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Operation and Control of the 50-Mw Closed-Cycle Helium Turbine Oberhausen

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The Oberhausen helium turbine plant will have a multi-compartment storage system for varying the pressure level and two separate bypasses, one for speed control during isolated operation and the other for emergency shutdown. A newly developed safety system with a multiple-protection effect is provided. The report contains the results of the extensive calculation work relating to the operating behavior of the plant, as well as important layout criteria resulting therefrom.

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INTRODUCTION

The control methods applied in the existing closed-cycle air turbine plants (1)[1] are used also on the 50-MW helium turbine of Oberhausen in their basic form, with certain modifications to suit the changed conditions as exist with helium as the working medium and with the resultant specific design features of the plant.

Fig. 1 shows the circuit diagram. The helium heated in the heater, a, to 750 C is expanded in the high-pressure turbine, b, from 27.0 bar to 16.5 bar and enters the low-pressure turbine, c, at 581.8 C, in which it is expanded to 10.8 bar. Then the gas enters the heat exchanger, d, in which a portion of its heat is transferred to the cold high-pressure gas. Another portion of the heat is given off in the heating part, e', of the precooler for heating purposes. In the cooling part, e", of the precooler, the helium is cooled to 25 C; in the low-pressure compressor, f, it is compressed to the intermediate pressure of 15.48 bar, and, subsequently, it is re-cooled in the intercooler, g, to 25 C. Then the gas is compressed in the high-pressure compressor, h, to the maximum cycle pressure of 28.76 bar. After being preheated in the heat exchanger, d, it re-enters the heater, a (2).

For the turbo set, a two-shaft design was chosen. The compressors and the high-pressure turbine rotate at 5500 rpm, and the low-pressure turbine runs at the alternator speed of 3000 rpm. The two shafts are connected by a gear to establish single-shaft characteristics from the dynamical point of view. The total turbine power is splitted into the outputs of the high-pressure and the low-pressure turbine so that at the design point, a small amount of power is transmitted from the low-pressure turbine to the high-pressure shaft. As power flows in this direction also at all nonsteady conditions (e.g., at load release), a reversal of power flow in the gear is not possible.

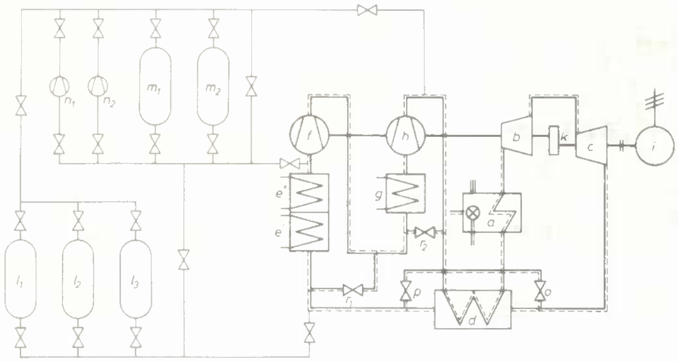
PRESSURE LEVEL CONTROL

Like all closed-cycle air turbine plants, the helium turbine plant is provided with a pressure level control system which allows any part loads to be adjusted with optimum efficiency of operation. For this the storage system shown in Fig. 1 has been developed, which serves to store circuit helium. The daily fluctuations in heat and power demand are adjusted by means of the multi-compartment storage system, which consists of the regulating reservoirs, l_1 to l_3. This system allows the pressure level to be varied without using transfer compressors and with minimum storage reservoir capacities (3). If the pressure level in the circuit is to be reduced, a certain quantity of gas is caused to flow from the tapping point downstream the HP compressor into the storage reservoirs, which are filled one after the other until the particular equilibrium pressure is attained. If the pressure level is to be raised again, the stored helium is allowed to leave the reservoirs in reverse order and to re-enter the circuit upstream the precooler. The three regulating reservoirs, l_1 to l_3, have a volume of 120 cu m each. The number and volumes of the regulating reservoirs are the results of an optimization calculation. They allow variation of inventory within limits of $\pm$ 20 percent at a power changing rate of approximately 60 percent/hr.

The storage reservoirs, m_1 and m_2, which also have a volume of 120 cu m each, are for long-term storage of the gas when the plant is to be operated at part load for a long period of time. For filling these reservoirs, the transfer compressors, n_1 and n_2, are required.

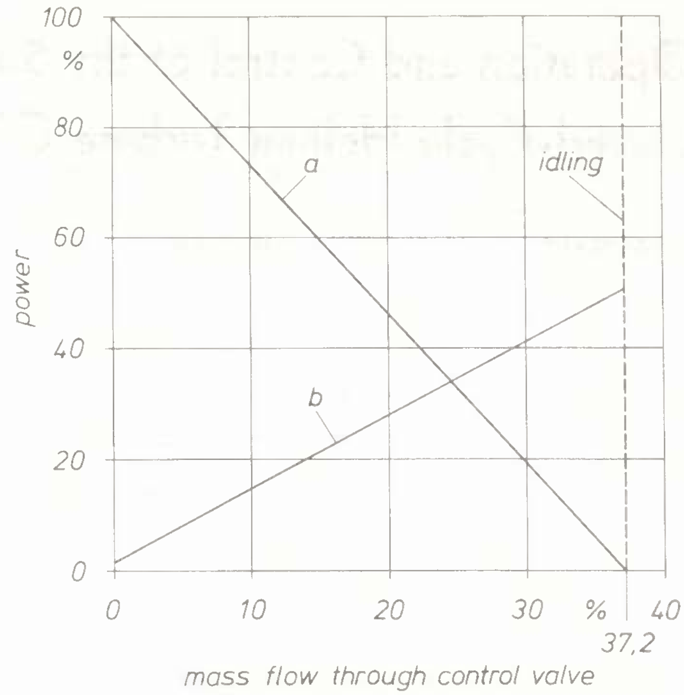
Before filling the circuit and the storage reservoirs with helium, the plant is evacuated down to 0.1 bar. Subsequently, helium is filled

[1] Numbers in parentheses designate References at end of paper.



a - heater
b - HP turbine
c - LP turbine
d - heat exchanger
e' - heating part of precooler
e" - cooling part of precooler
f - LP compressor
g - intercooler
h - HP compressor
i - alternator (starter motor)
k - gear
$l_1 \ldots l_3$ - regulating reservoirs
m_1, m_2 - storage reservoirs
n_1, n_2 - transfer compressors
o - control valve
p - shutdown valve
r_1, r_2 - recirculating valves

Fig. 1 Scheme of circuit and control



a - power at terminals
b - gear input

Fig. 2 Bypass control

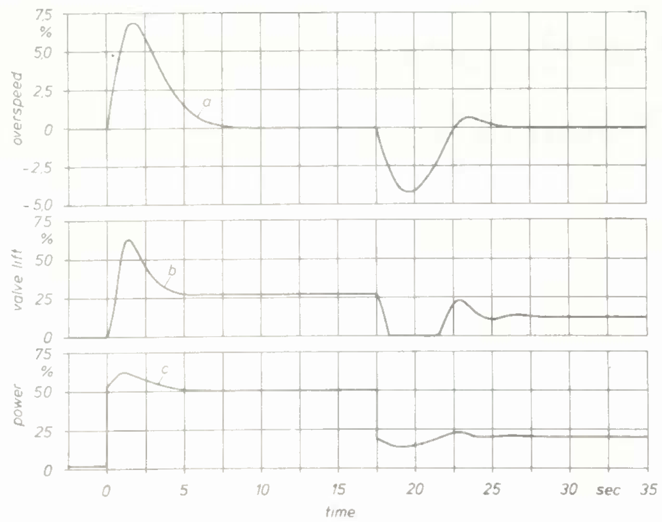
in and the residual air is extracted in the helium purification system at a pressure of approximately 3 bar.

BYPASS CONTROL

As shown in Fig. 1, two bypasses branch off the circuit downstream of the HP compressor, h. The control by-pass with the control valve o leads to the low-pressure-side heat exchanger inlet. By means of this bypass, which is known from the closed-cycle air turbines, the plant can be controlled during isolated operation and also can be kept on speed after a load release. When the bypass is opened, the turbine head decreases causing the turbine outlet temperature to rise. However, by adding the relatively cold bypass gas to the hot gas which comes from the turbine, thermal overstressing of the heat exchanger can be avoided. The bypass valve is controlled by a newly developed electro-hydraulic speed controller. As in the case of the closed-cycle air turbines (1), for better control behavior a high- and a low-pressure signal from the circuit taken as objective variables are fed into the controller.

The method of emergency shutdown, known from closed-cycle air turbines, with discharging the circuit inventory into the atmosphere, cannot be applied to helium turbines for cost reasons. Instead, in the event of disturbances the shutdown bypass valve, p (Fig. 1), is fully opened. This valve is rated to cause the pressure ratio to be reduced to the value 1 within a few seconds and the machine set to be stopped after a short time. To avoid thermal shocks, the gas bypassed in the case of emergency shutdown, which has a temperature of approximately 123 C, is led to the precooler inlet, where the nominal temperature is about 167 C. In order to protect the low-pressure-side heat exchanger inlet from excessive thermal stress due to the greatly increased turbine outlet temperature, cold gas is led to the heat exchanger inlet at the same time, by slightly opening the bypass control valve, o. This system allows the heat exchanger inlet temperature and the temperature at the heater inlet to be kept within specified limits.

The control and shutdown valves are of identical design with an outer stationary, uni-

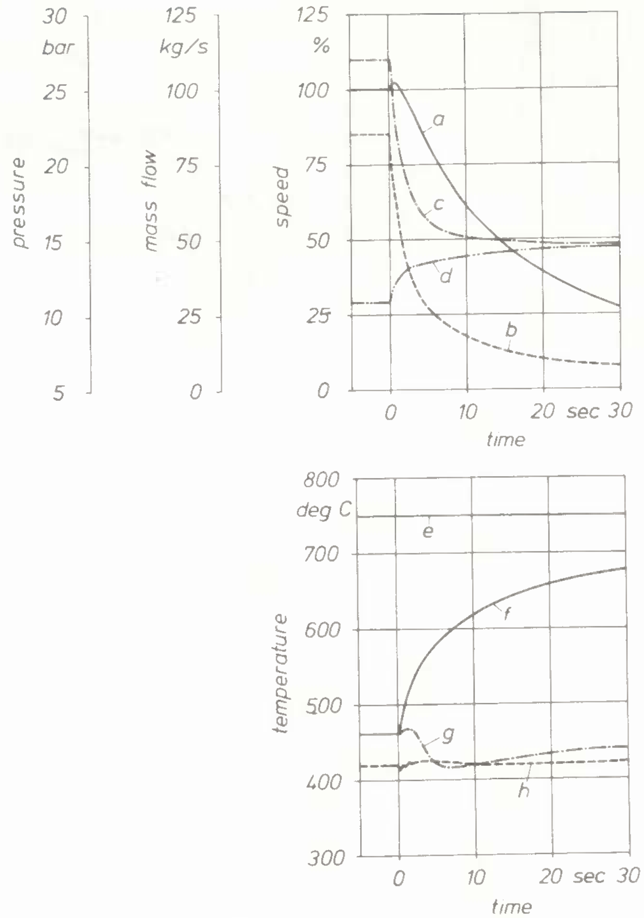


a - overspeed
b - control-valve lift
c - power input at gear shaft

Fig. 3 Calculated process of control

formly perforated cylinder and an inner cylinder which is moved in axial direction by a servomotor. This design offers several advantages over a double-seat valve: the noise level is lower, the valve closes more tightly, and the required valve characteristic is easier to realize. For the control valve, it was found that a linear characteristic curve ensures favorable results. The calculated maximum effective cross-sectional area of the control valve is 380 sq cm at full load release. As the valve also has a redundant emergency shutdown function — as explained later in this paper — it has been rated, like the shutdown valve, for an effective cross-sectional area of 600 sq cm.

Fig. 2 shows the power output at terminals and the gear power input as functions of the mass flow through the bypass control valve. In this graph, the power values are referred to the nominal power output at terminals, i.e., to 51.2 MW, and the bypass mass flow to the nominal mass flow of the HP turbine of 85 kg/sec. Both curves are for steady-state operating conditions at 100 percent mass flow, nominal speed and nominal temperatures at the turbo machine inlets. As can be seen, the power at terminals a decreases linearly and drops to zero at a bypass mass flow of 37.2 percent. At the same time, the gear input, b, rises from about 2 percent at the design point to approximately 50 percent when running idle. As it has to be taken into account that the plant will be operated —



a - speed
b - mass flow at heater outlet
c - HP-turbine inlet pressure
d - LP-turbine outlet pressure
e - heater outlet temperature
f - LP-turbine outlet temperature
g - heat exchanger inlet temperature, LP part
h - heater inlet temperature

Fig. 4 Emergency shutdown

if for a short time only — at no load, the gear had to be rated for at least this power.

For the layout of the control and safety equipment, an extensive calculating program was used, which had been developed at the institute for the calculation of the dynamic behavior of closed-cycle gas turbines within the HHT project.[2] This program considers the characteristics of the machines, the gas storage capacities of the plant components, the inertia of the gas flow, the heat-retaining capacity of the turbine blad-

[2] Development program for high-temperature reactor with helium turbine of large unit output.

ing, the dynamic processes in the internally insulated hot-gas pipe and the dynamic behavior of the heat exchanger (1, 4).

With the aid of this program, the layout power transmission of the gear, the required valve cross-sectional areas, and the handling of the bypass control valve in the emergency shutdown case were optimized. Further the controller parameters, i.e., the total amplification, the integral-action time, the time of delay, and the amplification of the pressure signals, were determined with regard to a perfect transient behavior and technical feasibility.

Fig. 3 shows a calculated process of control. From top to bottom, the overspeed, a, the related control-valve lift, b, and the power input at the gear shaft, c, are shown as functions of the time. At time zero, it was supposed that a full-load release occurred, and it was assumed that 50 percent of the nominal load was re-connected after steady-state conditions were reached again (here at t = 17.5 sec). Though during normal isolated operation abrupt connection of a load of this order is not to be expected, the mentioned value was used in the calculation in order to test the control system under extreme conditions.

During the entire control process examined, the speed, a, shows a highly damped transient response. After load release the overspeed reaches a calculated maximum of less than 7 percent and approaches the value zero quickly and aperiodically. On connection of the load the overspeed drops in the beginning, then reaches a minimum of -4.2 percent and, after a period of minor overshoot, quickly returns to zero. The somewhat less favorable transient behavior on load connection has its reason in the valve lift, b, which, after connection of the load, temporarily drops to zero and thus causes unsteadyness in the control operation. In this case, the valve lift is related to the maximum lift at full valve opening.

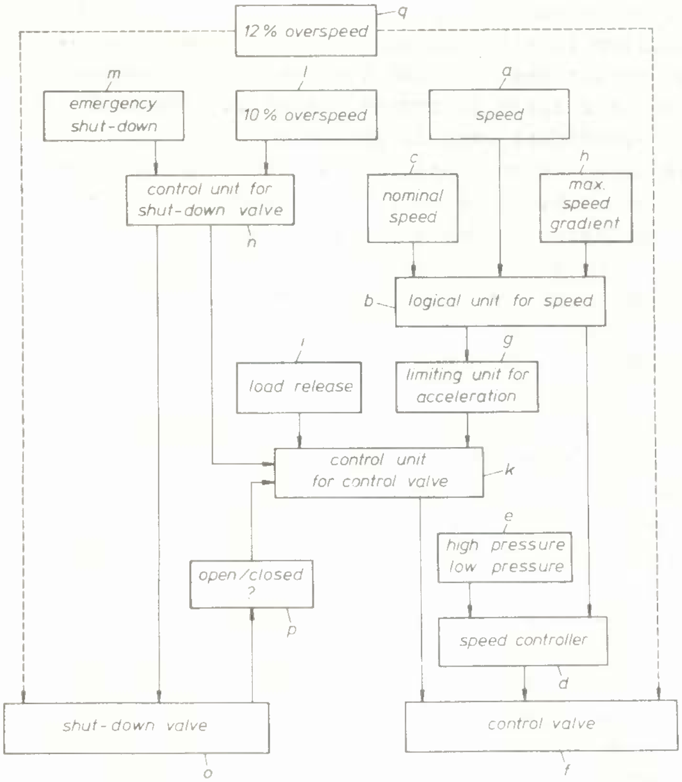
At the moment of load release (t = 0 sec), the power input, c, at the gear shaft first rises abruptly from 2 to 54 percent of the nominal power at terminals. Subsequently, it rises further and reaches a calculated maximum of 63 percent. The steady-state value of about 50 percent, which is reached after load release, corresponds with the value at idling in Fig. 2. One can see from Fig. 3 that the load on the gear is higher in the dynamic case than it is at steady idling, a fact which has been considered in the layout.

Fig. 4 shows the result of a dynamic calculation for the event of emergency shutdown occurring at nominal speed. At the time t = 0 sec, the alternator is disconnected from the mains, the heater is turned off and the emergency shutdown valve is fully opened with a maximum effective cross-sectional area of 500 sq cm. The speed, a (Fig. 4, at the top), drops within 30 sec to approximately 27 percent, and the mass flow, b, at the heater outlet decreases to about 8 percent. The pressures upstream and downstream of the two turbines, c and d, quickly approach an equilibrium value of 14.6 bar. This is the pressure for which the pressure shells of the heat exchanger and precooler, as well as the casings of the LP turbine and LP compressor, had to be rated in consideration of the operating temperatures. The pressure gradient in the internally insulated hot-gas pipe resulted at a maximum of 6.5 bar/sec in the emergency shutdown case.

The curves of some temperatures in the emergency shutdown case are shown in Fig. 4 at the bottom. As according to curve b the heater mass flow decreases considerably and the heater is turned off at time zero, the heater outlet temperature or the HP turbine inlet temperature, e, remains almost constant during the period of 30 sec considered. Since the expansion ratio decreases, the turbine outlet temperatures rise, especially the temperature, f, at the LP turbine outlet. However, the relatively high thermal capacity of the two turbines has the effect that the temperature balancing processes take place more slowly than the corresponding pressure balancing processes. To avoid thermal overstressing of the heat exchanger, as referred to previously, a small bypass stream is added to the gas leaving the LP turbine at increasing temperature, so that the mixed temperature, g, at which the gas enters the heat exchanger, neither exceeds the layout temperature to any remarkable extent nor has an inadmissibly high gradient. This measure also has a favorable effect on the heater inlet temperature, h, which remains almost unchanged.

SAFETY SYSTEM

The emergency shutdown valve and the control valve laid out as standby shutdown valve provide multiple protection of the plant. Fig. 5 is a diagrammatic representation of the safety system, the operation of which is explained hereafter by a few examples. In the case of load release, the speed, a, rises. The logical unit for speed b determines the deviation from the nominal speed, c, and passes the resulting signal to the speed controller, d, which also receives a



electric signals
hydraulic signals

Fig. 5 Safety system

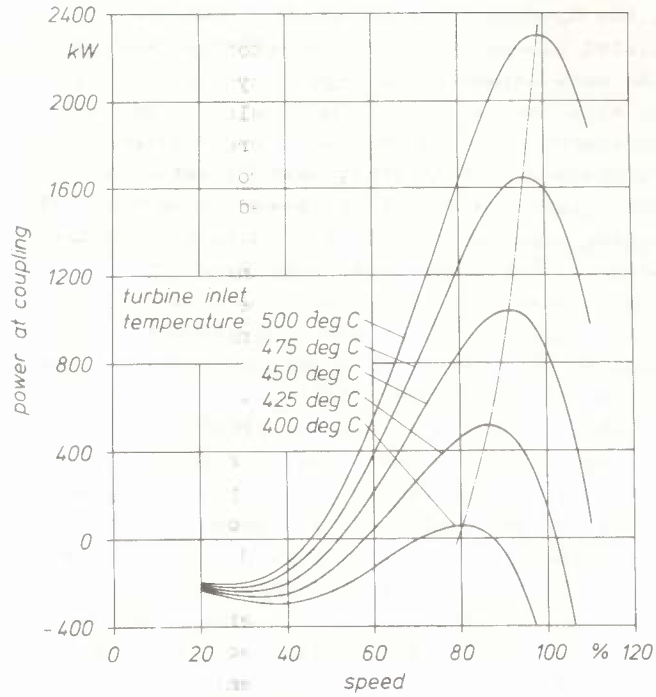


Fig. 6 Start-up of the turbine

high-pressure signal and a low-pressure signal from the circuit, e, and acts upon the control valve, f. The speed controller was rated to master even full-load release without the emergency shutdown speed of 110 percent being exceeded. For safety reasons, however, a limiting unit for acceleration, g, which receives a signal from the logical unit for speed, b, if a certain speed gradient, h, is exceeded, and a load release relay, i, are provided. The output signals of both these units open the control valve via the unit, k, for a short, adjustable time interval. Then the speed controller is brought into action and controls the machine set to nominal speed.

If, owing to a defect in this control system, the overspeed exceeds the value of 10 percent (l) or if the turbo set has to be shut down because of any other defect, m (e.g., defects in the oil system, bearing damage, shaft vibration, defects in the seal-gas system etc.), the shutdown valve, o, is fully opened via the control unit, n. At the same time, the control device, k, receives a command for the bypass valve, f, to be opened to a specific extent according to an adjustable function. If the shutdown valve remains closed owing to some damage, the reply signal, p, passed to the control device, k, makes the control valve take over the function of the shutdown valve.

The part of the safety system described in the foregoing works with electric signals, but the valves are operated hydraulically. Therefore, in order to be on the safe side in the event of an electric failure, a hydraulic shutdown device, q, is provided in addition. This responds at 12 percent overspeed and acts upon both valves direct in that it opens them entirely. The valve cross-sectional areas are rated to prevent a speed maximum of 115 percent being exceeded even if only one valve opens.

START-UP AND RUN-DOWN

For start-up of the Oberhausen helium turbine plant, no separate starting motor is used as with the existing closed-cycle air turbines. Instead, the machine set is started with the aid of the alternator, which is operated via a starting system as a motor. After reaching a certain speed, which depends on the turbine inlet temperature and the circuit inventory, the machine runs up without the aid of the starting system and is then controlled via the speed control system to the alternator speed of 3000 rpm. Subsequently, the alternator is synchronized with the regional power supply system. The frequency and the electric phase relationship are adjusted by means of a fine-control valve, which is mounted parallel to the control valve. During run-up, in the lower speed range, the compressor bypass valves, r_1 and r_2 (Fig. 1), are opened to prevent both surging of the compressors and operation within the range of extensive flow separation for a longer time. For the rest, the start-up operation is the same as that with the existing closed-cycle air turbines (5).

Fig. 6 shows the result of a calculation for the start-up behavior of the plant. Therein the power at coupling is plotted over the speed at an inventory of 20 percent and at several HP turbine inlet temperatures between 400 and 500 C. As can be seen, the coupling power is negative at the beginning, owing to the mechanical losses and the still low machine efficiencies. With increasing speed, the coupling power rises. When the power at coupling is zero, the self-sustaining speed is reached: At this point, the turbine power is just as high as the sum of the compressor power consumption and the power losses. One can see that the self-sustaining speed depends on the HP turbine inlet temperature. At a temperature of 500 C at turbine inlet, it is reached at a relatively early stage, at temperatures below 400 C, it is not attained at all. The power curves show distinct peaks — due to the influence of the turbine efficiencies — which, with rising turbine inlet temperature, move in the direction of higher speeds. For this plant, it is advantageous for several reasons to start up the machine at a turbine inlet temperature of approximately 450 C:

1 The self-sustaining speed will be reached relatively early (approximately 52 percent).

2 At low speeds, the low-pressure-side heat exchanger inlet temperature, being nearly equal to the turbine inlet temperature according to the low expansion ratio, is not above the layout value of 460 C.

3 The coupling power is still positive on reaching the nominal speed, so that the machine after disconnection of the starting system can be taken over by the internal control system.

The run-down procedure is about the same as that with the existing closed-cycle air turbines (5). The first step is to reduce the output at terminals by reducing the inventory and decreasing the HP turbine inlet temperature. When the power at terminals is at zero, the alternator is disconnected from the mains. Then, by further reducing the turbine inlet temperature, the speed is reduced as well. The critical speeds are quickly passed by opening the compressor bypass valves. In addition, the machine set can be electrically braked with the aid of the starting system. During cooling down of the plant, the turbo set is rotated at low speed by the starting system.

SUMMARY

The Oberhausen helium turbine plant is equipped with a three-compartment storage system for pressure level control, which allows the power to be varied by ± 20 percent with a gradient of 60 percent/hour without the aid of transfer compressors. Two further reservoirs, which are filled by compressors, allow long-term storage of circuit helium for longer periods of part-load operation. For quick power variation and for speed control during isolated operation, a control bypass system is designed. By opening a second bypass the plant can be shut down immediately. The equilibrium pressure in the circuit in that case had to be considered in the layout of the plant components. For operating the bypasses, a safety system is provided which covers all possible failures. A newly developed electro-hydraulic controller allows optimum speed control behavior both after a load release and during isolated operation. For start-up of the machine, the alternator is operated as a motor with the aid of a starting system. The starting system can also be used for braking the machine set during run-down of the plant.

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