AUTOMATIC CONTROL OF SOLAR POWER STATIONS

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The principles of automatic control of the heliostat field of a solar power station are considered and specific peculiarities noted.

Among the new energy sources which will be widely used in the future are atomic energy, thermonuclear synthesis, and solar energy. Fossil fuel shortages and the increasing pollution of the environment make the use of solar energy especially promising. In the USSR, as in other countries, intensive effort is being given to the design and construction of solar power stations.

The USSR contains regions in which the solar radiation intensity is high and quite stable. These include middle Asia, Kazakhstan, the Lake Baikal area (2000-3000 h/yr), the Caucasus, and the Crimean (2000-2200 h/yr). In order to integrate these new energy production methods into the country's economy, a program has been undertaken directed toward the construction of a 200-MW experimental-industrial solar power station (the SÉS-200). The SÉS-200 construction program provides for installation of four 50-MW tower-type stations, each of which will be capable of future expansion. In accordance with this solar power station construction program, below we will consider the problems of control of such a station.

Control systems used in a solar power station may be of three types: manual, automated, or automatic. It should be noted that only an optimal combination of these three methods will ensure highest efficiency of station operation. The amount of manual control is usually small and is being systematically decreased, so will not be considered further.

Automated control is the most widespread and effectively utilized form. It should be noted that we will not consider all the problems which can be solved successfully by automated control systems in a solar power station, but only the major ones.

The structure of the 200-MW solar station consists of two interconnected links (the individual modules and the equipment common to the entire station). The proposed automatic control system is a two-level one, consisting of a modular level to realize automated control of the individual modules and a stationwide (upper) level to automate control of the station as a whole and coupling to the power system. The two levels are based on electronic computers and local automated equipment, and in general operate as a single system, although in individual situations (e.g., accidents) their individual operation is possible. From the stationwide level, on the basis of energy system data and information on the state of peripheral equipment, control functions and coordination of the operation of module control systems are carried out.

The main task of the module control system is to ensure the most economic mode of module operation. Viewed as a whole, this is a quite complex problem, so that we divide it into several simpler ones. The most important of these are the problems involved in combining the entire system of information collection, processing, and output. Such a principle of control system construction permits further expansion of the system and provision of a sound mathematical basis for the power station control system. A block diagram of information links in the control system of one power station module is shown in Fig. 1.

Development of the modular control systems must be carried out in conjunction with design of the stationwide control system. With consideration of this fact, we must consider problems of operative control of the modules and stationwide equipment, and of the productive output of the station. The stationwide level of the control system must deal with problems of analysis of the activity of duty personnel, analysis of reliability of basic and ancillary equipment operation, load distribution between modules, removal of equipment from operation for repair, data transmission to higher levels, etc.

The system used to realize automated control of the solar power station is a two-level one, where each 50-MW module is provided with a peripheral computer, using a two-processor complex with available memory

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of 256 kbyte [1]. Upon failure of one of the processors in the peripheral computer, all operations can be performed by the second processor. The peripheral computers are connected by data links to the system to be controlled. The stationwide computer system will also have a two-processor structure, with external memory provided in the form of magnetic disks and drums, data links directly to the system and the peripheral computers, and means of outputting information to the operators.

As is well known, the most sophisticated form of control is automatic control. All the automatic systems used in the power station controller can be divided into two groups: standard and special. Among the standard control systems we have those for power supply, temperature, velocity, etc. Such systems, developed in thermal power stations, will operate equally effectively in solar stations.

The major special automatic system of the solar station is the automatic control system for the heliostat field [2, 3]. This system must meet requirements of high accuracy and reliability in operation in various regimes. The heliostat parameters to be regulated are the azimuthal and zenith displacement angles. The required accuracy in sun tracking is on the order of several angular minutes in the reflected ray direction. The maximum rate of angular displacement of the heliostats is ≈ 50 deg/h in the zenith direction and 250 deg/h along the azimuth. The automatic control system must constantly maintain normal operation of not less than 90% of the heliostats at all times. It is necessary to ensure: system turn-on at a specified solar radiation intensity (~ 150 W/m^2), tracking of visible and invisible displacements of the sun, system switch-off upon lengthy reduction in solar radiation below a specified level, turn-on and turn-off of heliostat banks to regulate station power, return of the heliostats to their initial position, heliostat defocusing in emergency situations, placement of heliostats in a protected position under bad weather conditions, etc. The equipment operating in the open air must operate reliably over a temperature range from −30 to +40°C, at humidity levels to 100%, and also in the presence of a medium which both encourages corrosion and is dusty. Specific peculiarities of the heliostat control system are that for a tower-type generator with power output on the order of 100 MW the number of heliostats comprises 20,000-30,000; the area over which the heliostats are placed comprises several square kilometers; the maximum distance of a heliostat from the center of the station is on the order of 1000 m, and the heliostat motion rules are complex and individual.

Based upon these requirements and peculiarities of the object to be controlled, we utilize a computer for the heliostat control function. The structure used in organizing the system for control of a significant number of objects is hierarchical, with each lower level processor communicating with only one higher level processor, so that the complexity of the interconnecting data bus is proportional to the number of processors at a given level. Considering the significant fraction of capital costs associated with the heliostat field of the power station, the design process should ensure minimization of capital expense on automation equipment.

There exist centralized and decentralized principles of heliostat field control. In comparing them, it can be noted that realization of the centralized principle over the entire system leads to a growth in capital expenditure and low reliability in system operation, while there exists a limiting number of possible heliostats which can be used. The more desirable control principle is the decentralized one, with solution of a number of individual problems at a single control center.

The design of the automatic heliostat control system is determined by many factors, of which the main ones are the technical characteristics of the heliostat field and of the individual heliostats. The basic requirements for heliostats imposed by the automatic control system may be formulated as follows: the optimum heliostat should: have kinematically unrelated mutually intersecting azimuthal and zenith axes of rotation; be of balanced construction about the axes of rotation; have no limits as to angle of rotation about the axes of rotation; show minimal moments of inertia about these axes; be installed on a base which remains rigidly fixed in space during use; have backlash-free means of transmitting motion to the axes from auxilliary motors which operate smoothly; have the necessary optical characteristics together with sufficient rigidity to permit rotation rates needed in emergency situations related to the state of the thermomechanical equipment; and finally, have a gap-free central reflector section.

Nonconsideration of these requirements in construction of the heliostat complicates the automatic control system, and requires increased expenditures in construction and installation.

Block diagrams of solar station heliostat field control systems are shown in Fig. 2. Each of the variants shown has both advantages and drawbacks. French specialists favor the open loop systems which accomplish control on the basis of calculated coordinates (Fig. 2a) [4]. This variant is simpler in operation and less costly than other possible solutions of the problem. We feel that the most promising variant is that depicted in Fig. 2c. The other variants are less desirable either because of cost considerations (Fig. 2b, d) or reliabil-

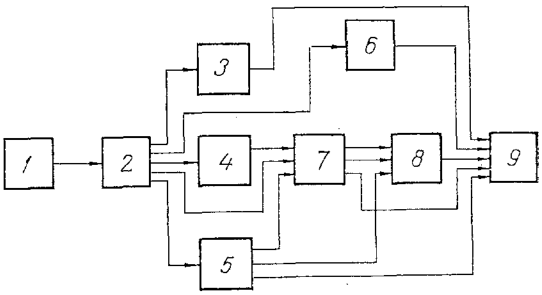

Fig. 1. Functional diagram of automated control system for one power station module: 1) automatic input and preliminary processing of information; 2) data reliability control; 3) control and recording of elementary on–off operations; 4) optimization of accumulator operation; 5) analysis of equipment states; 6) detection and evaluation of emergency situations and output of recommendations for alleviation; 7) calculation and analysis of technicoeconomic indices; 8) calculation of equipment energy characteristics; 9) presentation of current, periodic, and emergency information.

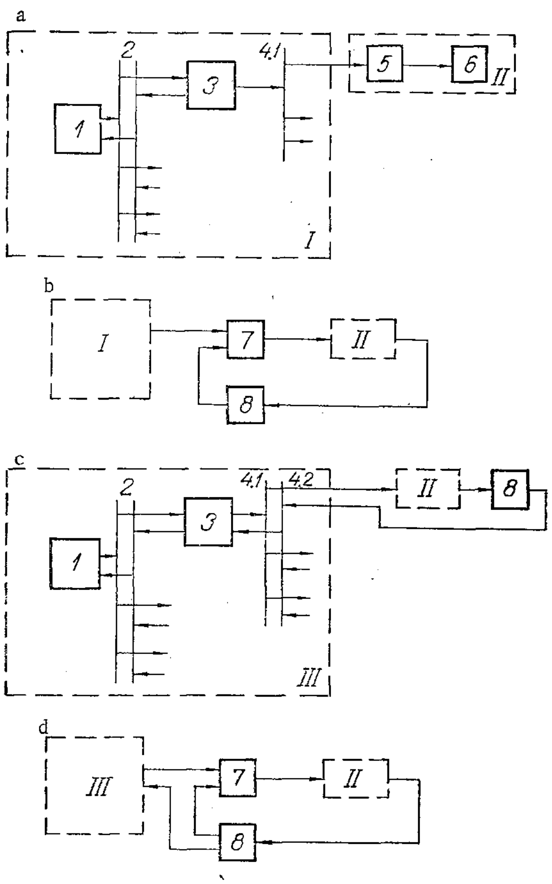

Fig. 2. Block diagram of solar station heliostat field control systems: 1) central control computer; 2) central computer input and output buses; 3) microprocessor; 4.1, 4.2) microprocessor output and input buses; 5) heliostat control devices; 6) heliostat; 7) heliostat mechanism controller circuits; 8) heliostat sensors.

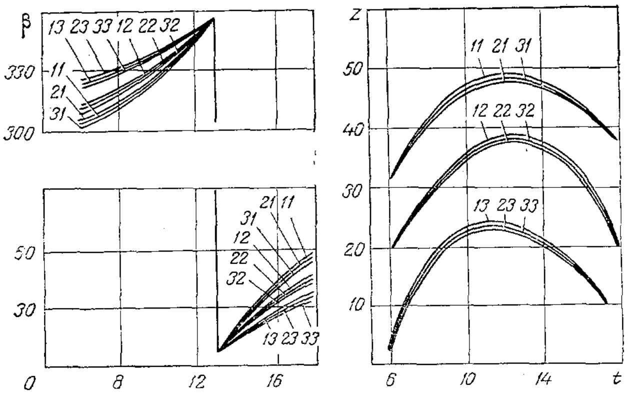

Fig. 3. Azimuthal and zenith angles of position of normal to heliostat mirror surface versus time of day and solar angle: 11, 12, 13) trajectory of heliostat 1 for $\delta = 23.5, 0, -23.5°$; 21, 22, 23) trajectory of heliostat 2 for $\delta = 23.5, 0, -23.5°$; 31, 32, 33) trajectory of heliostat 3 for $\delta = 23.5, 0, -23.5°$; β, z, deg; t, h.

ity and accuracy characteristics (Fig. 2a), etc. The circuits which drive the controllers are realized with medium and large-scale integration integrated circuits. The controller mechanisms themselves are electrical stepper drives. There is considerable interest in use of asynchronous motors for the steppers. Such motors have a number of good features which have ensured their wide use. Depending on their intended use, the sensors for the autonomous control system may be optical or nonoptical, and determine the position of the normal, axes, and base of the heliostat, etc. The most widely used sensor is of the optical type, monitoring passage of a reflected ray from the mirror surface of the heliostat. With such a sensor accurate tracking of visible and, to a certain degree, invisible (due to cloudiness) motion of the sun can be accomplished.

There are a number of scientific-research problems which arise in construction of an automatic heliostat control system. Among these are: study and establishment of principles of location and motion of heliostats which must track the sun; optimization of the structure and parameters of the automatic control system with respect to cost for a given degree of reliability; development of a special mathematical basis for the equipment complex, etc.

Of special interest are the trajectories of close-lying sun-tracking heliostats, since they are useful in developing general principles of field control. From an analysis of the equations of motion of individual solar station heliostats [2], it is evident that for a fixed solar angle the values of azimuth and zenith angles of heliostats with coordinates 1 (−450 m, 10 m), 2 (−460 m, 10 m), and 3 (−450 m, 20 m), located to the north of the tower, differ from each other over the course of a day of operation by a maximum of 1.3°, while with change in the solar declination angle from 23.5° to −23.5° the maximum difference in azimuthal coordinates of heliostat 1 (or 2, or 3) does not exceed 16°. For zenith displacements of heliostats 1, 2, 3, with change in solar declination there is a scattering of ~30° (Fig. 3). In a study of the motion of heliostats with coordinates (750 m, 20 m), (750 m, 10 m), and (740 m, 10 m), located to the south of the tower, no significant changes in the azimuth and zenith deviations noted above were observed. The results obtained were for a geographic location of the solar station at 45° north latitude.

These calculations make it possible to consider control of groups of heliostats (three or more) from a single circuit with a unified algorithm. Connection of the closest-lying heliostats into groups should be carried out on the basis of calculations of their motion while tracking the sun.

To solve the problem of group control of solar station heliostats it will be necessary to:

1) establish a scattering range of azimuth and zenith angles during operation over a specified time period;

2) use these scattering ranges for azimuth and zenith angle to create groups of close-lying heliostats, while permitting departure of individual heliostat angles out of the scattering range over brief time periods;

3) for each time segment, determine for the entire field the number of heliostats with azimuth and zenith angles outside the scattering range.

If the number of heliostats, the trajectories of which are outside the permissible range, does not exceed the admissable percentage over the given time period, then group control is effective, and thus, desirable. Use of the group control principle permits a significant reduction in the mathematical complexity of the heliostat field control system.

The operational efficiency of the solar power station is determined to a significant degree by the quality of automatic equipment operation. Results of an economic analysis of construction of the 200-MW electrical station indicate that the cost of the heliostat field can reach 50% of the cost of the entire plant, while the automatic control systems are responsible for about 25% of the cost of the heliostat field. These data show the desirability of further development of economically efficient automation measures for the solar power station.

NOTATION

β, z, azimuthal and zenith angles of normal to heliostat mirror surface; t, time; δ, solar declination.

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METHODS FOR CALCULATION OF COMPRESSIBILITY AND CRITICAL CHARACTERISTICS OF NORMAL LIQUID MIXTURES

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Rules for the concentration dependence of compressibility and critical parameters of mixtures are established, and calculation algorithms are developed.

In [1, 2] analysis of empirical material by the thermodynamic similarity method established a relationship describing the dependence of isothermal compressibility of normal nonassociating liquids $\beta_T = -\frac{1}{v}\left(\frac{dv}{dp}\right)_T$ on temperature and pressure in terms of a function of one variable, the reduced volume $\varphi = V/V_c$. In [3, 4] the possibility of extending this principle to the case of mixtures was noted. We will consider this question in detail below, commencing from a new formula

$$P \equiv \frac{\beta_T RT}{V} = 120\ \varphi^8, \tag{1}$$

which approximates the function in question for φ values from 0.28 to 0.44. A method of calculating mixture compressibility will be formulated on this basis. Data were analyzed for 10 systems from [5-10]. It developed that the V_c values for the mixtures, determined with Eq. (1) for various temperatures and pressures, were accurate to tenths of a percent. As an illustration, Table 1 presents values of V_c of the hexane–hexadecane system [6]. The mean-square scattering of the data in this example is 0.4%, which corresponds to 3% uncertainty in β_T. The V_c values determined in this manner will now tentatively be termed critical volumes. We cannot identify them with experimental values of critical volume, since the latter are known only with very high uncertainty. At the same time, it cannot be said that these values found characterize the true critical volume, and not some "pseudocritical" value. In fact, in Eq. (1) instead of φ some other reduced volume, such as V/V_0,

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