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(54) Title: METHOD AND APPARATUS FOR FUEL FLOW CONTROL IN AN INTERNAL COMBUSTION ENGINE

(57) Abstract: A control system to provide fuel flow to a motor cycle engine at a flow rate that matches the fuel demand of the engine. The motor speed of a turbine-style fuel pump may be varied, preferably by pulse width modulation (PWM) control. An Engine Control Module (ECM) determines desired fuel flow for any imposed operating condition or engine speed using a combination of engine input parameters plus voltage and flow calibration data maps on the particular fuel pump and motor in the engine, which calibration data maps may be revised periodically during the operating life of the fuel pump and motor. The pump speed may be determined by calibration and measurement of back EMF generated by the pump motor or by calibration and measurement of ripple in the current generated by the motor commutator. These electrical signals are inherent in the operation of the pump motor.

"METHOD AND APPARATUS FOR FUEL FLOW CONTROL IN AN INTERNAL COMBUSTION ENGINE"

TECHNICAL FIELD

The present invention relates to internal combustion engines; more particularly, to a method and apparatus for controlling fuel flow to a small engine; and most particularly, to a method and apparatus for regulating the speed of a turbine fuel pump in such an engine, especially a single-cylinder engine.

BACKGROUND OF THE INVENTION

Small internal combustion engines are well known. Such engines are widely used for powering small motorcycles, motorscooters, and mopeds. Typically, such engines are single-cylinder.

In the prior art, typical fuel delivery to an engine fuel injector is achieved by running a turbine-style fuel pump at a constant and high pump speed such that an excess of fuel is provided. Fuel pressure is regulated by a mechanical fuel pressure regulator in the fuel line. Fuel not consumed bypasses the fuel pressure regulator and is returned to the fuel tank. This arrangement has several shortcomings that are addressed by the present invention.

First, driving the fuel pump continuously at high speed produces excessive engine noise and shortens the working life of the pump motor brushes.

Second, the extra fuel being pumped and bypassed causes higher electrical energy consumption which results in elevating the temperature of fuel in the fuel tank, which in turn increases evaporative emission.

Third, higher electrical energy consumption, mentioned above, poses a burden on the engine dynamo which may have to be over-sized to cope with the extra consumption.

Fourth, pumping the extra fuel requires a larger and more expensive electric motor and pump.

Fifth, in fixed pressure operation it is needed that the fuel injector have a high linear range of operation for flex-fuel engines (i.e. those able to run on a variable ethanol percent on gasoline). This system allows for varying the fuel pressure in function of ethanol content in gasoline, thereby extending the linear range of a fuel injector.

What is needed in the art is a method and apparatus for controlling fuel flow to a small internal combustion engine at a flow rate that matches the fuel demand of the engine.

It is a principal object of the present invention to minimize the size and cost of a small engine assembly.

It is a further object of the invention to reduce hydrocarbon emissions from a small engine assembly.

SUMMARY OF THE INVENTION

Briefly described, the present invention comprises a system whereby fuel flow to a small internal combustion engine is automatically provided at a flow rate that matches the fuel demand of the engine. The engine is provided with a turbine-style fuel pump wherein the motor speed may be varied; preferably by pulse width modulated (PWM) control, to vary the output of the pump. An Engine Control Module (ECM) determines the correct fuel flow for any imposed operating condition or engine speed using a combination of engine input parameters plus voltage and flow calibration data on the particular fuel pump and motor in the engine, which calibration data may be revised periodically during the operating life of the fuel pump and motor. The instantaneous pump speed may be determined by, for example, calibration and measurement of back EMF generated by the pump motor; calibration and measurement of ripple in the current generated by the motor commutator; or by any other convenient means. These electrical signals are currently preferred as they are inherent in the operation of the pump motor and require no special or additional sensors.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

FIG. 1 is a curve showing pump voltage as a function of deadhead pressure (flow = 0);

FIG. 2 is a curve showing an empirically determined flow factor as a function of pump voltage;

FIG. 3 is a plurality of curves showing fuel flow as function of pump output pressure for a variety of pump voltage conditions;

FIG. 4 is a simplified diagram of a scheme for control of fuel pump pressure using a PWM signal;

FIG. 5 is a schematic diagram like that shown in FIG. 4 but incorporating pump speed feedback as a closed loop control element;

FIG. 6 is a curve showing pump motor back voltage as a function of duty cycle in PWM control;

FIG. 7 is a curve showing commutator ripple in a pump motor as a function of motor back voltage;

FIG. 8 is a schematic diagram showing routing of output voltage feedback to an analog-to-digital converter to enable measurement of pump speed in addition to diagnosing pump output;

FIG. 9 is an exemplary schematic diagram showing modeling of actual fuel pressure for correction of injection-controlling pulse width, as may be used in the system shown in FIG. 4;

FIG. 10 is an exemplary schematic diagram showing estimation of actual fuel pressure for correction of injection-controlling pulse width, as may be used in the system shown in FIG. 5; and

FIG. 11 is an exemplary schematic block diagram showing evaluation of a fuel pump duty cycle for PWM of the average fuel pump motor voltage.

The exemplifications set out herein illustrate presently preferred embodiments of the invention, and such exemplifications are not to be construed as limiting the scope of the invention in any manner.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

As noted above, the basis for fuel flow control in the present invention is a system (method and apparatus) wherein operation of a fuel pump motor, and hence of the fuel pump itself, is regulated in average rotation speed and average output pressure to deliver precisely the required flow rate of fuel at any engine condition. A presently-preferred control method is pulse-width modulation (PWM) of the duty cycle of the pump motor wherein a motor is either energized or de-energized in a rapidly alternating series of pulses having a controlled ratio of on and off pulse widths to provide a characteristic duty cycle defining time-averaged pump speed, voltage, pressure, and fuel flow. PWM control itself is well known in the motor control arts and need not be elaborated upon here.

Of course, alternatively the pump speed may be set directly to run at a selected constant speed in a continuous duty cycle, within the scope of the present invention; however, PWM control offers several well-known advantages and thus is preferred.

Thus the functional relationships between pump output pressure, fuel flow, and motor voltage must be established.

Referring to FIG. 1, when a turbine-style fuel pump for an internal combustion engine is operated in deadhead mode (no flow), it is seen that there is an essentially linear relationship (curve 10) between applied pump voltage and deadhead pressure.

In operation, output fuel pressure can be modeled as a function of flow and pump voltage in accordance with the linear equation:

Press(Vpump,Flow) = Press0(Vpump) – Factor(Vpump) x Flow (Eq. 1)

wherein actual pump output pressure at a given pump voltage and fuel flow is reduced from the deadhead pressure at the same voltage by the flow rate times a flow correction factor (FIG. 2, curve 12) that is readily determined empirically as a function of pump voltage. Thus, referring to FIG. 3, a family of real flow curves as functions of flow and fuel pressure may be generated for a range of pump motor voltages. Curves 14,16,18, and 20 represent these relationships for 8,10,12, and 13.5 volts, respectively.

Referring to FIG. 4, a first control scheme 100 for controlling a fuel pump using a PWM signal includes a motor-driven fuel pump 130 supplying fuel 132 to a fuel injector 134 mounted on an engine 136. Engine exhaust 138 is passed through an air/fuel ratio (AFR) “estimator” 140 that supplies a signal 142 to an engine control module (ECM) 144 that sends a command signal 146 that regulates the operation of fuel pump 130 and fuel injector 134. ECM 144 preferably receives input 148 from other system sensors and controls various engine actuators 150. AFR 140 may incorporate any of various sensors such as a linear O_2 sensor, a switching O_2 sensor, an ion sensor, and/or other AFR sensing devices or ECM algorithms.

ECM 144 controls the average voltage applied to fuel pump 130, causing the fuel pump to develop a desired fuel pressure at a given fuel flow. ECM 144 computes the necessary fuel flow and drives fuel injector 134 with a given pulse width (see figure 10). The air and fuel burn, and the effective air/fuel ratio (AFR) will be determined via the AFR estimator. The actual AFR value is used to learn and compensate for production variability of fuel pump characteristics. When the duty cycle of the PWM signal, which drives the fuel pump, changes, the fuel pump motor speed does not change immediately due to inertia and fuel physical characteristics. In order to take this effect into account, a modeling of actual fuel pressure is performed, as shown in FIG. 9.

Scheme 100 is an open-loop control scheme with respect to fuel pump 130 in that ECM 144 has no direct feedback as to the motor speed for fuel pump 130. However, scheme 100 is closed loop in that ECM 144 varies the output of fuel pump 130 to satisfy an internal set point 152 based upon a desired air/fuel ratio for the instantaneous operating condition imposed upon engine 136.

Referring to FIG. 5, a simplified block diagram of the concept of controlling the fuel pump uses a PWM signal with feedback of the back EMF from the fuel pump motor. Second control scheme 200 includes the same components as are shown for first control scheme 100. However, second control scheme 200 is a true closed loop control wherein ECM 144 issues commands 246 to the motor of fuel pump 130 to cause the fuel pump speed to match an internal pump speed setpoint 252 within ECM 144 in response to a pump speed signal 254 from fuel pump 130. As in first scheme 100, when the duty cycle of the PWM signal, which drives the fuel pump, changes, the fuel pump motor speed does not change immediately due to inertia and fuel physical characteristics. In order to take this effect into account, an evaluation of actual fuel pressure is performed based on feedback of back EMF of the fuel pump motor, as shown in FIG. 10.

FIG. 6 shows a curve 22 of pump motor back EMF as a function of duty cycle, for use in control scheme 200 as just described.

Referring to FIG. 7, it is seen that commutator ripple (curve 24) in the EMF signal is a substantially linear function of back EMF. Thus, commutator ripple may also be used as control signal 254 in scheme 200. It should be noted that using either back EMF or ripple requires no additional sensors in the motor control system, as the ECM can sense these motor signals directly.

FIG. 8 shows an exemplary driver and feedback circuit 300 for fuel pump 130. ECM controller 144 sends PWM signal 246 to a power MOSFET 350 that, in conjunction with free-wheel diode 352, controls the average voltage 354 applied to fuel pump 130. For diagnosis purposes, the output voltage 356 is fed back to the controller via a resistive divider 358 formed by resistors R2 and R3, which determines if the output is short to battery or to ground 359. For measuring the back EMF voltage generated by the fuel pump motor when power is not applied, the diagnosis feedback is directed to an analog-to-digital input 360 on controller 144. Thus, using the back EMF as feedback may implemented at no cost without losing the diagnosis capability.

FIG. 9 shows an exemplary block diagram 400 for the modeling of actual fuel pressure using information on the fuel pump motor average voltage 462 (FuelVpump) and fuel flow 464 (FuelFlow), according to control scheme 100 shown in FIG. 4. The actual fuel pressure is modeled using the value of the actual fuel pump motor average voltage 462 and a lag filter 465 (with parameters 466 KFiltPressUp and 468 KFiltPressDn) that models the fuel pump dynamics. The modeled effective average fuel pump voltage 470 (FiltFuelVpump) is used to estimate the actual fuel pressure 472 (EstFuelPress) using fuel flow (FuelFlow) information 464 and lookup maps FFuelPressVpump 476 and FfuelFlowCorr 478. The injector pulse width 480 is computed using the pressure difference 482 across the injector, i.e. between fuel pressure 486 and manifold air pressure 488 (MAP) and lookup 490 of mapped injector characteristics (FinjChar and F33Mult).

FIG. 10 shows a block diagram 500 of a scheme for the estimation of actual fuel pressure 486 using information on the fuel pump motor's back EMF 562 (FPumpBemf) and fuel flow 464 (FuelFlow), according to second control scheme 200 shown in FIG. 5. The fuel pump motor speed 570 is estimated using the value of the fuel pump motor back EMF 562 and a map lookup 564 (FFuelSpdBemf). The estimated pump speed is used to estimate the actual fuel pressure 486 using fuel flow 464 information and lookup maps FFuelPressSpd 576 and FfuelFlowSpd 578. This fuel pressure is corrected 579 by the inverse of individual fuel pump compensation 581 (see FIG. 11). The injector pulse width 480 is then computed as in FIG. 9. The back EMF follows the dynamics of the fuel pump when the average voltage applied to the fuel pump changes.

FIG. 11 shows a block diagram 600 of a scheme for the evaluation of the duty cycle 602 (DC) for PWM control of the average fuel pump motor voltage, as a function of fuel flow 464 (FuelFlow) and desired fuel pressure 604 (DsrdFuelPress). The pressure difference 606 due to the fuel flow is determined from the lookup of map 608 (FfuelFlowCorr), this difference is added to the desired fuel pressure to get the fuel pressure for zero flow 610 (FuelPress_0) which is converted to average fuel pump voltage 472 by the lookup of map 476 FPressVpump. In order to compensate for fuel pump characteristics variability, due to production tolerance and wear-out, the average fuel pump voltage is further multiplied 678 by a factor 680 (PressBLM). This factor is updated periodically during operation of engine 136 when proper learning conditions 682 hold (LearnEnCond) and is essentially a proportional and integral controller in function of the difference 684 between the desired air to fuel ratio 686 (DsrdAFR) and the estimated air to fuel ratio 688 (EstAFR) when the engine is run on a fuel of known characteristics. The resultant corrected average fuel pump voltage 690 is transformed in a duty cycle 602 (FuelPressDC) when divided 692 by the actual battery voltage 694 (Vbatt). The ECM's micro-controller feeds a PWM signal with duty cycle 602 to the driver circuit exemplified in FIG. 8.

While the invention has been described by reference to various specific embodiments, it should be understood that numerous changes may be made within the spirit and scope of the inventive concepts described. Accordingly, it is intended that the invention not be limited to the described embodiments, but will have full scope defined by the language of the following claims.

CLAIMS

1. A system for controlling fuel flow in an internal combustion engine, comprising:

a) a variable speed, electrically-driven fuel pump for providing a flow of fuel at a desired fuel pressure;

b) a fuel injector for receiving said flow of fuel from said fuel pump and injecting said fuel into said engine;

c) an air/fuel ratio estimator for measuring oxygen content of exhaust from said engine and providing a first output signal representative of an estimated oxygen content; and

d) an engine control module for receiving at least said first output signal and for providing a second output signal for controlling an operating parameter of said fuel pump and said fuel injector.

2. A system in accordance with Claim 1 wherein said operating parameter is selected from the group consisting of pump speed and pump output pressure.

3. A system in accordance with Claim 1 wherein said engine control module receives a signal from said electrically-driven fuel pump indicative of the speed thereof.

4. A system in accordance with Claim 3 wherein said signal is selected from the group consisting of back EMF of the pump motor and electrical ripple from the pump motor commutator.

5. A system in accordance with Claim 1 wherein said second output signal is a pulse width modulated signal.

6. A system in accordance with Claim 5 further comprising an algorithm programmed into said engine control module for computing said pulse width modulated signal from measured back EMF of said electrically-driven fuel pump.

7. A system in accordance with Claim 5 further comprising an algorithm programmed into said engine control module for computing said pulse width modulated signal from measured electrical ripple of said electrically-driven fuel pump.

8. A system in accordance with Claim 1 wherein said internal combustion engine is a motorcycle engine.

9. A system in accordance with Claim 1 wherein said electrically-driven fuel pump is a turbine pump.

10. A system in accordance with Claim 1 wherein said engine control module comprises an algorithm including the steps of determining a value of actual average voltage for operating said electrically-driven fuel pump; modeling said actual average voltage via a lag filter to provide an effective pump voltage; determining a value of actual fuel flow rate; calculating an estimated fuel pressure value from said filtered pump voltage and said actual fuel flow rate; calculating a fuel pressure drop across said fuel injector; and

calculating a control pulse width for a duty cycle for said fuel injector from said estimated fuel pressure value and said pressure drop.

11. A system in accordance with Claim 1 wherein said engine control module comprises an algorithm including the steps of determining a value of actual back EMF from said electrically-driven fuel pump; calculating an actual pump speed; determining a value of actual fuel flow rate; calculating an estimated fuel pressure value from said actual back EMF value, said calculated pump speed, and said actual fuel flow rate; applying an individual fuel pump compensation factor to said estimated fuel pressure value to provide a corrected estimated fuel pressure value; calculating a fuel pressure drop across said fuel injector; and calculating a control pulse width for a duty cycle for said fuel injector from said corrected estimated fuel pressure value and said pressure drop.

12. A method for controlling fuel flow in an internal combustion engine including a variable speed, electrically-driven fuel pump; a fuel injector for receiving the flow of fuel from the fuel pump and injecting fuel into the engine; an air/fuel ratio estimator for measuring oxygen content of exhaust from the engine and providing a first output signal representative of an estimated oxygen content; and an engine control module for controlling operation of said fuel pump,

wherein the method comprises the steps of:

a) determining a value of actual average voltage for operating said electrically-driven fuel pump;

b) modeling said actual average voltage via a lag filter to provide an effective pump voltage;

c) determining a value of actual fuel flow rate;

d) calculating an estimated fuel pressure value from said filtered pump voltage

and said actual fuel flow rate;

e) calculating a fuel pressure drop across said fuel injector;

f) calculating a control pulse width for a duty cycle for said fuel injector from said estimated fuel pressure value and said pressure drop; and

g) operating said fuel injector according to said control pulse width.

13. A method for controlling fuel flow in an internal combustion engine including a variable speed, electrically-driven fuel pump; a fuel injector for receiving the flow of fuel from the fuel pump and injecting fuel into the engine; an air/fuel ratio estimator for measuring oxygen content of exhaust from the engine and providing a first output signal representative of an estimated oxygen content; and an engine control module for controlling operation of said fuel pump,

wherein the method comprises the steps of:

a) determining a value of actual back EMF from said electrically-driven fuel pump;

b) calculating an actual pump speed;

c) determining a value of actual fuel flow rate;

d) calculating an estimated fuel pressure value from said actual back EMF value, said calculated pump speed, and said actual fuel flow rate;

e) applying an individual fuel pump compensation factor to said estimated fuel pressure value to provide a corrected estimated fuel pressure value;

f) calculating a fuel pressure drop across said fuel injector;

g) calculating a control pulse width for a duty cycle for said fuel injector from said corrected estimated fuel pressure value and said pressure drop; and

h) operating said fuel injector according to said control pulse width.

14. An internal combustion engine comprising a system for controlling fuel flow in an internal combustion engine, wherein said system includes

a variable speed, electrically-driven fuel pump for providing a flow of fuel at a desired fuel pressure,

a fuel injector for receiving said flow of fuel from said fuel pump and injecting said fuel into said engine,

an air/fuel ratio estimator for measuring oxygen content of exhaust from said engine and providing a first output signal representative of an estimated oxygen content, and

an engine control module for receiving at least said first output signal and for providing a second output signal for controlling an operating parameter of said fuel pump and said fuel injector.

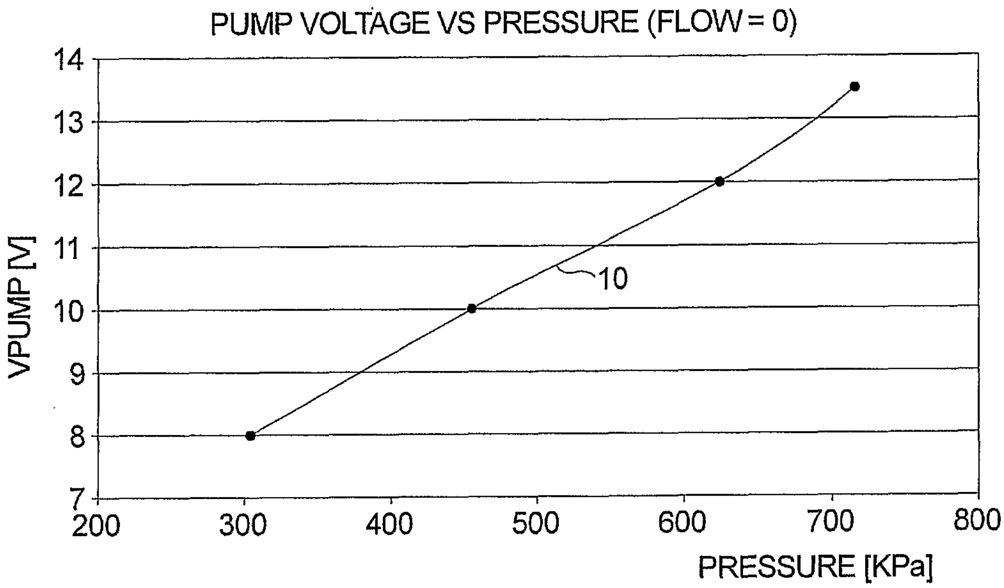

PUMP VOLTAGE VS PRESSURE (FLOW = 0)
14
13
12
11
10
9
8
7
VPUMP [V]
10
200
300
400
500
600
700
800
PRESSURE [KPa]

FIG. 1.

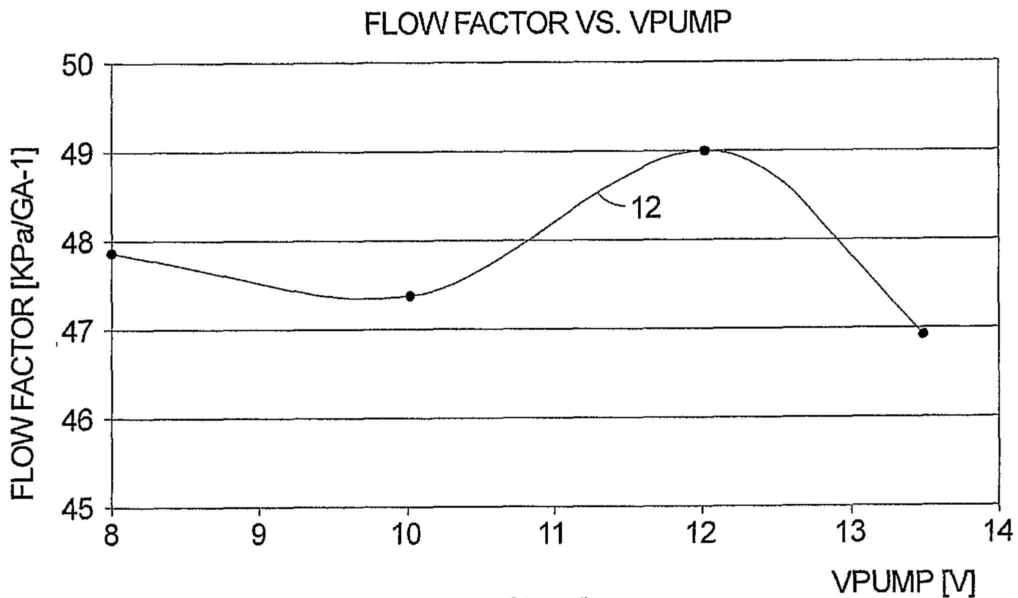
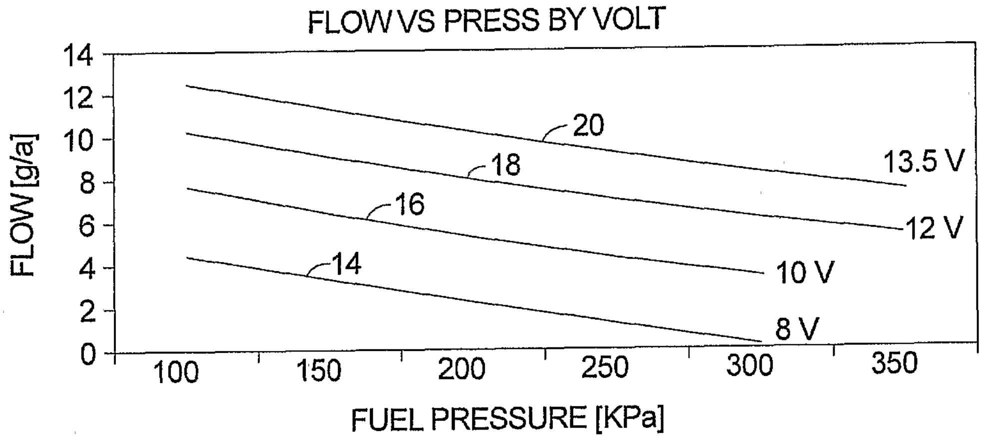

FLOW FACTOR VS. VPUMP
50
49
48
47
46
45
FLOW FACTOR [KPa/GA-1]
12
8
9
10
11
12
13
14
VPUMP [V]

FIG. 2.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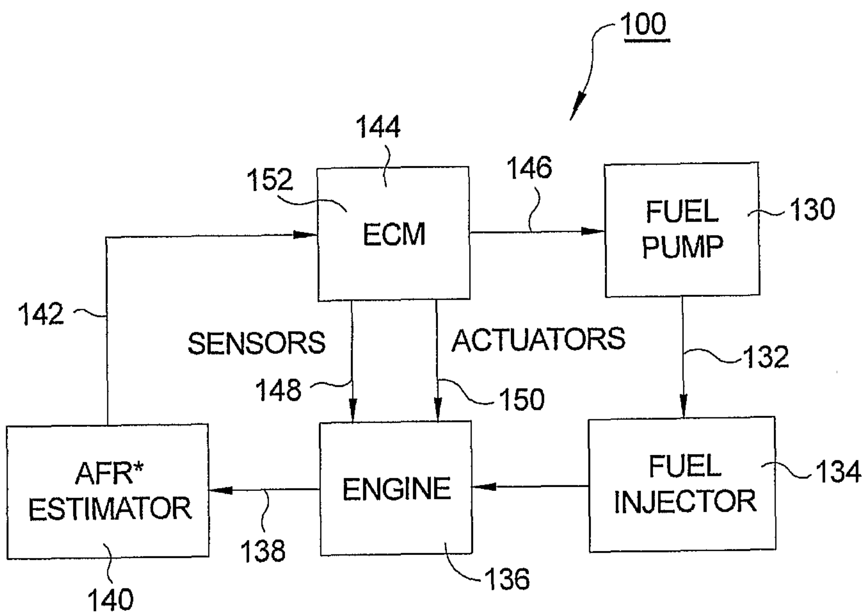
14
12
10
8
6
4
2
0
100
150
200
250
300
350
FUEL PRESSURE [KPa]
20
18
16
14
13.5 V
12 V
10 V
8 V

FIG. 3.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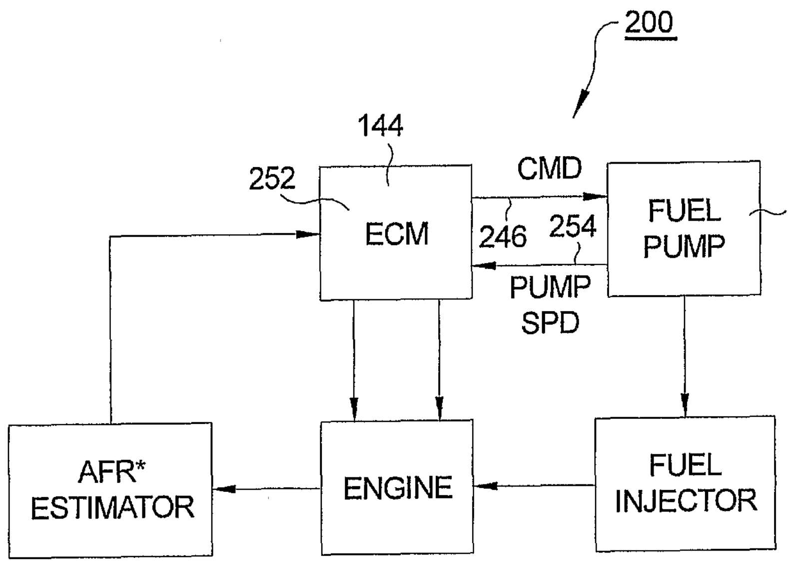
144
152
ECM
146
FUEL
PUMP
130
142
SENSORS
ACTUATORS
132
148
150
AFR*
ESTIMATOR
ENGINE
FUEL
INJECTOR
134
138
136
140

FIG. 4.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144
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ECM
CMD
246
254
PUMP
SPD
FUEL
PUMP
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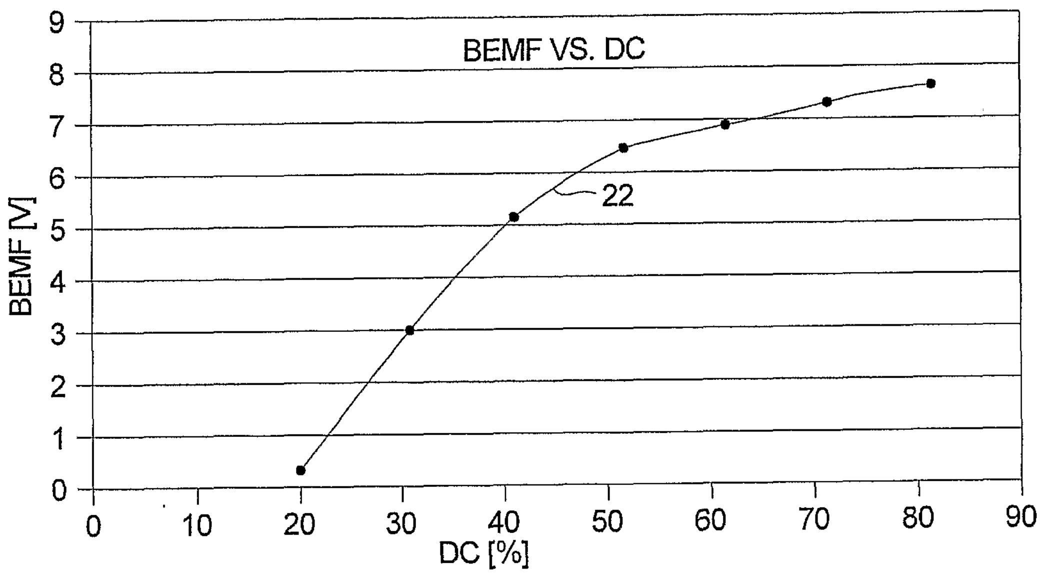
AFR*
ESTIMATOR
ENGINE
FUEL
INJECTOR

FIG. 5.


BEMF VS. DC
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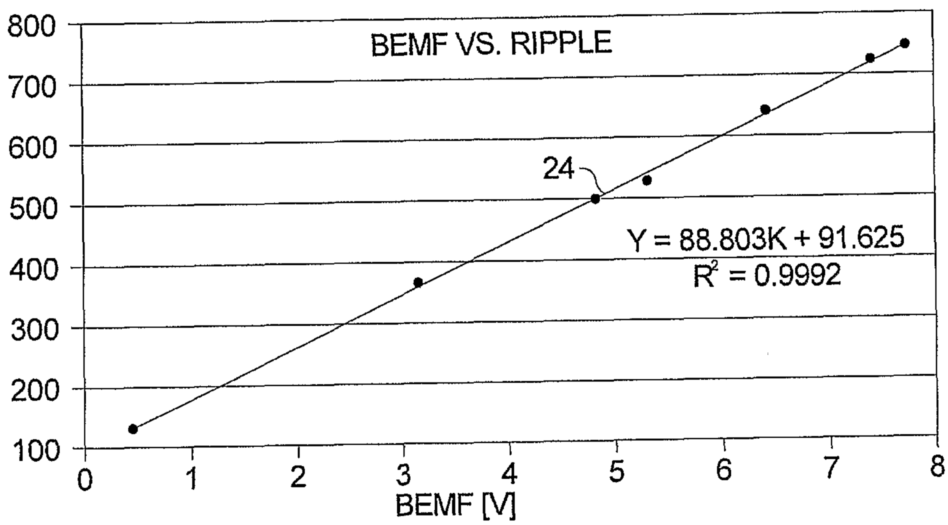
BEMF [V]
DC [%]
0
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90

FIG. 6.


BEMF VS. RIPPLE
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700
600
500
400
300
200
100
0
1
2
3
4
5
6
7
8
BEMF [V]
24
Y = 88.803K + 91.625
R² = 0.9992

FIG. 7.

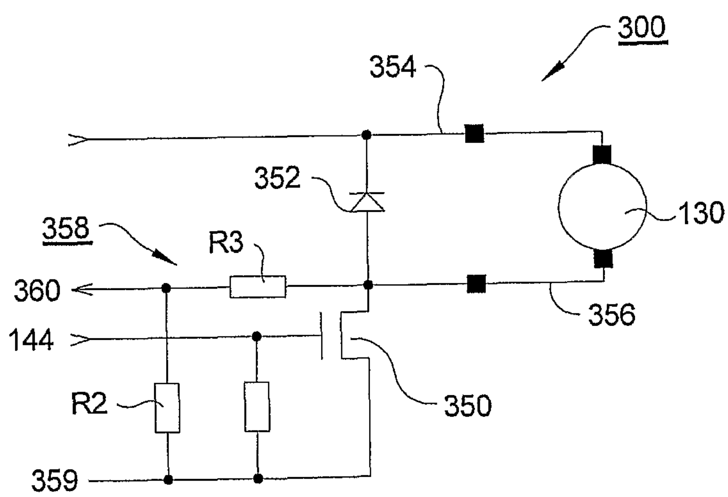

300
354
352
358
R3
360
144
R2
359
130
356
350

FIG. 8.

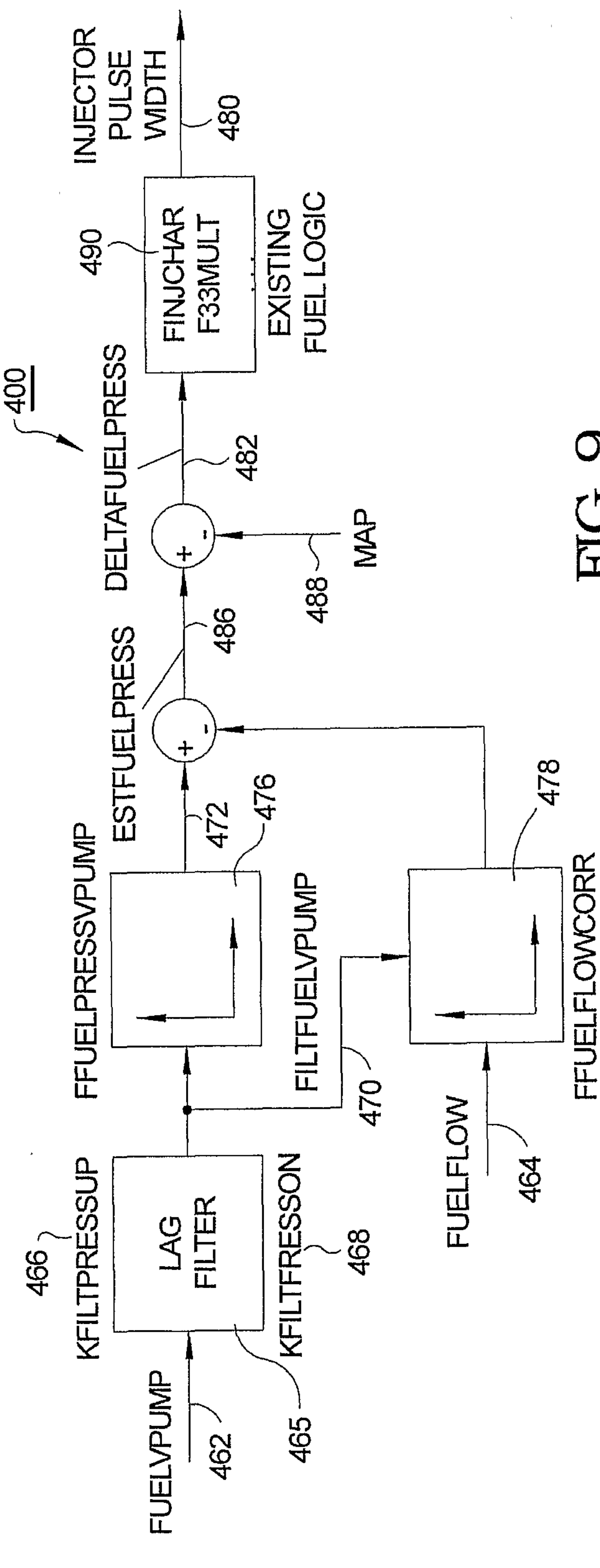
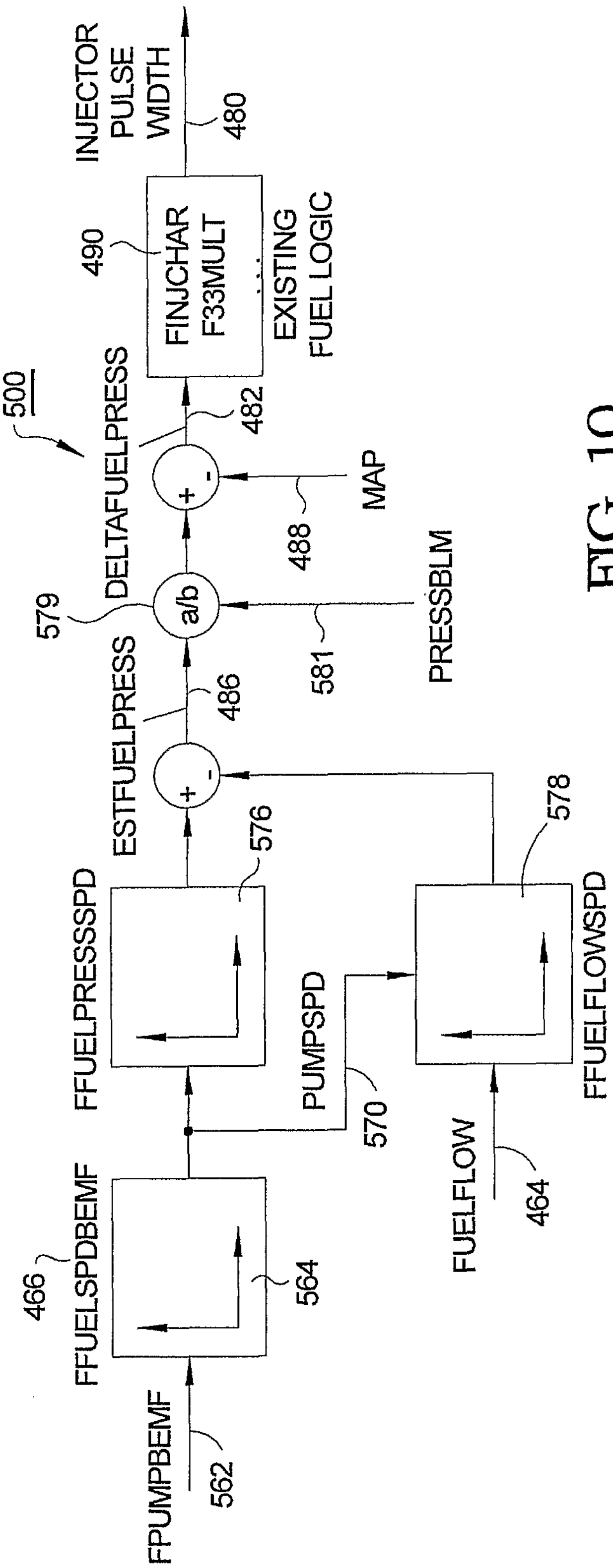

400
FUELVPUMP
462
465
KFILTPRESSUP
466
LAG FILTER
KFILTFRESSON
468
FUELFLOW
464
FFUELPRESSVPUMP
476
472
FILTFUELVPUMP
470
FFUELFLOWCORR
478
ESTFUELPRESS
486
DELTAFUELPRESS
482
MAP
488
FINJCHAR F33MULT
490
EXISTING FUEL LOGIC
INJECTOR PULSE WIDTH
480

FIG. 9.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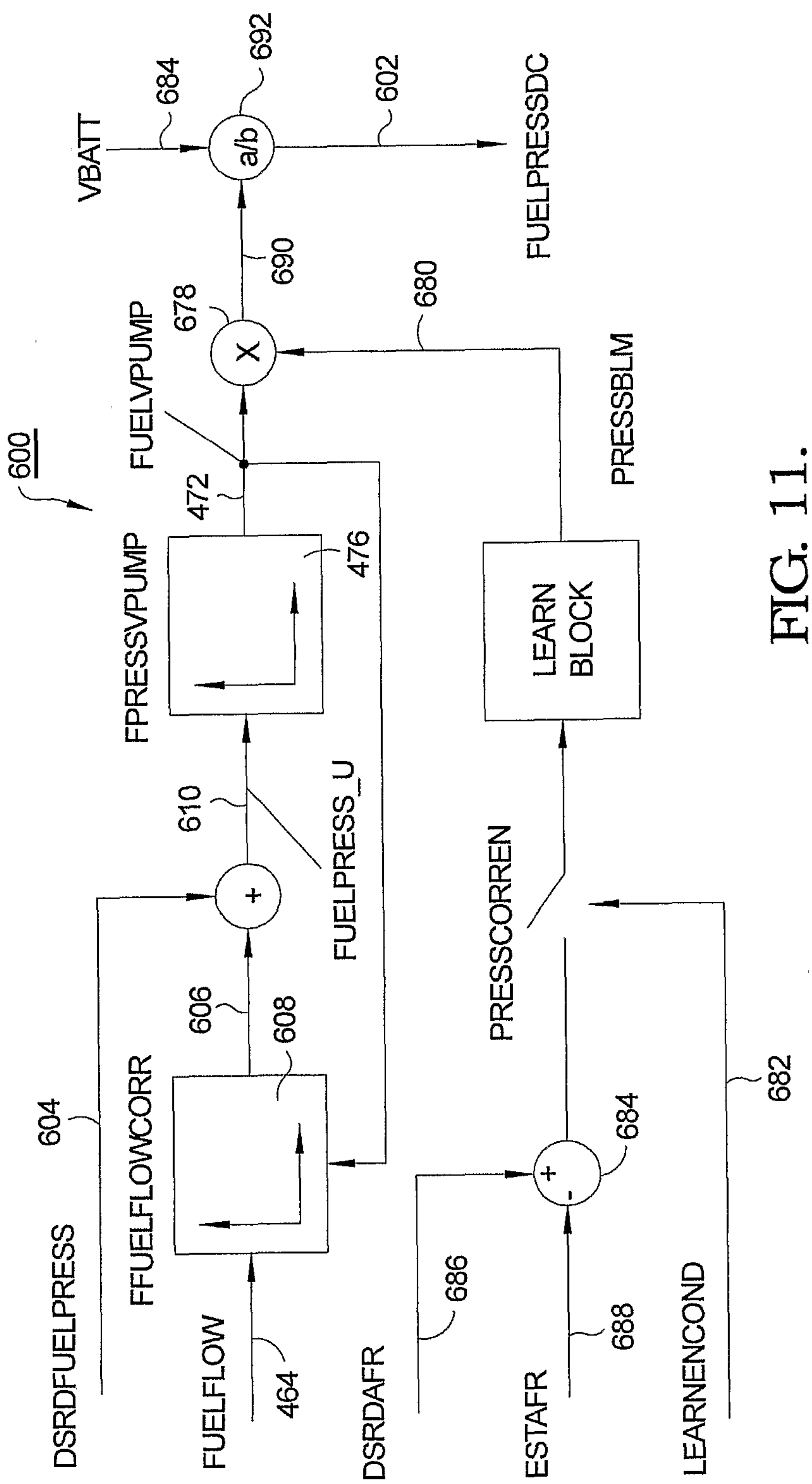
562
FFUELSPDBEMF
466
564
FFUELPRESSSPD
576
PUMPSPD
570
FUELFLOW
464
FFUELFLOWSPD
578
ESTFUELPRESS
486
a/b
579
581
PRESSBLM
DELTAFUELPRESS
482
488
MAP
FINJCHAR
F33MULT
EXISTING
FUEL LOGIC
490
INJECTOR
PULSE
WIDTH
480

FIG. 10.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VBATT
684
692
a/b
602
FUELPRESSDC
678
X
690
680
FUELVPUMP
472
FPRESSVPUMP
476
PRESSBLM
LEARN
BLOCK
610
FUELPRESS_U
+
PRESSCORREN
606
608
FFUELFLOWCORR
604
DSRDFUELPRESS
FUELFLOW
464
DSRDAFR
686
+
-
684
ESTAFR
688
LEARNENCOND
682

FIG. 11.