voltage, power and frequency. They use digital signal processing and achieve an accuracy of 0.05%. An image of the EWB Warwick turbine installed on the test rig is shown in figure 16.

Test procedure

3 Tests were carried out. The first test was to record the performance of the inverter and the effectiveness of the dump load and the dump load controller. This test was carried out from a 1kW bench variable DC supply. An image of the electrical board that was tested is shown in figure 15.

The dump load and controller was first tested with the inverter turned off to establish the ability of the dump load to handle the full 1kW produced by the bench supply, and to discover the voltage range the LDR could be set at. This will correspond to the maximum RPM that the turbine could be set to not exceed, provided the turbine did not produce more power than the dump load could dissipate. An oscilloscope and current probe was used to look at the current waveform of the dump load.

The inverter was then switched on and the DC supply voltage was increased in steps from 0 - 120V, the power transferred into the grid was recorded and the current waveform was analysed for harmonic content and phase shift. An image of the waveform is shown in figure 3 and a fast Fourier transform (FFT) of the current waveform is shown in figure 4, showing the amplitude of the harmonics. The cover of the inverter was removed and a thermal camera was used to record the temperature of the components of the inverter and dump load controller, to ensure that they were able to operate at full load without overheating.

The second test was to establish the integrity of the mechanical system under no load condition. The turbine was mounted on the test rig, the rotation speed of the turbine was increased from 0 - 650 RPM with a torque limit set and the voltage produced by the 3 phases of the turbine was recorded. The system was also checked for vibrations and other problems in the mounting before the loaded testing could begin. An image of the alternator mounted to the test rig is shown in figure 16.

The third test was a test of the complete system as will be installed at Warwick University. In this test the turbine was spun up to 450RPM and the rotation speed of the turbine was decreased in 50RPM increments to 150RPM. The torque, current and voltage from the alternator was recorded, as well as the DC link voltage and the power going into the grid. From these calculations the efficiency of the electrical system, and the alternator system could be calculated.

Results

Dump load and controller

The dump load controller worked as expected, it acted as a DC chopper on the dump load, and would only allow the DC link voltage to be increased above the set limit when the dump load was operating at 100% duty cycle. This set limit could be changed from 106V to 120V. The temperature of the PCB and MOSFETS of the dump load controller remained under 30^{o}C, and the gate resistors on the PCB increased to 60^{o}C at 80% load. This temperature does not represent a significantly increased chance of failure.

Inverter

The inverter was found to have a different power to DC link relationship and the measured results are shown with a red line in figure 14, the relationship given in the inverter data sheet is shown with a black line. This resulted in the turbine spinning at a lower RPM for the inverter to operate at maximum power. The inverter became quite warm when operating at 100% load for longer than 10 minutes, and the heatsink attached to the rectifier diodes in the inverter increased to 70^{o}C. As this is a commercial product which has been subjected to rigorous testing, it would be assumed that this temperature is within the safe operating limit of this device. The inverter incorporates thermal protection and over temperature derating to prevent damage from temperatures higher than it is designed to operate at.

Unloaded test

During testing the turbine and mount did not produce any measurable vibrations or noises and was mechanically sound for the duration of the testing. The stator did not increase in temperature due to its thermal mass, but when installed the turbine will be cooled by a strong wind whenever it is operating near its full rated power. The tests have shown that even when the turbine was operating over it's rated power, both the electrical and alternator systems showed no signs of stress and were clearly operating within the safe operating limit.

The equation for the relationship between voltage and RPM was derived from figure 8 and is shown in equation 1.

$$V = 0.2281 \times RPM \tag{1}$$

Test of complete system.

The complete system performed as expected and the measured output waveforms produced by the turbine are shown in figure 7. The DC link voltage and loaded RMS voltage are shown in figure 8.

One thing that was discovered was a 10% unbalance in power between the 3 output phases of the turbine. This could be due to magnet misplacement, coil misplacement or the number of turns on the coils being different. This will result in a decreased efficiency and an increased chance of failure with an extremely high current output (over 15A per phase or around 2kW output power).

A graph showing the efficiency of the mechanical system and coils, electrical system, and complete system is shown in figure 11. This graph shows that the system will operate with a total efficiency of around 74% when producing 150W − 500W. Figure 7 shows that at a rotation speed over 400RPM the dump load controller has switched on to protect the inverter and turbine and is operating correctly, while the power produced by the inverter remains at maximum of 500W.

Identify areas of inefficiency to highlight areas for improvement and potential points of failure

Alternator losses

The drop off of 4% efficiency at full load for the alternator system, and therefore the complete system, is due to the inverter operating at full output power as the RPM, and therefore DC link voltage, increases. This resulted in a decrease in current, and therefore torque, on the alternator. As the losses in the bearing of the alternator are rotation speed and not torque dependent, the efficiency of the system will decrease when the rotation speed increases if the total output power remains constant. In order to separate the losses in the inverter into the losses in the bearing and the losses in the coils, the efficiency of the coils first needs to be calculated, based on I^2/R.

As the turbine does not have an iron core, and the air gap is relatively large between the rotor and the stator, the current produced by the turbine will have the current characteristics of a capacitively smoothed bridge rectifier. The current waveform produced by the turbine was captured by a oscilliscope, and a FFT was performed on it. The waveform is shown in figure 5 and the FFT is shown in figure 6. In order to establish the effect the current harmonics have on the losses in the windings, an impedance meter was used to measure the resistance and impedance of the coils across a range of frequencies. This is shown in figure 2 and in figure 1 respectively. From these graphs, an equation for the resistance of the coil was derived and this is shown in equation 2, where 0.5676 is the DC resistance and 0.037 is the rate of increase in frequency due to the skin and proximity effects. This data was then combined with the frequency spectrum of the current waveform to establish the losses associated with each harmonic. The

results are shown in the blue line in figure 9. It was found that the 5^{th} harmonic and 9^{th} harmonic were large enough to reduce the ratio of the fundamental power losses to total power losses to 65%.
This result was compared with the derived coil losse and was found to be within the margin of error. The derived coil losses were calculated by subtracting the loaded coil voltage from the open circuit volatage, and multplying by the current. This result is shown on the graphs in figure 13 and figure 12.

The change in resistance as the frequency changes is mostly due to the skin effect, a situation where the current will only travel on the skin of the conductor at high frequencies. The copper used in the turbine had a surface area of $2mm^2$ and the theoretical resistance is compared with the measured resistance. In order to reduce the skin effect the number of insulated conductors should be increased, using Litz wire or similar. This is not practical in this situation as the added cost, and the added availability issues would not make this a worthwhile solution.

In order to improve this situation and the efficiency of the machine, the ideal solution would be to draw sinusoidal current at the fundamental frequency. This could be achieved by introducing an active PWM bridge rectifier, a boost converter to a higher voltage DC link or simply introducing some extra inductance would cause the turbine to produce more of a square wave current waveform at the fundamental frequency, which has a much lower harmonic frequency content compared with the unfiltered waveform. In order to establish the effect this would have on the efficiency of the coils, the losses from a FFT of a square wave were plotted on the red line in figure 9. From this graph the ratio of the fundamental to total losses was 72%. At 300RPM, the total alternator losses are 78W (from figure 12), and the fundamental current is 4.3A. This gives the fundamental resistive losses at 19W. The harmonic losses are 7W, giving the total coil losses as 26W and the total bearing losses as 52W. If the current drawn is a square wave, the harmonic losses would be reduced to 4.8W, and the total alternator losses would be reduced to 75.7W, increasing the efficiency of the whole system by 0.37% to 74.3%. If the current drawn was a sine wave with no harmonics, the efficiency would be increased by 1% to 75%. For a turbine of this size this improvement would not be economical, but for a larger turbine it may be.

$$R = 0.0037 \times frequency + 0.5646 \tag{2}$$

Inverter losses

The inverter was found to operate at around 87% efficiency when operating over 110W. A graph of the efficiency of the inverter is shown in figure. 11.

Diode losses

In order to calculate the losses in the bridge rectifier, the equation for the losses from the electrical system from the test of the complete system and the equation for the losses from the inverter were derived and subtracted from each other. The derived equations for the losses from the electrical system, inverter and bridge rectifier are shown in equation 3, 4 and 5 respectively. The diode losses equate to about 2% of the total losses. A graph of the losses from the inverter, electrical system and diode is shown in figure 13. The test rig that was set up only uses one pair of diodes from each bridge rectifier, in the final system both pairs of diodes will be used, halving the total current through each device.

$$P_{Electrical} = I^2 + 5.293I + 2.2262 \tag{3}$$

$$P_{Inverter} = 0.7839I^2 + 3.5606I - 1.0413 \tag{4}$$

$$P_{Diode} = 0.2161I^2 + 1.732I + 3.2675 \tag{5}$$

Recommendations

The dump load must be able to dissipate all current produced by the turbine, and should be rated at the maximum current that the dump load controller can handle; 15A. This corresponds to a resistance of 7Ω at 106v (400RPM) where it will dissipate 1.6kW. In order to allow the dump load controller some headroom, it would be wise to set this resistor to a value slightly higher, so that the peak current will remain under 15A if the voltage is unable to be clamped sufficiently. A resistor value of 8 – 10Ω would be suitable.

With only one inverter, the current drawn by the inverter, and therefore the torque on the blades, is much smaller than the turbine is designed for. As such the turbine will be operating with a very high tip speed ratio (TSR) over the operating range, resulting in lower efficiency in wind energy capture and increased wear of the bearing and leading edge of the blades. A recommendation would be to install two inverters in parallel, doubling the output power of the system. The efficiency will stay constant, but system will now operate with above 70% efficiency from 100 – 1000W instead of from 50 - 500W, and the system will produce twice as much power for a given roatation speed.

Diode and resistive losses will increases slightly but this will not noticeably affect the efficiency of the system, as the diodes and cabling are rated for 30A, and the system will be operating with a maximum current of 11A at full rated power. Due to the imbalance of the phases and the diameter of the copper wire in the coils, a sustained power output of over 2kW (or 15A current) may result in failure of the stator and it is recommended that the turbine be not regularly operated above 1.5kW for continued reliable operation. The furling action of the turbine should be calibrated so that any winds greater than $10m/s$ will cause it to fold out of the wind.

In order to avoid installing two inverters, the distance between the magnet disks could be reduced from 3mm to 1.5mm but this may lead to issues of reliability.

Appendix

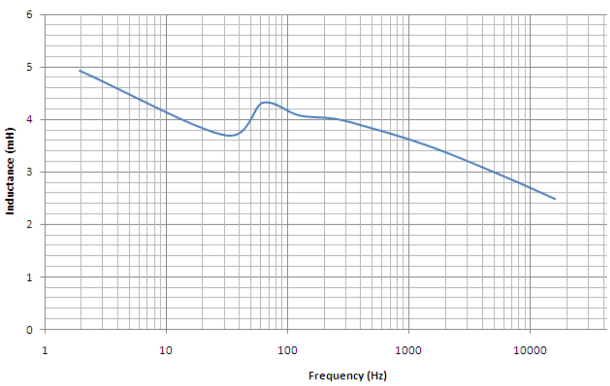

Figure 1: Stator inductance (line - line)

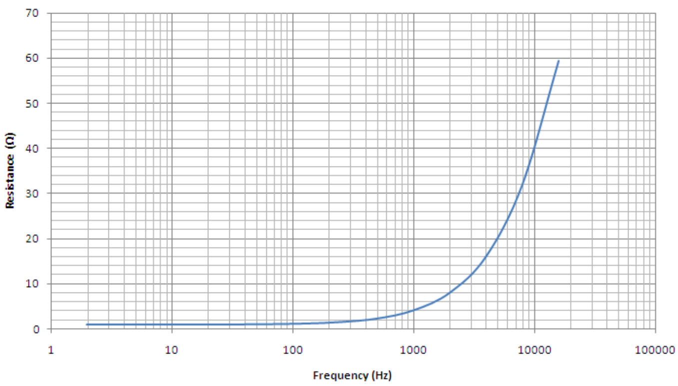

Figure 2: Stator resistance (line - line)

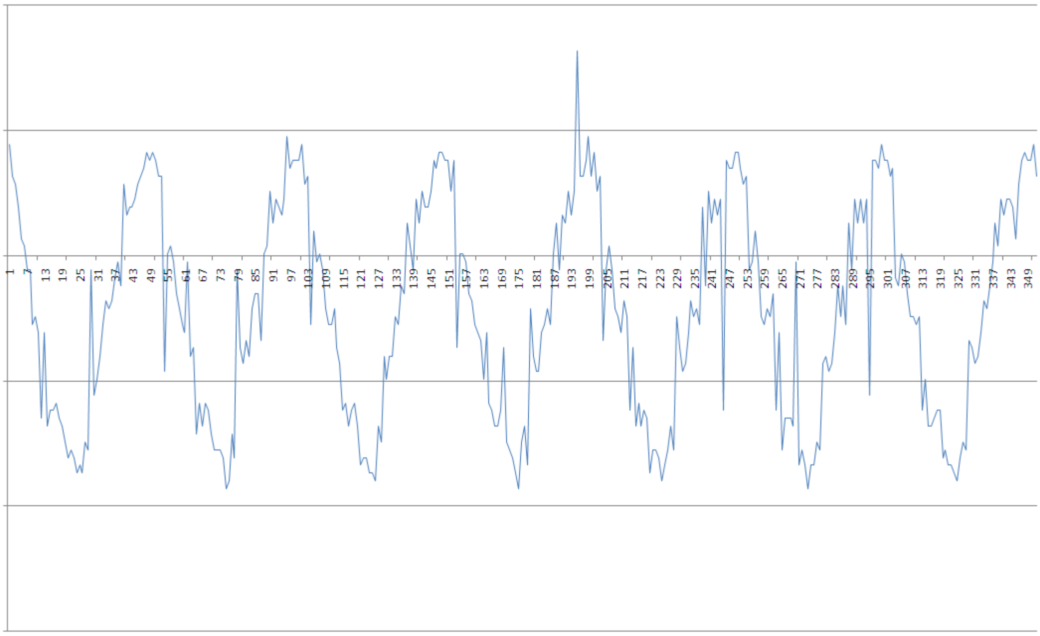

Figure 3: 230V Output current waveform

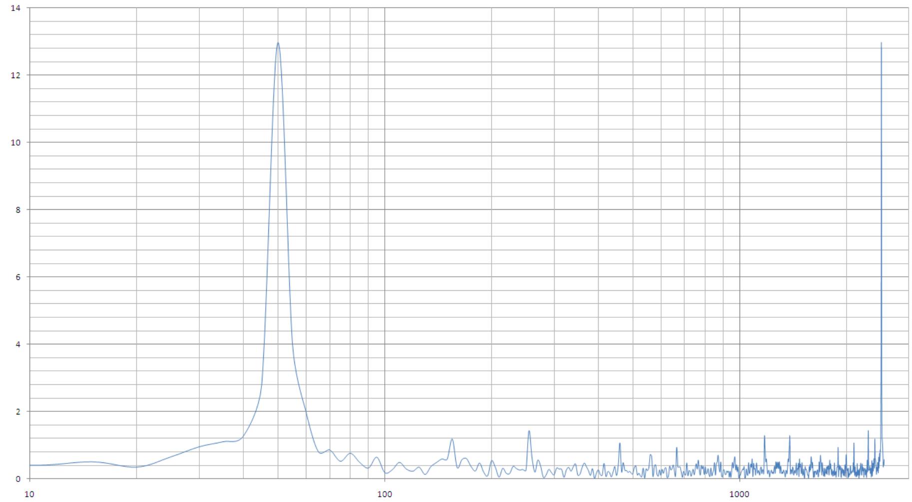

Figure 4: FFT of 230v output current waveform

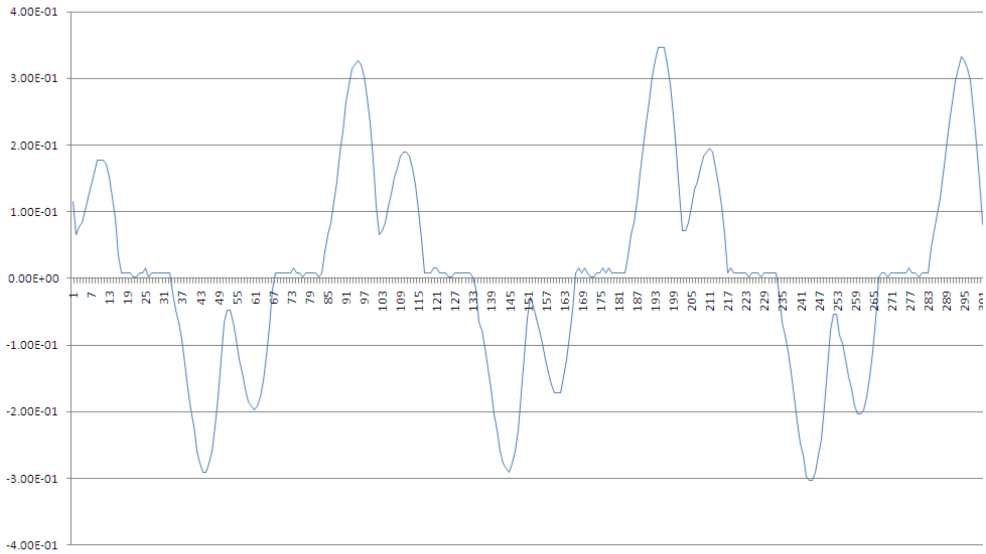

Figure 5: Rectifier current waveform

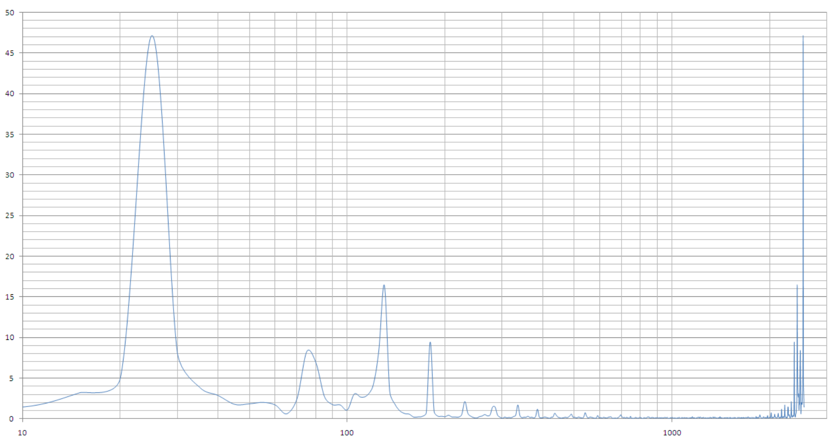

Figure 6: FFT of rectifier current waveform

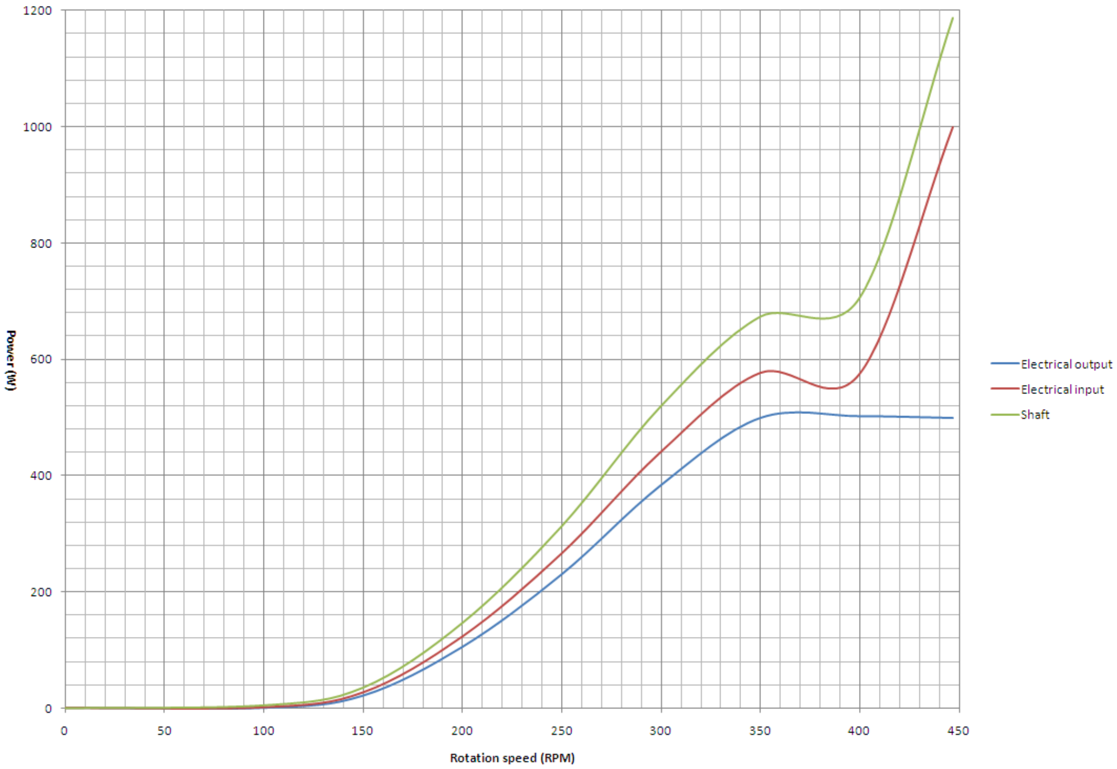

Figure 7: Output power against RPM

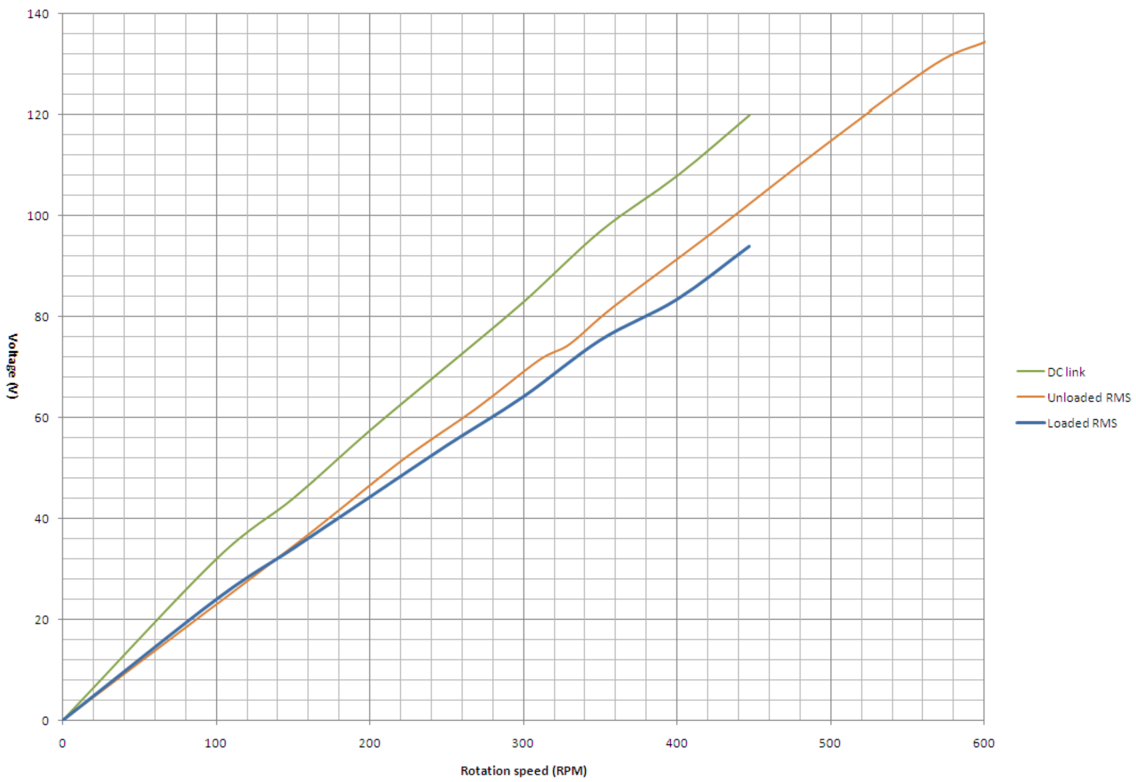

Figure 8: Voltage against RPM

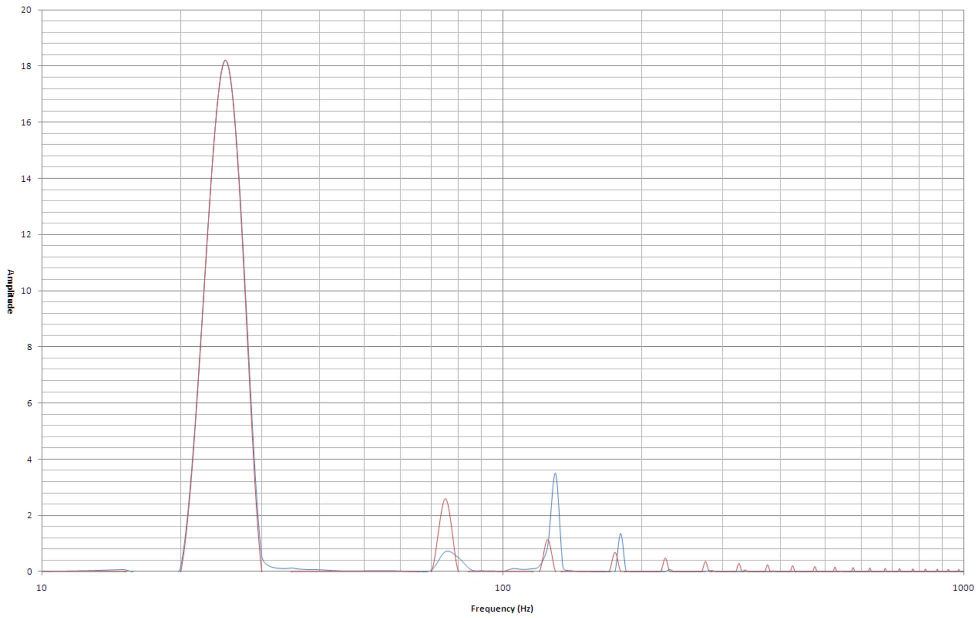

Figure 9: Theoretical coil losses (blue) and square wave losses (red) due to current harmonics

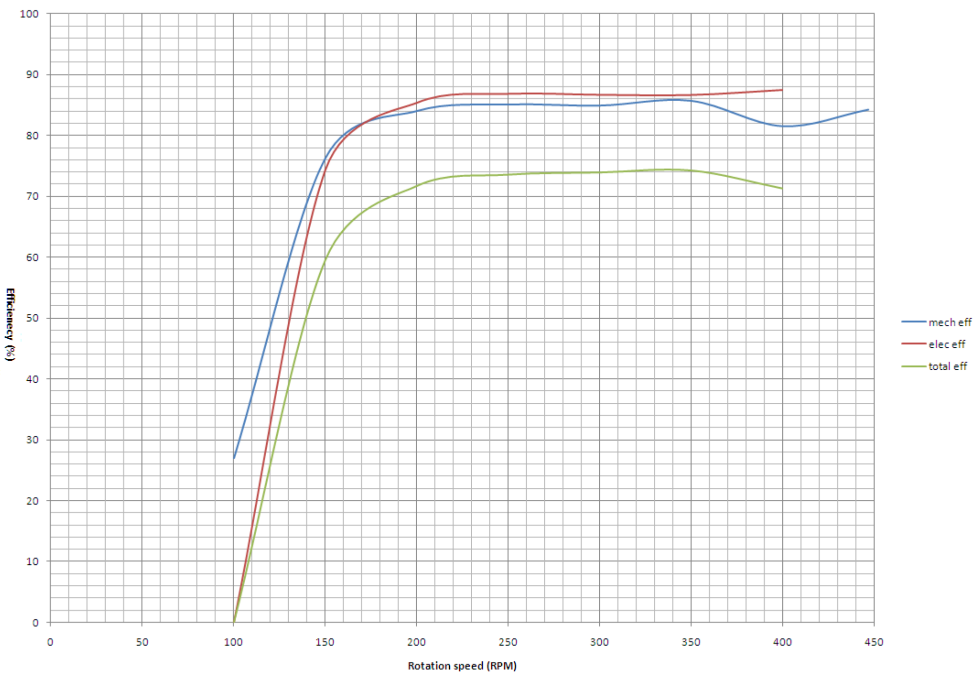

Figure 10: Speed against efficiency

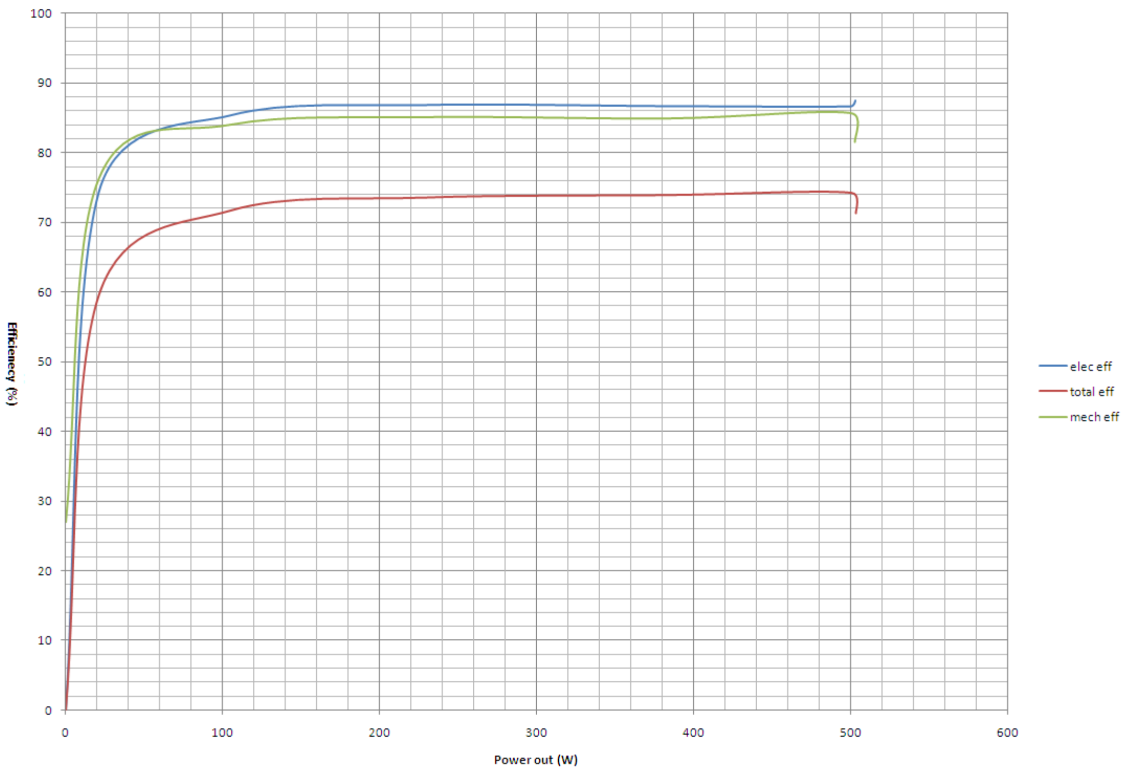

Figure 11: Power out against efficiency

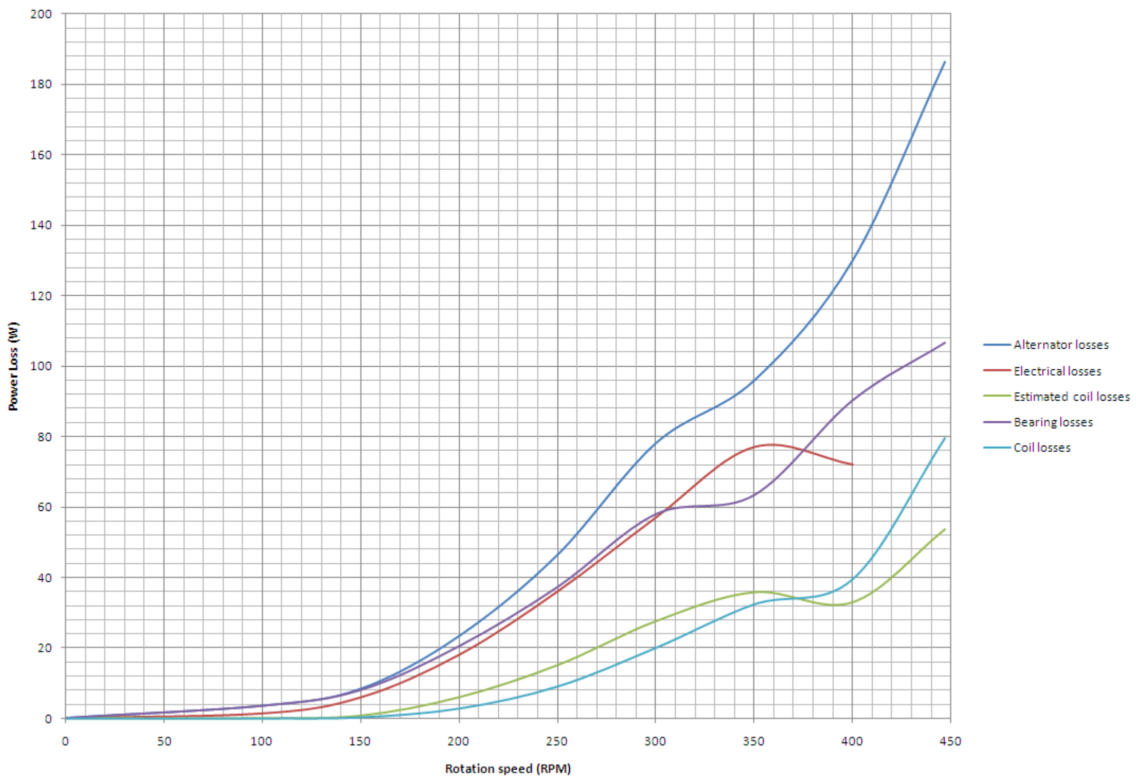

Figure 12: Power loss against power out

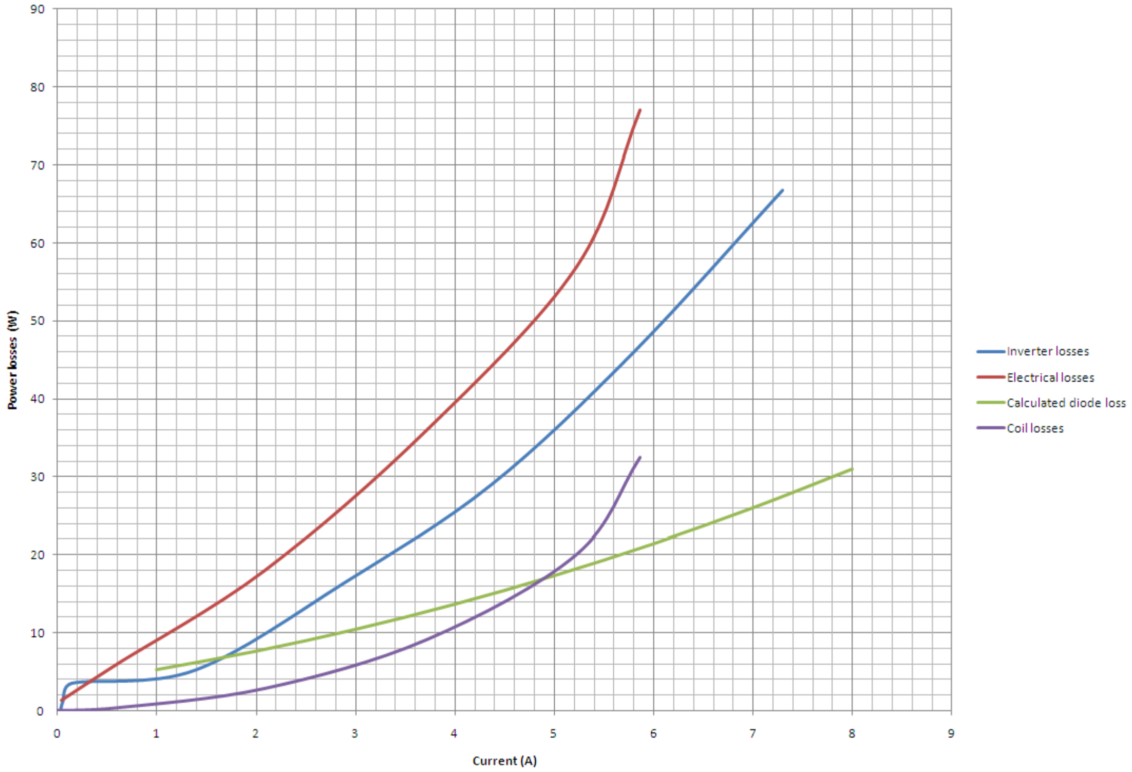

Figure 13: Power loss against current

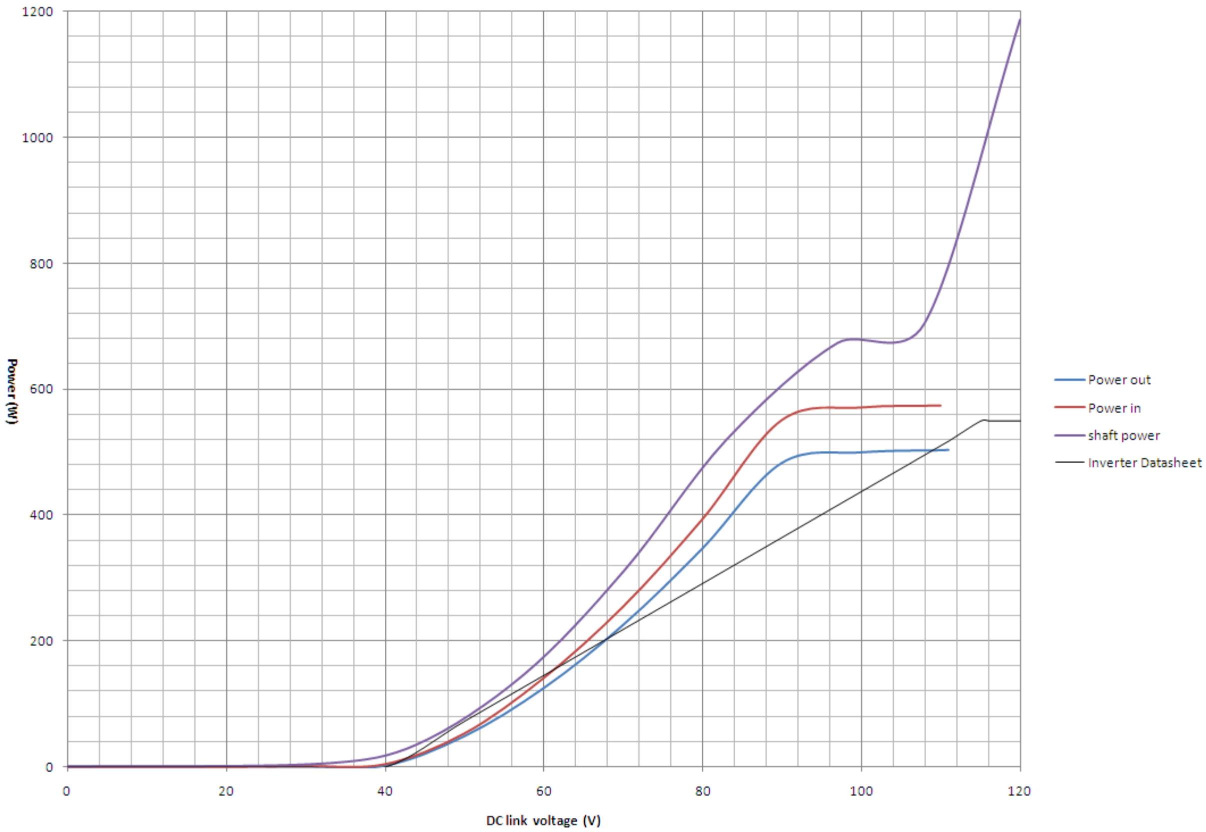

Figure 14: Power against DC link voltage

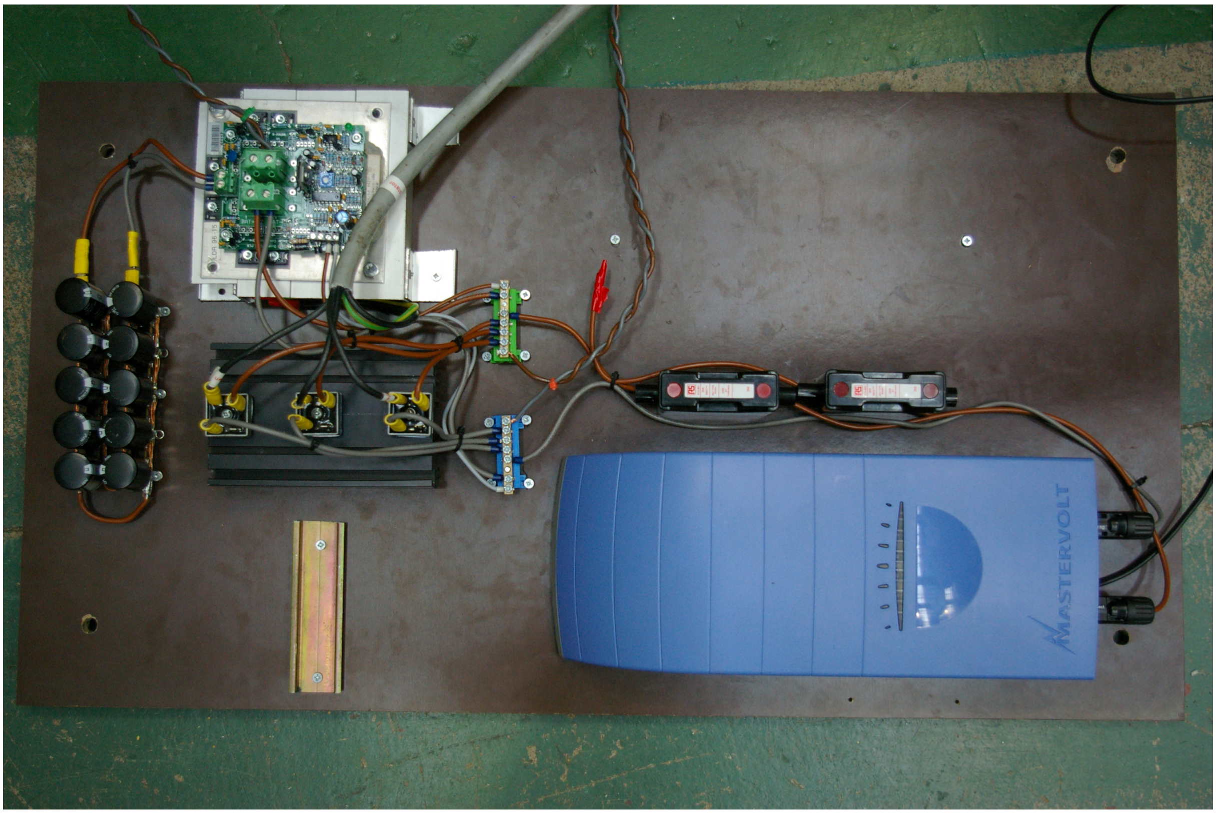

Figure 15: Electrical wiring

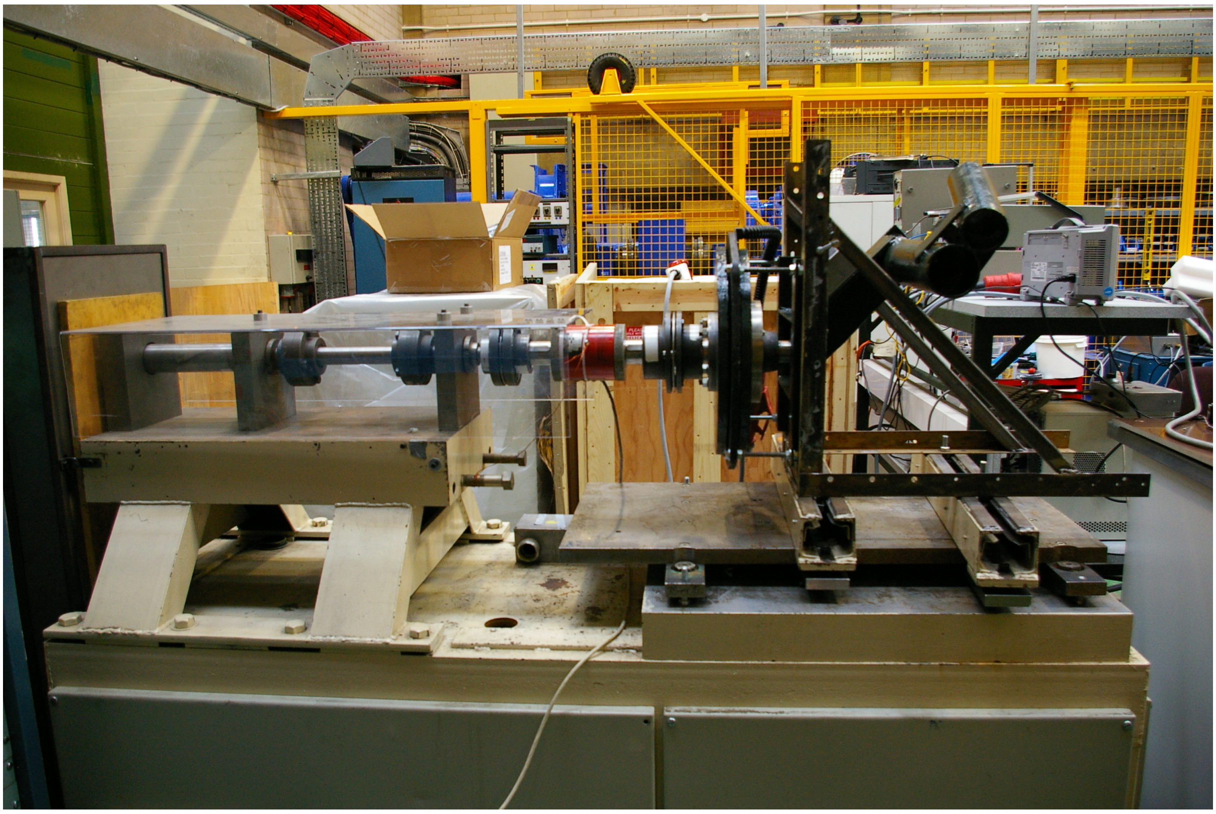

Figure 16: Test Rig