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[54] **APPARATUS AND METHOD FOR CONTROLLING A CENTRIFUGAL COMPRESSOR**

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[52] **U.S. Cl.** .... **317/13 A,** 318/452

[51] **Int. Cl.** **H02h 7/08**

[58] **Field of Search** .... 317/13 A, 135 R, 13 B, 317/13 R; 318/479, 487, 452

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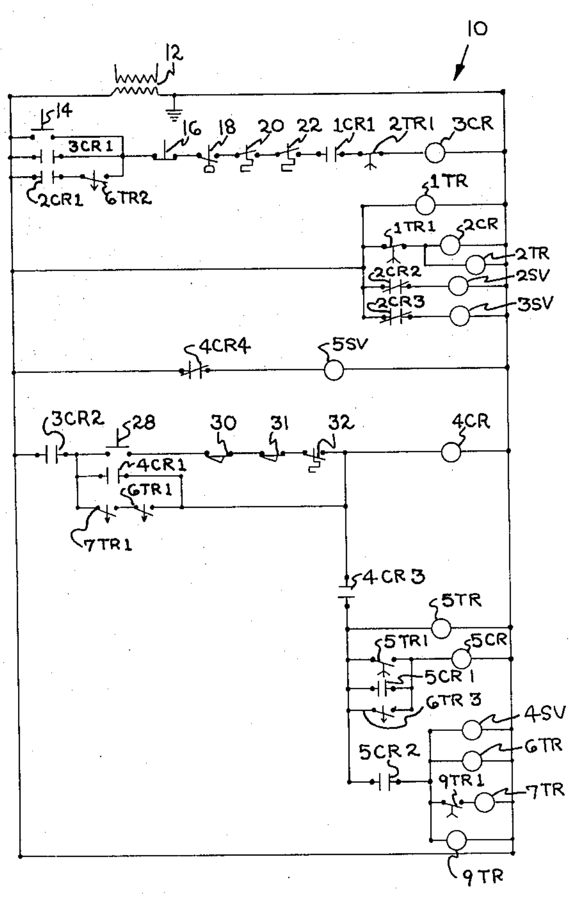
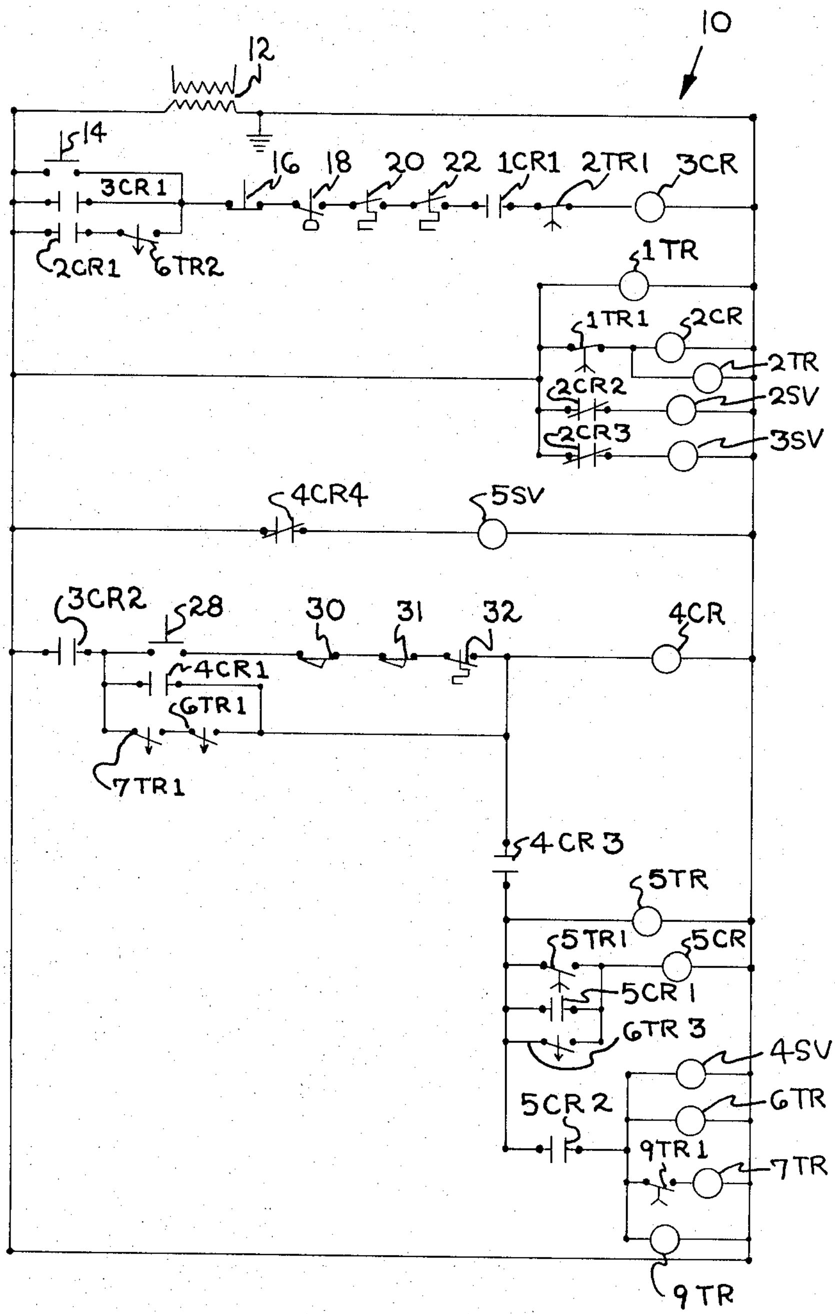
[57] **ABSTRACT**

In an electric motor driven centrifugal compressor, apparatus and method for controlling the compressor to prevent "surge" and operation at a motor current above the maximum rated motor current and for automatically restarting the compressor after a short-term power failure. The current to the compressor motor is sensed as an indicator of impending "surge." When the current falls below a pre-selected minimum value, a blow-off valve in the compressor outlet line is gradually opened to allow excess volume to escape to the atmosphere, thus avoiding "surge." The current to the motor is also sensed as an indication of compressor operation above the maximum rated motor capacity. When the motor current rises above a pre-selected level, an inlet value to the compressor is closed. This restricts the volume available for compression and prevents motor over-loaded operation. In the event of a short-term power failure or power dip, contact pairs controlled by time delay relays remain closed for a short period of time. These pairs provide parallel bypass circuits around the normal motor starting circuits and allow an automatic restart if the time period has not been exceeded. The compressor is powered by the flywheel effect of its main drive gear during these short-term power failures. If the power failure is of a long enough duration, the bypass contact pairs open, and the normal restarting procedures must be followed.

6 Claims, 3 Drawing Figures




10
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14
3CR1
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7TR1
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FIG. 1

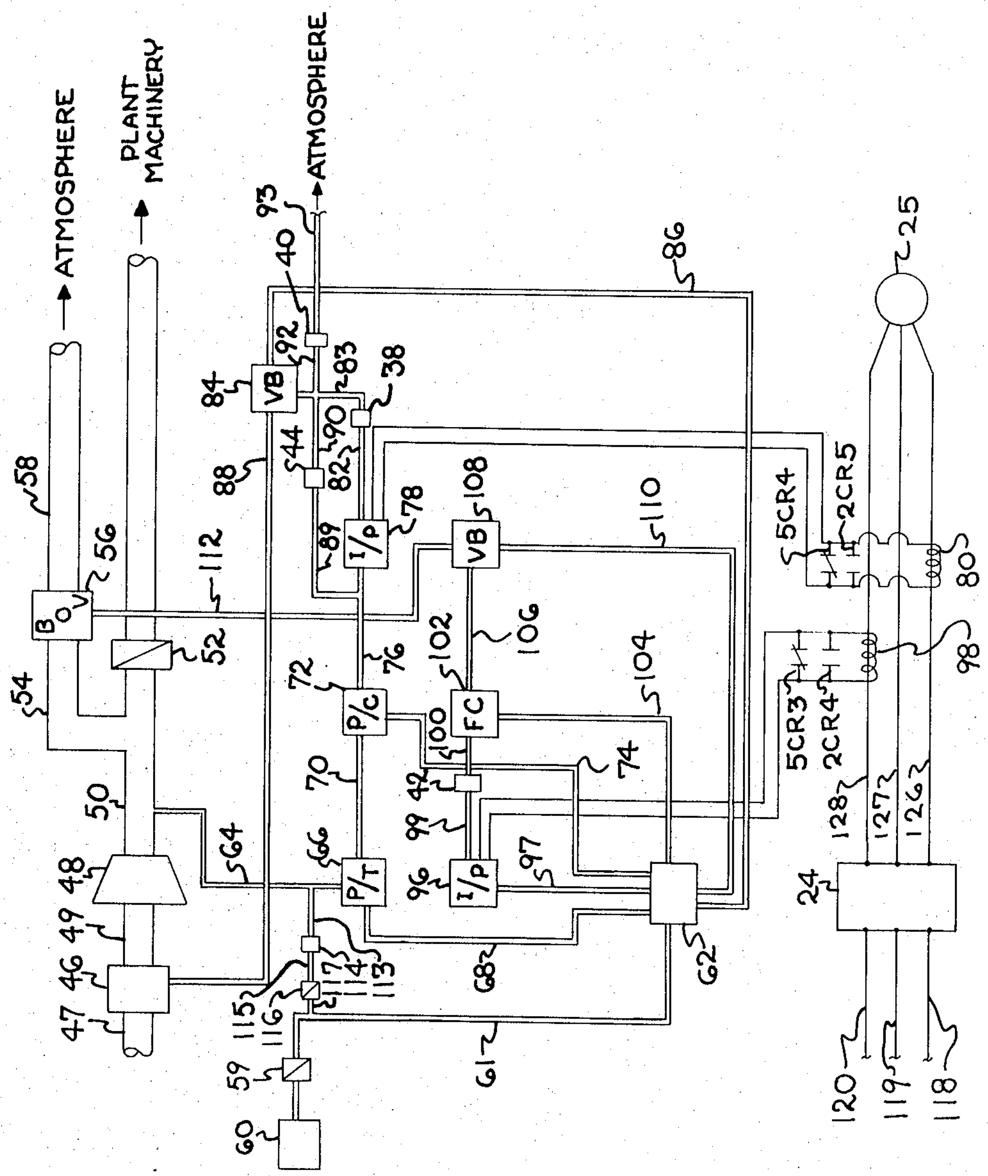
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FIG. 2

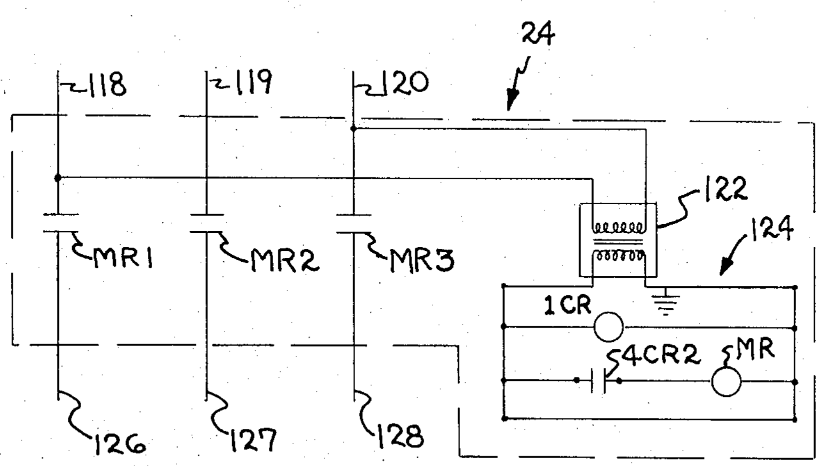

FIG. 3

APPARATUS AND METHOD FOR CONTROLLING A CENTRIFUGAL COMPRESSOR

This is a division of application Ser. No. 246,478, filed Apr. 21, 1972.

BACKGROUND OF THE INVENTION

This invention generally relates to centrifugal compressors. More particularly, this invention relates to control systems for such compressors. Specifically, this invention relates to an integrated control system for a centrifugal compressor which will prevent "surge," will prevent operation above the motor rated capacity, and will automatically restart the compressor after a short time duration power failure.

Centrifugal compressors have long been recognized as extremely useful devices and are in common use in industry. However, there are two very critical operational limits of centrifugal compressors which must be controlled. At one limit "surge" must be prevented. In the simplest sense, "surge" is a reverse-forward cycling of the gas being compressed which occurs when the back pressure of the process becomes greater than the compressor pressure. To avoid this, a blow-off valve is provided in the compressor outlet to vent the compressor when the flow falls below a preset minimum. Conventionally, a differential pressure (or ΔP) cell in the compressor outlet line measured the pressure drop across the ΔP cell, converted this pressure drop to a flow rate, and opened and closed the blow-off valve as the pressure (or flow, as it was actually used) reached a set point indicating impending surge. This system was not altogether satisfactory since the ΔP cells were very sensitive to dirt, were not automatically compensated for the inlet gas temperature, and required careful selection and calibration for every compressor. In addition, operation of two compressors in parallel to feed a common process outlet line was extremely difficult. If the two compressors' outlet pressures were not exactly the same, the ΔP cell of one compressor would be forced to read backward, falsely indicating a surge condition. This would cause the blow-off valve of that compressor to open unnecessarily, thus wasting compressed gas. In addition, the output of the other compressor would be partially vented through the open blow-off valve, again causing inefficiencies. The other critical limit occurs at the opposite extreme from surge. If the system restriction is very low, the compressor motor can draw sufficient current to allow operation above the rated current capacity of the motor. This will cause overheating of the motor and eventual shutdown due to overheating. In the prior art, an inlet valve was operated to limit the available inlet volume to the compressor. A pressure controller sensed the process pressure and controlled the inlet valve as a function of process pressure. The motor current was also sensed and fed, as a pressure signal, to a pneumatic flip-flop. The pressure controller signal was also fed to the flip-flop, whose output actually controlled the inlet valve. The flip-flop would always pass the lower of the two input signals into the inlet valve. When motor over-capacity operation became imminent, the signal from the motor would be lower, and the inlet valve would close. This would unload the motor, and the signal from the pressure controller would be passed. It can easily be seen that if the process condition which led to the motor over-capacity operation in the first place were not corrected, the flip-flop would then immediately pass the motor signal again, closing the inlet valve. This clearly led to an undesirable oscillatory type of control. My invention will control both surge and overrunning, as well as allowing parallel compressor operation, without any of the problems of the prior art. Finally, in the prior art, any power failure would force a compressor shutdown. This could be very disruptive to a sensitive process. I have found that my system will ride short duration power failures and allow automatic restart without shutdown when power is restored.

SUMMARY OF THE INVENTION

This invention is an apparatus and method for controlling an electric motor driven centrifugal compressor to prevent operation at a volume above the maximum rated flow, to prevent the occurence of surge and to automatically restart the compressor after a short time duration power failure. One aspect of the invention is to limit the flow to no more than the maximum rated capacity of the compressor; to do this, an inlet valve is controlled partially as a function of motor current. The process pressure in the compressor outlet is sensed and a signal proportional to this pressure is generated. This proportional signal is compared with a preset value of process pressure and a control signal proportional to the deviation of the proportional signal from the preset value is generated. In addition, the motor current is compared to a preset maximum current value. So long as the current remains below the maximum, the control signal is passed to the inlet valve without modification. If the current rises above the maximum value, the control signal is modulated as a function of the amount above the preset maximum, thus controlling the inlet valve as a function of the control signal whether modified or not. Another aspect of the invention is to prevent surge by operating a blow-off valve in the compressor outlet piping as a function of motor current. The motor current is sensed and a signal proportional to the motor current is generated. This proportional signal is compared with a preselected minimum value for the proportional signal. If the proportional signal falls below the pre-selected minimum value, a modulated control signal is generated which opens the blow-off valve as a function of the modulated control signal. Yet another aspect of the invention is to automatically restart the compressor after a short time duration power failure by providing time dependent bypass circuits around the normal means for initiating the motor start. If the power failure is less than a pre-selected time, the sequential operation will be automatically re-initiated without intervention of a human operator to thereby restart the motor.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic circuit diagram of the electrical control circuit of the present invention;

FIG. 2 is a schematic circuit diagram of the flow limiting and anti-"surge" controls of the present invention; and

FIG. 3 is a schematic circuit diagram of the motor starter circuit of the present invention.

DETAILED DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a ladder circuit diagram 10 for the electrical control system of the present invention. The ladder circuit 10 receives its power from a transformer

12, as is conventional practice. The configuration of the components in FIG. 1 is that assumed when the compressor is not running and power has been off for a long time. In addition, the notation used throughout in FIG. 1 will be that conventionally used in describing ladder diagrams. That is, the coil of a relay will be given a specific letter and number. Then, the contact pairs associated with that particular relay will be given the same letter and number as the coil and in addition will be given a unique identifying numeral. To start the compressor operating, the procedure is as follows: a momentary contact reset switch **14** is pressed by the operator. This, in turn, allows current to flow from side to side in the ladder diagram **10** through a relay coil **3CR**. It will be noted that a number of safety interlock elements **16, 18, 20, 22, 1CR1** and **2TR1** are located in series intermediate the reset switch **14** and the coil **3CR**. Element **16**, in the form of a switch, is used to bring the compressor to a complete halt when it is desired to shut the compressor off. In the startup procedure, the switch element **16** is closed. Element **18**, in the form of a pressure actuated switch is connected to the compressor lubrication system and senses when the pressure of the lubricating oil is too low for proper functioning and opens to stop the compressor. This switch element **18** would normally be closed in the startup procedure indicating that the oil pressure is sufficient to allow operation to begin. Element **20**, in the form of a temperature actuated switch, is located in the lubricating oil pressure line and senses the temperature of the lubricating oil. If the temperature of the lubricating oil becomes too high for proper operation, the switch element **20** opens, thus disrupting the circuit and causing the compressor to shut down. Again, in the normal startup procedure, the switch element **20** would be closed, indicating that the oil temperature was proper. Element **22**, a second temperature actuated switch, is connected to the outlet of the compressor and senses the outlet air temperature. The switch element **22** is set such that when the temperature of the outlet air reaches a predetermined maximum value, the switch element **22** opens, again disrupting the circuit. In the startup procedure, the switch element **22** would be closed, again completing the circuit. A relay coil **1CR** (see FIG. 3), connected across the power input line to a motor starter **24** for a compressor motor **25**, controls the element **1CR1**, in the form of a contact pair, in series with the elements **18, 20** and **22**. If there is power into the motor starter **24**, relay coil **1CR** is energized and the contact pair **1CR1** will be closed, again allowing current to flow to the relay coil **3CR**. Finally, element **2TR1**, in the form of a contact pair, is controlled by a coil **2TR** of a time delay type relay. The function of the contact pair element **2TR1** will be described later in conjunction with the discussion of the coil **2TR**. The functioning of the coil **3CR** closes the contact pair **3CR1** and locks in the safety reset circuit. Thus, if all the elements indicate that the compressor is in the proper mode for starting, the compressor start button may be pushed and the compressor will start. The coil **3CR** additionally energizes the contact pair **3CR2** at the lead into the compressor start circuit. With the contact pair **3CR2** closed, the operator will now press a compressor start button **28** to continue the startup procedure. The current flowing through the closed contact pair **3CR2** and the start switch **28** must flow through a limit switch **30** which is closed when an inlet valve **46** is closed. The inlet valve **46** must be closed before the compressor can be started. Next, the current flows through a limit switch **31**, which is closed when a blow-off valve **56** is fully open. The blow-off valve **56** must be in the fully open position before the compressor can be started. Finally, the signal must pass through a minimum oil temperature switch **32**. The minimum oil temperature switch **32** is set such that the circuit will be open if the lubricating oil temperature has not reached a pre-selected minimum value. Finally, the flow of electrical current energizes a coil **4CR** of a relay. Energizing the coil **4CR**, in turn, closes a contact pair **4CR1** and thus bypasses the compressor start switch **28**. At this point, the compressor start switch **28** may be released by the operator and the startup procedure will continue. In addition, it will be noted that bypassing the compressor start switch **28** additionally bypasses the limit switches **30** and **31** and the low oil temperature switch **32**. This function is permissible, since these three functions are monitored only for startup procedure and have no effect on the running operation of the compressor. With the contact pair **4CR1** in the closed position, current may now flow through the contact pairs **3CR2** and **4CR1** and thus keep the coil **4CR** energized. The coil **4CR**, in addition, operates a contact pair **4CR2** (see FIG. 3) in the motor starter **24**. Closing the contact pair **4CR2** allows current to reach the motor **25**, as will be explained later, thereby starting the compressor. Energizing the coil **4CR** additionally closes a contact pair **4CR3**, admitting current to a coil **5TR** of a time delay relay. The time delay relay with which the coil **5TR** is associated is of the type which delays the closing of a contact pair **5TR1** of the relay for a period of time after the coil **5TR** has been energized. The purpose of the time delay is to allow the motor **25** to reach full speed before the control circuit is placed in operation. This allows the drive motor **25** to be started in an unloaded condition and be at operational speed before the inlet valve **46** and the blow-off valve **56** come under control. I have found that a delay of approximately twenty seconds is sufficient to allow this condition to be established. Twenty seconds after the coil **5TR** has been energized, the contact pair **5TR1** closes, thus energizing a coil **5CR** of a conventional relay. Energizing the coil **5CR** closes a contact pair **5CR1**, locking the coil **5CR** into the circuit. In addition, a contact pair **5CR2** is also closed by the coil **5CR**, energizing a portion of the control circuit of the compressor. In particular, a coil **4SV** is energized to open a solenoid valve **38** (see FIG. 2). In addition, a coil **6TR** of a time delay relay is also energized at this time. The time delay relay with which the coil **6TR** is associated is of the type which delays the opening of its contact pairs a preset length of time when the power is turned off to the coil **6TR**. It will be noted that a contact pair **6TR1**, controlled by the coil **6TR**, is connected in parallel with the contact pair **4CR1**. The relay, controlled by the coil **6TR**, has been found to be most appropriately set to provide a delay of approximately five seconds before the contact pair **6TR1** will open after the coil **6TR** is de-energized. In addition, a coil **9TR** associated with another time delay relay is also energized by the closing of the contact pair **5CR2**. This time delay relay, controlled by the coil **9TR**, is provided to ensure that the compressor has been running a preset length of time, in this case approximately one minute, before the power interruption override function, to be described later, can be utilized. I have found that once the compressor has been running approximately 1 minute, it is assumed that the power source is stable and that the compressor is operating satisfactorily. Therefore, after a period of approximately 1 minute, the coil **9TR** allows a contact pair **9TR1** to be closed. Closing the contact pair **9TR1** energizes a coil **7TR** of yet another time delay relay. The time delay relay controlled by the coil **7TR** is again of the type which delays the opening of the contact pairs a preset length of time after the coil **7TR** has been de-energized. It will be noted that a contact pair **7TR1** is connected in series with the contact pair **6TR1**, which, in turn, are in parallel around the contact pair **4CR1**. I have found that the delay to be provided by the coil **7TR** may most appropriately be set at approximately 10 seconds. A normally closed contact pair **4CR4** controlled by the coil **4CR** has been caused to open at the time of energization of the coil **4CR**. This causes a loss of power to a coil **5SV**, which permits a "normally closed" solenoid valve **40** to close. When power is initially supplied to the ladder circuit **10**, a coil **1TR** of a time delay type relay is energized. The characteristics of the time delay relay controlled by the coil **1TR** are such that a contact pair **1TR1** will open a short period of time after the coil **1TR** has been energized. Thus, after an initial current flow to the coil **1TR**, the contact pair **1TR1** will be open. Initially, however, the contact pair **1TR1** will allow current to flow to the coil **2CR**. The current to the coil **2CR**, in turn, will close the contact pair **2CR1** connected in parallel around the contact pair **3CR1**. In addition, a coil **2TR** controlling another time delay relay is also energized during the time the coil **2CR** is energized. The characteristics of the coil **2TR** are such that the contact pair element **2TR1** will open a short period of time after the coil **2TR** has been energized. Thus, if for any reason, the time delay function generated by the coil **1TR** should fail and allow the contact pair **1TR1** to remain closed, the coil **2TR** will operate to open the contact pair element **2TR1** and halt the operation of the compressor. The coil **2CR**, when it is energized, will function to open a contact pair **2CR2** and a contact pair **2CR3**. The contact pairs **2CR2** and **2CR3** are normally closed and open only while power is initially provided to the ladder circuit **10**. The flow of current through the contact pair **2CR2** controls a coil **2SV** which causes a "normally closed" solenoid valve **42** (see FIG. 2) to open while power is on the circuit. The current flowing through the contact pair **2CR3** controls a coil **3SV** which is associated with a "normally open" solenoid valve **44** (see FIG. 2). Therefore, so long as current is provided to the ladder circuit **10**, the solenoid valve **44** will remain closed. Finally, a contact pair **6TR2** is connected in series with a contact pair **2CR1**, and a contact pair **6TR3** is connected in parallel around the contact pair **5CR1**. In Table 1, under the column labeled "Normal Operation," the conditions of the contact pairs and elements in FIG. 1 are tabulated for the normal "power on" operation.

TABLE 1

Contact Pairs and Elements	Normal Operation	Power Failure
14	Open	Open
3CR1	Closed	Open

TABLE 1-Continued

Contact Pairs and Elements	Normal Operation	Power Failure
2CR1	Open	Open
6TR2	Closed	Closed
16	Closed	Closed
18	Closed	Closed
20	Closed	Closed
22	Closed	Closed
1CR1	Closed	Open
2TR1	Closed	Closed
1TR1	Open	Closed
2CR2	Closed	Closed
2CR3	Closed	Closed
4CR4	Open	Closed
3CR2	Closed	Open
28	Open	Open
4CR1	Closed	Open
7TR1	Closed	Closed
6TR1	Closed	Closed
30	Indeterminate	Indeterminate
31	Indeterminate	Indeterminate
32	Closed	Closed
4CR3	Closed	Open
5TR1	Closed	Open
5CR1	Closed	Open
5CR2	Closed	Open
9TR1	Closed	Open
6TR3	Closed	Closed

Before considering the control system illustrated in FIG. **2**, it is necessary to point out a few basic factors relating to the operation of centrifugal air compressors. For those desiring more information on the specific operation of centrifugal air compressors, reference may be had to Chapter 3 of *Compressed Air and Gas Handbook*, 3rd Edition, 1961, Compressed Air and Gas Institute. The operational characteristics and, consequently, the control requirements of a centrifugal type air compressor and a reciprocating type air compressor are considerably different. The reciprocating type air compressor is essentially a constant volume output, variable pressure output device. A centrifugal compressor, on the other hand, is a variable volume output, constant pressure output type device. In the field of operation herein discussed, the centrifugal compressor is operated at essentially a constant speed by a drive motor. Operating at this speed, the compressor will deliver a variable capacity of air from approximately fifty percent to one hundred percent of the rated capacity at substantially a constant discharge pressure. There are two limits or extremes within which the operational range of the centrifugal compressor must be controlled. Heretofore, the control of these two extremes of the range of operation has been somewhat erratic, and the control system of the present invention has succeeded in accurately controlling both limits of the operational range of the centrifugal compressor. At one extreme, the restriction to the output of the centrifugal compressor becomes so low that the compressor may take in amounts of air grossly in excess of the rated capacity. When this occurs, the compressor motor mayy overload itself and thereby be burned up. This function has normally been in control by the use of an inlet control valve, but the control of this valve has not been completely integrated with the control to the compressor output. At the other end of the compressor operating range, a phenomenon known as surge may occur. Quoting from the *Compressed Air and Gas Handbook*, at p. 3–22, the phenomenon of surge can be explained as follows:

"At a particular speed, as the flow is reduced and the compressor 'back' pressure (which is the result of all the restrictions) is increased or kept the same, a flow point is reached where the back pressure exceeds the pressure ratio developed by the compressor, and a breakdown in the flow results. This immediately causes a reversal in the flow direction and reduces the compressor back pressure. The moment this happens regular compression is resumed and the cycle is repeated. The cycling action has been properly labeled as 'surge'."

It may be appreciated that the occurrence of surge can be very costly to a process and, if allowed to continue, will result in damage to the compressor itself. In order to prevent the occurrence of surge, a blow-off valve is generally provided in the outlet piping of the compressor. In prior systems, when surge occurs, the blow-off valve is opened to allow pressure to be vented to the atmosphere and increase the flow through the compressor. The operation of the blow-off valve has not been fully integrated with the total compressor circuit, thereby leading to inefficiencies in the operation of the compressor by allowing the blow-off valve to be open, wasting air unnecessarily or leading to the shutdown of the compressor if surge occurs.

Turning now to the control circuit of FIG. 2, atmospheric air is furnished through the inlet valve **46** to an inlet pipe **47.** The inlet valve **46** may be a Fisher Model 7810 with a 656 diaphram actuator manufactured by the Fisher Control Company of Marshalltown, Iowa 50158. The operation of the inlet valve **46** is such that it will be open an amount determined by the pressure of an air signal furnished to it. The inlet valve **46** is set such that when it is fully closed, admission of atmospheric air through the inlet pipe **47** is not completely blocked. This allows the compressor to start while the inlet valve **46** is essentially in the closed position. Atmospheric air passing through the inlet valve **46** is then introduced to compressor **48** through a compressor inlet pipe **49.** The compressor **48** may be any centrifugal type compressor currently available. For example, the compressor **48** may be a Clark Isopac 4, manufactured by Dresser Industries, Incorporated, Clark Turbo Compressor Division, Olean, N.Y. 14760. For the purposes of this explanation, consider that the compressor **48** will give an output of compressed air at approximately 50 pounds per square inch gauge pressure. This compressed air is furnished to an outlet pipeline **50.** A check valve **52** is provided in the outlet pipeline **50** to prevent gross reverse flows of air through the pipeline **50** to the compressor **48.** Upstream of the check valve **52,** in the pipeline **50,** is a blow-off branch pipeline **54** connected to the blow-off valve **56.** The blow-off valve **56** may be a Fisher Model EK with a 657 actuator manufactured by Fisher Controls, Marshalltown, Iowa 50158. The characteristics of the blow-off valve **56** are such that its degree of opening is governed by a signal pressure furnished to the operating mechanism of the blow-off valve **56.** Under normal operating conditions, the blow-off valve **56** is completely closed. The blow-off valve **56** is open only under conditions where surge in the system becomes imminent. The output of the blow-off valve **56** is vented to the atmosphere through an atmospheric vent line **58.** A source **60** of control air under pressure furnishes control air to a pipeline **61** to a control air manifold **62.** A pressure sampling line **64** is connected to the outlet pipeline **50** to sense the process pressure. The pressure sampling line **64** is connected to a pressure transmitter **66,** which may be a Foxboro Model M45, manufactured by the Foxboro Company, Foxboro, Mass. 02035. An additional input to the pressure transmitter **66** is through a control airline **68** from the control air manifold **62.** The pressure transmitter **66** functions so as to present an output, through an output pipeline **70,** of a control air pressure signal proportional to the pressure transmitted by the pressure sampling line **64.** Advantageously, the control air pressure will be in a range of 20 pounds per square inch gauge. The output of the pressure transmitter **66** will advantageously be of the range of from three to fifteen pounds per square inch gauge, again proportioned relative to the actual process pressure. The output line **70** from the pressure transmitter **66** is connected to a pressure controller **72.** The pressure controller **72** may be a Foxboro Model M/52A-7M4-B manufactured by the Foxboro Company, Foxboro, Mass. 02035. An additional input to the pressure controller **72** is a control airline **74** connected to the control air manifold **62.** The pressure controller **72** is preset to the desired process pressure. As the process pressure varies, the pressure controller **72** will generate a corrective signal and transmit this signal through an output line **76.** The process pressure, as was previously explained, is actually transmitted as a proportional signal by the pressure transmitter **66** to the pressure controller **72.** Thee pressure controller **72** compares this proportional signal with the preset value and produces an output of control air in the output line **76** proportional to the deviation from the actual set point pressure. The output signal, from the pressure controller **72,** in the output line **76,** is a modulated pressure signal. This modulated pressure signal transmitted by the output line **76** is connected to a current-to-pressure converter **78.** The current-to-pressure converter **78** may be a Model 775 with reverse acting transducer, manufactured by Moore Products Company of Spring Hill, Pa. 19477. The function of the current-to-pressure converter **78** is to prevent the compressor motor **25** from operating at a level above its' maximum rated capacity. A coil **80** in one phase of the input wiring to the motor **25** senses the current drawn by the motor **25.** It is well known that a measure of the work being done by any motor may be the current being drawn by the motor. Thus, as the compressor motor **25** begins to operate at higher and higher current values, the motor may overheat and eventually trip the motor overload safetys, thus shutting down the compressor **48.** To ensure that this can never occur, the current in the wiring to the motor **25** is transmitted to the current-to-pressure converter **78.** So long as the current sensed by the coil **80** and transmitted to the current-to-pressure converter **78** is below that current which would cause operation of the compressor **48** at an inlet volume above the maximum drive motor **25** rating, the control signal from the pressure controller **72** passes through the current-to-pressure converter **78** without deviation. However, as the current reaches the maximum level, the current-to-pressure converter **78** functions to modulate the pressure output in the output line **76** to a level which will cause the inlet valve **46** to assume a position such that the maximum inlet volume may not be exceeded. The output from the current-to-pressure converter **78** is transmitted in an output line **82** through a solenoid valve **38** and thence via an output line **83** to a volume booster **84.** The volume booster **84** may be a Foxboro Model B102RN, manufactured by the Foxboro Company, Foxboro, Mass. 02035. The volume booster **84** receives an input from the control air manifold **62** through a pipeline **86.** The function of the volume booster **84** is to increase the volume of the control signal coming in through the pipeline **83** to a level which will operate the inlet valve **46** quickly. That is, the inlet valve **46** is positioned according to the pressure signal received by the inlet valve **46** in an input line **88** from the volume booster **84.** If the volume booster **84** were not utilized, the output pressure in the line **76** could be used to operate the inlet valve **46,** but the operational speed of the inlet valve **46** would be relatively slow. Thus, the volume booster **84** allows more rapid operation of the inlet valve **46.** It will be noted that there is a bypass around the current-to-pressure converter **78.** This bypass line is made up of a pipeline **89** connected directly to the output line **76** from the pressure controller **72.** The pipeline **89** is connected to a solenoid valve **44.** The solenoid valve **44,** in turn, is connected to the output line **83** with a pipeline **90.** Under normal operational conditions, the solenoid valve **44** is closed, as previously discussed, and the bypass line is not in use. The bypass line comes into play only during power failures, a function which will be described later in detail. In addition, provision is made to allow any residual pressure in the output line **83** to be blown off to the atmosphere during periods of no operation. This function is carried out by a blow-off line **92** connected to the solenoid valve **40,** which then has an atmospheric exhaust line **93** connected to its output.

A second and independent control circuit shown in FIG. **2** controls the operation of the blow-off valve **56** to prevent surge from occurring within the system. As was previously explained with respect to the maximum volume limiting system, it is likewise possible to sense the imminence of surge in the system by monitoring the current being drawn by the motor **25.** For any given compressor, surge will occur at a unique value of current drawn by the compressor motor **25.** This point may be determined for any system by simple experimentation before the system is placed on stream. A current-to-pressure converter **96** receives control air through a pipeline **97** from the control air manifold **62.** The current-to-pressure converter **96** may be a Model 775 with forward acting transducer manufactured by the Moore Products Company of Spring House, Pa. 19477. A coil **98** senses the current in one phase of the input electrical wiring to the compressor motor **25** and transmits the current signal to the current-to-pressure converter **96.** The current-to-pressure converter **96** continuously transmits a pressure signal proportional to the current flow to the compressor motor **25.** The pressure signal is transmitted through a pipeline **99** to the solenoid valve **42** and thence through a pipeline **100** to a flow controller **102.** The flow controller **102** may be a Foxboro Model M/52A-7M4-B, manufactured by the Foxboro Company, Foxboro, Mass. 02035. The flow controller **102** receives a control air input from a pipeline **104** connected to the control air manifold **62.** The function of the flow controller **102** is to take the proportional signal pressure transmitted by the current-to-pressure converter **96** and convert this signal into a pressure signal recognizable by the blow-off valve **56.** That is, the signal pressure transmitted by the current-to-pressure converter **96** would not necessarily be of the proper range to operate the blow-off valve to avoid surge. Therefore, the flow controller interrupts the signal transmitted by the current-to-pressure converter **96** and transmits a signal through an output pipeline **106** which will operate the blow-off valve **56.** The flow controller **102** is preset to give a maximum output pressure signal, so long as the proportional signal pressure signal from the current-to-pressure converter **96** remains above a value indicating normal operation. This allows the blow-off valve **56** to be closed, since, as previously noted, the blow-off valve **56** is normally open and requires a pressure signal to keep it closed. However, as the signal from the current-to-pressure converter **96** begins to fall below the pre-selected level, the pressure output from the flow controller **102** to the blow-off valve **56** will begin to drop, and the blow-off valve **56** will start to open. The output line **106** is connected to a volume booster **108.** The volume booster may be a Foxboro Model B102RN, manufactured by the Foxboro Company, Foxboro, Mass. 02035. The volume booster **108** receives a source of control air through a pipeline **110** connected to the control air manifold **62.** As previously explained, the only function of the volume booster **108** is to increase the volume of the signal transmitted by the flow controller **102** through the pipeline **106.** This is to allow operation of the blow-off valve in a more rapid manner than would be possible if the pressure signal in the pipeline **106** were used. The output of the volume booster is transmitted to the blow-off valve **56** through an output pipeline **112.** As the current sensed by the coil **98** varies in the range in which surge is impending, the degree of opening of the blow-off valve **56** is controlled by the modulated signal received from the pipeline **112** to open and close the blow-off valve **56** in such a manner that surge would be prevented. So long as the operation of the entire system is in the pre-selected range, the blow-off valve **56** will be modulated open and closed. As surge becomes more imminent, as indicated by the current sensed by the coil **98,** the blow-off valve will become further and further open until, just prior to the surge point, the blow-off valve **56** will be fully open. With the blow-off valve **56** in the fully open position, it is impossible for surge to occur, since a vent is provided for the minimum capacity volume generated by the compressor **48.** As the conditions which were tending to create surge in the system correct themselves, the current sensed by the coil **98** will rise above the value which indicated the imminence of surge, the blow-off valve **56** will become fully closed again, and the system will be operating in a normal mode. Provision has also been made to allow the system to continue operating, even in the event of a failure of the source **60** of control air. A pipeline **113** is connected to the pressure sampling line **64.** The pressure in the pipeline **113** will be whatever the system pressure is, and generally will be too high for use as control air. Thus, the pipeline **113** is connected to a pressure regulator **114,** which reduces the pressure to a value slightly less than that of the control air source **60.** The pressure regulator **114** is connected to a check valve **116** by a pipeline **115.** The check valve **116** is connected to the line **61,** into the control air manifold **62,** by a pipeline **117.** So long as air is being furnished by the source **60** through the pipeline **61,** the balance of pressures in the check valve **116** will prevent air from flowing through the pipeline **115** into the pipeline **61.** However, in the event of a failure of the pressure from the source 60, the check valve 116 will open and allow air, reduced in pressure by the pressure regulator 114, to flow through the pipeline 117 into the pipeline 61 and thus continue to furnish air through the control air manifold 62. A check valve 59 interposed in the pipeline 61 between the control air manifold 62 and the control air source 60, prevents any backflow of air into the dead control air source 60 during such periods. The scheme just described for continuing operation in case of a failure of the source 60 of control air will also allow operation of the compressor 48 with no source of control air whatsoever. That is, under some circumstances, a source 60 of control air is not available, as in the case where a single compressor 48 is in use. Thus, the compressor 48 is initially started as previously described. The startup procedure requires the inlet valve 46 to be closed and the blow-off valve 56 to be open. In this configuration, the compressor 48 is in a stable operating mode. However, as soon as the compressor 48 begins to generate a system pressure, the pipeline 113 will begin to receive pressure through the pressure sampling line 64. When this occurs, the pressure may be then further transmitted to the control air manifold 62. Once the control air manifold 62 has been pressurized, the other elements of the anti-surge and maximum flow limiting control circuits may be energized from the control air manifold 62, allowing the blow-off valve to be closed and the inlet valve to be opened under control. In this situation, it is again emphasized, there is no source 60 of control air whatsoever present. The only source of control air is that furnished by the compressor 48 itself as it begins to operate.

The solenoid valve 40 is of the normally closed type. Thus, when power is first applied to the ladder circuit 10, the valve 40 will be open (receiving power through the normally closed contact pair 4CR4) and vent any residual pressure in the line 83 to the atmosphere. As the startup proceeds, the coil 4CR will be energized, thus opening the contact pair 4CR4, closing the valve 40. During a power failure, the valve 40 will remain closed, because no power is available in the ladder circuit 10 to energize the coil 5SV. When the power is restored, the valve 40 will be open for a very short period of time until the coil 4CR can be re-energized.

It should be pointed out that the surge prevention system is essentially self-compensating for changes in the ambient temperature of the gas being compressed. In the prior art systems using ΔP cells, the surge point could shift toward or away from the set point as the temperature varied, since surge is, in part, a volume phenomenon and thus a function of ambient gas temperature. In the present invention, the current to the motor 25 will rise and fall as the gas temperature rises and falls, since the work required to compress a fixed volume will depend on the gas density. Since surge in this invention is sensed as a function of motor current, the "floating" motor current compensates for the change in the surge point due to temperature variations.

In addition to completely controlling surge and overloading the compressor motor 25, the control system of the present invention will also allow the compressor 48 to survive short duration power interruptions without any significant loss of process pressure or the necessity of shutting the compressor 48 completely down and restarting it. Heretofore, it has been believed impossible to allow centrifugal compressors to remain in an operating mode during short periods of power interruptions. It has been the conventional practice to provide safety interrupt circuits in the main power control panel to force the compressor to shut down whenever the power fails, or due to conventional control schemes. This necessitates going through the entire laborious startup procedure to bring the compressor back on line, as well as a considerable loss of production. I have found that by proper design of the circuit as herein disclosed, the compressor may safely ignore power dips or failures of up to five seconds in duration and remain in the running mode. The power input, to maintain the compressor operation during these power dips, is provided by the main input drive gear to the compressor 48 which acts as a flywheel during these short power interruptions. The circuit which allows the restarting of the compressor 48 once the power is re-established without an operator or necessity of completely going through the startup procedure is as follows: Reference should first be made to Table 1 under the column labeled "Power Failure". This listing establishes the condition of each contact pair within the ladder diagram 10 shown in FIG. 1. Particular note should be paid to the contact pairs 6TR2, 7TR1, 6TR1 and 6TR3. It should be apparent from Table 1 that these terminals remain in the "on" condition, even though power has failed. This results from the characteristics of the coils 6TR and 7TR, which hold the contact pairs closed for a short period of time after the coils have been de-energized. To date, I have found that this period of time may most advantageously be held to around five seconds in duration before the flywheel effect of the compressor 48 main drive gear begins to dissipate sufficiently to cause difficulties in restarting of the compressor 48. Assuming now the terminal configuration described in Table 1 under the "Power Failure" column, it will be noted that the coils 2SV, 3SV and 4SV controlling the solenoid valves 44, 38 and 42 have been affected by the power failure. In particular, the solenoid valve 42 has been closed, the solenoid valve 38 has been closed, and the solenoid valve 44 has been opened. It should have been apparent that the control system for the compressor 48 which controls the inlet valve 46 and the blow-off valve 56 is largely pneumatic in nature and self-contained. Thus, an electrical power failure does not necessarily disrupt the ability of the inlet valves 46 and the blow-off valve 56 to operate. Closing the solenoid valve 42 locks whatever pressure signal was being introduced into the flow controller 102 through the inlet line 100 at the time of the power failure. This means that the pressure signal will remain constant to the blow-off valve 56 during the time of power failure and the blow-off valve 56 will remain in the position it had assumed just prior to the power failure until power is re-established. Likewise, when the solenoid valve 38 closed, the path from the inlet valve 46 to the pressure controller 72 was blocked. However, opening of the solenoid valve 44 provided a bypass through the pipelines 89 and 90 through the volume booster 48 and to the inlet valve 46. This allows the inlet valve 46 to be modulated during the periods of power failure through the pressure transmitter 66 and the pressure controller 72. The current-to-pressure converter 78 is effectively by-passed during this period of time, but since there is no electrical power, the coil 80 could not generate a signal to the current-to-pressure converter 78 and consequently it is of no influence whatsoever during power failure periods. It should be again kept in mind that the duration of the power failures which are herein discussed are generally of a short duration, 5 seconds or less. Thus, the time during which the control of the inlet valve **46** and the blow-off valve **56** is strictly under pneumatic control is of a relatively short duration. The provision for the control during this period of time, however, allows the compressor **48** to be restarted in a substantially stable operational mode and prevents the development of large oscillations as the control system again takes effect with the resumption of electrical power. Considering the ladder diagram **10** of FIG. **1** with the power off and assuming now that power is re-established after a short duration power failure or dip, the first devices which can receive power are the coils **1TR** and **2CR**. It will be noted that the control pairs **3CR1** and **2CR1** prevent power from entering the safety reset circuit, and the open contact pair **3CR2** prevents power from entering the motor starting circuit. The coil **1TR** opens the contact pair **1TR1** after a predetermined time. When closed, the contact pair **1TR1** energizes the coil **2CR** which, in turn, energizes the contact pair **2CR1**. In addition at this time, the coil **2TR** is likewise energized. It can be seen that closing of the contact pair **2CR1** in conjunction with the contact pair **6TR2**, which it will be recalled remains closed during the short duration power failures, effectively bypasses the reset switch **14** and allows current to flow through the elements **16, 18, 20** and **22**. In addition, the contact pair **1CR1** is now closed since power is re-established to the main power inputs to the motor starter **24**. The contact pair **2TR1** likewise remains closed provided **1TR1** functions correctly. Finally, the incoming current will energize the coil **3CR** as is the case in a normal procedure. At this point, the contact pair **3CR1** will again be locked in and the motor starting circuit will be energized just as if the reset button **14** had been pushed by the operator. Approximately 2 seconds after the coil **1TR** has been energized, the contact pair **1TR1** will open, thus cutting the power to the coil **2CR** and the coil **2TR**. This will open the contact pair **2CR1** as a safety precaution. In addition, the contact pair **2TR1** will remain closed since the current to the coil **2TR** was stopped before the contact pair **2TR1** could be dropped out. The coil **2TR** is provided strictly as a safety measure in case the contact pair **1TR1** should stick and not open properly as it should, thus leaving the contact pair **2CR1** closed and allowing the possibility of a false restart. In addition, the inrushing current will flow through the contact pairs **2CR2** and **2CR3**, thereby opening the solenoid valve **42** and closing the solenoid valve **44** after the coil **2CR** has been de-energized. Energizing the coil **3CR** will close the contact pair **3CR2**. It may be seen that there is now a parallel bypass around the contact pair **4CR1** and the start button **28** through the contact pairs **7TR1** and **6TR1**. Again, it should be kept in mind that the contact pairs **7TR1** and **6TR1** are controlled by relays which hold them closed a present length of time after power has failed to the coils **6TR** and **7TR**. The current may now flow through and energize the coil **4CR**. Energizing the coil **4CR** again closes the contact pair **4CR1**, and power is established to the motor **25** by closing the contact pair **4CR2**. Likewise, the contact pair **4CR3** is closed and power is re-established to the time delay relay coil **5TR** and to the coil **5CR** through the parallel circuit of the contact pair **6TR3**. Energizing the coil **5CR** further closes the contact pair **5CR1** and the coil **5CR** is again locked into the circuit. The contact pair **5CR2** is then closed, thus allowing power to the coils **4SV, 6TR** and **9TR**. Energizing the coil **4SV** opens the solenoid valve **38** and again allows control of the inlet valve **46** through the control system previously described. Energizing the coil **6TR** then resets the contact pairs **6TR1, 6TR2** and **6TR3** in preparation for any future power failures. Additionally, coil **9TR**, having been re-energized, begins again the timing cycle before the contact pair **9TR1** will be closed. The time period of the coil **9TR** is much longer than the time period of the coil **7TR**. Thus, the contact pair **7TR1** will open before the coil **9TR** has completed the timing cycle. It will therefore be impossible to restart the system if another power failure occurs within a relatively short period of time after the first. It is assumed that such rapidly occurring power failures indicate serious problems with the electrical supply, and the compressor **48** should be shut down in any event. Assuming, however, that a power failure does not occur within a short period of time, in this case 60 seconds, the contact pair **9TR1** will close once again, thereby energizing the coil **7TR**. Energiziing the coil **7TR** will once again close the contact pair **7TR1** and allow the parallel bypass of the contact pair **4CR1** to be once again completed and ready for operation in the event of a short duration power failure.

To avoid the introduction of excessively high electrical signals to the current-to-pressure converters **96** and **78** during the initial startup procedure or during the restarting of the motor **25** after a power failure, a series of shorting contact pairs are provided in parallel in the electrical wiring leading from the coil **98** to the current-to-pressure converter **96** and the wiring leading from the coil **80** to the current-to-pressure converter **78**. Considering first the circuitry from the coil **98** to the current-to-pressure converter **96**, a normally closed contact pair **5CR3** is provided in parallel with the coil **98**. Until the coil **5CR** has been energized, the contact pair **5CR3** will remain closed and provide a short circuit for any current in the coil **98**. Once the coil **5CR** has been energized during the startup procedure, the contact pair **5CR3** is open and thus eliminates the short circuit. A second contact pair **2CR4** is connected in parallel with the terminal **5CR3**. The normally open contact pair **2CR4** is closed only during periods in which current is flowing to energize the coil **2CR**. Thus, during the startup procedure, the coil **2CR** is energized for a short period of time, causing the contact pair **2CR4** to be closed and provide a short circuit. In addition, during the time of restart of the motor **25** after a power dip, the contact pair **2CR4** is again closed by the brief energization of the coil **2CR** during the restart procedure. This is necessary during the restart procedure after a power failure because the motor **25** continues to rotate even during the power failure, and once power is established, the motor must re-establish its' phase relationship with the input voltage. This period of re-establishment of phase relationship results in relatively large currents being generated in the coil **98**. These currents must be withheld from the current-to-pressure converter **96** to avoid distorted readings and consequent erratic operation of the blow-off valve **56**. A normally closed contact pair **5CR4** and a normally open contact pair **2CR5** are provided in parallel in the electrical wiring from the coil **80** to the current-to-pressure converter **78.** These two contact pairs **5CR4** and **2CR5** function identically with the previously described contact pairs **5CR3** and **2CR4** to prevent the introduction of excessively high currents to the current-to-pressure converter **78.** In this case, the excessively high currents might result in erratic operation of the inlet valve **46.**

FIG. **3** illustrates in schematic form the general configuration of the motor starter **24.** Incoming three-phase power is furnished to the motor starter **24** by three inlet electrical lines **118, 119** and **120.** A transformer **122** is connected to the incoming wiring **118** and **120.** The transformer **122** furnishes power to an electrical ladder circuit **124.** As previously discussed, connected in parallel across the ladder circuit **124** is a coil **1CR** whose functioning has been discussed in conjunction with the contact pair **1CR1.** This coil **1CR** ensures that main power is available to the motor. A second parallel branch contains the contact pair **4CR2** in series with a coil MR. When the contact pair **4CR2** is closed, the coil MR may likewise be energized. Energizing the coil MR closes the contact pairs MR1, MR2 and MR3. This then allows power to flow to the motor **25** through the main output lines **126, 127** and **128.**

This control system has found particular utility in glass container manufacturing plants. Glass container manufacturing machinery is almost entirely air operated. Thus, either "surge" or the shutdown of the plant air compressors due to a power failure or power dip is extremely costly. For example, a power failure leading to compressor shutdown of three seconds in a typical plant generates a production loss of $11,000. One other plant typically experienced eighteen such shutdowns per year. Most of the power failures were of the very short duration type which this control system successfully ignores. With the present control system, shutdowns due to short duration power failures have been virtually eliminated. As an example, one plant suffered a total of approximately 26 short-term power interruptions in one day due to an ice storm. The present control system allowed the compressors to successfully "ride" all of these power interruptions without a single compressor shutdown or surge.

It may be of value in a fuller understanding of the present invention to break down the components previously described into sub-components with functional designations to better understand their interrelationship. For example, the ladder diagram **10** is actually made up of a number of sub-circuits which can be readily identified and labeled by function. For example, the circuit which includes the reset switch **14,** the contact pair **3CR1,** the safety interlock elements **16, 18, 20, 22, 1CR1** and **2TR1,** and the coil **3CR** may be labeled or termed a safety interlock circuit. It is the function of this circuit to monitor the status of critical components of the compressor **48** and prevent starting or continued operation of the motor **25** in the event of an abnormal status of any one of the critical components thus monitored. The reset switch **14** and the circuit locking contact pair **3CR1** provide parallel paths for power to enter the safety interlock circuit thus described. With the circuit thus described, a power failure would result in an inability for power to re-enter the circuit, since the locking contact pair **3CR1** would become open at the time of a power failure and the reset switch **14** requires manual operation for it to function. However, the contact pairs **2CR1** and **6TR2,** connected in parallel around the reset switch **14** and the locking contact pair **3CR1,** provide a separate circuit which may be described or termed as a safety interlock restart circuit. This safety interlock restart circuit allows bypassing of the previously described parallel components so that power may be re-introduced into the circuit after a short-term power failure. The circuit which includes the contact pair **3CR2,** the start switch **28,** the locking contact pair **4CR1,** the limit switches **30** and **31,** the minimum oil temperature switch **32** and the coil **4CR** may be considered to be an enabling circuit. The purpose of the enabling circuit is to allow the motor starter **24** to receive a signal which will allow current to be delivered to the motor **25.** Again, it should be realized that upon a power failure, the enabling circuit may not be automatically restarted due to the presence of the open contact pair **3CR2,** the open start switch **28** and the open circuit locking contact pair **4CR1.** The contact pairs **7TR1** and **6TR1** connected in parallel with the locking contact pair **4CR1** constitute an enabling restart circuit which allows the enabling circuit to be re-energized after a power failure. The sub-circuit in the ladder diagram **10,** which includes the contact pairs **4CR3, 5TR1, 5CR1, 6TR3, 5CR2** and **9TR1,** and the coils **5TR, 5CR, 6TR, 7TR** and **9TR** may be considered to be a power dip timing circuit. That is, it is the function of this circuit to time the duration of a power dip and determine whether or not the compressor **48** may be restarted without the necessity of going through the normal startup procedure. This timing function, as previously described, is primarily carried out by the coils **6TR** and **7TR,** but the entire circuit described is desirable to make the power dip timing circuit function in its intended manner. As a final sub-circuit, the coil **1TR,** the coil **2CR,** the coil **2TR** and the contact pair **1TR1** make up a redundant, fail-safe restart circuit. The function of all of these components and their interrelation has been previously described, so it is believed unnecessary to completely redescribe these functions again. However, the name given to this circuit, it is believed, is sufficiently descriptive of its function to allow one to understand the interaction of this circuit with the other sub-circuits just defined. Of the sub-circuits defined, the safety interlock restart circuit, the enabling restart circuit, the redundant fail-safe restart circuit and the power dip timing circuit all function together to make up a circuit means which is interconnected with the safety interlock circuit and the enabling circuit for automatically re-energizing the safety interlock circuit and the enabling circuit when the duration of a failure of the main electrical supply is of a duration less than a pre-determined period of time. The re-establishment of these connections will of course allow power to be again supplied to the drive motor **25** and will consequently cause a restart of the compressor **48** without intervention of an operator.

In a similar manner, it may be helpful to consider the control system for preventing compressor surge and the control system for preventing overrunning of the compressor motor **25,** in a functional sense. The elements making up this control scheme have been described as pneumatically operated components. However, in a broader sense, these elements may be electrical type controllers, and the pneumatic controllers described herein may be considered simply to be by way of a preferred example. Thus, in the maximum flow rate limiting control scheme, the pressure transmitter **66** may be considered to be a signal generating means which senses the process pressure and generates an output signal proportional to the process pressure. Similarly, the pressure controller **72** may be considered to be a control means which is responsive to the proportional signal for comparing the proportional signal with a pre-selected process pressure value and generating a control signal which represents the deviation of the proportional signal from the pre-selected process value. Finally, the current-to-pressure converter **78** may be considered to be a means which is responsive to the electrical current delivered to the motor **25,** which will pass the control signal without deviation so long as the current value remains below a pre-selected value, and will modulate the control signal as a function of the motor current above the pre-selected value to adjust the inlet valve **46** in response to the modulated control signal to avoid exceeding the maximum permissible flow rate of the compressor **48.** Similarly, in the surge avoidance control scheme, the current-to-pressure converter **96** may be considered to be a means responsive to the electrical current delivered to the electric motor **25** for generating a signal proportional to the motor current. The flow controller **102** may then be considered a control means for comparing the generated proportional signal with a pre-selected minimum value of the proportional signal and generating a modulated control signal to open the blow-off valve **56** as the proportional signal falls below the pre-selected value and close the blow-off valve **56** as the proportional signal rises above the pre-selected value.

What I claim is:

1. Apparatus for preventing shutdown of a centrifugal compressor driven by an electric motor during short-term power failures, comprising: a source of electrical power connected to said motor; switch means interposed said power source and said motor; electrically operated switch actuating means connected to said switch means and to said power source, said switch actuating means normally opening said switch means upon power failure; and circuit means electrically interconnecting said switch actuating means and said power source for automatically reactuating said switch means when a power failure is of a duration less than a first pre-determined period and for not actuating said switch means when said power failure is of a duration greater than said pre-determined period and when a second power failure occurs within a second pre-determined time period from the end of an original power failure greater than said first pre-determined time period.

2. In the method of operating an electric motor driving a centrifugal compressor, wherein said motor is normally connected to a source of electrical power and started through the sequential operation of electrical circuit means initiated by the action of a human operator, and wherein an electrical power supply failure results in a shutdown of said motor requiring human intervention to re-initiate the normal starting sequence, the improvement of automatically restarting said motor after a short time duration power failure, comprising the steps of:

a. electrically measuring the time duration of said power failure;

b. automatically initiating the sequential operation of said electrical circuit means if said measured time is less than a first pre-selected value to thereby cause said motor to be restarted;

c. electrically measuring a second pre-selected time period beginning with the automatic initiation of the sequential operation of said electrical circuit means; and

d. inhibiting the automatic initiation of the sequential operation of said electrical circuit means if a power failure occurs during said second pre-selected time period.

3. Apparatus for preventing shutdown of a centrifugal compressor, driven by an electric motor, during short-term power failures, comprising, in combination: a main electrical supply; a safety interlock circuit electrically connected to said main electrical supply for stopping said motor and for monitoring the status of critical components of said compressor and to prevent starting or continued operation of said motor in the event of an abnormal status of any one of said critical components, said safety interlock circuit including a power inlet portion comprising a momentary contact reset switch and a first circuit locking relay contact pair connected in parallel such that electrical power into said safety interlock circuit must flow through either said reset switch or said first circuit locking contact pair and electrical power will not be automatically re-established to said safety interlock circuit through said reset switch or said first circuit locking contact pair when electrical power is re-established after an electrical power failure;

a motor starter circuit electrically connected to said main electrical supply and said drive motor for transferring electrical current to said motor;

an enabling circuit electrically connected to and energized through said safety interlock circuit, said enabling circuit being electrically connected to said motor starter circuit for controlling said motor starter circuit to allow current to flow to said drive motor, said safety interlock circuit and said enabling circuit, upon failure of the main electrical supply, becoming de-energized to thereby open the connection of said main supply to said drive motor to prevent reconnection of said main electrical supply to said motor upon resumption of power to said main electrical supply, said enabling circuit including a power inlet portion comprising a momentary contact start switch and a second circuit locking relay contact pair connected in parallel such that electrical power into said enabling circuit must flow through either said start switch or said second circuit locking contact pair and electrical power will not be automatically re-established to said enabling circuit through said start switch or said second circuit locking contact pair when electrical power is re-established after an electrical power failure; and

circuit means connected to said main electrical supply and interconnecting said supply with said safety interlock circuit and said enabling circuit for automatically re-energizing said safety interlock circuit and said enabling circuit when the duration of the failure of said main electrical supply is of a duration less than a pre-determined period to thereby re-establish connection of said main electrical supply to said drive motor, said circuit means including a safety interlock reset circuit connected in parallel with said reset switch and said first circuit locking contact pair for allowing re-energization of said safety interlock circuit after a power failure.

4. The apparatus of claim **3,** wherein said circuit means further includes an enabling restart circuit connected in parallel with said start switch and said second circuit locking contact pair for allowing re-energization of said enabling circuit after a power failure.

5. The apparatus of claim **4,** wherein said circuit means further includes a power dip timing circuit electrically connected to said safety interlock restart circuit and said enabling restart circuit.

6. The apparatus of claim **5,** wherein said circuit means further includes a redundant, fail-safe restart circuit electrically connected to said power dip timing circuit and said safety interlock restart circuit.

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