

## The Development of a Small High Speed Steam Microturbine Generator System

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**Abstract.** The efficient use of energy is paramount in every kind of business today. Steam is a widely used energy source. In many situations steam is generated at high pressures and then reduced in pressure through control valves before reaching point of use. An opportunity was identified to convert some of the energy at the point of pressure reduction into electricity. This can be accomplished using steam turbines driving alternators on large scale systems. To take advantage of a market identified for small scale systems, a microturbine generator was designed based on a small high speed turbo machine. This gave rise to a number of challenges which are described with the solutions adopted. The challenges included aerodynamic design of high efficiency impellers, sealing of a high speed shaft, thrust control and material selection to avoid steam erosion. The machine was packaged with a sophisticated control system to allow connection to the electricity grid. Some of the challenges in packaging the machine are also described. The Spirax Sarco TurboPower has now concluded performance and initial endurance tests which are described with a summary of the results.

### 1. Background

#### *1.1 Expertise of partners*

Spirax-Sarco Limited has over 70 years of experience in research and innovation in most aspects of saturated steam generation and transmission. The company provides expert advice to UK government and other organizations to formulate strategies and standards around steam systems, boiler operations and sterilization. Spirax Sarco offers an extensive portfolio of products and services, creating solutions for steam-using organisations worldwide.

Corac Energy Technologies have considerable experience in the design and development of innovative turbo-machinery for specialist applications in the oil and gas and industrial markets.

The two companies applied their combined expertise to this development project

#### *1.2 Market need & drivers*

Energy costs are of significant concern to industry worldwide, and play a significant part in the viability and profitability of many processes. According to the UK manufacturers' organization, EEF



Executive Survey 2014 [4], gas is the dominant energy source for manufacturing and accounts for 60% of use. Yet electricity prices are of particular concern because they represent the larger cost, with 66% of utility spend on electricity. In its survey, EEF found that the cost of electricity was the most cited energy challenge for UK companies over the next two years.

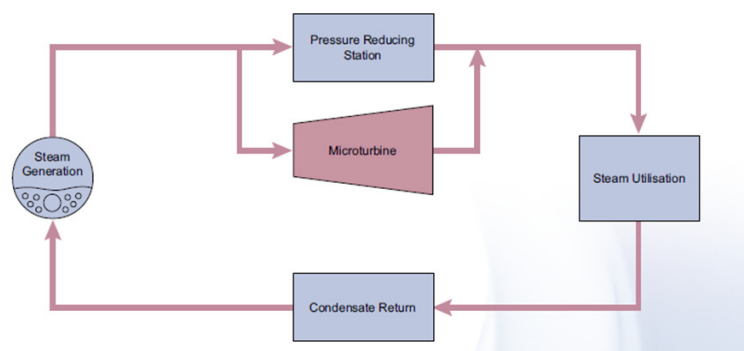
Figures from the DECC Quarterly Energy Prices December 2014 report [3] highlight that the average price of electricity for the industrial sector, including Climate Change Levy, has risen by 108 per cent in real terms since 2003, and by 3.3 per cent in the latest year.

Against this backdrop of rising energy costs, an opportunity was identified to reduce the energy costs of small to medium industrial steam users by enabling local, small scale power generation.

Industrial steam boilers are typically designed to operate at higher pressures than required by the end use application. Generating and distributing steam at higher pressure offers two advantages: Firstly, the boiler's thermal storage capacity is increased, helping it to cope more efficiently with fluctuating loads and minimising the risk of producing wet and dirty steam; secondly, smaller bore steam pipes can be used for distribution.

Having distributed the steam from the boiler, its pressure needs to be reduced to that required by the application. This reduction is conventionally performed by a pressure reducing station comprising a pressure reducing valve and various items of ancillary equipment.

An alternative approach is to pass the plant steam through a microturbine installed in parallel with a pressure reducing station, which allows the energy released by the resulting pressure drop to supplement the electricity supply (Figure.1). The outlet steam is used by the downstream application as in a conventional system.



**Figure 1.** Proposed installation of system.

A microturbine can generate high value electrical energy for the consumer to be fed back into the grid and consumed locally or exported. While this approach is used by large steam users, the opportunity identified is for smaller steam users with boilers typically, less than 6MWth. Industries with potential for using the Spirax Sarco TurboPower include food and drink, chemicals processing, pharmaceuticals and hospitals.

## 2. Outline Machine Specification

### 2.1 General Requirements

A specification for the prototype machines was developed by the partner companies:

The use of a microturbine should provide low cost electricity generation from low steam flows. To make an attractive investment, it must have low life cycle costs. For the widest application, there should be no possibility of steam contamination.

To embrace the widest range of applications the microturbine was specified so as to have an electrical output power from the package of 50kW. By using two microturbines in one package a 100 kW unit was specified.

The microturbine should offer a solution to those who produce steam at medium pressure up to 20 BarG before reducing it through a pressure reducing valve to a lower pressure, typically between 1BarG and 4BarG for use.

The target flow range for the application was 1,000 kg/h to 4,000 kg/h.

The unit would be likely to be installed near a steam using process, driving the decision to specify the operating ambient temperature for the unit at 40°C. A self-contained air cooling system was required to maximise installation flexibility. The package should allow ducting of cooling air to the machine.

The steam quality and pressure ranges were specified to embrace the widest range of applications with the steam quality being dry saturated. Wet steam provides a significant challenge for this type of high speed machine and it was accepted that the machine should be preceded by a separator to protect the rotating parts from damage by 'slugs' of water.

Most importantly, the machine should be able to produce the maximum amount of energy from the widest range of steam supply and exhaust pressures. This was to embrace not only a wide range of applications but also large variations in steam flow rates.

A high speed machine with the turbine and generator on a single shaft was specified to provide an efficient solution with few moving parts having, inherently, low maintenance requirements and few wearing components.

## *2.2 Efficiency Targets*

The generation efficiency of the unit must be high for the system to provide an attractive investment for a steam user. The use of the downstream steam by a process means that the outlet steam is not a loss from the system, giving more efficient electricity generation than a condensing turbine.

Generating efficiency is the electricity generated, divided by the energy input that is used to perform this generation, and figures in excess of 70% are expected from the steam microturbine. To realise this, any losses of steam from the system must be minimised as they significantly affect efficiency making effective sealing paramount. A maximum steam loss of 2% of the mass flow rate through the microturbine was specified. Losses in the conversion process through the generator and inverters must also be minimised along with loads from ancillary equipment in the package, for example cooling fans and pumps.

## *2.3 Physical Requirements*

Steam pressure reduction usually occurs near the point of use. The Spirax Sarco TurboPower is intended to be used at pressure reducing stations rather than in the boiler house. This presents a challenge as space and access is often restricted at these locations, and it is likely that there will be people working nearby. This means that the unit has to be compact and easily transportable by forklift or pallet truck, should fit through standard size double doors and be quiet enough not to necessitate hearing protection when working nearby.

## *2.4 Legislation Requirements*

The machine was specified to comply with European legislation with easy adaptation to global requirements.

Within the UK, the connection of generation devices to the National Grid is subject to regulation. If the current is greater than 16A per phase, the requirements of the Energy Networks Association Engineering Recommendation G59/2 "Recommendations for the Connection of Generating Plant to the Distribution Systems of Licensed Distribution Network Operators (DNOs)" [3] must be met before connecting to the network. Requirements outside of the UK vary, but it is common to find similar requirements to those of G59/2.

### 2.5 Consideration of Alternative Technologies

A number of technologies were considered for this application:

Axial turbines were found to be too expensive for the low flow rates involved.

A number of manufacturers are offering screw expanders in similar sizes. These tend to have lower efficiency due to the number of rotating parts and friction with higher steam losses due to the larger number of seals required.

Reciprocating engines may be used but have lower efficiencies and high costs.

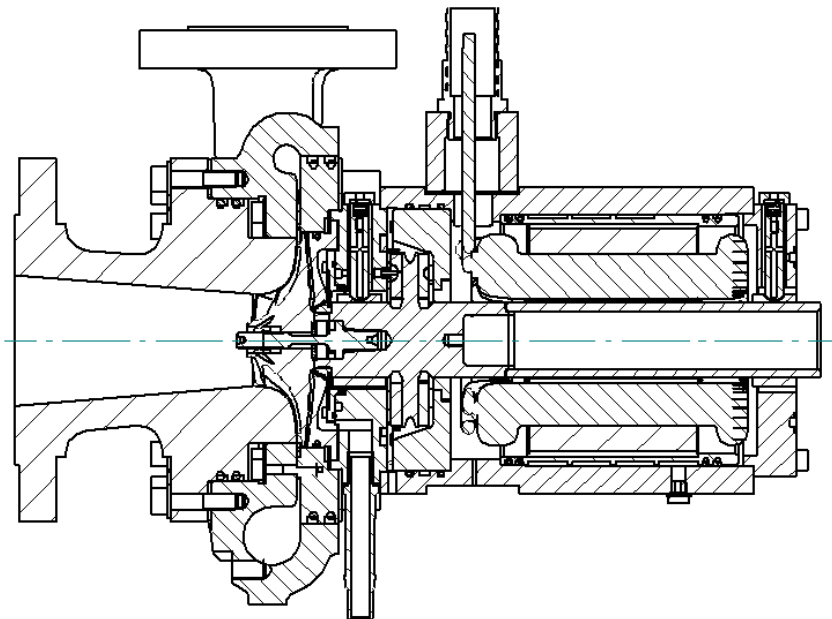
The high speed radial machine was selected as it promised high efficiencies and lower costs. It should also be noted that the proposed unit has an integral generator so that there is no gearbox or drive coupling with associated lubrication and cooling systems. Gear transmissions have higher losses due to friction and higher maintenance requirements than a single shaft gear-less system.

## 3. Prototype Machine

### 3.1 Overview

The prototype machine to meet the specification was based upon an integral high speed air compressor that was described in a previous paper. [1]

The rotating unit is a radial flow turbine driving a permanent magnet generator on a single shaft. The shaft is supported on hybrid tilting pad air bearings. One end of the shaft retains the magnets for the generator and the opposite end of the shaft supports the turbine and shaft seal. The machine contains no lubricant so the risk of steam contamination is negligible. See Figure 3.



**Figure 3.** Section through microturbine.

### 3.2 Bearings

An early decision was taken to use Corac's hybrid tilting pad air bearings for this range of machines. The high speeds, expected high temperatures and economic considerations precluded the use of any other bearing technology. The system specified had been proven in previous applications.

The journal bearings consist of three tilting pads supported on hardened stainless steel supports. The supports allow the bearing pads to tilt freely in all directions. The top bearing pad is spring loaded to allow for thermal expansion and providing a pre-load that may be adjusted to improve shaft stability. Whilst the choice of materials means the bearings are capable of sustaining many 'dry' starts and stops

it was decided to use a hybrid design for these machines to ensure extended bearing life in harsh environments. Compressed air is supplied to the journal bearings via small ports in the pads to allow the shaft to float before the machine starts to rotate. Thus the bearings operate in a hydrostatic mode. When a pre-set speed has been reached the compressed air is switched off so the bearings operate hydrodynamically.

The thrust bearing consists of two sets of opposing tilting pad air bearings. Due to the high loads encountered it was necessary to maximise the capacity of the bearings within a very confined space. The disc on the shaft that provides the counter-face for the bearings is limited in diameter by the stresses imposed by rotating at such high speeds. This has the effect of limiting the bearing surface area available. The system employed uses a combination of hydrostatic and hydrodynamic operation. An external compressed supply is fed to the bearings when required under command of the machine controller.

### 3.3 Turbine

A radial inflow turbine was selected for this duty. Design metrics for the duty fall within normal bounds for this class of device and in the absence of condensation a high adiabatic efficiency would be expected. As the steam entering the package is dry saturated, condensation would occur within the stage, leading to a reduction in adiabatic efficiency and potentially to erosion. It was established that good design should allow these risks to be mitigated.

### 3.4 Generator

The generator is a two pole permanent magnet machine which is integrated on the same shaft as the turbine. The windings are formed as six turns around an electrical steel stator in an aluminium casing. A challenge with this type of machine is to limit the length of the end turns so as to keep the overall shaft length as short as possible. In this machine the end turns are formed after winding to control the shape.

The machine uses water cooling in a jacket around the stator and forced air cooling in the air gap. Performance was optimised to give the desired output with a margin within the capability of a Class H insulation system.



**Figure 4.** Prototype Spirax Sarco TurboPower Package.

### 3.5 Package

The approach to the package design was to employ best practice used in packaging of similar machinery to produce a robust, compact and aesthetically pleasing unit. See Figure 4. It was

determined that the package should be capable of being configured as a single 50kW machine or a dual 100kW machine.

The package was designed to be lifted into position and connected directly to steam supply and outlet via external flanges. The unit was also designed to be connected directly to the electricity network having the necessary protection devices in the control panel.

The package was designed to house the expander unit with the steam control valves, an inlet steam strainer, and the pneumatic controls for the steam valves and air bearings. Integral to the package was a control panel housing the electrical system for the generator.

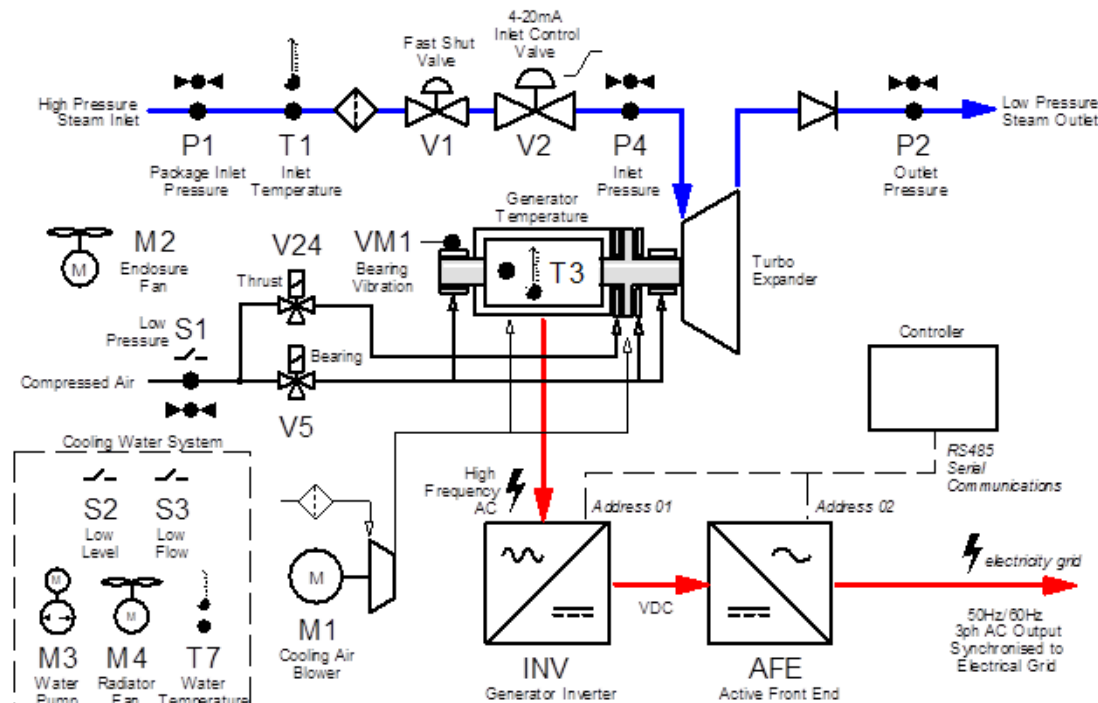
The specification was for an integral water to air cooling system for the generator and power electronics, provided by a fan-cooled radiator and water circulating pump within the unit. To maximise efficiency both the radiator fan and the control panel fans were thermostatically controlled. The package was clad with sound attenuating panels designed to be easily removed for maintenance.

### 3.6 Controls

The entire machine was designed to be controlled by a single high speed micro-controller with bespoke software developed for this range of machines. A touch screen HMI provides continuous running information, alerting the user to fault or maintenance conditions and logging energy efficiency data.

Steam flow is controlled by a pneumatically operated valve on the inlet of the turbine, the primary control parameter being the outlet pressure of the steam to the users' process. The secondary control parameter is the electrical power output of the machine controlled to be the maximum available from the prevailing steam conditions. See Figure 5.

An inverter and Active Front End (AFE) unit is installed in the panel to control the running of the generator and the supply of power to the grid. In simple terms, the inverter converts the high



**Figure 5.** System Schematic Diagram.

frequency AC output of the generator into DC and the AFE converts the DC into 50Hz or 60Hz AC power to be fed into the grid.

To meet the UK regulations for supplying power to the grid it was necessary to install a compliant relay that monitors the power being exported to the grid.

The inverter selected uses a vector-less system needing no external speed sensor. Values of speed, voltage, current and power are continually calculated by the inverter and AFE and fed directly to the controller. An integral over speed avoidance system was built into the package.

#### **4. Technical challenges & solutions**

##### *4.1 Aerodynamic System Design*

Initial design work was carried out using a 1D package with a perfect gas assumption. This achieved a basic design which was optimized using a 3D CFD package (Ansys CFX v.14.0). The characteristics to be optimized centred on the reduction in impeller diameter and mass, and the ability to maintain efficient and reliable operation in a two-phase condensing steam flow. Impeller diameter had to be minimized to reduce thrust and back plate windage. To ensure the rotor had the required margin below the first bending critical speed the impeller mass had to be minimized. Both of these requirements tended to reduce stage adiabatic efficiency.

Further trade-offs against efficiency resulted from the need to keep the relative velocity at the impeller tip as low as possible to reduce droplet erosion, but high enough to maintain entrainment of these droplets and ensure their clearing from the impeller against the centrifugal field. These seemingly conflicting requirements were initially addressed using a perfect gas model due to computational speed, though it was known that condensation would occur within the stage. Impeller diameter reduction was achieved by using a non-radial blade angle at inlet which also allowed high blade loading without increasing gas relative velocities. A reduction in axial length was achieved while controlling secondary flows by adding splitter blades. This helped diameter minimization by reducing blade loading.

Once the required specification was achieved, design moved to a non-equilibrium condensing steam model within the CFD package. At this point, large secondary flows and a significant reduction in adiabatic efficiency were demonstrated by the use of this more realistic model. The model took approximately 4 times as long to converge as the perfect gas model, and a significant number of further design iterations were necessary in order to return the stage efficiency at previously modelled levels.

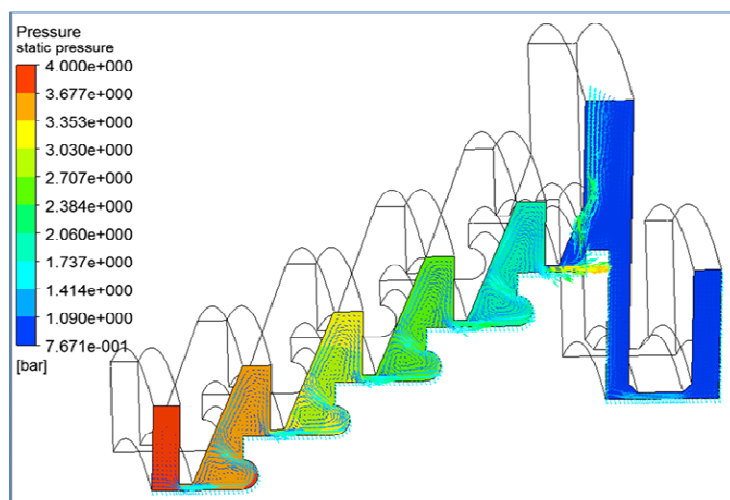
This model estimated the droplet size generated within the stage and tracked the droplet path and the degree to which the droplet lagged the vapour flow. This allowed the establishment of droplet clearing in the free stream. The effects of wall wetting and liquid re-entrainment were not modelled. Significant uncertainty therefore remained beyond the design stage regarding the reduction in efficiency which would be experienced in the tested machine due to these phenomena. Though a small number of radial inflow condensing turbines have been reported in literature,[2] very few provide any information on design choices to assist a designer.

##### *4.2 Shaft sealing*

A tight specification of 2% steam flow at an inlet pressure of 10 BarG was specified for the seal. A number of configurations were experimented with to establish the best configuration. Experiments were carried out on a test rig that demonstrated that the use of a single labyrinth seal would be likely to achieve a leakage rate of around 1.6 % with a seal inlet pressure of 4BarG

The key to operation of the shaft seal was to reduce the pressure reaching the seal from the inlet to the turbine. The use of vanes to create an opposing pressure behind the turbine was assessed but it was found that the windage losses would have resulted in unacceptable heating and a reduction in efficiency. The method adopted was to have an axial toothed labyrinth seal at the back of the turbine and controlling the pressure behind the wheel to maintain the inlet pressure to the atmospheric shaft seal at a reasonable level. The final geometry of shaft seal can be seen in Figure 6.

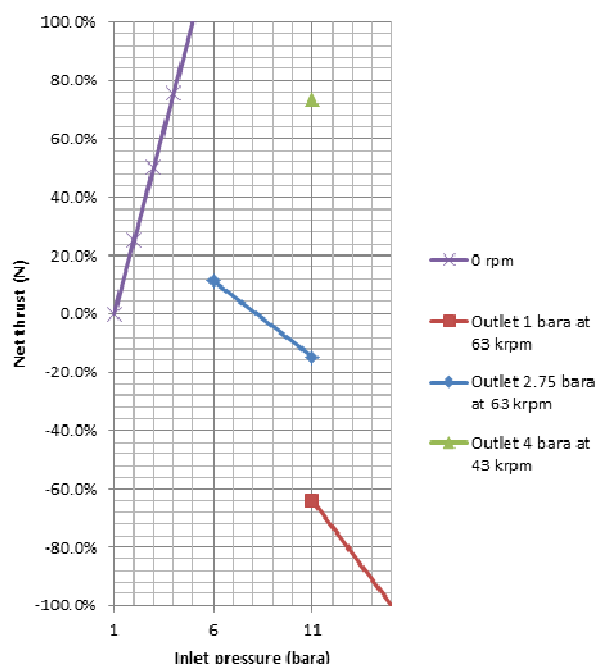




**Figure 6.** Streamlines in CFD analysis of shaft seal geometry.

#### 4.3 Thrust Load Control

Maintenance of thrust loads during running within the capabilities of the gas thrust bearing was initially addressed by the minimization of impeller diameter. A further parameter which influences thrust load is the effective diameter of the shaft seal. Though a large diameter shaft seal will reduce thrust loads when running at the design point, it will increase static thrust load when starting.



**Figure 7.** Graph of thrust bearing load under different operating conditions

To maintain thrust loads within the capacity of the thrust bearing during machine starting, it was necessary to use the smallest diameter seal that could be fitted to the shaft. It was also necessary to balance thrust loads by the use of a seal on the impeller back and partial venting of the impeller back-plate region.

Extensive modelling of this passive thrust control system was necessary to ensure that the loads generated were sufficiently low through the entire operational envelope with adequate margin of safety. Figure 7 shows the resultant thrust loads under various operating conditions.



Thrust loads act in both directions, depending on the operating point, necessitating a double-sided thrust bearing design. To support heavier loads acting in one direction, the corresponding side of the thrust bearing was configured to be a hydrostatic bearing with higher capacity than the hydrodynamic bearing on the opposite face.

#### *4.4 Material choices*

Using expertise within Spirax Sarco, material choices were made for the critical components in areas that would be exposed to steam. Of concern was the need to have impellers that would last for extended periods when exposed, not only to dry saturated steam but also to impact by water droplets from wet steam reaching the turbine or condensation taking place within the turbine. Some research gave assurance that titanium provides good erosion resistance in this environment. The light weight, high strength and reasonable machinability of titanium also made it a natural choice for this application.

At the conclusion of an endurance running test, the impeller, in particular, was examined for signs of erosion. After 1000 hrs there was no visible damage or measurable weight loss. Other components in contact with the steam such as the volute and nozzles were made from 316 stainless steel and have been found to give excellent service

#### *4.5 Over speed Avoidance System.*

It was necessary to design a system that would prevent the generator 'running away' in the event of grid loss or a failure of the inverter. Traditional low speed machines may be controlled by 'governor' systems that shut off the steam supply as the speed rises. In this case the low inertia of the machine giving rise to very high potential acceleration rates means that such a system would not act quickly enough. The system employed has a fast acting steam shut-off valve on the inlet to the turbine that is directly operated in the event of grid loss or other potential over speed event. This valve is pneumatically operated with a normally closed function so that in the event of loss of air pressure or power it will close. In the event of failure of this valve, the slower acting, inlet control valve was also designed to close automatically.

A secondary system was designed to act with the steam valves: In the event of grid loss, other over speed event or inverter fault the generator windings are connected via a pair of fail-safe contactors to air-cooled resistors that are sized to absorb the output of the generator until the steam valves operate. These systems are designed to operate, even in the event of a failure of the central controller. Thorough testing has proved the efficacy of this system under a number of dual failure modes.

## **5. Performance testing**

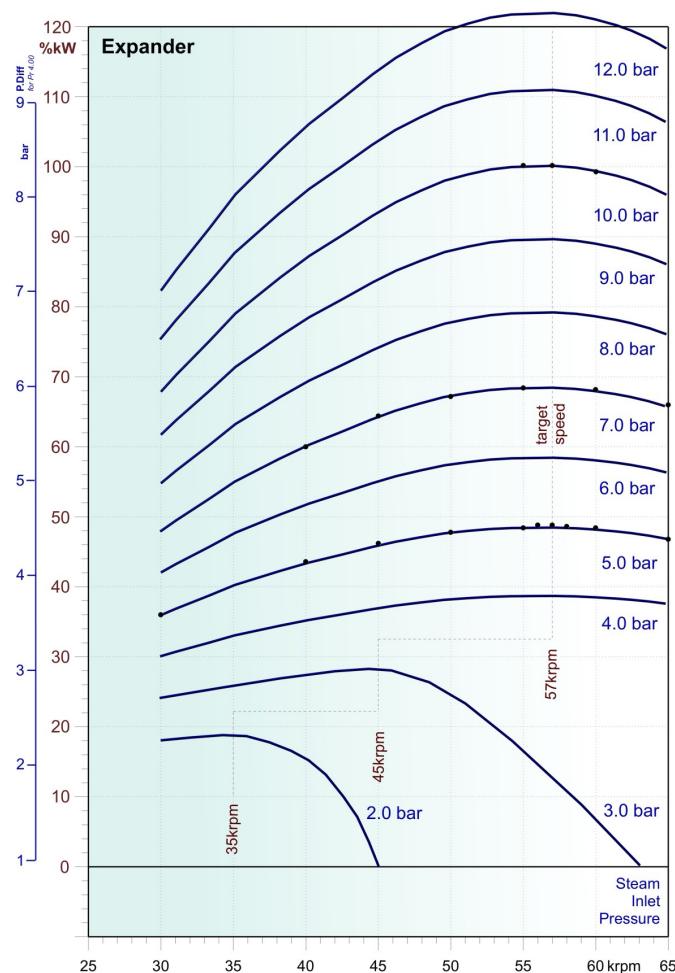
A rig was constructed to test the microturbine package across a range of steam and environmental conditions. It was important to provide an installation that matches conditions with industrial steam users. The unit was installed in parallel with a pressure reducing valve, and the facility to vary running conditions and record test parameters as enabled.

The test rig was supplied with a 30BarG steam supply reduced to test pressures in the range of 4 to 14 BarG. The supply of saturated steam was conditioned via a steam separator. Temperature and pressure measurements were used to confirm saturated conditions.

A valve placed downstream of the microturbine provided the facility to control the load, mimicking a downstream application. A power meter was used to measure the net power output from the prototype package. An inline variable area steam flow meter was used to measure the steam mass flow rates passing into the microturbine.

The unit was tested at a wide range of conditions, with varying upstream and downstream pressures resulting in a range of steam mass flow rates passing through the device. Power output was recorded at each set of conditions. The plot shown in Figure 8 illustrates the power output recorded over a range

of steam inlet and outlet pressures and different turbine speeds. Useful electrical power achieved, even at low steam flow rates providing a useful turndown range.



**Figure 8.** Performance map

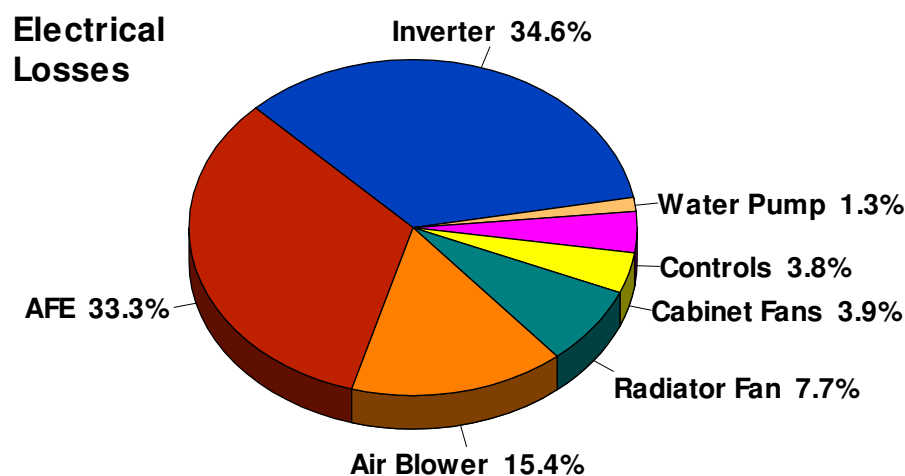
## 6. Minimising losses

Minimising losses is essential to achieve an attractive investment for a customer. Live steam tests were conducted to measure the seal leakage rates to ensure that they were within expectations and it can be seen the table in Figure 9 that the leakage rates were below 1% of the flow rate through the turbine. The tests also validated CFD models of the labyrinth seal.

<i>Inlet Pressure (Barg)</i>	<i>Leakage (%) of Steam Mass Flow</i>
6.9	0.79
9.9	0.88
10.3	0.82

**Figure 9.** Table of steam seal leakage rate measured as a proportion of the total steam mass flow rate through the turbine.

Electrical losses were measured and are summarised in Figure 10. It should be noted that the overall value of these losses is very low and would compare very favourably with a traditional turbine driving a generator through a gear box.



**Figure 10.** Breakdown of Electrical Losses on Test Package

## 7. Endurance test

The unit was run within the test facility for 1000 hours before being disassembled and thoroughly inspected. Aerodynamic components, bearings, steam sealing components and generator electrical performance were all assessed and no significant signs of wear or degradation were observed.

## 8. Conclusions and recommendations

This highly innovative machine has performed in terms of efficiency, reliability and flexibility in a way that met all the expectations.

The prototype machine is capable of being developed with relatively little effort into a competitive product that will bring energy recovery to a range of small steam users.

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