GAS TURBINES FOR ELECTRIC POWER GENERATION

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Summary

Current gas turbines for power generation cover the range from 1 MW to 250 MW per unit. Large units can be combined with steam turbines in blocks, providing base load power stations with capacities of up to 2500 MW with thermal efficiencies of 55 per cent or more. Large heavy frame gas turbines use a single-shaft arrangement with a rotational speed of 3000 rpm for 50 Hz, applications and 3600 rpm for 60 Hz avoiding the use of a gearbox. Aero-derivative engines are derived from aircraft jet engines, using a power turbine in place of the propelling nozzle of the jet engine; these typically have powers of 25 - 35 MW with a maximum rating of about 50 MW. They are widely used in off-shore applications and also for co-generation schemes. A third type is the light industrial engine, covering a range from approximately 4 MW to 15 MW; these are also used in off-shore applications and are now finding extensive use in small scale cogeneration applications. In the near future gas turbines with a unit capacity of 300 MW will be available for 50 Hz applications. Current high turbine inlet temperatures

are obtained using air-cooled blades, and the substantial bleeds required incur a considerable parasitic loss. Development on steam cooled blades is currently being carried out for use in large scale units for combined cycle plant, eliminating the parasitic loss resulting from air cooling. A great deal of research and development into dry low emissions (DLE) combustion systems is being pursued by all major manufacturers, and this will eliminate the requirement to use water or steam injection for NOx control.

1. Introduction

In the early post World War II years the gas turbine played an insignificant role in electricity generation, but started to make inroads in the 1960s as both thermal efficiency and power output increased. Penetration of the market increased steadily but for many years the gas turbine was limited to applications with relatively low running hours, such as peaking and emergency duty, due to high operating costs and limited power outputs. Gas turbines for base load plant were first used in oil rich countries where fuel cost was not a major issue and difficulties of water supply made the steam turbine a difficult proposition. The advent of gas turbines with ratings of well over 100 MW, combined with steam turbines, provided very high thermal efficiencies and large capacity systems, allowing the combined cycle to emerge as a major source of base load power, primarily operating on gaseous fuels. The 1990s saw the combined cycle capture a significant proportion of the world power generation market and this is expected to continue.

It should be recognized that there are several distinct markets where gas turbines play a major role, with powers ranging from 5 to 250 MW; in the future there is a good possibility that units of less than 1 MW will also make a major impact. The following power systems have quite separate requirements:

a) Large scale base-load
b) Peak-load and emergency
c) Co-generation or Combined Heat and Power (CHP)
d) Off-shore power generation
e) Distributed small scale base load
f) Repowering

1.1. Large Scale Base Load

The prime requirement for a base load plant is low cost of electricity sent out. This depends on both capital and fuel costs; while low fuel cost obviously requires high thermal efficiency, the gas turbine was at a major disadvantage when it had to burn high priced distillate fuel. The real gas turbine cycle needs both high pressure ratio and high turbine inlet temperature to obtain a satisfactory thermal efficiency, and the high temperatures required could not be achieved when burning low quality fuels because of corrosive attack of the turbine blades due to impurities such as sulfur. The widespread distribution of natural gas starting in the 1960s led to the availability of a high quality fuel permitting the gas turbine to operate reliably at increased turbine inlet temperatures, which in turn led to increasing exhaust gas temperatures which permitted the bottoming steam turbines in a combined cycle to operate with higher pressures and temperatures leading to higher efficiencies.

It is generally found that for the cycle conditions appropriate to a heavy industrial gas turbine the power that can be generated by a bottoming steam turbine is about 50 per cent of the gas turbine power. As an example, two gas turbines of 200 MW could be combined with waste heat boilers to drive steam turbines of 100 MW each, giving a power of 600 MW with a thermal efficiency of greater than 50 per cent; several 'blocks' could be combined to produce a station of up to 2400 MW. There are many ways in which gas turbines and steam turbines can be combined. A single gas turbine and steam turbine could drive a single generator; mechanical couplings could be used to connect the prime movers so that either could be shut down for maintenance. Another possibility is to use 2 or 3 gas turbines, each with their own WHB and a single steam turbine.

There are many advantages to building a large power station with several identical blocks. First of all, the construction time for the gas turbines is significantly less than for the steam turbines because of the extensive civil engineering work required for the latter. The gas turbines can be commissioned and operational well before the combined cycle is completed; the utility can then meet its growth requirements by bringing on incremental blocks of power. With a conventional coal fired steam plant, for instance, no power would be available until the entire plant was constructed. A further advantage is that scheduled maintenance can be carried out on relatively small components of the whole system while maintaining a high proportion of the design output; this is even more important in the case of forced outages.

Base-load systems are expected to run for extended periods without shutting down and normally operate at constant load. This mode of operation, with long running hours per start, does not subject the plant to the cyclic thermal stresses corresponding to start-up and shut-down. The mechanical design of the highly stressed turbine rotating components would be primarily based on creep life and stress rupture considerations.

1.2. Peak-load and Emergency Systems

Units designed for peak-load applications may be required to operate for short periods such as one hour (possibly even for as little as 15 minutes) two or three times per day. Obviously thermal efficiency is not the prime driver of the design because of the low running hours, perhaps 2 - 500 hours per year. The mechanical design must pay particular attention to the cyclic nature of the operation, with a large number of starts. The time required to come on load must be carefully considered, and excessively fast loading has a major effect on overhaul life. Start reliability is of major importance, and a variety of starting systems are used ranging from diesel engines to steam turbines and gas expansion starters. In general, simple cycle gas turbines would be selected for peak-load applications. Both heavy duty single shaft units and aero-derivatives have been widely used in this role. Combined cycles would not be used because of their increased complexity and the time required to come on load, remembering that thermal efficiency is not as important in this application. Heat exchanger cycles would not be used, because of thermal stress problems causing cracks and leakage in the heat exchanger with repeated starts; in addition, the very large thermal inertia of the heat exchanger would severely restrict the capability of the unit to come up to full load in a short period.

Emergency power units would be designed specifically to come up to full power in a very short time; aero-derivative gas turbines were originally designed to be capable of producing full power from cold metal in 120 seconds. This was possible because of the light weight construction of the casings and rotor components, resulting from engine weight being one of the key drivers of aircraft gas turbine design. Start reliability is even more critical than for the peak-load units, and the engine configuration plays an important role; a free turbine engine, for example, is started by bringing the gas generator up to speed whereas in the case of the single-shaft engine it is necessary to drive the whole machinery train of compressor, turbine and generator. If the gas generator has separate LP and HP compressors, in a twin-spool arrangement, it is only necessary for the starter to turn over the HP rotor, which has a much smaller moment of inertia than the rotor of a single-shaft unit of comparable power. An important requirement for emergency power units is the need for a 'black start' capability, i.e., the ability to start on its own batteries with no external power available. By their very nature, emergency power units would operate for very low hours, which could be as low as 25 hours per year. Clearly thermal efficiency is of little or no consequence, and units are primarily selected for their power, simplicity and ease of starting.

1.3. Co-generation or Combined Heat and Power

The exhaust gas temperature in a gas turbine is typically 500 - 600°C and this can be used in a Waste Heat Boiler (WHB) also known as a Heat Recovery Steam Generator (HRSG) to raise steam. The steam may be used in a steam turbine to generate more power with no further addition of heat, resulting in a very high thermal efficiency. Alternatively, the steam raised can be used as process steam in applications such as chemical plant, paper mills, hospitals, breweries and university campuses. The steam may be bled off at different pressures and temperatures for different processes.

The co-generation market is growing rapidly, and many applications use gas turbines in the 5 - 40 MW range, with both heavy duty industrial and aero-derivatives widely used. A major problem facing many potential users is the balance between heat and power; in some applications there may be a reasonably constant power demand throughout the year, but the demand for heat may vary greatly between summer and winter. In some applications the gas turbine is selected on the basis of the heat requirement and this may result in substantially more electric power that can be exported to the local utility. Gas turbines are also used in district heating systems where the exhaust heat is used to provide hot water. In tropical locations they may also be used for district cooling systems, with the exhaust heat used in an absorption refrigeration cycle.

1.4. Off-shore Power Generation

Off-shore platforms require considerable amounts of base load power, which is required for oil pumping, gas re-injection, water flood pumps and also the hotel load. All this power must be generated on board the platform, and obviously space is at a severe premium; less obviously, weight is also critical because all machinery units should be capable of being lifted by the platform's own cranes. If this were not the case, major costs would be incurred for floating cranes and their associated manpower. The power plants must be operated in close proximity to the platform operators so machinery noise must be minimized. Reliability and availability are key drivers of the design process. In the past, fuel economy has not been critical and simple cycle units have been universally used. In Scandinavian countries, however, the imposition of a heavy CO_2 tax has made high efficiency much more important, and in the late 90s a few simple cycle units were converted to combined cycles. Large platforms may require power in excess of 125 MW, and aero-derivatives of 25 - 30 MW have been widely used. A large number of units around 5 MW are in service, and these may be heavy duty industrials or aero-derivatives. These off-shore units require special attention to inlet filtration, being affected by both salt spray and dust or mud from drilling operations.

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Biographical Sketch

H.I.H.Saravanamuttoo graduated from the University of Glasgow in 1955 and spent a decade working in the Canadian gas turbine industry on both aircraft and industrial engines. In 1964 he became a faculty member at the University of Bristol and worked as a consultant to Bristol Siddeley , Rolls Royce and British Aircraft Corporation on the Concorde engine development progarm, being awarded his PhD in 1968. From 1970-1998 he was at Carleton University , where he was Chairman of Mechanical and Aerospace Engineering for 10 years. During this period he was actively involved with gas turbine users on both sides of the Atlantic working on naval, aircraft, pipeline and utility applicatons. Since retirement in 1998 he has been Professor Emeritus at Carleton.
He is a Fellow of the American Society of Mech Engineers, the Institution of Mechanical Engineers and the Canadian Aeronautics and Space Institute and is a Past President of CASI. In 2002 he was the Guggenheim Memorial Lecturer, in 2004 recipient of the R.Tom Sawyer Award of ASME and in 2005 the MacCurdy Award of CASI.
He is co-author of " Gas Turbine Theory " now in its 5 th Edition and in continuous print since 1951.