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(71) Applicant: **Energy Control Technologies, Inc.**
Urbandale, IA 50322 (US)

(72) Inventors:
- **Narayanan, Krishnan**
West Des Moines, IA 50266 (US)
- **Reinke, Paul**
West Des Moines, IA 50266 (US)

(74) Representative: **Walker, Ross Thomson**
Forresters IP LLP
Skygarden
Erika-Mann-Strasse 11
80636 München (DE)

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(54) **METHOD OF ANTI-SURGE PROTECTION FOR A DYNAMIC COMPRESSOR USING A SURGE PARAMETER**

(57) A method of surge protection for a dynamic compressor (12) that has a corresponding compressor map (32). A control system continually calculates an equivalent polytropic head parameter heq in order to define a surge limit line (38). The system then calculates a control parameter and determines the distance of the control parameter from the surge limit line wherein the control parameter is dynamic to changes in compressor load and invariant to changes in suction conditions and gas compressibility. As a result of the distance of the control parameter to the surge limit line, a surge valve (20) of the dynamic compressor is actuated to prevent surge.

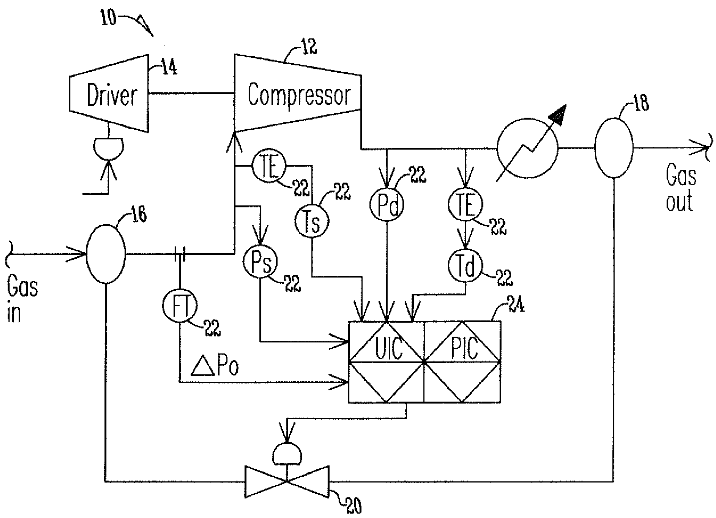

Fig.1

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Description

BACKGROUND OF THE INVENTION

[0001] The present invention is directed toward a dynamic compressor. More specifically, the present invention is directed toward a method of surge protection utilizing an equivalent map surge parameter.

[0002] A typical dynamic compressor has a gas inlet and a gas outlet wherein the compressor is driven by a compressor driver so that the gas, while flowing through the compressor, is compressed. A problem associated with dynamic compressors is the amount of gas that passes through the compressor. Specifically, if an insufficient amount of gas flows through the compressor, a surge occurs within the system causing damage to the compressor. Because of the high price of compressors great care must be taken to ensure that compressors are not damaged.

[0003] To minimize damage to compressors as a result of lack of gas flow at an inlet an anti-surge or recycling valve is utilized by dynamic compressors to take gas from the outlet of the compressor and recycle it back to the inlet of the compressor to ensure that there is always sufficient gas flowing though the compressor to prevent surges from occurring.

[0004] As a result of the need to protect against surge, control systems have been provided to control the operation of the anti-surge valve. Compressor surge control systems (also known as anti-surge controllers) use a PID controller for regulating the anti-surge valve when flow rate decreases below a predefined point.

[0005] Control systems in the art monitor the dynamic compressor system and determine a corresponding compressor map as can be seen in USPN 4,156,578 to Agar and USPN 4,949,276 to Staroselsky. In both references, a function of volumetric flow at the inlet of the compressor is charted against the polytropic head of the compressor to determine a surge line or surge limit line. The surge limit line represents the line on the graph that once passed (a point immediately to the left of the surge limit line) surging of a compressor can occur.

Thus, to prevent surging a safety margin is determined and a surge control line is plotted to the right of the surge limit line. The control system then continuously calculates a control parameter that measures a distance to the surge limit line. If the control parameter reaches or is to the left of the surge control line, the controller actuates the anti-surge valve to increase gas flow through the compressor to prevent the control parameter from reaching the surge limit line and causing a surge within the compressor.

[0006] Problems in systems such as that taught by Agar and Staroselsky exist because measuring the volumetric flow and the polytropic head in practice is not practical. There are problems associated with molecular weight and gas density determinations causing these measurements to be inadequate for real time surge protection. Hence, controllers in the industry employ either fan law method or use similitude theory to derive surge control parameters that in theory are invariant to changes in suction conditions or gas composition. However, existing methods for invariant parameter calculations do not completely account for variability in gas compressibility or gas specific heat ratio. As a result, variations in gas composition tend to make the surge parameter and surge limit line move resulting in operating problems. In addition, existing methods for the distance to surge calculation method is dynamically insensitive or sluggish especially as the compressor load increases. Thus, for the existing methods, changes in distance to the surge line is smaller for a given change in compressor load.

[0007] Therefore, a principal objective of the present invention is to provide a method of surge protection for a dynamic compressor that prevents damage to the dynamic compressor.

[0008] Yet another objective of the present invention is to provide a method of surge protection for a dynamic compressor that accounts for multiple variables in determining a control parameter.

[0009] These and other objectives, features, or advantages of the present invention will become apparent from the specification and claims.

BRIEF SUMMARY OF THE INVENTION

[0010] A method of surge protection for a dynamic compressor having a corresponding performance map. The method includes continually calculating an equivalent polytropic head parameter and an equivalent flow parameter. Next, the method involves defining a surge limit line on the compressor map as a function of the equivalent polytropic head parameter. Then a control system continually calculates a distance a control parameter is from the surge limit line wherein the control parameter is dynamic to changes in compressor load. Based on the distance an anti-surge valve is adjusted.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011]

Fig. 1 is a schematic diagram of a dynamic compressor;
Fig. 2 is a block diagram of a control system of a dynamic compressor;

Fig. 3 is a schematic diagram of a surge control system of a dynamic compressor; and
Fig. 4 is a graph having equivalent flow squared versus equivalent polytropic head.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0012] Fig. 1 shows a dynamic compressor 10 that includes a compressor 12 that is driven by a compressor driver 14. The compressor driver is of any type including a motor, gas turbine, steam turbine, expander or the like. The compressor 12 has a gas inlet 16 and a gas outlet 18 wherein gas flows through the compressor 12 to be compressed. An anti-surge or recycle valve 20 is fluidly connected between the gas inlet 16 and gas outlet 18 so that when the anti-surge valve 20 opens a fluid flow path exists to convey gas from the gas outlet 18 to the gas inlet 16. A plurality of sensors 22 including pressure sensors, temperature sensors, flow measurement sensors and the like are placed throughout the dynamic compressor 10 in order to determine processed conditions for the components of the dynamic compressor including the compressor 12, the driver 14, the gas inlet 16, and gas outlet 18 and the anti-surge valve 20. The plurality of sensors 22 are electrically connected to the control system 24 where the control system 24 is in communication with all of the components of the dynamic compressor and controls the opening of the anti-surge valve 20.

[0013] Fig. 2 shows a control system 24 used for a dynamic compressor 10. Specifically, a controller 26 such as a Network Master controller is utilized in combination with a load controller 28 that monitors the inlet 16 of the dynamic compressor 10 and a surge controller 30 that monitors and operates the anti-surge valve 20. The arrangement and set up of the control system 24 shown in Fig. 2 is merely an example of a control system 24 for a dynamic compressor 10 and is shown as exemplary. Specifically, other control arrangements that utilize Master controllers, load controllers, and surge controllers in series cascade and parallel cascade can be used without falling outside the scope of the present invention.

[0014] Fig. 3 is yet another exemplary embodiment of the control system 24 used with another dynamic compressor 10. In this embodiment the station and load controllers are not used and instead the control system 24 takes readings straight from the plurality of sensors 22 to determine an input to the surge valve 20.

[0015] The control system 24 of the present invention, like prior art control systems, determines a compressor map that corresponds to the dynamic compressor 10 as best shown in Fig. 4. In the present invention the compressor map 32 presents a horizontal axis 34 that measures the square of an equivalent flow $\mathbf{q^2_{eq}}$ and has a vertical axis 36 that presents an equivalent polytropic head. On the map 32 is a surge limit line 38 that is calculated by the control system 24 wherein at points to the left of the surge limit line 38, surge within the dynamic compressor 10 typically occurs. Spaced at a predetermined distance that is considered a safety margin 40 is a surge control line 42 wherein when a control parameter reaches a point either on or to the left of the surge control line 42 the control system 24 actuates the anti-surge valve 20 to provide flow through the anti-surge valve 20. Additionally seen on the map 32 are operating control lines 44 that represent additional control lines that are used if the safety margin 40 is desired to be increased to protect against a surge within a compressor.

[0016] The compressor map 32 of the present invention is an equivalent compressor map wherein instead of attempting to measure inlet volumetric flow and apply it against polytropic head the present invention calculates an equivalent flow parameter $\mathbf{q^2_{eq}}$ and an equivalent polytropic head parameter h_{eq}. Specifically:

$$q_{eq}^2 = \frac{Q^2}{V_c^2}$$

$$q_{eq}^2 = \frac{Q^2}{(nZRT)}$$

and:

$$h_{eq} = \frac{H_p}{V_c^2} = \frac{H_p}{(nZRT)}$$

wherein:

$$V_c^2 = nZRT = \frac{dP}{d\rho}$$

Where:

- **Q** = volumetric flow
- $\mathbf{V_c}$ **=** sonic velocity of gas at flow conditions
- $\mathbf{H_p}$ = polytropic head
- **n** = polytropic exponent
- $R = \frac{Ro}{MW}$ where **Ro** is the universal gas constant and MW is molecular weight
- **Z** = compressibility of gas at flow conditions
- **T** = temperature of gas at flow conditions

[0017] Thus, because, for a polytropic compression process:

P_v^n = constant and $\frac{P}{\rho^n} = \text{constant}$ Where:

- **P** = pressure at flow conditions
- ρ = gas density at flow conditions
- **v** = specific gas density at flow condition

[0018] Therefore:

$$q^2_{eq} = c_1 \frac{\Delta Po}{P} * \frac{1}{n} = \frac{q^2_r}{n}$$

$$h_{eq} = c_2 \frac{\left[R_c^{\frac{n-1}{n}} - 1\right]}{\frac{n-1}{n}} * \frac{1}{n} = \frac{h_r}{n}$$

Where:

- $\mathbf{c_1}$ **and** $\mathbf{c_2}$ **are constant**
- $\mathbf{R_c}$ **= pressure ratio across the compressor**
- Δ**Po** = **differential pressure across flow measuring device**

so

$$h_r = c_2 \frac{\left[R_c^{\frac{n-1}{n}} - 1\right]}{\frac{n-1}{n}}$$

and

$$q^2_r = c_1 \frac{\Delta Po}{P}$$

[0019] Thus, if variations in n are neglected then invariant surge limit parameters are $\mathbf{q^2_r}$ **and** $\mathbf{h_r}$**;**

Therefore, a surge parameter is represented by:
P : q^2_{eq}|surge = f(h_{eq})
and surge limit line = **f(h_{eq})**

[0020] In addition to the above a control parameter (R) is defined as the process variable for surge controller 24 and shown as:

$$R = \frac{q^2_{eq}|op}{q^2_{eq}|surge} - SM$$

$$= \frac{q^2_{eq}|op}{f(h_{eq})} - SM$$

Where:

q^2_{eq}|op = the equivalent volumetric flow parameter at an operating condition
q^2_{eq}|surge = the equivalent volumetric flow parameter at a surge condition
f(h_{eq}) = a function of the equivalent polytropic head
SM = surge margin set point

so that when **R**≥ **1.**0 anti-surge control valve 20 is closed and when **R< 1.0** the anti-surge recycle valve 20 is open.

[0021] In addition, the control system 24 determines the distance to the surge control line δ:

$$\delta = [((q^2_{eq}|op)/\ f(h_{eq}))- SM] - 1 = (R - 1)$$

so when δ is ≥ 0 the valve is closed and when δ is < 0 the valve is open. Thus the surge controller acts on δ to actuate the surge valve and prevent surge.

[0022] In operation, as the dynamic compressor 10 is operating the control system 24 continually monitors the dynamic compressor 10. The control system 24 continually calculates an equivalent polytropic head parameter and an equivalent flow parameter in the manners discussed above. A surge limit line 38 is defined on the compressor map 32 as a function of the equivalent polytropic head parameter. The control system 24 continually calculates a distance δ that a control parameter R is from the surge limit line 38 wherein the control parameter is dynamic to changes in the compressor load. Then, as a result of the distance the control parameter is from the surge limit line the control system 24 actuates the anti-surge valve 20 accordingly.

[0023] Thus, provided is a dynamic compressor control system that utilizes an equivalent compressor map 32 to improve upon the state of the art. The equivalent compressor map 32 bases a surge parameter on the polytropic compression process equation and modeling of the dynamic compressor 10 based on flow, pressure, speed (or inlet guide vane), compressibility and temperatures of the dynamic compressor 10. The equivalent polytropic head parameter and equivalent flow parameter are based on the dynamic similitude theory, a mach number determination using sonic velocity of gas at flowing conditions and gas compressibility.

[0024] When determining control parameter (R), the parameter is dynamic to changes in compressor load, both in the increasing and decreasing direction. Therefore, presented is a control parameter that has high dynamic sensitivity along with invariance of the surge equivalent parameter due to changes in suction pressure, temperature, gas composition, rotation speed or inlet guide vane geometry. Thus, at the very least all of the stated objectives have been met.

[0025] It will be appreciated by those skilled in the art that other various modifications could be made to the device without departing from the spirit and scope of this invention. All such modifications and changes fall within the scope of the claims and are intended to be covered thereby.

[0026] The Present Invention will now be described by way of reference to the following clauses:

1. A method of surge protection for a dynamic compressor having a corresponding compressor map steps comprising:

    continually calculating an equivalent parameter with a controller;
    defining a surge limit line on the compressor map as a function of the equivalent parameter;

continually calculating a distance a control parameter is from the surge limit line, wherein the control parameter is dynamic to changes in compressor load; and
actuating an surge valve based on the distance.

2. The method of clause 1 wherein the equivalent parameter is an equivalent polytropic head parameter.

3. The method of clause 2 wherein the equivalent polytropic head is a function of $\frac{Hp}{V_c^2}$ where **Hp** is polytropic head and

V_c^2 is equal to **NZRT** where **N** is a polytropic exponent, **R** is equal to $\frac{Ro}{MW}$ where **Ro** is a gas constant and **MW** is molecular weight and **T** is the temperature of gas at flow conditions at the compressor.

4. The method of clause 2 wherein the surge limit line is defined based on the polytropic compression process equation, $Pv^n =$ constant.

5. The method of clause 2 wherein the surge limit line is defined based on modeling of the compressor based on flow, pressure, speed, compressibility and temperature.

6. The method of clause 2 wherein the equivalent polytropic head parameter is based on similitude theory.

7. The method of clause 2 wherein the equivalent polytropic head parameter is based on polytropic head correction using sonic velocity of gas at flowing condition of the compressor.

8. The method of clause 2 wherein the equivalent polytropic head parameter is based on gas compressibility.

9. The method of clause 2 wherein the equivalent polytropic head parameter is based on **n** = constant.

10. The method of clause 1 wherein the control parameter is determined based on an equivalent flow parameter.

11. The method of clause 10 wherein the equivalent flow parameter is a function of q^2_{eq} wherein q^2 equals $\frac{Q^2}{V_c^2}$ where **Q** is volumetric flow and V_c is the sonic velocity of gas at flowing conditions.

12. The method of clause 10 wherein the equivalent flow parameter is based on similitude theory.

13. The method of clause 10 wherein the equivalent flow parameter is based on mach number determination using sonic velocity of gas at flowing condition of the compressor.

14. The method of clause 10 wherein the equivalent flow parameter is based on gas compressibility.

15. The method of clause 10 wherein the equivalent flow parameter is based on n = constant.

16. The method of clause 1 wherein the control parameter is determined based on $R = (q^2_{eq}|op)/(q^2_{eq}|surge)$ where $q^2_{eq}|op$ = an equivalent volumetric flow parameter at an operating condition and $q^2_{eq}|surge$ = an equivalent volumetric flow parameter at a surge condition.

17. The method of clause 1 wherein the distance a control parameter is from the surge limit line is determined based on the control parameter and is a function of $[((q^2_{eq}|op)/f(h_{eq})) - 1]$ where $q^2_{eq}|op$ is an equivalent flow parameter at an operating condition and $f(h_{eq})$ is a function of the equivalent polytropic head parameter.

18. The method of clause 17 wherein when the distance a control parameter is from the surge limit line is greater than 0 then the compressor is operating to the right of the surge limit line and when the distance a control parameter is from the surge limit line is less than or equal to 0 then the compressor is operating to the left of the surge limit line.

19. The method of clause 1 further comprising the step of continually calculating a distance the control parameter is from a surge control line.

20. The method of clause 19 where the surge control line is determined based on the control parameter and is a function of **[((q^2_{eq}|op)/f(h_{eq})) - SM] - 1** where **q^2_{eq}|op** is the equivalent flow parameter at an operating condition, **f(h_{eq})** is a function of the equivalent polytropic head parameter defining the surge limit line and SM is the safety margin.

21. The method of clause 20 wherein when the distance a control parameter is from the surge control line is equal to or greater than 0 the surge valve is closed and when the distance the control parameter from the surge control line is less than 0 the surge valve is opened.

22. A method of surge protection for a dynamic compressor having a corresponding compressor map steps comprising:

continually calculating an equivalent parameter with a controller;
defining a surge limit line on the compressor map as a function of the equivalent parameter;
continually calculating a distance a control parameter is from the surge limit line, wherein the control parameter is dynamic to changes in compressor load; and actuating an surge valve based on the distance.

23. The method of clause 22 wherein the equivalent parameter is an equivalent polytropic head parameter.

24. The method of clause 23 wherein the equivalent polytropic head is a function of where $\frac{Hp}{V_c^2}$ is polytropic head and **Vc²** is equal to NZRT where N is a polytropic exponent, R is equal to $\frac{Ro}{MW}$ where **Ro** is a gas constant and **MW** is molecular weight and T is the temperature of gas at flow conditions at the compressor.

25. The method of clause 23 wherein the surge limit line is:

a) defined based on the polytropic compression process equation, **Pv^n** = constant; or
b)defined based on modeling of the compressor based on flow, pressure, speed, compressibility and temperature.

26. The method of clause 23 wherein the equivalent polytropic head parameter is based on:

a) similitude theory;
b) polytropic head correction using sonic velocity of gas at flowing condition of the compressor;
c) gas compressibility; or
d) **n** = constant.

27. The method of clause 22 wherein the control parameter is determined based on an equivalent flow parameter.

28. The method of clause 27 wherein the equivalent flow parameter is:

a) a function of q^2_{eq} wherein q2 equals $\frac{Q^2}{V_c^2}$ where Q is volumetric flow and **V_c** is the sonic velocity of gas at flowing conditions;
b) based on similitude theory;
c) based on mach number determination using sonic velocity of gas at flowing condition of the compressor;
d) based on gas compressibility;
e) based on n = constant.

29. The method of clause 22 wherein the control parameter is determined based on R = **(q^2_{eq}|op)/(q^2_{eq}|surge)** where **q^2_{eq}|op** = an equivalent volumetric flow parameter at an operating condition and **q^2_{eq}|surge** = an equivalent volumetric flow parameter at a surge condition.

30. The method of clause 22 wherein the distance a control parameter is from the surge limit line is determined based on the control parameter and is a function of **[((q^2_{eq}|op)/f(h_{eq}))-1]** where **q^2_{eq}|op** is an equivalent flow parameter at an operating condition and **f(h_{eq})** is a function of the equivalent polytropic head parameter.

31. The method of clause 30 wherein when the distance a control parameter is from the surge limit line is greater

than 0 then the compressor is operating to the right of the surge limit line and when the distance a control parameter is from the surge limit line is less than or equal to 0 then the compressor is operating to the left of the surge limit line.

32. The method of clause 22 further comprising the step of continually calculating a distance the control parameter is from a surge control line.

33. The method of clause 32 where the surge control line is determined based on the control parameter and is a function of **$[((q^2_{eq}|op)/f(heq))-SM]-1$** where **$q^2_{eq}|op$** is the equivalent flow parameter at an operating condition, $f(h_{eq})$ is a function of the equivalent polytropic head parameter defining the surge limit line and SM is the safety margin.

34. The method of clause 33 wherein when the distance a control parameter is from the surge control line is equal to or greater than 0 the surge valve is closed and when the distance the control parameter from the surge control line is less than 0 the surge valve is opened.

Claims

1. A method of surge protection for a dynamic compressor, comprising the steps of:

continually calculating a surge parameter with a control system;
continually calculating an operating parameter with the control system;
defining with the control system a surge limit line based upon the calculated surge parameter on a compressor map;
continually calculating a surge control parameter with the control system by dividing the calculated operating parameter by the calculated surge parameter; and
actuating a surge valve based upon a distance, continually calculated by the control system, the calculated control parameter is from the surge limit line.

2. The method of claim 1 further comprising the step of continually calculating with the control system a polytropic exponent.

3. The method of claim 1 further comprising the step of continually calculating the compressibility of gas at flow conditions.

4. The method of claim 2 wherein the polytropic exponent is calculated by the control system using the equation:

$$n = \frac{1}{1 - \frac{\log\left[\frac{Z_d}{Z_s} \times \frac{T_d}{T_s}\right]}{\log\left[\frac{P_d}{P_s}\right]}}$$

5. The method of claim 1 further comprising the step of continually calculating an equivalent polytropic head with the control system using the equation:

$$h_{eq} = c_2 \left[\frac{\left[R_c \frac{n-1}{n} - 1\right]}{\left[\frac{n-1}{n}\right]}\right] * \frac{1}{n} = \frac{h_r}{n}$$

6. The method of claim 1 wherein the calculated surge parameter is a function of an equivalent polytropic head.

7. The method of claim 1 wherein the calculated operating parameter is determined by the equation

$$c\frac{\Delta P}{P_s} \times \frac{1}{n} = \frac{q_r^2}{n} = q_{eq}^2 \mid \text{op}$$

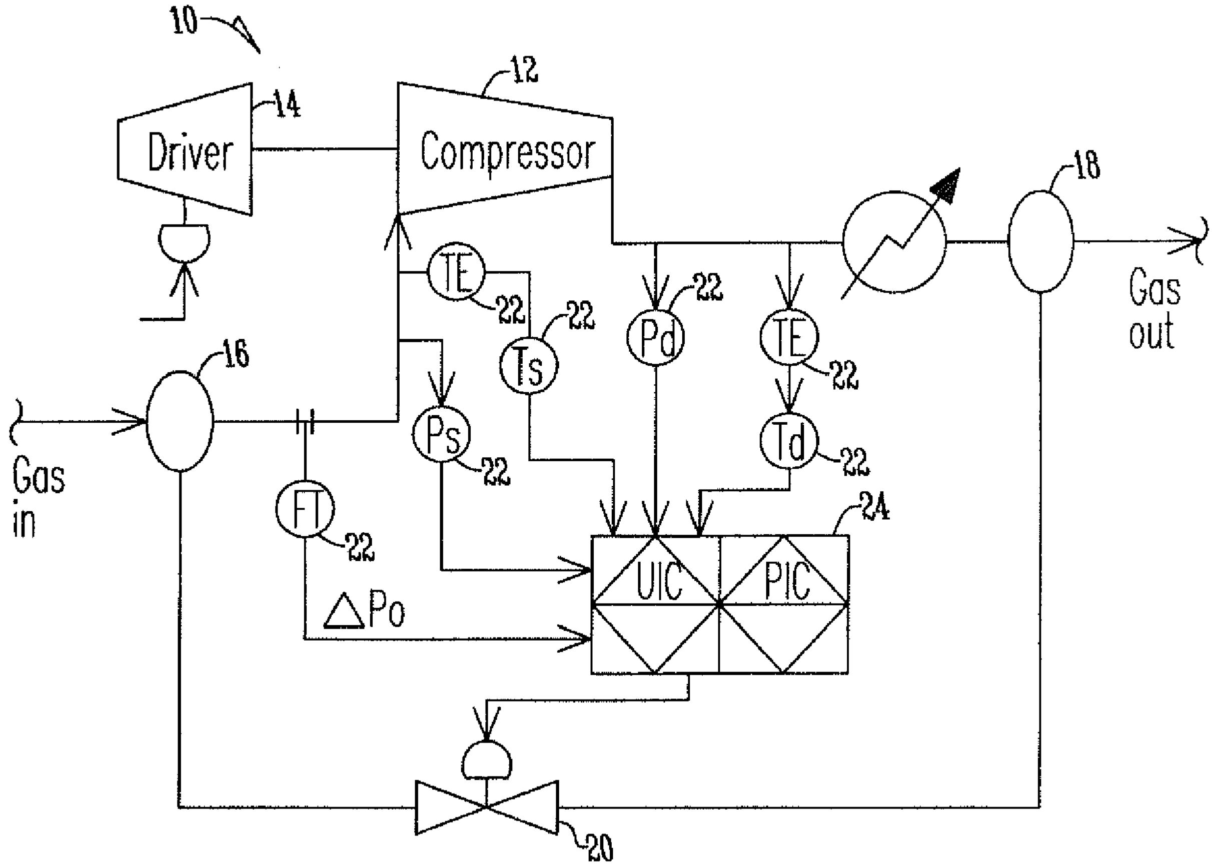
8. The method of claim 1 wherein the distance the control parameter (R) is from the surge limit line is determined based on the control parameter (*R*) and is a function of $[((q^2_{eq}|p)/f(h_{eq})) - l]$ where $q^2_{eq}|$op is an equivalent flow parameter at an operating condition and $f(h_{eq})$ is a function of the equivalent polytropic head parameter a surge limit line.

9. The method of claim 8 wherein when the distance the control parameter (R) is from the surge limit line is greater than 0 then the compressor is operating to the right of the surge limit line and when the distance the control parameter (R) is from the surge limit line is less than or equal to 0 then the compressor is operating to the left of the surge limit line.

10. The method of claim 1, further comprising the step of continually calculating a distance the control parameter (R) is from a surge control line.

11. The method of claim 10, wherein the surge control line is determined based on the control parameter (R) and is a function of $[((q^2_{eq}|op)/f(h_{eq})) - SM] - 1$ where $q^2_{eq}|op$ is the equivalent flow parameter at an operating conditions, $f(h_{eq})$ is a function of the equivalent polytropic head parameter defining the surge limit line and SM is the safety margin defining the surge control line.

12. The method of claim 11 wherein when the distance a control parameter (R) is from the surge control line is equal to or greater than 0 the surge valve is closed and when the distance the control parameter (R) from the surge control line is less than o the surge valve is opened.


10
12
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Compressor
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22
Ts
Pd
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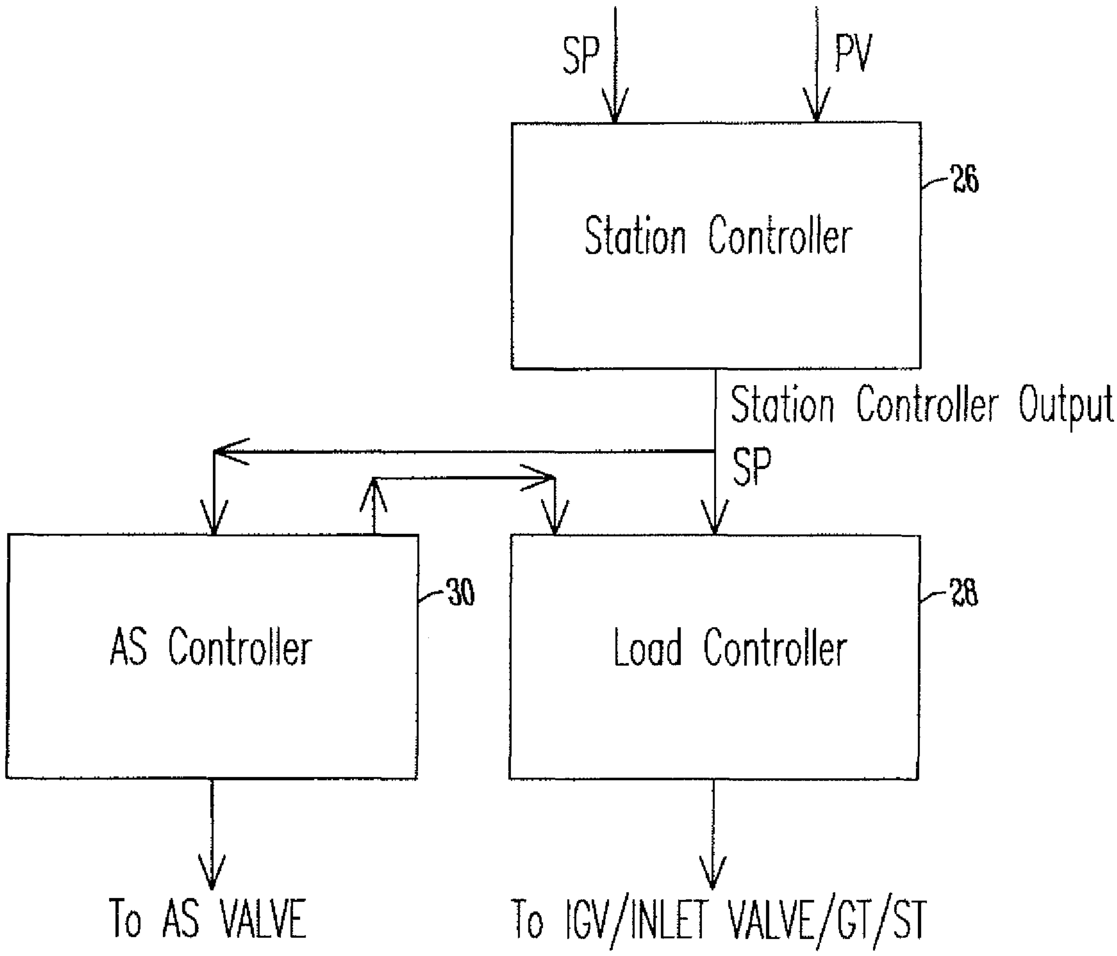
Gas
in
Ps
Td
24
FT
UIC
PIC
△Po
20

Fig.1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Station Controller Output
SP
AS Controller
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Load Controller
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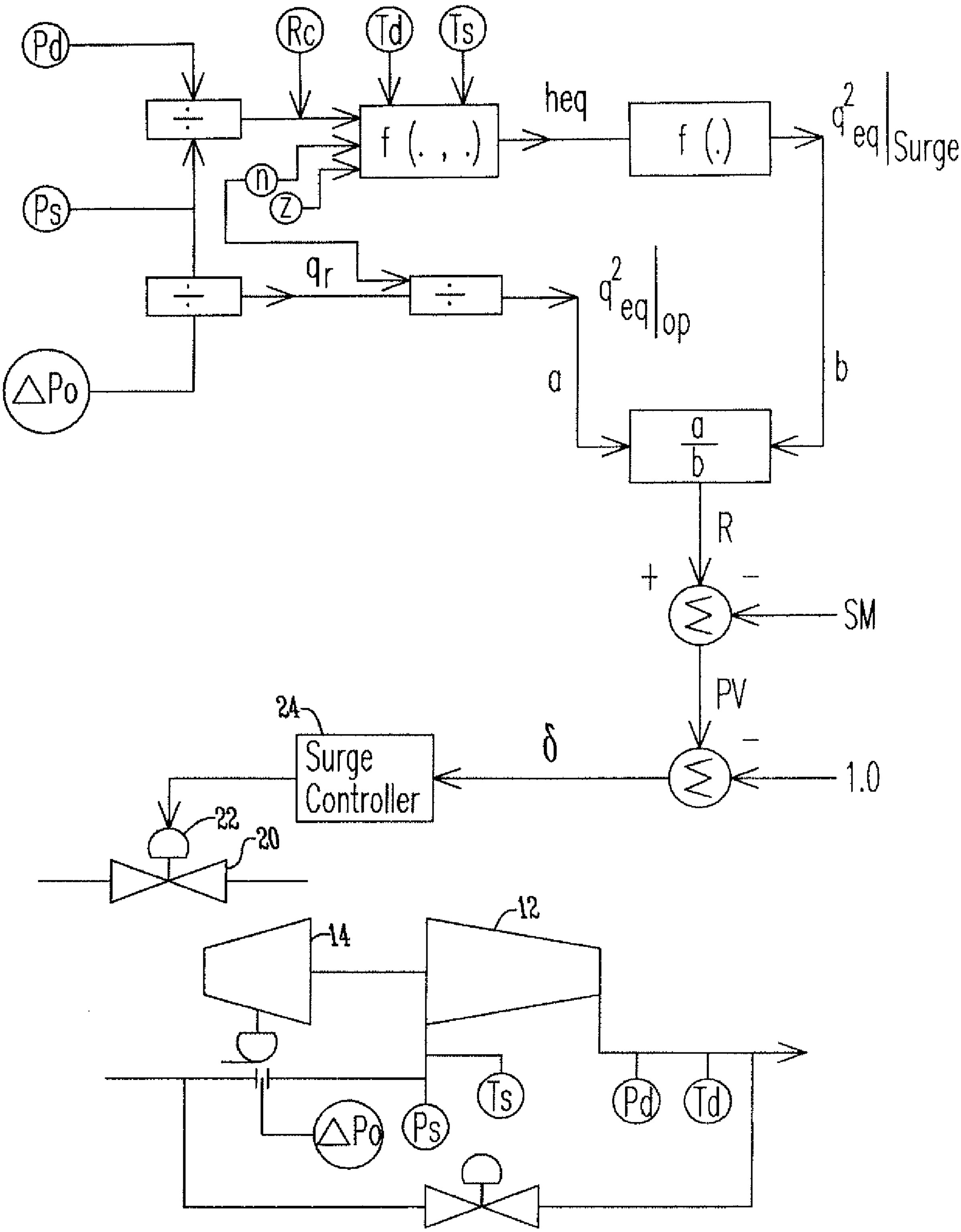
To AS VALVE
To IGV/INLET VALVE/GT/ST

Fig.2



Pd
Rc
Td
Ts
heq
f (. , .)
f (.)
$q^2_{eq}|_{Surge}$
n
Z
Ps
q_r
$q^2_{eq}|_{op}$
ΔPo
a
b
a/b
R
+
−
SM
PV
24
Surge Controller
δ
−
1.0
22
20
12
14
ΔPo
Ps
Ts
Pd
Td

Fig.3

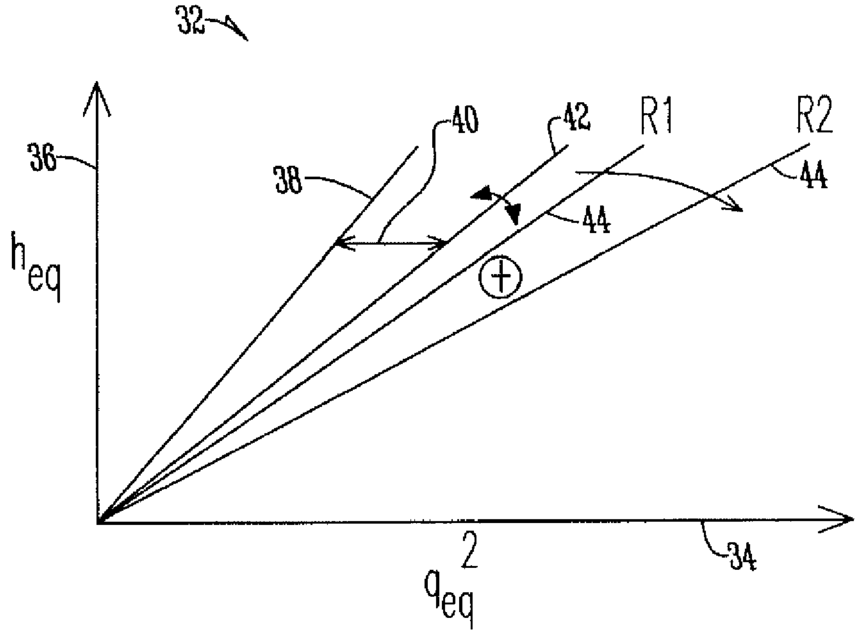


Fig. 4

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EUROPEAN SEARCH REPORT

Application Number
EP 18 17 8650

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	US 4 971 516 A (LAWLESS BRIAN S [US] ET AL) 20 November 1990 (1990-11-20) * column 4, line 52 - column 5, line 7; figures 1,3 * -----	1-12	INV. F04D27/02
X	US 5 195 875 A (GASTON JOHN R [US]) 23 March 1993 (1993-03-23) * claim 1; figure 5 * -----	1-12	
X	US 5 908 462 A (BATSON BRETT W [US]) 1 June 1999 (1999-06-01) * claims 1,10; figures 4,5 * -----	1-12	
X	US 4 156 578 A (AGAR JORAM [US] ET AL) 29 May 1979 (1979-05-29) * sentences 47-61, paragraph 4; figure 6 * -----	1-12	

TECHNICAL FIELDS SEARCHED (IPC)

F04D

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	24 September 2018	de Martino, Marcello

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
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EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 18 17 8650

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
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24-09-2018

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82