Design Study and Demonstration Project:

Stirling Engine hybrid electric bus for city centre transport

The purpose of the project is to demonstrate the reliable and efficient operation of a small hybrid electric bus operating in a city centre. The emission target is to achieve effective zero emissions (less than 10% of Californian "Ultra Low Emissions Vehicle" standard - ULEV) within the city centre and at the extremes of the route. This approximates the emissions currently produced by the average UK power production and so represents the same global emission value as a 100% electric vehicle as well as achieving ultra-low emissions at point of use.

Electric vehicles provide the opportunity to overcome environmental damage associated with ssential transport services both on a local and global scale. Particulate emissions from diesel internal combustion engines in particular pose a serious threat to air quality and health.

The project aims to demonstrate a viable alternative to existing diesel powered buses within the city and ultimately to displace all such polluting vehicles with clean, quiet electric hybrid vehicles.

The proposal builds on the work already being undertaken in Oxford, where four all-electric buses are currently in service using overnight and opportunity charging. The experience of these buses has identified two potential areas of improvement: 1) the provision of a reliable and efficient cabin heating and demisting system and 2) reduced battery size/improved storage capacity.

A 5kWe Stirling Engine generator set will be series connected to a reduced capacity battery system to provide continuous battery charging throughout the operating period of the bus. The Stirling Engine to be installed is based on the Sigma SCP1-75, a 3kWe unit currently being successfully demonstrated as a stationary CHP unit.

The current battery capacity of 64 kWh is enhanced by the use of opportunity charging. However, the addition of a 5kWe on-board battery charger will provide an additional 50 kWh during the 10 hour operating day. The exact reduction in battery capacity possible will be evaluated during the first phase of the project with respect to the final route selected. This capacity reduction will have significant cost benefits as well as reducing the space required for batteries (with resulting improved passenger capacity) and vehicle weight.

Hybrid Electric Vehicles

Hybrid electric vehicles have significant potential for the more efficient use of fossil fuels and the reduction of CO_2 and other polluting emissions and noise. They also offer the possibility of reduced infrastructure requirements (and consequent environmental impact), compared with all-electric vehicles, both in terms of large scale generators and the associated transmission and distribution and charging facilities.

The majority of hybrid electric vehicles use internal combustion engines either in series or parallel with a battery driven electric drive unit. Whilst these provide zero emission capability in urban areas using the electric drive and range extension using the internal combustion drive outside these areas, the global impact is not reduced and they still suffer the same maintenance costs as conventional vehicles. They also require some form of cabin heating even in the city centre, which entails the provision of a separate heater in addition to the internal combustion engine.

Stirling Engines offer better energy efficiency and reliability and lower exhaust emissions and noise levels. Indeed, the emissions are so low that they may be run in the city centre with no environmental penalty whenever there is a demand for heating. On a global scale they are actually cleaner than all-electric buses (UK generation mix) as a proportion of the electricity consumed is effectively a free by product of the cabin heating.

Stirling Engines have, however, traditionally been too complex and costly for direct drive automotive applications due to the difficulty of engine regulation. The use of the Stirling engine as a battery charger for an electric drive system overcomes these problems as the drive regulation is based on the electric components.

The Oxford Study

The objective of this programme is to install one Sigma Stirling engine unit in an existing electric bus in Oxford. An existing vehicle has been selected because:

1) there is monitored data and practical experience of running the vehicles in an all-electric mode
2) the operating parameters and likely problems have already been identified
3) there is a commitment from the existing project members to extend the scope of low emission vehicles and implement the Oxford Transport Strategy
4) there is political acceptance of novel technological solutions in Oxford

The specific objectives are:

* to demonstrate the technical and commercial viability of the Stirling engine series hybrid bus in Oxford city centre
* to determine the matching generator capacity and range/route profile requirements
* to evaluate the user reaction to the hybrid bus concept
* to evaluate the implications of integrating on-board, opportunity and overnight charging particularly with regard to the potential DSM benefits

Anticipated results

The results of the monitoring programme will be made available to other bus operators, manufacturers, potential distributors, investors and transport planners and the successful completion of the development program will form the basis of the commercialisation of the technology. Continuing studies indicate a significant potential market for the Stirling engine generator unit and it is now proposed to proceed to the demonstration phase of the programme with a view to eventual commercial exploitation.

State of the art

The concept of hybrid electric buses is relatively novel with only a few projects currently in place within the EU, either in series or parallel hybrid options. None of these uses Stirling Engine technology, which is ideally suited to series applications as this overcomes the perennial problem with Stirling engines of complexity and inefficiency of regulation. The electric drive component permits clean, quiet operation in city centres with regenerative braking and torque characteristics ideally suited to the stop-start operating regime. The thermal engine component on the other hand permits extended range and power availability outside urban areas.

Series hybrids permit the use of constant charging at fixed load, hence optimising the operation of the generator set. However, they do suffer from losses both from generation and charging. Parallel hybrids overcome the losses associated with battery charging, but tend to be more complex and impose a wide range of loads on the thermal engine, with consequent losses in efficiency.

Both types of conventional hybrid vehicles use spark or compression ignition internal combustion engines. Consequently they have relatively short service intervals, high maintenance costs and limited life compared with an external combustion Stirling Engine. Due to their combustion characteristics they also produce high levels of CO2, SO2, and NOX as well as being relatively noisy and, whilst an improvement on conventional power plants, are less than ideal for city centre operation.

Stirling Engines, being external combustion machines, have a number of advantages in terms of reliability and performance and ultimately should have a cost between that of spark and compression ignition automotive units. Service intervals of between 3,500 and 5,000 hours (equivalent to more than one year's economic operation) are expected compared with 750-1000 hours for IC engines in hybrid and 200-300 hours in conventional applications. Life expectancy should be 50-60,000 hours compared with 10,000 hours for an IC engine and it is these characteristics as well as the reduced emissions which the project aims to demonstrate.

The 3kWe Sigma SCP1-75 unit has demonstrated overall efficiencies in excess of 90% and similar efficiencies are anticipated for the 5kWe version. Service intervals will be shorter than for the stationary version, but still considerably longer than for internal combustion engines. The use of an external combustion also permits the use of a wide range of fuels with obvious infrastructure and operating benefits.

Demand Side Management (DSM) & Environmental Impact

Infrastructure costs and availability are major disincentives to public and private electric vehicles if they are to make a significant contribution to reduction of emissions. However, using the Stirling hybrid option, the electricity utilities may be able to avoid the cost of constructing extensive charging facilities. The facility to continuously trickle charge during operation (and possibly overnight) should also prevent excess demand during peak travel times for charging facilities and power, which might otherwise have an adverse effect on the network both in terms of additional generating capacity and the associated reinforcement of the distribution infrastructure.

In the UK, there are 77,518 buses currently licensed and in use. The combustion characteristic of Stirling engines also offers a significant reduction in other atmospheric contaminants compared with internal combustion engines, but also compared with existing UK generation emissions. The annual reduction in emissions achieved by each Sigma Stirling Engine is 20 tonnes CO_2, 0.5 tonnes of NOx and SO_2 combined. The eventual market for the units is estimated at 7 MWe in the UK, giving a total of 50,000 tonnes CO_2 , and 1200 tonnes of NOx and SO_2 combined. However, the local impact on air quality and noise pollution is of proportionally greater significance.

Background of the Sigma Stirling engine

The Stirling engine is an external combustion engine invented in Scotland in 1816 by Robert Stirling. The Stirling engine principle was historically successful in a number of applications such as rotating fans and for pumping.

The modern development of the Stirling engine was started by the Philips company in Holland, and today Philips has a company in the cryogenics field using the results of their development work for the commercial production of very low temperatures.

In Sweden, United Stirling was created, with licence rights from Philips and started extensive development work on the Philips Stirling engine in 1968 for automotive, solar and submarine applications. The vehicle application was developed together with American car manufacturers, but did not result in an engine that could compete with the conventional Otto engine, mainly because of the high cost of engine regulation. However, the development of a large engine has resulted in commercial success in the submarine propulsion market.

TEM started research and development work on a small scale Stirling engine in 1986. The base for the development was the new Stirling engine invention made by one of the leading Stirling scientists in the world, the late Professor Stig Carlqvist. He was the leader of all the Stirling development work in Sweden and started the development work at TEM with a small hermetically sealed Stirling engine together with other leading researchers and designers in the Stirling field. The first goal was to create a battery charger for electric cars. The integration of the Stirling Engine and generator set into a series hybrid drive system overcomes the problems of complexity, efficiency losses and cost associated with Stirling engines in direct drive automotive applications. Although the interest for hybrid electric cars has not yet been fully realised, current developments in Norway and Europe indicate a substantial potential market in the medium term.

The engine has also shown promise as a basic component of a CHP system and is currently being demonstrated at sites in UK, Denmark and Norway.

The Stirling engine principle

The Stirling engines are closed cycle engines characterised by an external heat supply. An external heat supply allows the use of any heat source operating at a sufficient temperature level.

The Stirling engine operates by continuous heating and cooling of a fully enclosed working gas. The alternate compressing and expanding of a fixed amount of high pressure helium gas is transformed into a rotating movement to which the electric generators are connected. The continuous external combustion process of the Stirling engine provides good combustion control and low exhaust emission levels. Within the closed Stirling cycle, pressure variations of the working gas follow an almost

sinusoidal curve, which is one of the basic reasons for the low noise and vibration level of a Stirling engine.
Compared to internal combustion engines, heat losses in a Stirling engine are more concentrated into the cooling water. This characteristic can be utilised to allow the Stirling engine to provide the necessary heat for cabin heating and demisting.

The Sigma engine

The main goal for the TEM development work was to achieve a small, reliable, low priced Stirling engine with good long term running characteristics. The result now is a single cylinder, completely sealed Stirling unit with a high potential for low cost manufacturing, high efficiency, low emissions and long life with low maintenance requirements. The present burner design is based upon natural gas, but there is potential for other liquid or gas fuels to be used.

Any machine such as the Stirling engine which contains a special working medium needs to be hermetically sealed in order to guarantee the containment of the working medium, as for example in a refrigeration compressor. This is also possible with a Stirling engine, due to the Carlqvist innovation. The Carlqvist innovation is to provide the engine with a completely sealed pressurised crankcase with permanently lubricated anti-friction bearings. This closed system solves one of the fundamental problems of earlier Stirling engine designs, namely the helium leakage to the surroundings. The pressurised crankcase design eliminates the need for a high performance, high loss connecting rod seal between the power piston rod and the displacer piston rod. This contributes to increased mechanical efficiency. Another very important part of the Carlqvist innovation was to create a new type of mechanism in the engine that made it possible to integrate the electric generators within the crankcase. The need for a cross head was then eliminated, contributing to a further decrease of mechanical losses, and to a reduction in crankcase volume.

Sigma Elektroteknisk has acquired the manufacturing rights for this engine and is now developing a range of units with various outputs. For example, a slower running engine (1500 rpm) with larger cylinder capacity has been developed for micro CHP applications and is expected to provide even longer life and reliability. It is proposed to use this improved engine operating at 3000 rpm to provide 5kWe as a hybrid vehicle on-board battery charger.

The proposed hybrid bus application

Oxfordshire County Council is currently supporting the operation of four electric buses on a route within Oxford city centre. These have been operational since November 1993, but have experienced problems with batteries and cabin heating. In order to minimise the capital cost of the project it is proposed to modify one of the eixsting buses by removing a proportion of the batteries and installing a 5kWe Stirling engine on-board battery charger, LPG tank and associated controls. A diagram of the existing bus is shown in the appendix. There will be net reduction in weight of the bus as the Stirling engine unit and ancillaries are lighter than the batteries which they displace. The current batteries weigh a total of 2280kg representing a significant proportion of the total vehicle weight of 7000kg and exceeding the carrying capacity of 1840kg.

The Stirling engine unit will run continuously during the operating period of the bus (08.00 to 18.30) providing a charge of 5kW to the batteries and 15kW of available heat for demisting and cabin heating. (Additional studies will examine the benefits of running the Stirling engine battery charger overnight as it would theoretically be possible to avoid the costs associated with fixed charging equipment). The majority of this heat is concentrated in the cooling water, which will be fed to a conventional fan coil for distribution; any excess not required will be dumped externally. Although this might appear to contradict the zero emissions argument, the fact that heater emissions are currently acceptable in the city centre justifies local pollution targets, whilst the extremely low emissions of the Stirling engine justify the global argument. Throughout the day the bus will lose charge as the power requirement is substantially in excess of the 5kW being produced (30kW average). However, controls will prevent overcharging during long stationary periods, particularly at the beginning of the day.

The buses currently operate a 12 minute frequency 2.9 mile route, although it is anticipated that the hybrid version could operate a longer and more typical city bus route to/from the suburbs.

Current Status

The project was originally proposed for 1998-2000 and EU funding was approved. However, despite the enthusiasm of all parties, budget cuts in Oxfordshire led to the cancellation of the project. It is now hoped that another transport authority will be able to act as host to demonstrate the Sigma Stirling technology in what promises to be a significant contribution to clean transport.