Microturbines for dispersed generation

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Abstract

The use of turbines having electric powers below 1 MW, or *microturbines*, as dispersed generation sources is analysed, with particular attention to the combined heat/electricity generation.

Some technical details of these devices are discussed, along with possible schemes for using them when they are either the only source of electricity or in parallel with an external network.

In some case-studies the economic feasibility of the proposed systems is analysed.

Some experimental results obtained on a 45 kW turbine are also shown.

Introduction

Changes have been recently made in a number of electric power systems all over the world to increase the opportunity for competition. Also in Italy an electricity market liberalisation process is in progress: new opportunities rising from this situation will have an important role especially for the generation system; in fact the idea of continuing to build expensive central power plants that take years to build, require kilometres of distribution wires, and take decades of pay off has been virtually abandoned. In this framework small dispersed generation could represent a competitive solution especially when it is associated with thermal energy production (cogeneration). It is the case, for example, of density populated areas where electricity demand is associated with heat demand both for winter heating and for summer conditioning.

The small turbine generators, or microturbines, seem to be a good solution; in fact they are quieter and cleaner than the bigger turbines, and relatively free of maintenance. Moreover, they can burn a variety of fuels including natural gas, diesel, gasoline and methane. They are very simple and compact because the gas turbine is directly connected with an high speed turbo generator (about 100.000 rpm). Low emissions and relatively low investments costs are base characteristics of this class of generators.

In order to determine the real economic convenience of these small generation plants, it is very important to define adequate management structures because they could strongly influence the total production costs. A centralised management structure using new signal networks can be adopted.

Small cogeneration plants made by microturbines

Principle scheme of a cogeneration turbine

Very often industrial or tertiary energy customers have both thermal and electrical needs. If their electrical peak load is in the range 0.1-1MW and the ratio thermal/electric powers is in the range 2-6, thermal and electrical loads can be fed by a systems based on cogeneration microturbines as indicated in fig. 1.

The scheme shows that the turbine has two inputs relating to the power generation (air and fuel, often natural gas), and tow kinds of control variables. The latter are:

- a variable controlling the position of the bypass-flow modulation valve. This variable is of great importance, since it allows to tune the microturbine behaviour to the ratio of load thermal and electric powers. Just to give an idea, for the turbine [6], a ratio from 2 to 5 can be obtained, depending on the valve position;
- variables controlling the forced-commutated inverter. From the load terminals point of view, the inverter can be seen as an three-phase bipole constituted by an e.m.f. in series with an internal impedance. The e.m.f. can be controlled in amplitude and phase, and the control variables can be assumed as proportional to these two scalar quantities. In alternative, the two control variables can be assumed as proportional to active and reactive load powers.

The block called *electric load* in the figure is the user's load, either an industrial or tertiary user. In the following paragraphs some example of use of microturbines to feed some specific load are given. In general, this electrical load can be fed:

- by one or more cogeneration microturbines;
- in addition, possibly, the supply from the utility (indicated in the figure as *electricity distributor*).

It is to be explicitly noted that the possibility of what is often called *islanded* supply (i.e., without connection to the electricity distributor) is included in the scheme, and, in fact, appears feasible, as discussed in the following. On the other hand, the use of single turbines or clusters of turbines is also possible, although in case of islanded operation the use of single turbines is often not acceptable.

This solution appears potentially competitive in comparison with feeding the thermal load with a pure-thermal boiler and the electric loads totally from the utility because of two main reasons. The first one is related to the recent improvements in turbine efficiencies, that have lead to microturbines having electric efficiencies of up to 30%. The second is that it not only takes advantage from the combined generation of head and electricity, but also allows the generation of the power close to the load, with corresponding savings in transmission and distribution costs.

Technical characteristics of a cogeneration microturbines

As well known, large gas turbines have been used for years, also for cogeneration purposes.

However, only very recently it has been possible to produce turbines having low powers (from some tens of kW) and good efficiencies. To obtain this result several technological problems had to be solved. In particular, the rotational speed has been rised up to speeds of 100 krpm and above.

To give an idea of the characteristics already available from microturbines on the market, some data are reported in Table I, extracted from documentation taken from [6], related to a 45 kWe turbine.

Note, that the thermal load as shown in fig. 1 is fed by means of hot water (70-90°C).

In addition the manufacturer states that, under a linear load varying from 0 up to 100%, the Total Harmonic Distortion (THD) on the voltage at the turbine terminals is always below 2.2%

Table I: Some technical data of a 45 kWe cogeneration microturbine.

by-pass-flow level	%	0	20	40	60
Electrical power	kW	45	45	45	45
Water Flow	kg/s	1.24	1.65	2.06	2.49
Water in Temperature	°C	70	70	70	70
Water out Temperature	°C	90	90	90	90
Fuel Consumption	m^3/h	22.12	24.44	27.32	30.96
Engine Speed					
System Efficiency	%	69	77	82	85
Electrical Efficiency	%	21.00	19.00	17.00	15.00

A turbine of this type has been jointly tested in the ENEA (Italian agency for energy and environment) electric vehicle testing facility [9].

Two of the test results are shown in fig. 2 and 3. It can be noted in the figures that:

- the start-up time, measured as the time from which the start-up operations begin, up to when the speed reaches the rated value of 116 krpm, and the turbine is ready to accept load, is around 20 sec;
- during both load ramps and steps (especially significant in fig. 3) the load voltages remains highly stable, with maximum dynamic voltage deviations below 4%.

In addition, not reported in the figures, it has been experimentally verified that during the tests the frequency remains extremely constant, and the voltage shape shows a negligeable distortion.

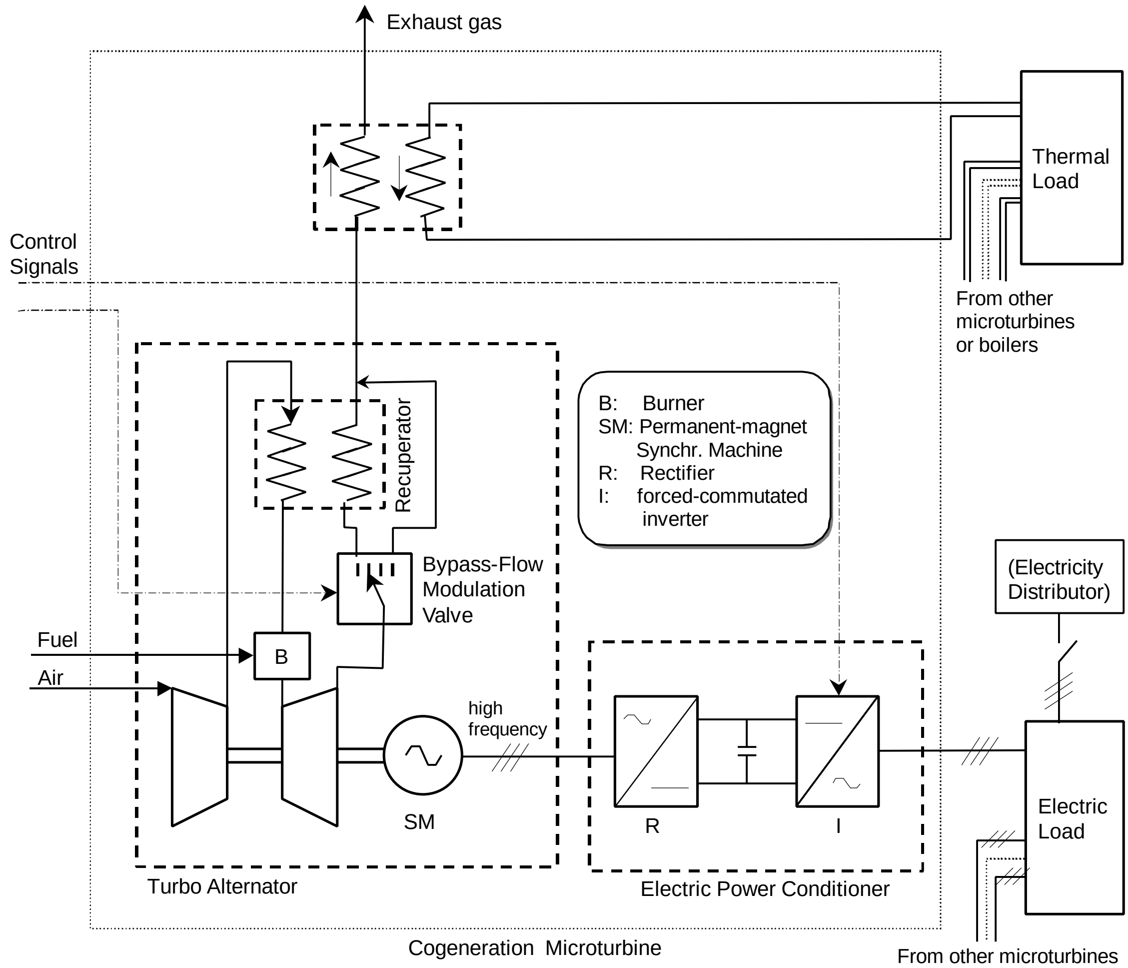

Fig. 1: Principle scheme of the feeding system of a mixed thermal/electrical load using a cogeneration microturbines.

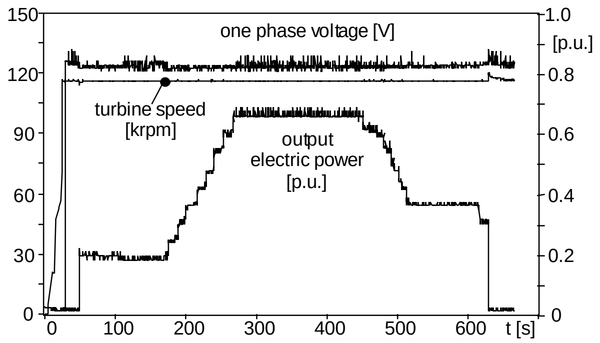

Fig. 2: A sample test on a microturbine.

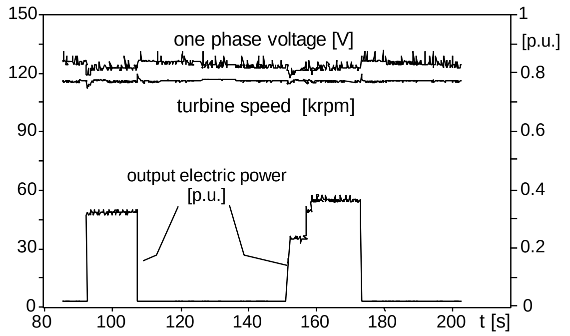

Fig. 3: A sample test on a microturbine.

Clustering of microturbines

In the principle scheme of fig. 1 it has been indicated that more than a *cogeneration microturbine* can be used to feed a combined electrical/thermal load. This arrangement will be called in the following as a *cluster* of turbines (fig. 4).

Note that in the figure between the rectifier and the inverter an electrochemical battery is inserted instead of the condenser shown in fig. 1 for DC voltage stabilisation. The use of the battery has the following advantages:

- allows the turbine start-up. In fact, for the start-up, the forced commutated inverter can be disconnected from the load and connected to the three-phase electrical output of the turbine, and controlled so that the synchronous machine of the turbo alternator is started-up at a variable frequency. During this phase, the necessary energy is taken from the battery;
- the battery can be used to support turbine overloads. In fact, if the microturbine inverter is made capable of overload and the battery energy is adequate to the energy required during the overload, no overload capability is needed on other turbine components.

The clustering of microturbines implies several advantages on the management of feeding system of electrical and thermal load.

It allows a good exploitation of the characteristic of these turbines of being very rapidly switched on/off. Above-reported experimental tests show that they can be put in service from a fully-cold state in around 20 seconds. Therefore, a cluster of turbines can easily follow the user load diagram, while maintaining each of the turbine in service in high efficiency range, normally around 50-100% of the rated power.

In fig. 4 the principle scheme of the cluster of turbine is shown with reference to the islanded supply. In addition, only the electric part of the load is shown.

This arrangements requires the following issues to be tackled:

<u>Unit scheduling.</u>

Units of the cluster must be switched on and off according to the load needs. The choice of which is the next unit to be unit in or out of service is to be made so that during the year all the single turbines are uniformly exploited, so that to cause a uniform unit ageing.

<u>Load following</u>.

The cluster has to follow both thermal and electrical load evolution. Obviously, the load can be followed only if the ratio thermal/electrical load is within the allowed range, depending on the turbine construction.

Two power thresholds are to be defined, e.g. 50% and 90% of the rated turbine power; the actual values of the two thresholds depend on the number of turbines actually in service.

So:

- when the electric load power is within the two thresholds, both loads can be easily supplied. For instance, the inverter control could regulate the electric output, the bypass-flow modulation valve the thermal output, and the fuel input can automatically adapt to the global power needs operating to keep the turbine speed constant.
- if the electric load becomes larger than that allowed by the higher threshold, or smaller than that allowed by the lower threshold, a new unit is put in or out of service, respectively.

If the electric load has a sudden increase, so that during the start-up of the turbine to be put in service the increase of load is shared between the turbines already in service. This will require some overload capability of the inverters. To avoid a similar overloading capability of Turbo Alter-

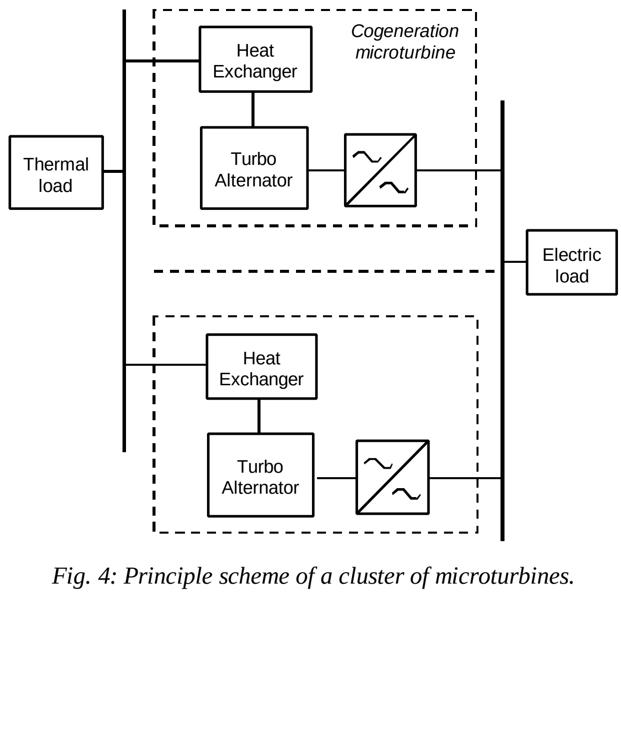

Fig. 4: Principle scheme of a cluster of microturbines.

nator, the necessary energy can be supplied by batteries added in the DC section of Electric Power Conditioners. Since the start-up times are very short, only a small battery capacity is needed,

Sudden variations of the thermal load are not of concern, since the thermal system, having relatively large time constants, can tolerate the delay in the heat supply caused by the starting up of a turbine.

Finally, note that the uniform sharing of the electric load among the turbines is not a problem since it is very easy to control the inverters to comply with this requirement.

Comparison with diesel co-generation systems

The proposed use of microturbines for supplying heat and electricity to loads comes from the recent availability of these devices.

A more conventional way make the same service is the use of diesel co-generation systems.

However, the turbines have several advantages over diesel systems. Some of the are the following ones.

Much reduced maintenance costs. The diesels require frequent and onerous maintenance: the ratio working hours/maintenance hours is around 20, while in case of microturbines this ratio is around 500-1000;

Much better controllability. The dynamic response to load variations of a diesel generator is limited by the very high internal reactance of the synchronous generator, joined with the large time constants of the excitation system. On the contrary, since the last stage of the Electric Power Conditioner is constituted by a forced-commutated inverter (plus some filtering) it allows very effective and fast voltage regulation. In addition, the de-coupling between the user three-phase system and the alternator system allows maintaining on the user side an extremely stable frequency of the generated voltages

Possibility to adapt the thermal/electric power ratio. As already explained, acting on the bypass-flow modulation valve the thermal/electric power ratio can be varied according to a control law. This is useful for adaptation to the load characteristics,

Microturbine dispersed electricity and heat cogeneration: three case-studies

To evaluate the economic competitiveness of the use of microturbines as dispersed generators, in this paragraph three case studies are presented. They are two industrial examples with different load profile and a tertiary load.

In the three cases the proposed solution is to replace the existing supply from the mains with the electrical generation of the turbines and to replace the boilers with the turbine heat recovery system.

If the turbines are intended to completely replace the energy supply from an external network, they have to supply the load with a voltage having a satisfying quality in terms of:

1. constancy of voltage amplitude
2. constancy of frequency
3. reduced harmonic contents
4. sufficient reliability.

While the conditions 1÷3 are reasonably met by the turbines already on the market, there is still some concern about condition 4.

However in the present study, taking into account that clusters of around 10 turbines are considered, it is assumed that a simple redundancy (a cool reserve constituted by a single turbine unit) will be sufficient for granting adequate reliability of supply.

Obviously, more study is needed to verify the validity of this assumption.

Apart from the particularities of each case the following items need to be considered to evaluate the convenience of the proposed solutions

Investment costs

Considering currently available forecasts of price evolution in the next years, in this study a cost of 500 Euro/kWe is considered for the cogeneration microturbine.

Other investment costs (piping, buildings, etc), with proper system design, are modest and are neglected. It has been supposed that the new system is connected to already existing electricity and heat distribution systems.

Operation and Maintenance costs

This item is in turn composed by the following sub-items

- cost of fuel consumption
- cost of remote supervision. Because of the high level of automation reachable, supervision can be performed from a remote site, based on a discontinuous connection obtained by means of wired or cellular phone lines.
- cost of scheduled and forced maintenance.

The second and third sub-items can be purchased as a service from an external service provider. The cost of this service is estimated as equal to 5% of the investment cost per year.

Electricity savings

Presently, in the three examples electricity is bought from the Italian distribution grid at a 15kV level; the corresponding cost are, obviously, a consequence of the structure of Italian tariffs. For this study it has been adopted the most convenient tariff for each kind of user.

Heat savings

Under this assumption the heat cost that the installation of the turbines can save, is the cost of heat produced with a conventional boiler, and therefore it depends on the fuel supply tariff (about 0.02Euro/kWh_t).

Microturbine for a small industry with largely variable load

Let consider a small Italian industry that processes leather. Its typical, simplified, working-day electrical and thermal load diagram is shown in fig. 5.

To make simplified computations, these diagrams can be taken as reference for working days (Mon-Sat), while during Sundays and other holiday days a constant base load of 50 kWe, 300 kWt can be assumed. The total number of equivalent hours of peak utilisation is about 3000.

Here is advisable to install a set of turbines able to completely cover the electrical load, therefore allowing the disconnection from an external electricity distributor. Considering the above-reported electric load, 6 turbines having a nominal electric power of 85 kWe are sufficient to cover the electric load, therefore, including a one-unit reserve, the purchase of 7 of such turbines is considered.

It is to be noted that the choice of a larger number of smaller turbines is also possible. An accurate choice of the right number/size couple would require additional studies, that are not performed in this paper, for sake of simplicity.

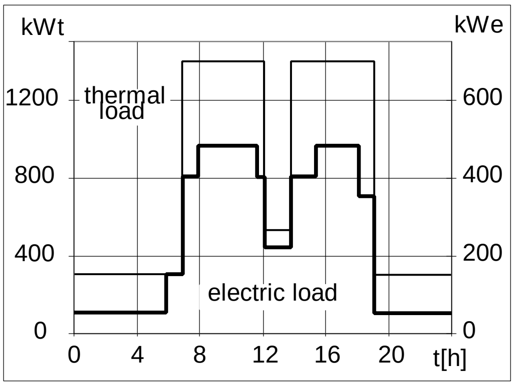

Fig. 5 Thermal and electric load of a leather company.

Acting on the Bypass-Flow Modulation Valve, turbines already on the market [6] allow ratios thermal/electric load between 2 and 5. Acting on this valve, therefore, the 6 turbines considered are able to cover, for the majority of time, the thermal load diagram. During the low load hours however the thermal/electric power ratio is 6. If it is impossible to vary the productive process to keep the ratio inside the range 2÷5, an alternative solution is to be adopted.

A possible economic solution to solve this problem is to install an electric resistor using the electric power to produce part of the lacking thermal power and to increase the turbine thermal output. For example in the hours in which 50kWe and 300kWt are requested by the load, the insertion of a 10kW resistor brings to a turbine electric output of 60kWe. Then the resulting turbine thermal request is of 290kWt, compatible with technical constraints.

Considering all the cost/savings items, the following table can be built:

Item	Value
Investment costs [kEuro]	238
Maintenance costs [kEuro/y]	11.9
Operation costs [kEuro/y]	125
Electricity savings [kEuro/y]	122
Heat savings [kEuro/y]	92
Payback [year] (rate 8%)	3.5
Payback [year] (rate 12%)	4

Microturbine for a small industry with continuous production cycle

The second case study deals with a plant for industrial waste process. The industrial process is a continuous production cycle with a quasi-constant thermal and electric power load (load variations during a day can be 10-15% of the average value). The peak load is 500kW and the total hour number of peak utilisation is 6000. This value derives from the plant stopping rather than from daily load fluctuations. The thermal load has the same shape of the electric load.

Moreover the clustering of several microturbines gives the possibility of optimising the total system efficiency. So, for the calculations performed in this study, it has been hypothesised that the plant operates at its full load for 6000 hour per year.

The installation, as for the previous case, of 7 microturbines of 85kWe allows covering the load with a reserve of one machine.

The following table can be built considering different values of the ratio thermal/electric load around 3:

Item	Value
Investment costs [kEuro]	240
Maintenance costs [kEuro/y]	12
Operation costs [kEuro/y]	250
Electricity savings [kEuro/y]	210
Heat savings [kEuro/y]	150
Payback [year] (rate 8%)	2.5
Payback [year] (rate 12%)	3

Microturbine used within the energy system of a medium tertiary aggregate load

The main difference between an industrial and a tertiary environment is that in the latter case the need of heat does not come for the production process, but is related exclusively to the air conditioning. During winter the heat can be used directly for conditioning, while during summer it could contribute to the air conditioning through the interposition of a chiller system.

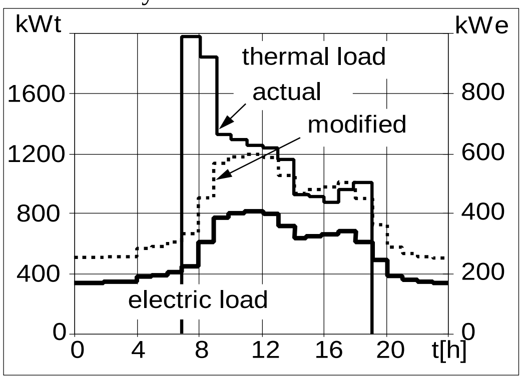

Fig. 6: A sample tertiary thermal and electric load.

Fig. 6 shows the electrical and thermal load diagrams of a typical working winter day measured at the faculty of engineering at the University of Pisa.

The yearly total electric and thermal consumption is 1.6GWh and 1.9GWh respectively.

The thermal load is supposed to be as reported in fig 6 for all the winter days while no load is foreseen for the summer days. During the night the boiler is switched off.

Looking at the actual thermal/electric load ratio of the graphs reported in fig 6, it’s worth noticing the high value of the first two hours of the morning (6÷9). This value is due to the high thermal inertia of the heat distribution system (boiler, water and heaters).

Given the high thermal inertia of the buildings (having thermal time constants of several tens of hours), the shape of the thermal load diagram can be modified at least keeping a constant value for the above-mentioned ratio. The chance of acting on the by pass valve give the possibility to have a range for optimising the total efficiency and to satisfy to particular request of very cold days.

The particularity of the tertiary load is not to have needs of heat during summer. To exploit the advantages of co-generation, it is therefore possible to install a chilling system with adsorption cycle.

Calculation of the related savings can be done under the following hypotheses:

- a conventional electric chilling system requires about 320MWh/y of electric energy to serve the entire building.
- no installation cost difference between a conventional solution and an absorption cooling system is considered
- heat availability deriving from electricity generation is largely sufficient for summer conditioning.

Under these hypotheses and considering an average electric efficiency of 23% (with a thermal/electric ratio of 2.5) cost and savings of the proposed solution are shown in the following table, in which the data of columns A and B indicate computations without and with summer conditioning, respectively.

Item	**A**	**B**
Investment costs [kEuro]	238	238
Maintenance costs [kEuro/y]	11.9	11.9
Operation costs [kEuro/y]	108	108
Electricity savings [kEuro/y]	130	150
Heat savings [kEuro/y]	30	30
Payback [year] (rate 8%)	9	5
Payback [year] (rate 12%)	12	6

Remarks on the three case studies

The comparison of the three case studies shows clearly that the use of cogeneration microturbines can be economically feasible if there is high utilisation of the installed electric and thermal powers. In particular, in the case of a tertiary customer economic convenience is obtainable if heat is exploited during winter for heating and in summer for cooling.

Dispersed generation by microturbines: network considerations

In the previous paragraphs the opportunities brought by the uses of microturbines in electric systems isolated by the utility electric network, were discussed.

In addition to those considerations, other opportunities can derive from different arrangements of the turbines. These are discussed in this paragraph.

Networks of cogeneration microturbines

Cogeneration turbines can be installed within the control of a single user.

A different organisation can however be foreseen.

It is possible to imagine a company that owns and maintains these devices, and installs them in the user's area. It could therefore sell the service of electricity and power supply, according to a *turnkey* formula.

Such an organisation could take advantage of a number of favourable conditions, the main of which are reduced turbine and maintenance costs, reduced reserve.

Another, very important, advantage of these networks of microturbines is the possibility of obtaining better fuel prices by contracting the fuel supply of all the installed turbines ad a whole sale. In the present contest of gas market liberalisation, the fuel can even be bought from a remote supplier and wheeled through the gas network.

Turbines operating in parallel with the electric network

In fig. 1 the possibility of connecting the electric load of the user not only to the electric supply of the microturbines, but also to the grid of an electricity distributor (utility) is considered.

In this case the turbines operate not only in parallel among themselves, but also in parallel with the external network.

This, while not creating problems in the control of the microturbine inverters, creates the possibility to contribute, with the microturbines, to the operation of the utility network, by means of supplying several services. Some of them are discussed in the following.

Reduction distributor grid load. Consider the case in which the turbine installation site is in the proximity of lines near to their thermal limit. It could be economically convenient, during the day hours in which the lines are more loaded, to make the turbines to supply an electric power larger than that required by the user's own load: this way, the turbine feeds the distributor network and relieves the loaded line (fig. 7).

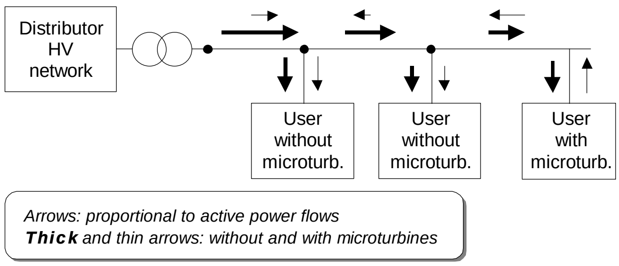

Fig. 7: Principle scheme of reduction of distribution line load by means of microturbines

Contribution to voltage regulation and power factor compensation. The last stage of the electric path of cogeneration microturbines is a forced-commutated inverter. These devices are able to exchange with the load to which they are connected reactive power no matter if it is to be absorbed or delivered. And the level of reactive power exchanged can be varied very fast, as a consequence of the big controllability of power electronics devices.

These characteristics can be effectively exploited to give a contribution to the voltage regulation and power factor compensation of the distributor grid.

Conclusions

- Low power turbines are becoming an attractive option to feed the load of small users, especially when the generation of both electricity and heat can be exploited.
- They can be used as the only source of electricity or work together with the utility grid satisfactorily.
- The analysis of some case studies, covering two different types of industrial loads and a tertiary load shows that their use can be often economically convenient.
- There are several different options to utilise the great

flexibility of these turbines in dispersed generation; more study is therefore needed to analyse them with a sufficient degree of detail, with special attention devoted to the reliability issues.

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