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(54) AUTOMATIC CONTROL SYSTEM WITH GAIN SWITCHING

(71) We, BARBER-COLMAN COMPANY, a Corporation organised under the laws of the State of Delaware, United States of America, of 1300 Rock Street, Rockford, Illinois 61101, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates generally to automatic control systems. More specifically, it relates to electric control systems wherein the control signals utilized are combined functions of a proportional signal and the integral and derivative thereof.

Automatic control systems are known in the art. Such systems receive electrical signals representative of a condition of an element to be controlled and compare that signal with a reference to produce an error signal. A particular application of such control systems has been as governors controlling the speed (RPM) of internal combustion engines.

In many applications it is desired to control engine RPM to maintain constant speed in spite of variations of engine load. It is desirable to provide a system wherein the transient response, that is, the response time of the engine and the control system, due to a change in operating conditions, is minimized. This avoids over speed, hunting and instability conditions potentially damaging to the system.

An automatic control system having the characteristics desired for the aforementioned uses is disclosed in U.S. Patent Specification No. 4,070,609. In that Specification an automatic control system is described in which engine speed is sensed by a magnetic pick-up coil. After wave shaping and amplification the wave form is applied through an isolating switch arrangement to the input of an operational amplifier. This amplifier compares the average DC level against a reference to generate an error signal. The error signal is then differentiated and integrated with respect to time. A

signal proportional to the error signal, its integral and its derivative are combined to produce a control signal for operating an actuator device coil. Various protective circuits are incorporated in the controller, such as, a current limiter and a fault detector for determining engine failure. By use of a feedback element associated with the actuator, accurate control over that device is obtained.

The gain of the automatic control system or, more specifically, the gain of the difference amplifier which generates the error signal must be selected according to the characteristics of the prime mover. These characteristics include system inertia, operating speed, rated horsepower, loading, and the like. If the gain is too high for a given application, the automatic control system will hunt, i.e., alternately overshoot and undershoot its desired set point and in severe cases become increasingly unstable. In the case of too little gain from the error signal amplifier, the desired constant RPM cannot be maintained with sufficient accuracy. That is, the transient response is too long.

A special problem is produced where the characteristics of the prime mover change significantly during a period of operation. Under those circumstances, it is necessary to alter the gain of the difference amplifier for each set of operating conditions if maximum performance is to be obtained.

According to one aspect of the invention there is provided an automatic control system for use with a prime mover controlled thereby, the prime mover having in use a variable acceleration rate, the system comprising:—  
 (a) means for detecting an operating condition of said controlled device and generating a proportional signal,  
 (b) amplifier means receiving said proportional signal and producing an error signal representative of the difference between the detected condition and a preset value thereof,  
 (c) means for switching the gain of said amplifier means between at least two preset values, and

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(d) means for controlling said switching means in accordance with the acceleration rate of the prime mover.

5 According to another aspect of the invention there is provided an automatic control system for use with a prime mover controlled thereby, the prime mover having in use a variable acceleration rate, the system comprising:—

10 amplifier means for producing an error signal representative of the difference between the detected condition and a preset value thereof,

15 means for switching the gain of said amplifier means between at least preset values, and

means for controlling said switching means in accordance with the acceleration rate of the prime mover.

20 An embodiment of the invention will now be described by way of example with reference to the accompanying drawings in which:—

25 Figure 1 is a block diagram of an automatic control system according to the present invention.

Figure 2 is a partial schematic of the control system illustrating the details of the gain change circuitry.

30 Figure 3 is a schematic representation of a typical application of a control circuit according to the invention.

Referring to Figure 1, a block diagram of a control system according to the invention is illustrated. The RPM of a prime mover, such as a diesel engine or similar internal combustion engine, is detected by a magnetic pick-up coil 10. The sinusoidal wave form produced by the coil is received by a wave shaping and amplifier circuit 12 which produces square wave pulses therefrom. The series of pulses, the frequency of which is proportional to the detected RPM of the engine, is fed through an electronic switching and noise isolation circuit 14. This circuit produces an average DC voltage level proportional to the received pulses from the wave shaper block 12. The average DC signal is applied to the difference amplifier circuitry 16 for producing an error signal at junction 18. The error signal is integrated by integrator 20 and differentiated by a signal is applied to the difference amplifier and its derivative are then applied to a control signal generator 24, the output of which is provided at junction 26.

A control element, the state of which is controlled by the signal at junction 26, may be constituted by any number of devices. 60 In the case of an engine governor, the control element may be a valve controlling fuel to the engine. The position of the valve is determined by the energization state of a solenoid coil, such as, coil 28. The state of energization is, of course, a function of the

average current through the coil. In order to provide a signal representative of the actual position of the valve, a feedback element, such as a potentiometer, is mechanically connected to the solenoid actuator 70 so as to produce a feedback voltage representative of position. The feedback element 30, therefore, also applies a voltage to the junction 26. Junction 26 is the input to a difference amplifier, which amplifier compares the magnitude of the control signal with the magnitude of the feedback signal from the actuator potentiometer. The difference between the signals, if any, is supplied as one input to the amplifier circuit. A sawtooth wave oscillator 34 is applied to the other input of the difference amplifier to produce a pulse width modulated signal at the output of the amplifier which determines the average current flowing through the coil 28. 85

The circuit thus far described provides an automatic control circuit to maintain an engine or other prime mover at a regulated operating condition, for example, constant speed. Additional optional features of the circuit include the provision of an external limit override circuit 36 which can override the signal from the control signal generator 24 upon detecting selected conditions, such as, high temperature, excessive smoke, improper manifold pressure, etc.; a current limiter 38 and a fault detector circuit 40, the latter ceasing operation of the circuit upon detection of engine failure. 100

Of particular importance is the electronic switching circuit 14 and the difference amplifier 16. These circuits, in conjunction with a circuit now to be described, permit the automatic control circuit to cope with change 105 in engine acceleration rate. Specifically, where a significant change in acceleration rate of a prime mover occurs, it is necessary to adjust the gain of the difference amplifier circuit 16. This is accomplished by use of a switching arrangement including buffer circuit 42, transistors 44 and 46, and resistors 48. These components, responsive to an external switch (which may be a mechanical contact switch, a relay contact or a mercury switch) indicated schematically at 115 will switch feedback resistor 48 in or out of the feedback circuit of the difference amplifier 16. As will be apparent, inclusion of resistor 48 in the feedback loop of the difference amplifier reduces the gain while excluding the resistor increases the gain. 120

Referring to Figure 2, a portion of the Figure 1 circuit is illustrated in schematic form, which portion includes an electronic switching block 14 and the differential amplifier circuit 16 as well as the buffer circuit 42. The magnetic pick-up coil wave form is applied to the wave shaping and amplifier circuit 12. The square wave pulse 130

which is produced therefrom is applied to the electronic switching circuit 14. Preferably, the switching circuit employs a number of electronic switching devices as, for example, FET's. A typical FET switch commercially available is a type CD4016 in which four bi-lateral switches are provided on an integrated circuit chip. These switches are shown in the drawing as field effect transistors 60, 62, 64 and 66. The pulses provided from the wave shaper 12 are received at junction 68 and are applied to switch 60 for connecting one side of capacitor 70 to ground. Also connected to junction 68 is a further switch comprising transistor 72 for connecting junction 74 to ground. Also connected to junction 68 is a further switch comprising transistor 72 for connecting junction 74 to ground. Junction 74 controls operation of switch 64 which connects junction 78 to junction 80 at the input of the operational amplifier 82. Switch 66 is controlled from junction 84 and connects line 86 to a positive reference voltage.

The purpose and function of the three switches 60, 64 and 66 is fully described in U.S. Patent Specification No. 4,070,609. In summary, each time switch 60 is closed, the charge on capacitor 70 is removed to ground. Switching transistor 72 acts as an inverter with respect to the output signal from the wave shaper 12 and applies its inverted output to the junction 74. The switch 64 connects the capacitor 70 to the summing junction 80. The circuit described is one in which the switch means 60 conducts substantially in phase with the square wave output from wave shaper 12 removing charge from the capacitor 70 in an amount proportional to the frequency of the input signal. Because of the inverter action of the switch 72, switch 64 conducts substantially 180° out of phase with the input signal and pulsating DC current appears at the summing junction 80. This pulsating current has an average value which is proportional to the frequency of the input signal. The summing junction 80 is at a fixed voltage established by the potential source and the resistor 90 applied to the positive input.

It will be evident that the capacitor 70 alternately charged by current flow from the summing junction 80 through the switch means 64 and then discharged to ground through switch means 60. Each cycle of charge and discharge transfers a fixed amount of stored charge causing the pulsating DC current to flow from the summing junction. The purpose of this switching arrangement is to eliminate the effect of transient signals since the voltage at the summing junction 80 is produced from a regulated source isolated by the switching arrangement from the input signals of the wave shaper 12.

In order to produce the desired error signal, the feedback signal from the summing junction is compared to a reference signal provided on line 92. The reference may be supplied through a filter circuit 94 and may be an internal reference 96 or an external reference voltage applied on terminal 98.

Regardless of the source of reference signal, the reference signal and the proportional DC signal are summed at junction 80 and applied to the negative input of operational amplifier 82. The output of amplifier 82 is provided at junction 98. Connected from the output junction 98 of the amplifier to its negative input are a number of feedback elements, which elements directly control the amplifier gain. These include resistor 100 and variable resistor 102 and capacitor 103 to smooth out the pulsating signals. Also provided in the feedback circuit is a feedback resistor 104. It is by alternately switching resistor 104 into and out of the feedback circuit that the gain of the system is altered. One side of resistor 104 is connected to the summing junction 80. The other side of the resistor is connected to switch 62. The output of switch 62 is connected via line 106 to the junction 98 at the amplifier output. The control gate 108 of switch 62 is connected to the buffer circuit 42.

It will be seen that closing external switch 50 produces an output from the buffer circuit 42 effective for disabling switch 62. This, in turn, removes resistor 104 from the feedback path of the amplifier 82 significantly increasing the amplifier gain. When switch 50 is open, the reverse conditions exist, namely, switch 62 is closed, resistor 104 is in the feedback path of amplifier 82 and the gain is significantly lower.

Referring to the details of buffer circuit 42, a Zener diode 110 is employed to reduce noise while diode 112 prevents negative transients from causing false triggering of inverting transistor 114. When switch 50 is closed, transistor 114 conducts dropping the collector from a positive voltage to ground. The collector of transistor 114, via line 116, is the control input to gate 108 of switch 62. Zero voltage on line 116 disables switch 62 for the purpose just described.

Having explained the structure and function of the gain switching circuit, it is desirable to indicate the reasons for its presence and in particular one application where its presence is highly desirable. Where a prime mover is subjected to loading conditions which vary considerably, proper operation of a control system is difficult to achieve. For example, where the inertia of the prime mover system is very high, the acceleration rate of the prime mover will be very low. That is, a correction in speed requires a

relatively long period of time to effect. Under those conditions high gain from the control circuit is desirable in order to minimize this transient period.

5 Alternatively, where the system inertia is low and the motor can rapidly respond to any desired speed change, the control circuit gain must be lower to avoid instability and, in particular, the tendency of the control circuit to hunt for the set speed. By  
10 actuating the switch 50 in accordance with the gain requirements of the prime mover, these alternative conditions can be achieved.

Referring to Figure 3, a specific application of the gain switchable control circuit is illustrated. It should be recognized that this application is merely exemplary for there are many other applications of the circuit which do not employ the structure  
20 illustrated in Figure 3. In Figure 3 electric power from conventional means, such as a utility, is provided to an electric motor 120. This motor drives a generator 122 to produce electricity for use in a factory, etc. Such an arrangement is common where it is  
25 desired to isolate the internal power from the external source.

If, in addition, it is desired or necessary to maintain a very precise voltage and phase relationship as, for example, for use with  
30 a computer system, a heavy flywheel 124 can be provided on the output shaft 126 of the generator set. Due to the high inertia of the flywheel 124, small changes in engine speed of the electric motor are minimized and will  
35 not adversely affect the generator output.

As is often the case in critical applications, provisions are made to keep the generator set running in the event of an external power  
40 failure. This may be accomplished by use of a diesel engine, such as engine 128, connected via a clutch mechanism 130 to the shaft 126 and the flywheel. It is the engine 128 which is controlled by the automatic control system indicated schematically  
45 at 132. In the event of a power failure, the engine is started by using the energy in the flywheel. With clutch 130 engaged the diesel engine drives the generator shaft and flywheel. Its acceleration rate is extremely low,  
50 on the order of one-half percent per second. Under these conditions the engine control must have a high gain in order to maintain the set speed with reasonable accuracy and response time. Thus, when clutch 130  
55 is engaged, switch 50 is closed causing switch 62 to open and remove resistor 104 from the feedback circuit.

When the external power source is restored, the diesel engine will come off line as the clutch disengages. At this point in  
60 time the load inertia of the system is very low, and the engine has an acceleration rate potential on the order of 300 percent per second. For such a situation low gain is

required for the control circuit 132. Thus, the resistor 104 is switched into the feedback circuit to permit stable control of the engine. This is accomplished by opening  
70 switch 50 in conjunction with disengagement of the clutch 130.

While we have shown and described embodiments of this invention in some detail, it will be understood that this description and illustrations are offered merely by  
75 way of example, and that the invention is to be limited in scope only by the appended claims.

#### WHAT WE CLAIM IS:—

1. An automatic control system for use with a prime mover controlled thereby, the prime mover having in use a variable acceleration rate, the system comprising:—

(a) means for detecting an operating condition of said controlled device and generating a proportional signal,

(b) amplifier means receiving said proportional signal and producing an error signal representative of the difference between the detected condition and a preset value thereof,

(c) means for switching the gain of said amplifier means between at least two preset values, and

(d) means for controlling said switching means in accordance with the acceleration rate of the prime mover.

2. The system according to Claim 1 wherein said prime mover is an internal combustion engine.

3. The system according to Claim 2 wherein said detected operating condition is engine RPM.

4. The system according to any preceding Claim wherein said amplifier means is an operational amplifier connected as a difference amplifier.

5. The system according to Claim 4 wherein the gain of said operational amplifier is controlled by the feedback resistance connected from its output to its input.

6. The system according to any preceding Claim wherein said switching means includes:

(a) a resistor connected in the feedback path of said amplifier means,

(b) a transistor switch in series with said resistor for effectively adding and removing said resistor from the feedback path to change the gain of said amplifier means, said transistor switch being controlled by said control means.

7. The system according to Claim 6 further including means for buffering the signal from said control means to said transistor switch to eliminate noise.

8. The system according to Claim 7 wherein said buffering means includes an emitter follower transistor operating said transistor switch.

9. The system according to any preceding Claim, wherein said control means includes a switch which is either closed or opened when the acceleration rate of the prime mover is low to produce higher amplifier means gain and is opened or closed, as the case may be, when the acceleration rate of the prime mover is high to produce lower gain. 20
10. The system according to Claim 9 wherein said switch is a mechanical contact switch, a relay contact or a mercury switch. 25
11. An automatic control system for use with a prime mover controlled thereby, the prime mover having in use a variable acceleration rate, the system comprising:—  
amplifier means for producing an error signal representative of the difference between the detected condition and a preset value thereof, 30  
means for switching the gain of said amplifier means between at least two preset values, **and**  
means for controlling said switching means in accordance with the acceleration rate of the prime mover.
12. An automatic control system for use with a prime mover controlled thereby, substantially as herein described with reference to the accompanying drawings. 30

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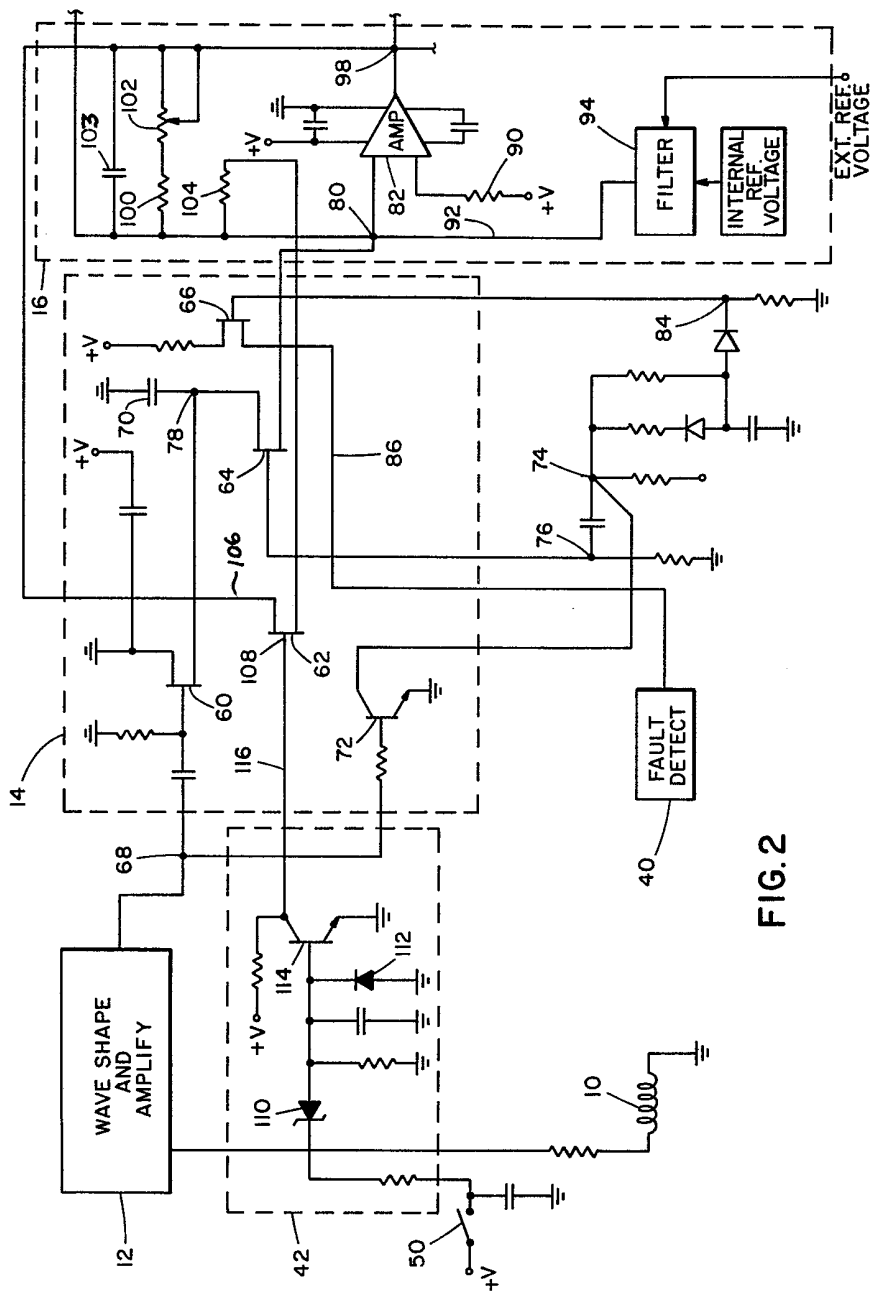


FIG. 2