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(54) **METHOD OF CONTROLLING A STEAM TURBINE AND STEAM TURBINE PLANT**

(57) A method of controlling a steam turbine comprises: defining a simplified model (M) of a rotor (5c) of a steam turbine in the form of a homogeneous and isotropic cylinder; determining a stress distribution in the rotor (5c) from parameters of the simplified model (M) and temperature values (ST) of steam (Q_{HP}) supplied to

the steam turbine (5); comparing the stress determined in the rotor (5c) with a stress threshold (σ_{TH}); and controlling the steam turbine (5) on the basis of a comparison between the stress determined in the rotor (5c) and the stress threshold (σ_{TH}).

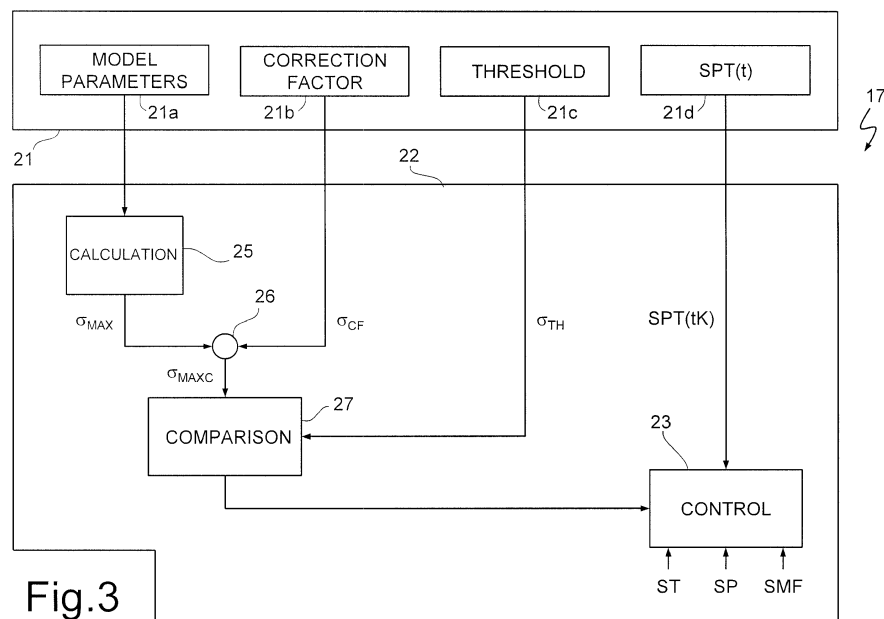


Fig.3

Description

[0001] The present invention relates to a method of controlling a steam turbine and steam turbine plant.

[0002] As is known, the start-up phase of a steam turbine may prove critical because of the forces induced on the rotor by both the inertia of the system and the considerable temperature fluctuations. The temperature fluctuations are due to the fact that the steam temperature should increase to a steady state value in a relatively short time, considering the mass and the geometry of the rotor.

[0003] In order to prevent problems and conditions that could result in damage or premature ageing of the rotor, profiles for load acceptance and steam temperature increase during equipment start-up have been studied which ensure, at least theoretically, that dangerously high stresses are avoided. It is however appropriate to maintain monitoring of the rotor temperature during operation and implement control actions to reduce stress levels when necessary.

[0004] A significant problem derives from the difficulty of detecting the temperature distribution in the rotor, which is not suitable to accommodate sensors. In order to overcome this, temperature estimates derived from measurements on the stator part are normally used. Estimates of this type are however not very precise and have a significant margin of error. Hence, on the one hand the limited precision makes it necessary to maintain a conservative approach in the design of the profiles for load acceptance and temperature increase, to the detriment, however, of equipment performance. On the other hand, even a reasonably conservative approach cannot prevent with sufficient confidence the occurrence of anomalous conditions as a result of which danger or damage may occur because of stresses inside the rotor. Control actions based on estimates derived from stator temperature measurements may thus not be sufficient to respond in a timely manner and to ensure that the machine is operated in conditions of safety.

[0005] The purpose of the present invention is therefore to provide a method of controlling a steam turbine and steam turbine plant that make it possible to overcome or at least mitigate the limitations described above.

[0006] According to the present invention a method of controlling a steam turbine and steam turbine plant is provided as defined respectively in claims 1 and 9.

[0007] The present invention will now be described with reference to the accompanying drawings which illustrate a non-limiting embodiment example, wherein:

- figure 1 is a simplified block diagram of a steam turbine plant in accordance with an embodiment of the present invention;
- figure 2 illustrates a simplified model used in the plant of figure 1;
- figure 3 shows a more detailed block diagram of a portion of the plant of figure 1;

- figure 4 is a graph that illustrates quantities relating to the plant of figure 1.

[0008] As shown in figure 1, a combined cycle power plant for the production of electrical energy comprises a gas turbine set 3, a steam turbine 5, two generators 8, 9, respectively coupled to the gas turbine set 3 and the steam turbine 5 and connected to a distribution network (not shown), a heat-recovery boiler 10, which operates as a steam generator, a condenser 11 and a control apparatus 12. The plant 1 also has an actuator assembly 13 and an actuator assembly 14, on both of which the control apparatus 12 acts so as to respectively control the gas turbine set 3 and the steam turbine 5.

[0009] The gas turbine set 3 produces a flow of hot exhaust gases, which is conveyed to the heat-recovery boiler 10 and is used for the production of steam.

[0010] The steam turbine 5, which in the example described comprises a high pressure section 5a and a medium-low pressure section 5b, receives a flow of high-pressure steam Q_{HP} and a flow of medium-low pressure steam Q_{LP} from the heat-recovery boiler 10 and supplies a flow of steam to the condenser 11 through the exhaust of the medium-low pressure section 5b and through a bypass system of a known type and not shown here for simplicity.

[0011] The condenser 11 cools the steam received from the steam turbine, causing the steam to condense.

[0012] The control apparatus 12 comprises a plant regulator 15, a gas turbine regulator 16, a steam turbine regulator 17 and a data acquisition interface 18, for receiving measurements from sensors and transducers of the plant 1 indicating the status of the plant 1 itself. Through the data acquisition interface 18, in particular, the control apparatus 12 receives from a sensor assembly 20: a temperature signal ST, indicating the steam temperature at an inlet to the high pressure section 5a of the steam turbine 5; a pressure signal SP, indicating the steam pressure at an inlet to the high pressure section 5a; and a flow signal SMF, indicating the flow rate Q_{HP} of steam supplied to the high pressure section 5a of the steam turbine 5.

[0013] In order to control the plant 1, the control apparatus 12 acts on the actuator assembly 13 of the gas turbine set 3, which may comprise fuel feed valve actuators and inlet guide vane (IGV) actuators, and on the actuator assembly 14 of the steam turbine 5, which may comprise inlet valve actuators 14a, 14b for the stages 5a, 5b of the steam turbine 5, bypass valve actuators 14c and boiler attemperators 14d.

[0014] The plant regulator 15 determines a general power reference (set-point) W_M for the entire plant 1 and, furthermore, determines a partial power reference W_{TG} for the gas turbine 3, by subtracting the power supplied by the steam turbine 5 from the general power reference W_M (the steam turbine 5 normally operates in sliding pressure conditions and is not choked).

[0015] The gas turbine regulator 16 receives the partial

power reference W_{TG} and acts on the actuator assembly 13 so that the gas turbine 5 provides the required power.

[0016] The steam turbine regulator 17 supervises the operating conditions of the steam turbine 5 and intervenes in the start-up phases of the plant 1 or as a result of abnormal operating conditions, as described below, in order to maintain the desired pressure, temperature and flow rate conditions for the steam fed to the steam turbine 5.

[0017] With reference to figure 2, the steam turbine regulator 17 is based on the use of a simplified model of the rotor 5c of the steam turbine 5 to determine the temperature distribution and the stress distribution. The rotor 5c is represented by the simplified model M in the form of a homogeneous and isotropic cylinder (a cross-section of which is shown in figure 2) with uniform thermal conductivity, immersed in a steam flow with working temperature TW set at a distance DB from the axis A of the rotor 5c itself. The rotor 5c may be represented with a radius R0 given by an average of the distance of the rotor blades from the axis A in the high pressure section 5a. Furthermore, the working temperature TW is variable in time, for example according to a programmed profile. The working temperature TW, which defines a boundary condition for calculating the temperature distribution of the rotor 5c via the simplified model M, is determined on the basis of the temperature signal ST of the steam at an inlet of the high pressure section 5a of the steam turbine 5.

[0018] It has also been observed by the inventors that the approximate values of the stresses determined on the basis of the simplified model M described are in a constant ratio with the values of the same stresses as determined accurately using, for example, finite element methods. In other words, the actual values of the stresses can be obtained with good approximation by the values calculated with the simplified model M of the rotor 5c by applying a correction factor which is constant and independent of temperature. The use of the simplified model M to determine temperature distributions and stress distributions does not represent a significant increase as regards the processing capacity of the entire system. It is therefore possible to monitor in real time conformity of instantaneous stresses with the defined threshold criteria. The correction factor may be determined once and for all during the design phase.

[0019] The steam turbine regulator 17 is configured to determine the temperature distribution in the rotor 5c on the basis of the distance from the axis A and of the steam temperature TB, to determine the stresses (σ) inside the rotor 5c on the basis of the temperature distribution, to determine a critical region of maximum stress and to compare the maximum stress in the critical region with a reference threshold.

[0020] With reference to figure 3, the steam turbine regulator 17 comprises a memory unit 21 and a processing unit 22.

[0021] The memory unit 21 comprises various sec-

tions, in which information is stored for use during operation of the steam turbine regulator 17, including:

a parameters section 21a containing the parameters of the simplified model M of the rotor 5c for the calculation of the temperature distribution and the stress distribution (for example, and not exhaustively, radius, elastic modulus, density, thermal conductivity of the rotor);

a correction section 21b, containing a correction factor σ_{CF} for the calculation of stresses;

a threshold section 21c, containing a stress threshold σ_{TH} ; and

a profiles section 21d, containing at least one transient profile SPT(t), representing a series of values of steam temperature references SPT(tK) for the actuator assembly 14 of the steam turbine 5 during a transient (in particular, a start-up transient; the profiles section 21d may contain additional transient profiles for different transient situations that may occur during operation of the steam turbine 5, other than profiles for load acceptance, in addition to the temperature profiles).

[0022] The processing unit 22 comprises a control module 23, a calculation module 25, a correction module 26 and a comparison module 27.

[0023] The control module 23 receives the transient profile SPT(t) and sets a series of values of steam temperature references SPT (tK) for the steam fed to the high pressure section 5a of the steam turbine 5 in accordance with the transient profile SPT(t). In addition, based on the temperature signal ST, the pressure signal SP and the flow signal SMF received from the data acquisition interface 18, the control module 23 acts on the actuator assembly 14 of the steam turbine 5, to obtain operating conditions in accordance with the transient profile SPT(t).

[0024] The calculation module 25 receives the parameters of the simplified model M of the rotor 5c from the parameters section 21a of the memory unit 21 and the temperature signal ST from the data acquisition interface 18. The calculation module 25 is configured to determine the temperature distribution inside the rotor 5c (represented as a homogeneous and isotropic cylinder) starting from the temperature of the steam measured via the temperature signal ST, which is assigned as the working temperature TW. The calculation of the temperature distribution may be based on a solution of the heat equation for a homogeneous and isotropic cylindrical body.

[0025] The calculation module 25 is further configured to determine a distribution of the stresses from the calculated temperature distribution and the load condition of the rotor 5c. The calculation module 25 further determines a critical region of the rotor 5c in which there is a maximum instantaneous stress σ_{MAX} and iteratively calculates the value of the maximum instantaneous stress σ_{MAX} .

[0026] The value of the maximum instantaneous stress σ_{MAX} is supplied to the correction module 26, which receives the correction factor σ_{CF} from section 21c of the memory 21. The correction module 26, for example a multiplier module, determines a value of the corrected maximum instantaneous stress σ_{MAXC} from the value of the maximum instantaneous stress σ_{MAX} and the correction factor σ_{CF} .

[0027] The value of the corrected maximum instantaneous stress σ_{MAXC} is then compared by the comparison module 27 with the stress threshold σ_{TH} received from section 21c of the memory 21. The stress threshold σ_{TH} may be determined based on a limit region, for example defined on the basis of Von Mises or Tresca criteria.

[0028] If the value of the corrected instantaneous maximum stress σ_{MAXC} exceeds the stress threshold σ_{TH} , intervention occurs on the control module 23, for example to correct or stop the control action, so as to avoid operating conditions that are inappropriate or that could potentially cause damages to the rotor 5c. In particular, knowledge of the instantaneous stress state also allows correction of the steam attemperation in real time in order to optimise start-up. The corrections make it possible to react to any unexpected deviations with respect to the stored and selected transient profiles.

[0029] The processing of transient profiles may be advantageously performed off-line once again using the simplified model M of the rotor 5c. In particular, it has been observed that, when the rotor 5c has a uniform temperature (and is therefore in a condition of low stress), the metallic material of which it is constituted can be placed in contact with steam at a significantly higher temperature. On the other hand, when the rotor 5c is in conditions of high stress, i.e. with a high internal temperature gradient, contact with hot steam must be avoided. Furthermore, for very low steam flow rates, the heat transfer coefficient already assumes values that are so high that the temperature of the metal surface of the rotor 5c is close to the temperature of the steam. For this reason, limitation of the steam flow rate is not very effective in controlling thermomechanical stress, while control of the steam temperature has practically immediate effects on the surface temperature and thus on the thermal stress of the rotor 5c. Also in the light of the comments just made, various transient profiles SPT(t) may be defined and, after verifying the internal stress distributions and the compatibility with stress thresholds for each temperature reference SPT(tK) defining the transient profiles SPT(t) (i.e. checking that the maximum stress corresponding to each temperature reference SPT(tK) of the transient profile SPT(t) is lower than the threshold stress σ_{TH}), one or more optimal profiles may be selected that make it possible to combine a large margin of safety and reduced transient times. The response of the equipment can thus be improved without impacting safety. Selected profiles may then be stored in the memory 21 and recalled when needed.

[0030] Figure 4 shows a comparison between maxi-

mum instantaneous stresses during the steam turbine start-up phase carried out in a conventional way (dashed line) and those with steam temperature control according to a given profile as described above (solid line). The conventional start-up causes a peak of high stress, albeit of short duration, while starting up with temperature control according to the invention is smoother and has a much lower maximum stress value. Taking into account that the life expended for low cycle fatigue depends mainly on the maximum value attained by the stress, start-up with the temperature control described is much less onerous for the rotor.

[0031] Alternatively, using a different profile, it is possible to reduce load acceptance times without causing critical stresses inside the rotor.

[0032] Finally, it is evident that the method and the apparatus described may be subject to modifications and variations without departing from the scope of the present invention as defined in the appended claims.

Claims

1. A method of controlling a steam turbine comprising:

defining a simplified model (M) of a steam turbine rotor (5c) in the form of a homogeneous and isotropic cylinder;
determining a stress distribution in the rotor (5c) from parameters of the simplified model (M) and from temperature values (ST) of steam (Q_{HP}) supplied to the steam turbine (5);
comparing the stress determined in the rotor (5c) with a stress threshold (σ_{TH}); and
controlling the steam turbine (5) based on the comparing the stress determined in the rotor (5c) and the stress threshold (σ_{TH}).

2. The method according to claim 1, wherein determining the stress distribution comprises:

determining a temperature distribution in the simplified model (M) of the rotor (5c) from the temperature values (ST) of the steam (Q_{HP}) supplied to the steam turbine (5);
determining an approximate stress distribution in the simplified model (M) of the rotor (5c) from the temperature distribution in the simplified model (M) of the rotor (5c); and
applying a programmed correction factor (σ_{CF}) to the approximate stress determined, the correction factor being constant and independent of the temperature.

3. The method according to claim 2, wherein the correction factor (σ_{CF}) is a multiplying factor.

4. The method according to any one of the foregoing

claims, wherein controlling the steam turbine (5) comprises:

- setting a temperature reference ($SPT(tK)$) for the steam (Q_{HP}) supplied to the steam turbine (5);
 - detecting the temperature values (ST) of the steam (Q_{HP}) at an inlet of the steam turbine (5); and
 - acting on an actuator assembly (14) of the steam turbine (5) to take the detected temperature values (ST) to the set temperature reference ($SPT(tK)$).
- 5. The method according to claim 4, wherein determining a stress distribution in the rotor (5c) comprises iteratively determining a maximum instantaneous stress (σ_{MAX}) and controlling comprises acting on the actuator assembly (14) of the steam turbine (5) so as to limit the temperature of the steam (Q_{HP}) supplied to the steam turbine (5) if the maximum instantaneous stress (σ_{MAX}) is greater than the stress threshold (σ_{TH}).
- 6. The method according to claim 5, wherein the actuator assembly (14) comprises boiler attemperators (14d) and acting on the actuator assembly (14) of the steam turbine (5) so as to limit the temperature of the steam (Q_{HP}) comprises acting on the boiler attemperators (14d).
- 7. The method according to any one of claims 4 to 6, comprising:
 - defining at least one transient profile ($SPT(t)$), comprising a sequence of temperature references ($SPT(tK)$);
 - determining the stress distribution in the rotor (5c) from the parameters of the simplified model (M) and from the temperature values (ST) of the steam (Q_{HP}) supplied to the steam turbine (5) for each temperature reference ($SPT(tK)$) of the transient profile ($SPT(t)$);
 - comparing the stress determined in the rotor (5c) for each temperature reference ($SPT(tK)$) of the transient profile ($SPT(t)$) with the stress threshold (σ_{TH}); and
 - storing the transient profile ($SPT(t)$) if the stress determined in the rotor (5c) for each temperature reference ($SPT(tK)$) of the transient profile ($SPT(t)$) is lower than the stress threshold (σ_{TH}).
- 8. The method according to claim 7, wherein the temperature reference ($SPT(tK)$) is selected in accordance with the transient profile ($SPT(t)$).
- 9. A steam turbine plant comprising:

a steam turbine (5);
 a sensor assembly (20), configured to provide a temperature signal (ST), indicating a steam temperature at an inlet of the steam turbine (5);
 a memory unit (21), containing parameters of a simplified model (M) of a rotor (5c) of the steam turbine (5) in the form of a homogeneous and isotropic cylinder; and
 a processing unit (22) configured to determine a stress distribution in the rotor (5c) from the simplified model (M) and from the temperature signal (ST), to compare the stress determined in the rotor (5c) with a stress threshold (σ_{TH}) and to control the steam turbine (5) based on comparing the stress determined in the rotor (5c) with the stress threshold (σ_{TH}).

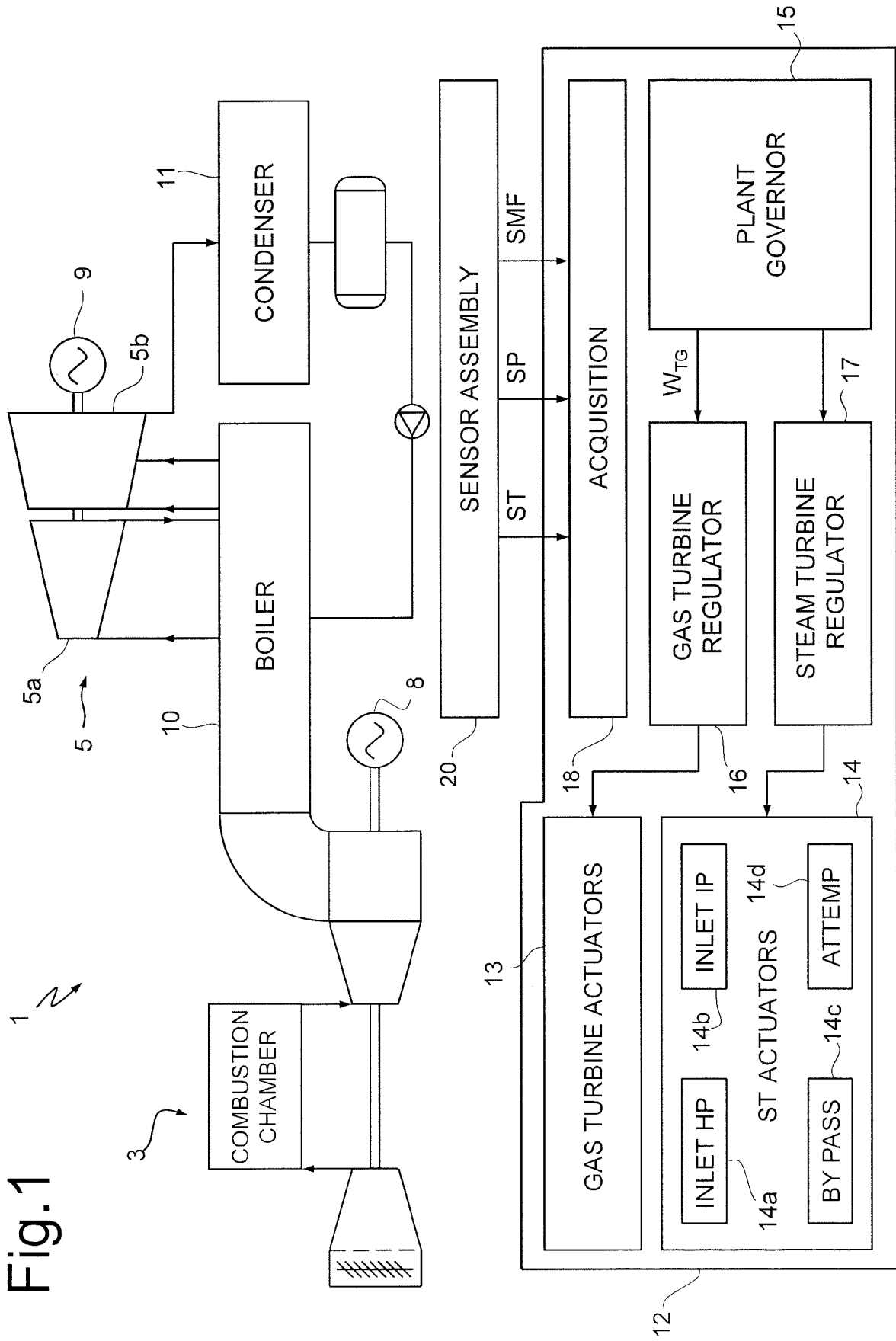
- 10. The plant according to claim 9, wherein the processing unit (22) comprises:

a calculation module (25), configured to determine a temperature distribution in the simplified model (M) of the rotor (5c) from the temperature signal (ST) and to determine an approximate stress distribution in the simplified model (M) of the rotor (5c) from the temperature distribution in the simplified model (M) of the rotor (5c); and
 a correction module (26), configured to apply a programmed correction factor (σ_{CF}) to the approximate stress determined, the correction factor being constant and independent of the temperature.

- 11. The plant according to claim 9 or 10, wherein the processing unit (22) comprises a control module (23) configured to act on an actuator assembly (14) of the steam turbine (5) on the basis of a temperature reference ($SPT(tK)$) and of the temperature signal (ST).
- 12. The plant according to claim 11, wherein the actuator assembly (14) comprises boiler attemperators (14d) and the control module (23) is configured to act on the boiler attemperators (14d) so as to limit the temperature of the steam (σ_{HP}).
- 13. The plant according to claim 11 or 12, wherein:

the memory unit (21) comprises at least one transient profile ($SPT(t)$), defined by a sequence of temperature references ($SPT(tK)$) selected so that the stress determined in the rotor (5c) for each temperature reference ($SPT(tK)$) of the transient profile ($SPT(t)$) is lower than the stress threshold (σ_{TH}); and
 the control module (23) is configured to select the temperature reference ($SPT(tK)$) in accordance with the transient profile ($SPT(t)$).

Fig. 1



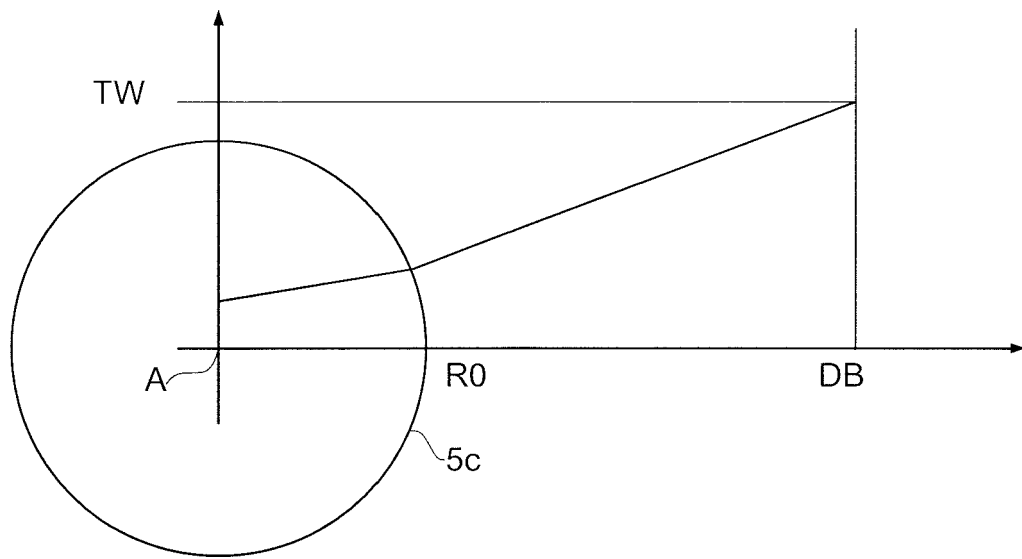


Fig.2

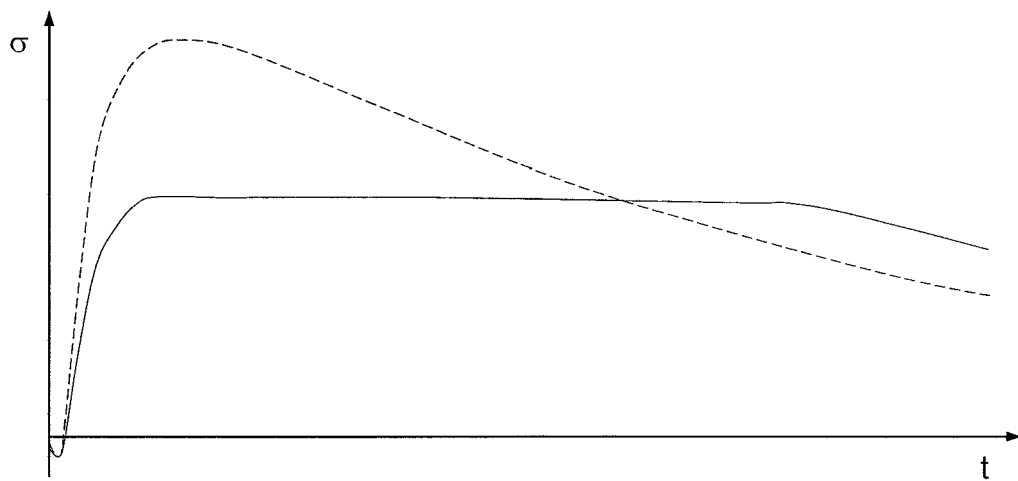
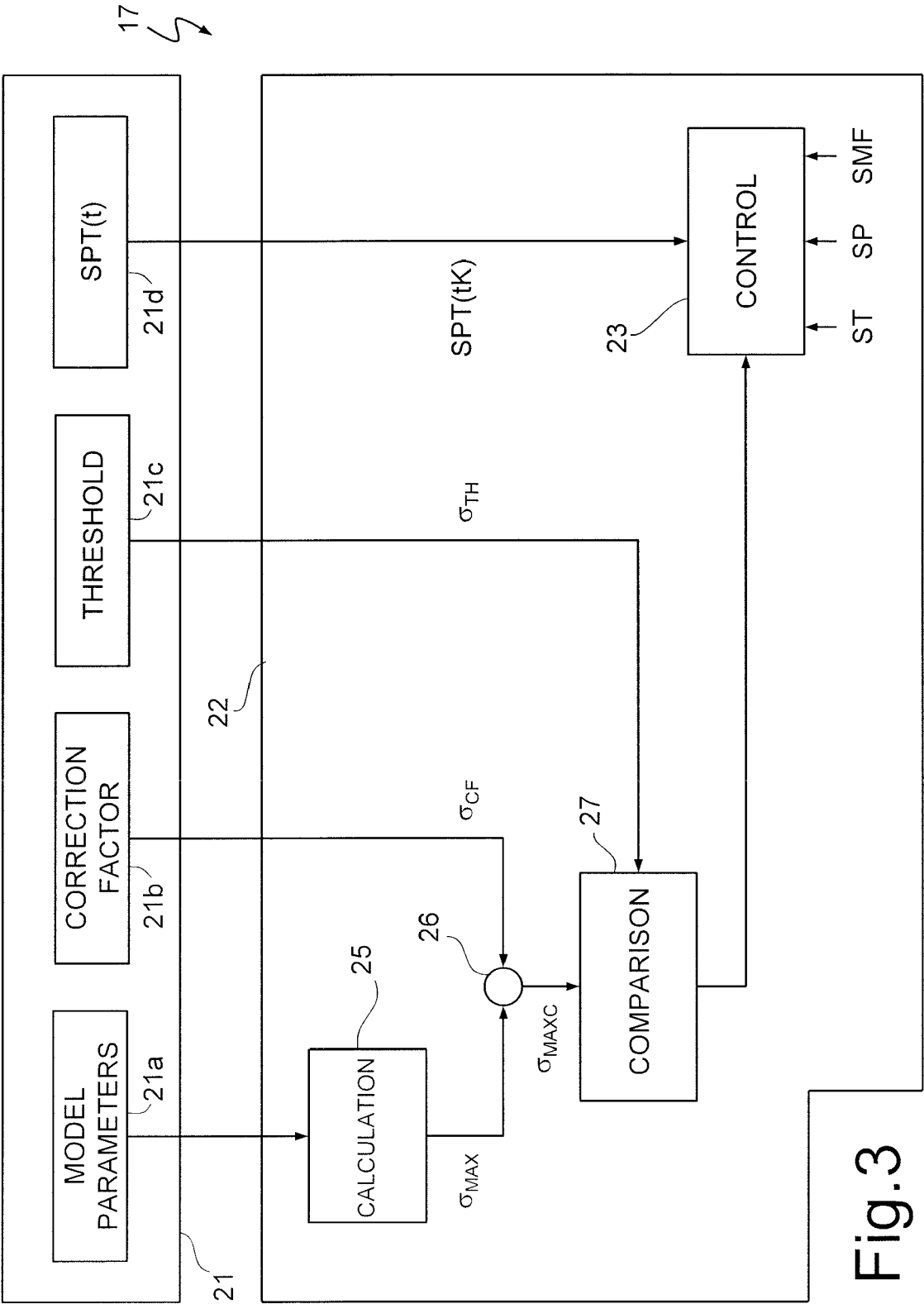


Fig.4





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Place of search Munich		Date of completion of the search 14 March 2017	Examiner Zerf, Georges
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