

Specificity of automatic control of micro-turbines (steam or gas -driven and expanders) in dispersed generation system of heat and electric power

Zygfryd Domachowski

Abstract

This paper presents specific problems of automatic control of steam micro-turbines and expanders intended for the dispersed, combined generating of heat and electric power. The investigations concern ensurance of certainty of energy supply and its required quality.

Keywords: micro-turbine, heat-and-electric power plant, structures, automatic control.

Introduction

Dispersed electric power generation has many important advantages: it makes it possible to use local primary - energy sources (of water, wind, biomass or geothermal ones), it lowers electric power transmission losses, increases electric supply safety (in the case of state of emergency of large electric power system), improves stability conditions of electric power system (except of windmill electric generator farms). Application of biomass to electric power generation has an additional advantage: it facilitates the developing of coordinated economy, i.e. combined generation of heat and electric power.

On the other hand the dispersed electric power generation introduces certain problems dealing with cooperation of dispersed electric power sources with an external (large) electric power system. Apart from technical requirements concerning the switching-on of such dispersed sources to an external electric power system, the problems result from necessity to ensure suitable quality of electric energy (its frequency and voltage). The bigger they are the greater power developed by such source and the greater variability of its power. For this reason the greatest operational (control) difficulties are produced by windmill electric generator farms – their nominal power reaches from a few dozen to several hundred MW, and power fluctuation may be significant. In view of required quality of frequency control of electric power system the windmill electric power generating plants requires to be aided by conventional ones driven by water, steam or gas turbines [4], or by diesel engine.

Mini heat-and-electric power plants working on biomass, develop nominal electric power reaching from a few dozen, or even several, to a few hundred kW. Therefore from the point of view of frequency control their role in electric power system is incomparable with that of windmill electric generator farms. Nonetheless they should be also supported by conventional electric power sources due to the following reasons. Firstly, as a rule they do not take part in frequency control of

electric power system since their controlled quantity is heat power, and electric power is an additional product whose quantity is associated with amount of produced heat. Secondly, total electric power of mini heat-and-electric power plants installed over a given territory, can be significant. Hence further considerations are focused only on selected variants of automatic control systems of mini heat-and-electric power plants and on specific operational aspects associated with them.

Specificity of a separate electric power system fed by a microturbine

Mikroturbines can be used, and are used to delivering electricity and heat to:

- dwelling houses, especially individual houses,
- schools,
- hospitals,
- hotels,
- office buildings,
- small firms,
- consumers of heat and electric power on ships.

In such a role they are topics of various publications and patents, however it mainly concerns gas microturbines. From the point of view of electric power generation role of both types of microturbines (gas and steam driven) is analogous, therefore role of their automatic control systems is also the same. It makes that such considerations associated with a concept of automatic control of gas microturbine [2, 3, 6÷13] can be also related to a steam microturbine.

Steam microturbine first of all intended for heat delivering, delivers as much electric power as it results from amount of delivered heat. Therefore internal electric power system (internal electric network) fed by it, should be connected to an external electric power system in order - in the case of lack of balance between amount of electric

power produced by the microturbine and that absorbed by the internal electric power system -to supplement possible shortage from the external system or to deliver possible surplus to it, see Fig. 1.

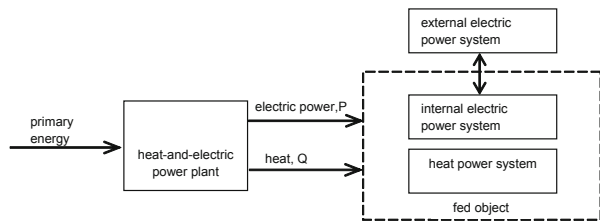


Fig.1. Simplified schematic diagram of feeding an object with heat and electric power

And, in land applications possible periodical breaks of connection between internal and external electric power system due to various emergency situations should be taken into account. On ships the internal electric power system is the only one. Its connection to an external electric power system may be only considered in the case of ship's stay in port. In such situation if amount of generated electric power (resulting from delivered heat amount) is smaller than the demanded (let's say critical) for feeding e.g. a refrigerator, necessary lighting, pumps, computers, then steam pressure control at outlet from turbine should be replaced by electric power control (current frequency control). For this reason the U.S. Patent [9] shows various structures of connection between a micro-gas turbine intended for the feeding of computer network with electric power and internal and external electric power systems.

In accordance with the concept described in the patent the internal electric power system is split into two parts: that unconditionally demanding to be fed (critical power demand) and the remaining part (non-critical power demand). The part of the internal electric power system, which is subjected to the critical feeding, is not connected to any external electric power system, but the remaining part of the internal electric power system is connected to it. Hence, in accordance with the concept presented in the patent in question in normal conditions the microturbine feeds separately (by separate converters) both the parts of the internal electric power system, see Fig. 2. In normal conditions to the internal system's part connected to an external electric power system only a surplus of electric power generated by the microturbine over that absorbed as critical demand, is transferred. Moreover, if the amount of electric power transferred by microturbine to that part of the internal electric power system is greater than the demanded, then the resulting surplus is directed to the external system; if it is smaller

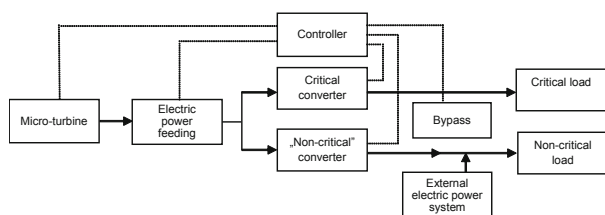


Fig.2. General concept of connection between micro-turbine and internal and external electric power systems

the demanded shortage is absorbed from the external system.

When internal electric power system is switched-off from external one then in the case of application of steam backpressure microturbine it is necessary to pass from steam pressure control at outlet from the turbine to electric power control (frequency). Schematic diagram of feeding the internal electric power system is presented in Fig. 3 (such concept is not covered by the patent in question. It concerns micro-gasturbines only).

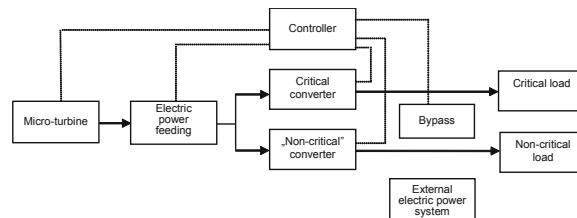


Fig. 3. Concept of feeding the internal electric power system after its switching-off from the external system

When microturbine is excluded from operation (for instance due to its failure, unserviceability, overhaul or repair) then the feeding of the internal electric power system is ensured by its connection to the external system, see Fig. 4. To the part of the internal power system, which constitutes non-critical load, electric power is transferred from the external system directly, and to the part which constitutes critical load – by means of a „non-critical” two-way converter (i.e that which allows for sending electric power in two directions). However, the direct feeding of both the parts of internal power system, i.e. without making use of any converters, is deemed more appropriate, see Fig. 5.

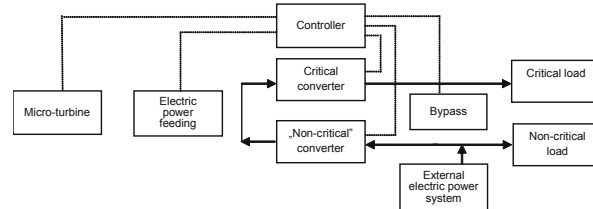


Fig.4. Concept of feeding the internal electric power system after switching-off the micro-turbine

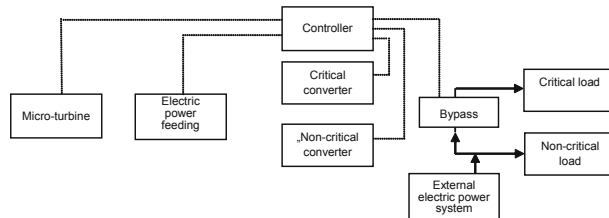


Fig.5. Concept of feeding the internal electric power system directly from the external system after switching-off the micro-turbine

Large objects can be fed, also for reliability reasons, by several microturbines operating in parallel. An example of such co-operation realized by four microturbines is presented in Fig. 6.

Electric current parameters in separate electric power system

It is assumed that current parameters in the internal electric power system, there by parameters of electric

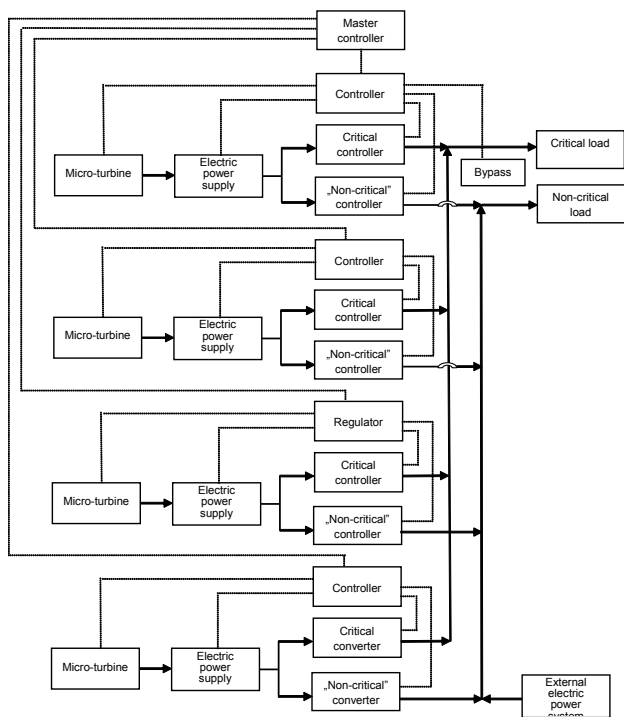


Fig. 6. Example of feeding the internal electric power system, by means of four micro-turbines

power delivered by microturbine are the same as standard ones in a low-voltage electric power distribution system, i.e. 50 Hz frequency (in Europe), and 230V voltage. However values of rotational speed of microturbine rotors are contained in the range of 45000÷120000 rpm, that corresponds to electric current frequency in the range of 750÷2000 Hz. Therefore it is necessary to apply an electric power converter at output from microturbine-driven generator so as to adjust parameters of the current delivered by the microturbine (frequency, voltage) to appropriate quantities relevant to low-voltage electric power system.

A concept of such converter is presented in Fig. 7. Alternating current of frequency in the range of 750÷2000 Hz, produced by microturbine-driven generator, is rectified (by rectifier as shown in Fig. 7). Direct current can feed consumers which require such feeding, as well as electric accumulators. The feeding of internal electric power system requires an inverter which converts direct current into alternating one of the parameters necessary for feeding the consumers in the internal electric power system (50 Hz frequency, 400V phase-to-phase voltage), to be applied.

Purposefulness of direct current (DC) application to separate electric power systems fed with electric power obtained from renewable sources, has been also considered [1]. Such concept is presented in Fig. 8. In separate electric power system DC voltage amounts to about 800V. Such system is fed from DC voltage sources

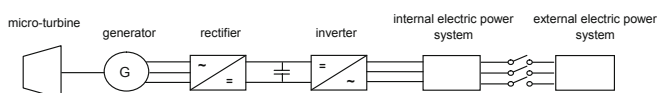


Fig. 7. Structure of connection of micro-turbine to internal and external electric power systems by means of converter and inverter

(e.g. dispersed renewable sources) as well as -through rectifier -from external electric power system. An inverter is necessary to make delivering electric power from such separate system to an external AC power system possible. For feeding AC consumers in the separate internal DC power system individual inverters at their inputs are necessary.

Ship electric power system is an example of separate system. Application of direct current to such system is deemed worth paying attention.

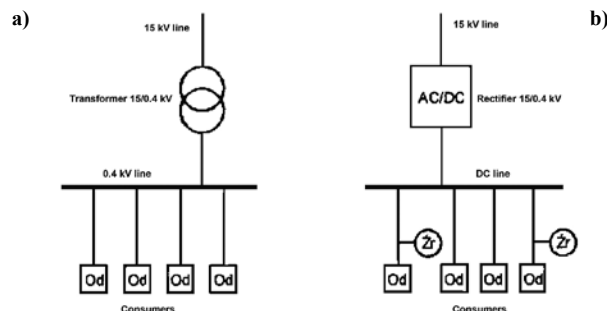


Fig. 8. A concept of replacement of alternating current (a) by direct current (b) in separate internal electric power system

Automatic control of heat generated by heat-and-electric power plant connected to external electric power system

Automatic control of heat-and-electric power plant is aimed at ensuring generation of demanded amount of heat of determined parameters. Amount of simultaneously generated electric power is associated with generated heat amount, but not subjected to control. Nonetheless in such conditions it should be intended to generate as large amount of electric power as possible. Hence, if heat delivered to an object is used both to space heating and service-water warming-up then two steam flows of different temperature values should be controlled. Simplified schematic diagram of automatic control system of heat-and-electric power plant, relevant to such situation, is presented in Fig. 9. Then to apply a multi-stage -extraction -backpressure turbine would be appropriate.

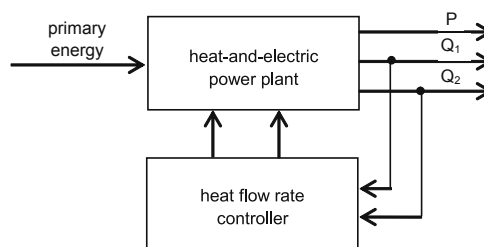


Fig. 9. Simplified schematic diagram of automatic control system of heat flow rate for space heating (Q1) and service-water warming-up (Q2)

In the case of application of backpressure turbine, only heat flow rate at turbine outlet is subjected to control (by controlling outlet steam pressure). It must correspond to the higher value out of the two temperature values: of service water and of space heating medium. In the case of floor heating it is reduced to choice of heating water temperature, from which limitation for amount of

generated electric power results. For this reason if a heat accumulator is applied to warming-up service water then steam pressure at outlet from turbine could be controlled with regard to space heating medium temperature. It would be then necessary to increase periodically the pressure in order to supercharge the heat accumulator.

When delivered heat is used only for service-water warming-up (in the periods when accommodations are not heated) then steam pressure at outlet from turbine has to correspond to a required value of service-water temperature.

If also other renewable sources (solar collectors, geothermal water) were used for delivering heat to an object then heat-and-electric power plant will be put in operation to supercharge heat accumulators, only if necessary.

Automatic control of heat generated by heat-and-electric power plant not connected to external electric power system

In the case of lack of connection between internal electric power system and external one as well as in the case of a break of the existing connection (e.g. in states of emergency of external electric power system) the heat-and-electric power plant is expected to deliver both required amount of heat and required amount of electric power [5]. In such situation two variants corresponding to two types of turbine assumed to be used in a given heat-and-electric power plant, should be considered.

Delivery control of heat and electric power if backpressure turbine is used

In backpressure turbine only one quantity can be subjected to automatic control, i.e. only one signal can be controlled. It can be either flow rate of delivered heat – the controlled signal is then steam pressure at outlet from turbine, or electric power – the controlled signal is then rotational speed of turbine-set rotor. In the considered situation (lack of connection between internal and external electric power systems) turbine-set electric output power must be controlled in order to ensure the required feeding of electric power consumers in internal electric power system. Amount of heat delivered by the turbine depends on its output power only.

If heat flow rate at outlet from the turbine is lower than the demanded (both for space heating and service-water warming-up) then the lacking heat amount is directly delivered from boiler by starting-up a reduction – and – cooling station (see the simplified schematic diagram of control of delivery system of heat and electric power, shown in Fig. 10).

During heating period, steam pressure at outlet from the turbine should correspond to a demanded temperature of working medium (in the case of floor heating); in this case the controller R_{p1} controls the reduction-and-cooling station SRS_1 . Heat used to warming-up service water

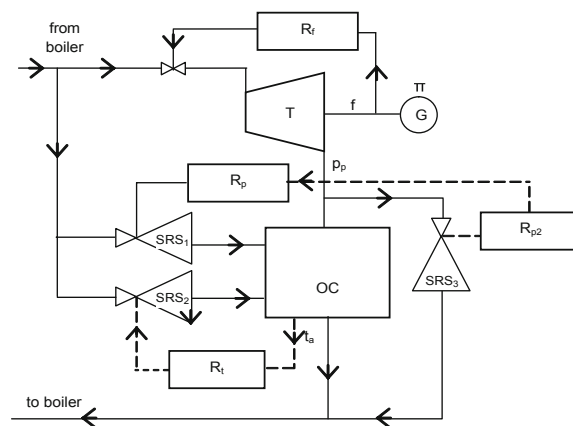


Fig.10. Simplified schematic diagram of control of delivery system of heat and electric power in heat –and –electric power plant fitted with backpressure turbine.

Notation: T – turbine, G – electric generator, OC – heat consumers, SRS – reduction-and-cooling stations, f – frequency, p_p – steam pressure behind the turbine, t_a – water temperature in heat accumulator, R – controller.

would be then delivered by means of the reduction-and-cooling station SRS_2 which feeds heat accumulator, being switched-on periodically. Outside the heating period steam pressure at outlet from the turbine should correspond to a demanded temperature of service water.

When heat amount resulting from quantity of generated electric power is greater than the demanded then steam surplus at outlet from the turbine is sent directly to boiler, bypassing the heat consumers, see Fig. 10; in this case the controller R_{p2} controls the reduction-and-cooling station SRS_3 .

Delivery control of heat and electric power if extraction – and – backpressure turbine is used

In the extraction – and – backpressure turbine two quantities can be controlled for the reason of possible impact on two kinds of control valves: before the turbine and behind the extraction. Therefore, apart from electric power, steam pressure in the extraction or behind the turbine can be also controlled. Fig. 11 presents a concept of control of steam pressure in the extraction when the steam absorbed from the extraction is used to warming-up service water, and the steam taken from turbine's outlet is used to space heating. Flow rate of the steam used for warming-up service water, is subjected to control. To this end, the valves behind the extraction are used. Flow rate of the steam at outlet from the turbine, used to space heating, is not controlled.

When steam flow rate at outlet from the turbine is not sufficient to maintain temperature demanded for accommodations then the lacking amount of heat is absorbed from the extraction. To this end, the reduction – and – cooling station SRS_1 , controlled by the behind the turbine pressure controller R_{p1} , see Fig. 11.

When steam flow rate at outlet from the turbine is greater than the demanded for space heating then the steam surplus is sent directly to boiler – the controller R_{p2} in Fig. 11.

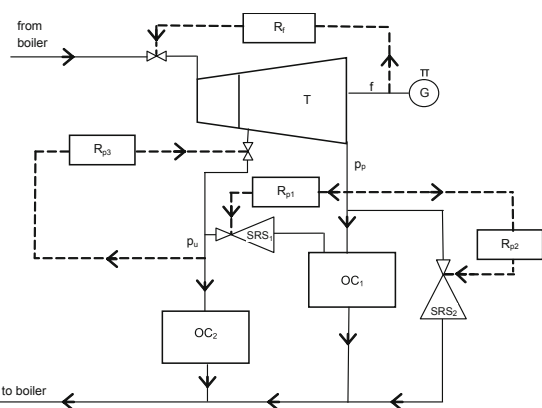


Fig.11. Simplified schematic diagram of control of delivery system of heat and electric power in heat-and-electric power plant fitted with extraction-and-backpressure turbine of controlled flow rate of the steam used for warming-up service water.

Notation: T – turbine, G – electric generator, OC_1 – heat consumer for space heating, OC_2 – heat consumer for service water warming-up, SRS – reduction-and-cooling stations, f – frequency, pp – steam pressure behind the turbine, p_u – steam pressure in the extraction, R – pressure controller.

In another variant the control valves behind the extraction can be applied to control steam flow rate at outlet from the turbine, used for space heating. Then, steam pressure at outlet from the turbine serves as the controlled signal. Such concept of delivery control of heat and electric power is presented in Fig. 12.

Steam pressure behind the extraction is subjected to control. Its change resulting from a change of flow rate of the steam used for space heating, triggers off action of the controller, R_p , onto control valves behind the turbine extraction. The steam used for warming-up service water is periodically taken from the turbine extraction. The service-water temperature controller R_t is applied to this end, see Fig.12.

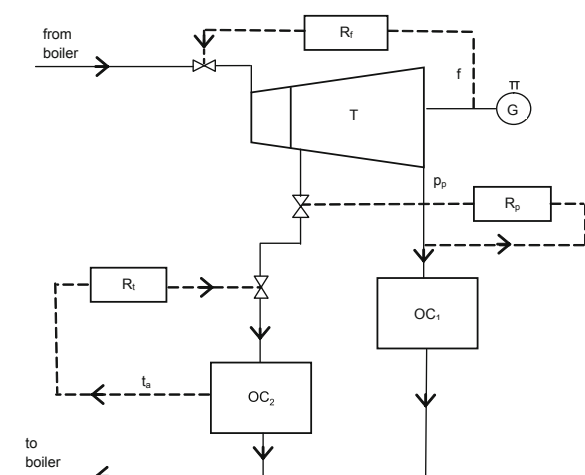


Fig.12. Simplified schematic diagram of delivery control of heat and electric power in heat-and-electric power plant fitted with extraction-and-backpressure turbine of controlled flow rate of the steam used for space heating.

Notation: t_a – service water temperature in accumulator, R_t – temperature controller; as to the remaining symbols – see Fig. 11.

Outside heating period, steam from turbine outlet should be directed to service-water heater when turbine extraction is shut-off; it corresponds to the backpressure turbine control whose concept has been presented in the preceding section.

Final remarks

Application of steam microturbines to the dispersed, combined generating system of heat and electric power, brings many specific problems in the area of automatic control. From this point of view various operational situations both dealing with microturbine set connection to an external electric power system and with its operation in a separate electric power system, have been reviewed. In both the above mentioned variants structure of microturbine automatic control system must ensure feeding the so called critical consumers with electric power. A concept of microturbine's automatic control system which fulfils the requirement has been presented in this paper. Structure of automatic control system for microturbines, both of backpressure and extraction-backpressure type, intended for the feeding heat consumers of two types and different steam pressure values, has been proposed and discussed.

Bibliography

1. Biczal P.: Direct current versus alternating current. Systems-Journal of Transdisciplinary Systems Science, Vol.13, special issue 1/2, 2008
2. Cruz T.V.G., de Mericia J.G., Veras C.G, Borges G.A.: Instrumentation, Architecture and Real-Time Control of Microturbine. Proc. of 18th International Congress of Mechanical Engineering, Ouro Preto, MG, Brazil, 6÷11 November 2005
3. Degobert Ph., Krenawan, X.Guilland S.: Micro-grid powered by photovoltaic and micro turbine. Proc. of International Conference on Renewable Energy and Power Quality, Palma de Mallorca, Spain, April 2006, (CD-ROM record)
4. Domachowski Z.: Counteracting Windpower Fluctuations within a Separate Electric Power Grid. Proc. of 5th ASME Turbo Expo 2007: Power for Land, Sea and Air, Montreal, Canada, 14÷17 May 2007, Paper No. GT 2007-28218
5. Domachowski Z., Klimacki Z.: Automatic control of frequency and active power of separate electric power system (in Polish). Prace Instytutu Maszyn Przepływowych Reports of Fluid Flow Machinery Institute, Polish Academy of Sciences), issue no. 92, 1990
6. Felthi O., Dessaint L.A., Al-Haddad K.: Modeling and Simulation of the Electric Part of a Grid Connected Micro Turbine. Proc. Power Engineering Society General Meeting, IEEE, 6÷10 June 2004
7. Hangwitz S.: Modelling of Microturbine Systems. Doctoral thesis, ISSN 0280-5316, Department of Automatic Control, Lund Institute of Technology, May 2002
8. Jurando F., Cano A., Carpio J.: Biomass based microturbine plant and distribution network stability. Energy Conversion and Management, vol. 45, issue 17, October 2004.
9. Mackay R.: Microturbine Precise Power Systems. U.S. Patent 6 977 466 (granted on 20 December 2005)
10. Sacha A.K., Chowdhury S., Chowdhury S.P., Crossley P.A.: Microturbine Based Distributed Generator In Smart Grid Application. Proc. CRED Seminar 2008: Smart Grids for Distribution, Frankfurt, 23-24 June 2008.
11. Setiawan E.A.: Dynamic Behavior of a 30 kW Capstone Microturbine. Institut für Solare Energieversorgungstechnik, e.V. (ISET), Kassel, Germany, 2007
12. X.C.Shan, Hang Qide, Sun Yaofeng, Wang Zhenfeng: Design, fabrication and characterization of fan air-driven micro turbine device. Journal of Physics, Conference Series 34 (2006), International MEMS Conference 2006
13. Torres E., Larragneta J.M., Equia P., Mazon J., San Martin J.I., Zamora I.: Dynamic Performance of a Microturbine Connected to a Low Voltage Network. Department of Electrical Engineering, ETUI – Bilbao, UPV/EHU, 2006
14. Woodward: Comprehensive Steam Turbine Control for Various Applications. Application Sheet 51 237.