The development of a control system for a small high speed steam microturbine generator system

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\textbf{Abstract:} 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. 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 machine was packaged with the necessary control valves and systems to allow connection of the machine to the grid. Traditional machines vary the speed of the generator to match the grid frequency. This was not possible due to the high speed of this machine. The characteristics of the rotating unit had to be understood to allow a control that allowed export of energy at the right frequency to the grid under the widest possible range of steam conditions. A further goal of the control system was to maximise the efficiency of generation under all conditions. A further complication was to provide adequate protection for the rotating unit in the event of the loss of connection to the grid. The system to meet these challenges is outlined with the solutions employed and tested for this application.

1. Background
This machine was developed in a joint project between Spirax-Sarco Ltd and Corac Energy Technologies Ltd.
Spirax-Sarco Limited has over 70 years of innovation and research in almost every aspect of saturated steam generation and transmission. The company frequently provides expert advice and consultations to UK government and other autonomous organizations to formulate strategies and standards around steam systems, boiler operations and sterilization.
Corac Energy Technologies Ltd has considerable experience in the design and development of innovative turbo-machinery for specialist applications in the oil and gas and industrial markets.
2. Introduction
Steam is usually generated in boilers at high pressures to simplify transmission. 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. Secondly, smaller bore steam pipes can be used for distribution. On leaving the distribution system the pressure needs to be reduced to that required by the application. This pressure reduction is conventionally performed by a pressure reducing station comprising a pressure reducing valve and ancillary equipment (Figure 1a).

![Figure 1. Conventional pressure reducing valve (a); Microturbine expander generator (b)](image)

An alternative to this approach is to pass the high pressure steam through a microturbine, typically installed in parallel with a conventional pressure reducing station, enabling operators to use the energy released by the pressure drop to supplement their electricity supply (Figure 1b). The outlet steam is used by the downstream application as in a conventional system.

![Figure 2. Steam generation and utilisation cycle](image)

A microturbine generator in this application can produce high value electrical energy for the consumer which will be fed back into the local grid. See figure 2. This approach is not uncommon for large steam users, such as oil refineries, the opportunity identified is for smaller steam users with boilers sized under 6MWth. Industries with particular potential for microturbine generators include food and drink, chemicals processing, pharmaceuticals and hospitals.
Traditional, grid-scale fixed speed steam generation turbines are supplied with steam at reasonably constant pressure and exhaust to a condenser so that the steam inlet and outlet pressures are fairly constant. The turbine reacts to changes in electrical load by throttling the steam inlet valve to maintain the generator at constant output frequency within tight limits, as this dictates the frequency of the electricity supplied. Micro-turbines with directly grid connected induction generators will not influence grid frequency and can therefore be operated over a wide range of conditions dictated by process conditions only. The downside to this is that the expander cannot have its speed adjusted to enable it to operate at peak efficiency over a wide range of inlet and outlet conditions. The system under consideration has to respond to changes of steam inlet pressure and flow rate to ensure that the downstream process is not adversely affected. The variable speed capability of a system with inverter control can allow the expander to be operated at peak efficiency, taking into account turbine efficiency, generator efficiency and frictional losses amongst others. From an electrical demand point of view it was assumed that the grid has an infinite ability to accept power.

3. The machine
The machine consists of a microturbine driving a high speed generator on a single shaft running on air bearings. The machine is installed in a package with controls, steam valves and a power conversion system. The prototype unit is shown in Figure 3 ready for testing.

![Prototype Spirax Sarco TurboPower package](image)

4. Control objectives
The control objectives for this system were dictated by the needs of the typical applications identified during market research. As shown in Figure 2 the system must produce the maximum electrical power whilst maintaining the steam supply needs of the downstream process. This is summarised as:

- Maintain downstream pressure to a predetermined target
- Generate optimal electrical output power under all operational conditions
- Maintain the safety and integrity of the system.
Downstream steam pressure must be maintained to a pre-determined level, the production of electricity may be compromised to allow this.

5. Electrical System design
The system to extract energy from the steam and convert it to electricity which is then fed into the grid is as follows:
With reference to Figure 4 the microturbine drives a permanent magnet synchronous generator on a common shaft; high frequency AC current is fed into an inverter; the inverter converts the AC current into DC current; the DC current is then fed into an Active Front End (AFE) which converts the DC current into AC current at the grid frequency. The inverter is also used to control the speed of the generator.

![Figure 4. Expander generator package schematic diagram](image)

Key components of the power converter system are line filters, inverter, DC-link capacitors, AFE or grid-tie inverter and electrical braking system.

6.1 Inverter drive
An inverter operated in power generation mode offers a readily available solution for generator power conversion, monitoring and control.
A generator is driven by an external rotational force which is high pressure steam applied to the turbine. The inverter, which is connected to the generator, provides variable voltage and frequency in active rectification mode during normal operation when the machine is generating, and variable voltage and frequency inverting mode when the machine is motoring. Using power from the grid to
motor the generator is necessary for the start-up sequence, which is described later. The D.C. link voltage is kept constant independent from the mains voltage, whilst current varies according to demand.

6.2 Active front end
An active front end (AFE), or grid-tie inverter, converts DC power, in this instance generated as output by the inverter, to AC power matched and synchronised to the electricity supply grid. The AFE acts autonomously, monitoring available DC input power and regulating power output in proportion. This allows the control of power factor and transfer of power from the D.C. bus to the grid and vice versa. The AFE also acts as a commutating reactor, minimising harmonics at current switching between power switches and free-wheeling diodes within the inverter. A benefit of this approach is that the output frequency and voltage of the system can be changed at will merely by adjusting inverter parameters.

To supply electricity into the grid in the UK it is necessary to comply with a set of regulations known as G59. The AFE provides the necessary control and monitoring to meet the limits set by these regulations.

6. Controller selection
A controller was specified to provide control, protection and sequencing to the machine. The controller had to provide an HMI, control by communications connection to the inverter and provide connections for all sensors and valves.

![Controller, concept](image)

**Figure 5.** Controller, concept

The sensor input and control output requirements were assessed to be within the scope of either a typical PLC (Programmable Logic Controller) or a customised embedded controller. The concept for the chosen controller is shown in Figure 5.

After assessing the specification requirements, the selection criteria were driven by three key factors:

- Volume manufacturing cost
- Human interface specification
- Control response speed
9.1 Controller cost considerations
The client required a solution that could be readily implemented, without modification, on a production unit. Projected volumes were not high but sufficiently large to question the cost of a standard PLC in comparison to a standard or custom embedded controller. A typical embedded industrial controller offers a single unit solution incorporating processing, memory, I/O, data connectivity, power supply and human interface. In general this configuration exhibits a lower cost than the modular generic configurations offered by a PLC. A potential draw back when considering an embedded controller is coping with changes in requirement.

9.2 Human interface requirements
The client’s human machine interface (HMI) requirement was for a high resolution, full colour, touch screen with high visibility illuminated indicators for power, status and fault indication. High resolution touch screen HMI options are readily available for PLCs. Industrial machine embedded controllers usually offer both graphic screen and LED indicators as standard.

9.3 Controller Connectivity
Part of the client requirement was for the controller to be able to communicate with other control and monitoring systems either by digital signals or by use of standard communication protocols. For the future having a controller that may be accessed via the Internet was deemed to be desirable. The embedded controllers available offer these features.

9.4 Controller speed of response
The required speed of response of the controller is critical in this application. Certain functions: high vibration and over speed avoidance, for example, demanded a very fast response. The required application program cycle needed to be in excess of ten times a second. Although PLC’s exist that happily satisfy this requirement the total program cycle times of PLCs in the project cost range tended to be in the order of 150-250ms, 4-6 times a second. A typical industrial embedded controller has response times in the order of 50ms, 20 times a second. The cycle time requirement was the most important factor leading to the choice of the embedded controller.

![Figure 6. Steam control schematic](image)

7. System configuration
Figure 6 shows the basic schematic diagram for the machine: Steam flow to the generator turbine (3) is regulated by an inlet control valve (2). Emergency shutdown, over speed protection and steam
isolation are provided by a fast acting shut-off valve (1). The generator (4) is connected to an inverter drive, operated in generation mode, providing output power rectification, monitoring functions and speed control.

![Figure 7. Electrical power generation schematic](image)

With reference to Figure 7: The rectified output of the inverter is connected to an active front end inverter (AFE) which has the sole purpose of inverting available D.C. power from the inverter to an output matched and synchronised to the electricity grid. The AFE inverter also offered functions to export electricity into the grid. The package was designed for connection to a non-island power grid system; that is a system that is connected to the national or local electricity grid.

8. Control of the microturbine

This section describes some of the special control routines that were developed to meet some of the difficulties unique to a steam machine. Unpredictable behaviour of the machine due to thermal effects of steam was something that had to be understood during the development process. Of particular concern were the effects experienced when expansion of steam through a control valve tends towards superheating and the presence of, even small, amounts of condensate holds the steam in a saturated condition at saturation temperature. Over time, condensate will evaporate and temperatures unexpectedly rise in association with density changes. Any re-introduction of condensate will cause temperatures to fall to saturated levels again. Even with the most effective condensate management practises in place, condensate can appear periodically. The systems control engineers on this project had to take the potential variability of this parameter into account.

9.1 Start-up routine

It was found that Condensate tends to accumulate, particularly in lower voids within control valves and similar components, after a short period of cooling. Introduction of steam into a cool system obviously generates condensate. During a cold start sequence, steam introduced to the turbine is likely to be two phase with a degree of suspended condensate. The effects of this were alleviated by designing a cycle to pre-heat the system prior to operation. A small flow of steam was allowed to exert a low pressure within the stationary turbine system which pre-heated the components; remaining condensate was drained through steam traps. During this cycle it was necessary to prevent unintentional rotation of the turbine: the inverter was used to energise the generator to hold the turbine shaft stationary during this process. A small
amount of power is consumed for a short period during this cycle. A greater challenge was the discharge of pockets of condensate collected within components on the inlet line to the turbine: As flow increased there was a tendency for the condensate to be carried into the turbine. On occasions this lead to 'water hammer' effects sufficiently severe to disrupt turbine stability.

Mitigation for this was challenging: Experimentation demonstrated condensate pick-up was associated with a particular steam flow rate. Knowing this a turbine speed was calculated that matched turbine injection angle velocity to impeller blade velocity with the goal of allowing condensate to pass through the impeller with minimal blade impact. To achieve this, the turbine had to be driven. ‘Motoring’ the turbine at this calculated speed while steam flow was slowly increased through the condensate pick-up flow range allowed the condensate to pass through the turbine with minimal stability disruption. Again the trade-off for this process is a small consumption of electrical power.

9.2 Acceleration, ‘winning back lost power’

The pursuit of maximum efficiency identified an opportunity to recover power consumed during the warm-up and condensate management cycle. This was implemented by using carefully controlled steam flow to accelerate the turbine rather than electrically driving the turbine to operational speed, this resulted in the acceleration cycle power consumption being eliminated. This function was found to be simpler than originally anticipated, relying predominantly on timing, with sufficient margin to accommodate varying circumstances. The key constraint was turbine bearing stability, where care had to be taken to accelerate sufficiently fast to avoid any power consuming assistance from the inverter drive but slow enough to avoid affecting the shaft stability with excessive changes of torque. The end result of tuning this function was generation of power throughout the acceleration cycle with power output increasing as operational speed was approached. Once at operational speed, flow could be proportionally increased to provide optimum power generation for the given steam conditions using measurements of power and generator speed provided by the inverter.

9.3 Turbine shaft bearing stability

The low friction, gas bearings utilised in the micro turbine design could experience instability, indicated by transient shaft orbit measurement deviations, in response to rapid, transient rates of change of turbine loading. The stability boundaries turned out to be roughly analogous to the percentage of the change referenced to the mass flow rate: At lower steam flow rates a small rate of change had a similar impact to a higher rate of change at a higher flow rate. At lower valve openings the rate of change of position of the inlet valve control needed to be constrained to a greater degree, being proportionally relaxed as the valve opened further and steam flow rates increased. Although this constraint impacted heavily on control response a compromise was achieved with acceptable limitations.

9.4 Control of the steam inlet valve

Initial models suggested steam flow control, from which outlet pressure control is derived, would be influenced by turbine speed. This concept relied on the principle that higher impeller speeds would restrict flow due to the generation of a higher $\Delta P$ opposing flow. In practise, the degree of variation of steam flow across the speed range (defined by the torque limit) was measured to be less than 5%, the load control tasks were therefore required to be dealt with by control of the inlet steam valve.
This presented a significant challenge with the inlet control valve being simultaneously tasked with a number of key control functions as can be seen in Figure 8. Attention was given to understanding the interaction of control functions with strategies implemented to mitigate undesirable effects from conflicting requirements whilst meeting the original control system specification.

To be able to successfully implement proportional inlet valve control, with a differential rate of mass flow change curve, could have required the expense of additional monitoring and modified valve control or the requirement to map and implement logic for all conditions. These requirements were avoided by using a readily available valve with an inverse flow coefficient characteristic. The inverse curve provided lower rates of mass flow change at lower percentage open values. The characteristics of the valve used are shown in Figure 9.

9. Generator control

9.1 Control Concept

In this system the output frequency is controlled by the inverter and the steam inlet valve is used to control the pressure ratio across the microturbine. The generator speed was adjusted to provide maximum output power for a given set of steam conditions.
Figure 10. Performance curves

Figure 10 shows the results of a series of characterization tests for the microturbine and generator. In these tests steam inlet and outlet conditions were established and the generator was run at a range of speeds with output power and other data being recorded. As can be seen the maximum output power for given steam inlet and outlet pressures occurred within a relatively narrow speed range. Across this range, steam mass flow and expander efficiency varied; it is therefore practical to vary the machine rotational speed to achieve maximum efficiency and therefore maximum power output for a given steam demand and required downstream steam pressure.

9.2 Transient steam fluctuations

Abrupt increases in mass flow resulting from rapid inlet pressure or outlet pressure changes were found to exceed the operational torque limit of the inverter and generator system. Loss of inverter synchronisation with the generator rotor resulted in attempts by the inverter to regain synchronisation, leading to excessive currents causing high temperatures in power switching components. When synchronisation was completely lost, over speed events occurred. To mitigate these effects, the
decision was taken to temporarily increase the generator speed to reduce torque during the duration of excessive mass flow events while the inlet control valve opening was reduced to limit the mass flow. Failure of this method to maintain torque at manageable levels causing loss of synchronisation triggers the over speed protection system.

9.3 Over speed avoidance and protection

The turbine impeller and shaft assembly has low mass and low inertia. There is a potential for uncontrolled acceleration at a high rate with a risk of rotating unit damage due to over speeding. Turbine speed is regulated and maintained by the inverter predominantly by varying the electrical loading of the generator. The higher the electrical loading, the greater the braking forces. In the event of a sudden removal of electrical loading due to grid loss or an inverter failure, the generator would accelerate in an uncontrolled manner. To prevent the speed from exceeding safe limits a fast acting, fail-safe shut-off valve was fitted to the steam inlet. Although the valve can isolate the steam supply within 1.5 seconds this is not fast enough to prevent over speeding in all situations. Without any loading it was estimated the turbine could accelerate at circa 20krpm/second. Extremely fast acting valve types were reviewed but were found to be prohibitively expensive. An alternative strategy was introduced: a fixed resistive electrical load was employed, that was switched across the output of the generator in the event of over speed or grid loss. This system, which was independent from the controller, offered a simple, reliable and low cost method of arresting acceleration while the fast shut-off valve was closing. With inlet steam flow and pressure at full output power level, tests demonstrated this method prevented acceleration then slowed the turbine once the shut-off valve had closed. The combination of a readily available fast shut-off valve and resistive braking proved to be highly successful under all testing regimes.

With the turbine driven by steam supplied remotely from a source beyond the control boundary of the package, the potential for abrupt changes of pressure without warning also had to be considered. The initial defence against an abrupt increase in steam pressure is the inlet control valve. The rate of closing of the inlet control valve had to be restricted in order to avoid causing shaft instability issues. In the event of the inlet control valve being unable to arrest acceleration sufficiently the emergency over speed avoidance mechanism detailed above was activated using the speed signal from the inverter.

9.4 Linking to the grid

Within the UK, the connection of any form of electricity generation device to run synchronised with the National Grid is subject to regulation. If the power generation 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)” must be met before connected to the network. The regulation ensures a process is followed within which a proposal is submitted to the DNO, the connection is detailed, and a connection agreement is made between the generator and the DNO. Testing and commissioning is also completed in conjunction with the DNO.

To meet this regulation, a G59 compliant mains protection relay must be installed between the generator and the grid connection. This is an electronic monitoring device which examines the quality and stability of the electricity being exported. Pre-programmed limits of certain parameters such as voltage, frequency, phase angle etc. as dictated by the DNO are held within the device. Should any of these parameters exceed limits; the relay will open a protective circuit breaker, disconnecting the generator from the grid.
In theory the control systems for this machine met these requirements. In practice it was found necessary to fit an approved grid connection protection relay that had been approved to these regulations.

Requirements outside of the UK vary from country to country, but it is common to find similar requirements to those of G59/2.

The G59 approval process involves demonstrating that each and every criterion of the standard is met by test and measurement. This process took around four hours and placed a heavy reliance on the power generation package to be able to tolerate, and immediately recover without repair, from each test. The G59 approval process focuses totally on the grid interface and interfacing variables, paying little attention to the generating equipment itself. The steam microturbine generator system survived this process without issue and the installation was approved.

10. Conclusions
The control system deployed achieved all of the objectives that were identified in the specification and has proved to be inherently reliable. The use of standard control equipment such as inverters has ensured short development times and reasonable costs.

The problems identified with condensation and wet steam in the supply are believed to be realistic problems in most industrial installations and the design of the control system has given a high degree of robustness to what might be viewed as a sensitive high speed machine.

A highly robust and cost effective method of preventing over speed and damage due to loss of grid connection was developed and successfully implemented.

The high speed generator with an electronic power conversion system offers immense flexibility and consistency of control compared to fixed speed gear driven machines.

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