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(54) **METHOD AND APPARATUS TO MONITOR AN ELECTRIC MOTOR IN A RETURNLESS FUEL SYSTEMS**

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F04B 49/10	(2006.01)
F02M 37/00	(2006.01)
F02D 33/00	(2006.01)
F02D 41/30	(2006.01)
F02M 63/02	(2006.01)

(52) **U.S. Cl.**

CPC ***F02M 37/08*** (2013.01); ***F04B 49/06*** (2013.01); ***F04B 49/103*** (2013.01); *F04B 2203/0201* (2013.01); *F04B 2203/0209* (2013.01); *F04B 2205/03* (2013.01); ***F02M 37/0058*** (2013.01); ***F02D 33/003*** (2013.01); *F02M 63/0295* (2013.01); ***F02M 63/028*** (2013.01)

(58) **Field of Classification Search**

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USPC 123/497, 516; 417/45; 701/105, 29.1, 701/29.4

See application file for complete search history.

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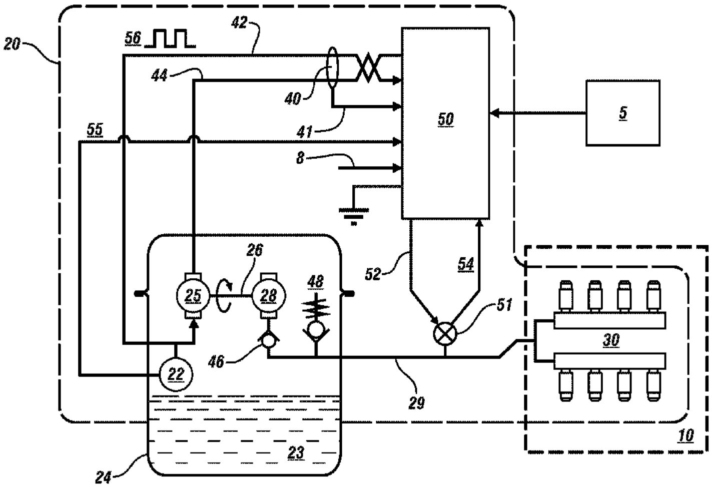
(57) **ABSTRACT**

A method for monitoring the fuel pump includes estimating a pump speed and a nominal pump motor current in relation to a pump motor control signal and a fuel pressure. An armature resistance and a back-emf constant for the electric motor are determined corresponding to the estimated pump speed, a monitored pump motor current, and the pump motor control signal. A nominal armature resistance and a nominal back-emf constant for the electric motor are adjusted in relation to a pump motor temperature. Residuals are calculated based upon the adjusted nominal armature resistance, the adjusted nominal back-emf constant for the electric motor, the estimated armature resistance and the estimated back-emf constant for the electric motor. The residuals are compared with corresponding thresholds. A fault in the electric motor is detected based upon the comparisons of the residuals with the corresponding thresholds.

18 Claims, 3 Drawing Sheets



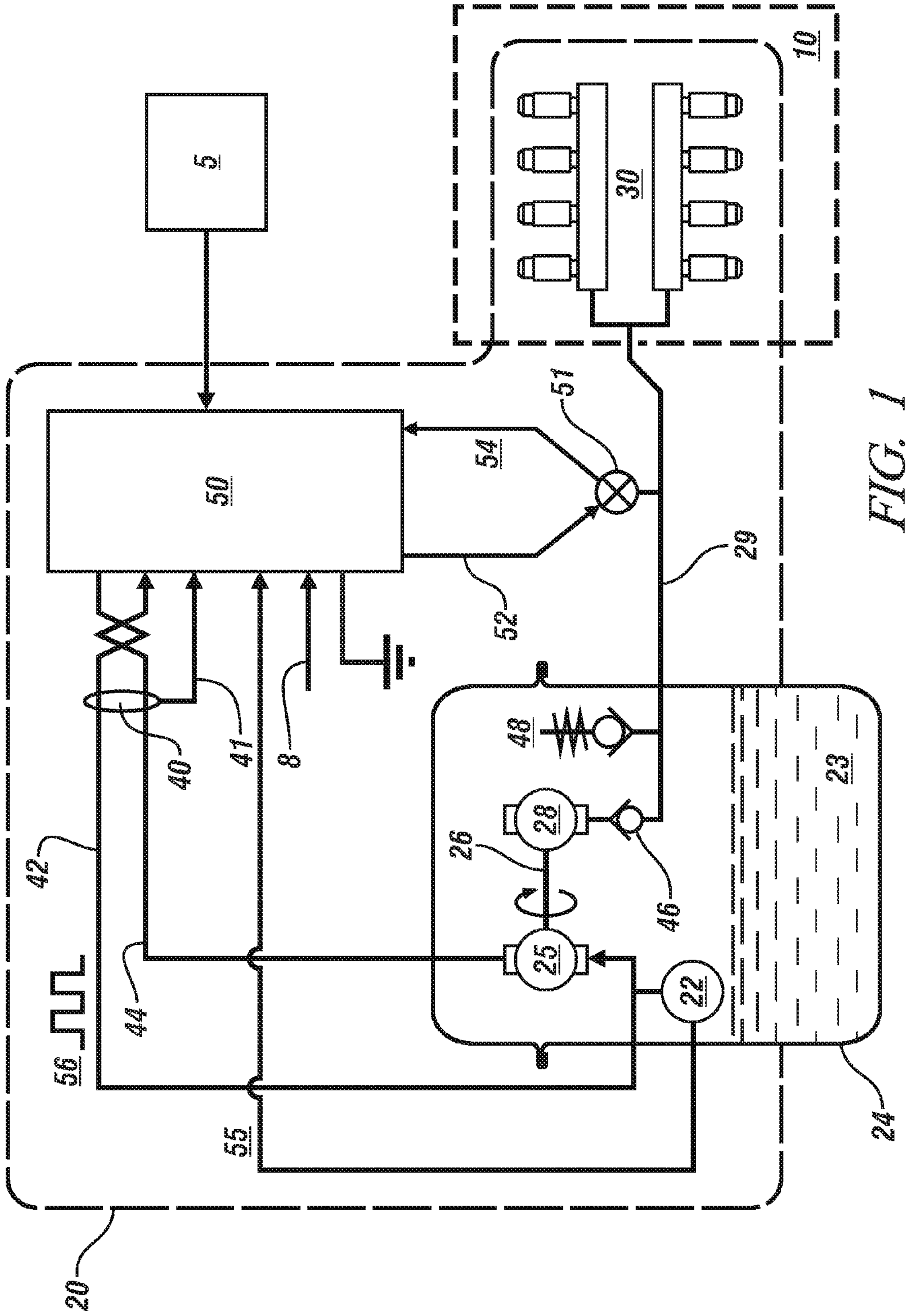
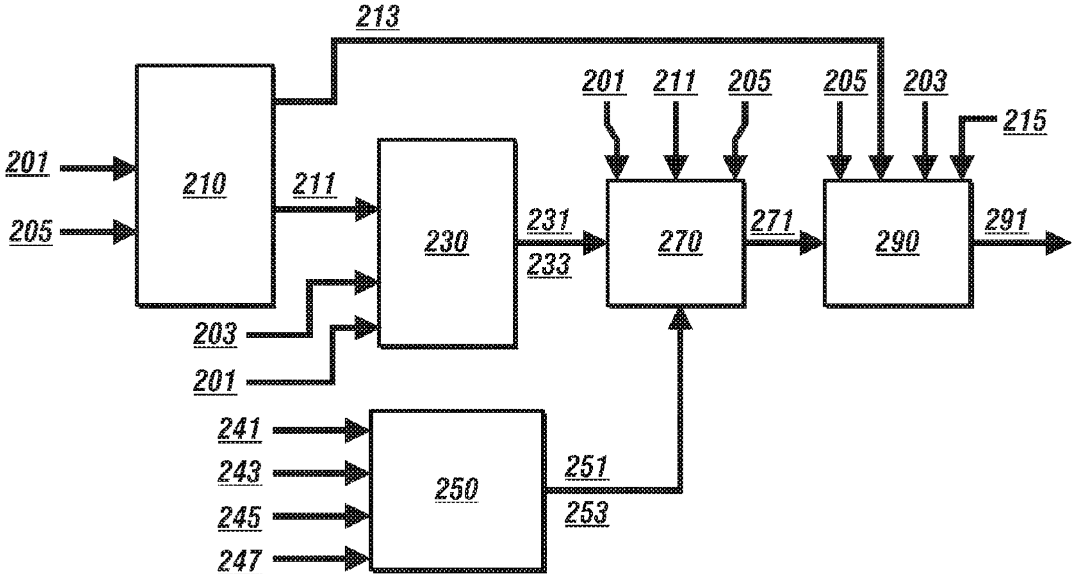


FIG. 1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201
211
205
205
203
215
201
205
210
211
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231
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203
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241
243
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247
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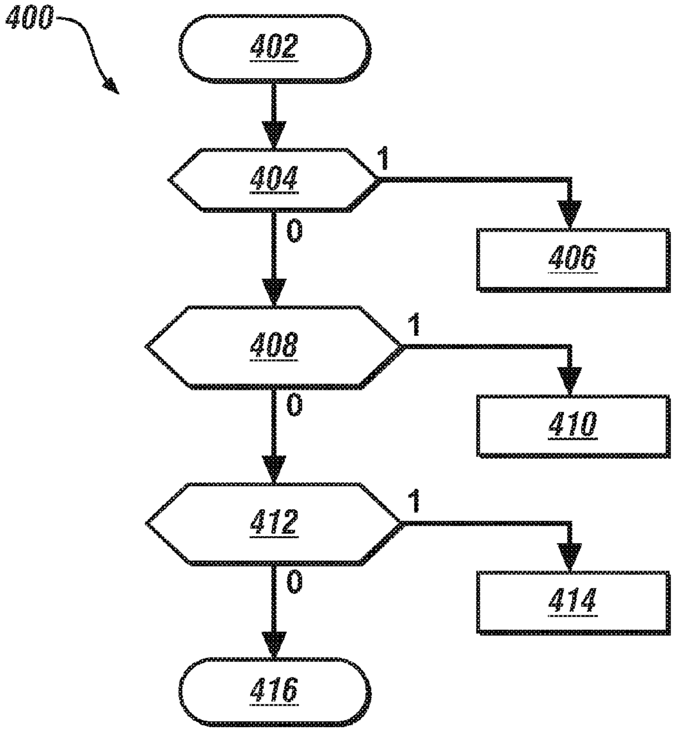
251
253

FIG. 2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406
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FIG. 4

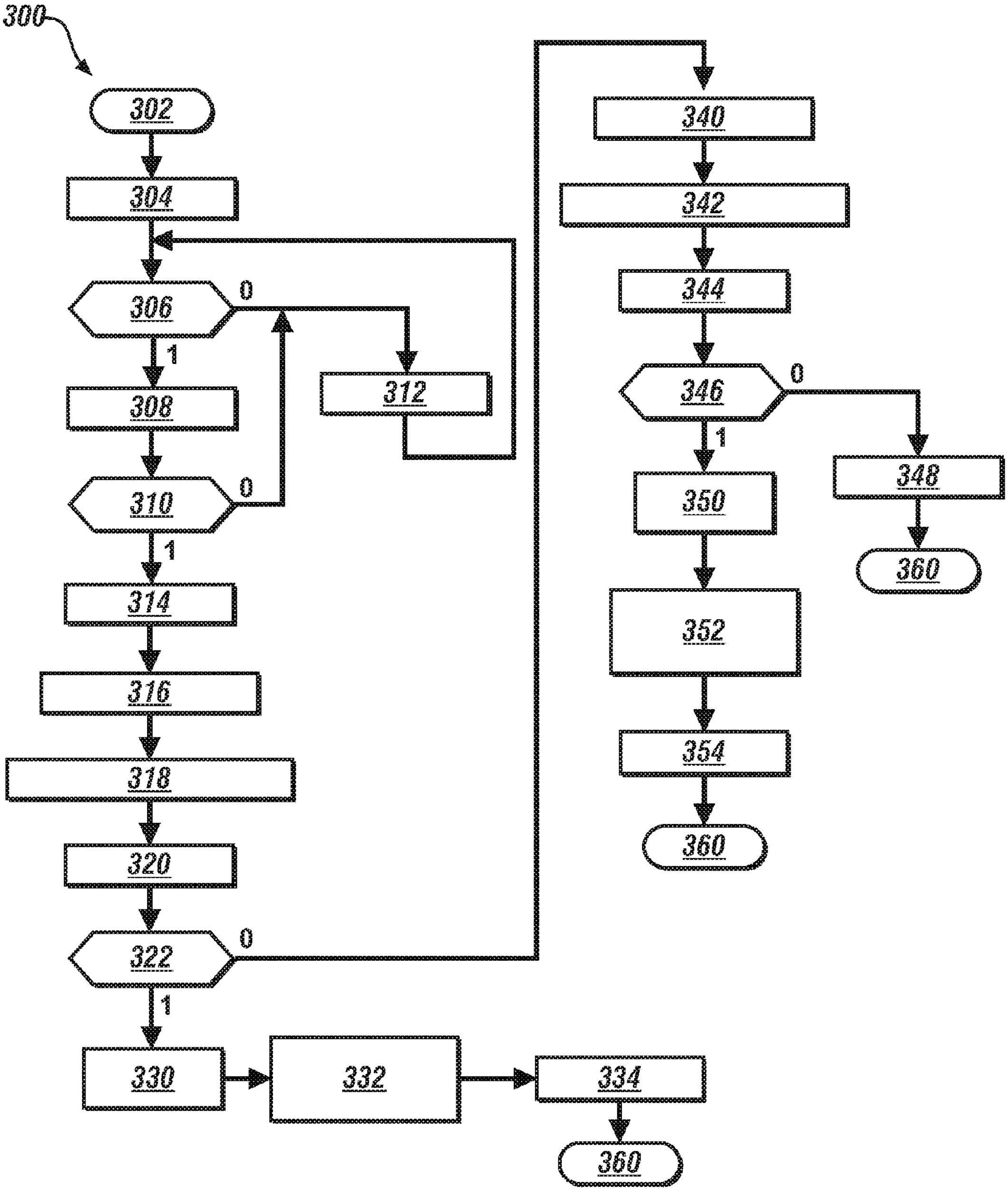
300
302
304
306
0
1
312
308
310
0
1
314
316
318
320
322
0
1
330
332
334
360
340
342
344
346
0
1
348
360
350
352
354
360

FIG. 3

METHOD AND APPARATUS TO MONITOR AN ELECTRIC MOTOR IN A RETURNLESS FUEL SYSTEMS

TECHNICAL FIELD

This disclosure is related to fuel delivery systems.

BACKGROUND

The statements in this section merely provide background information related to the present disclosure. Accordingly, such statements are not intended to constitute an admission of prior art.

Fuel systems supply fuel to internal combustion engines. One known fuel system includes a fuel pump and electric motor that are submerged in a fuel tank. A fuel filter and a pressure regulator may be positioned on the intake and outlet sides of the fuel pump, respectively. Filtered fuel is delivered to a fuel rail for injection into the engine cylinders. One embodiment of a fuel system includes a returnless fuel system that is assembled into a fuel tank and is characterized by a single fuel line fluidly connected to a fuel rail. A returnless fuel system lacks a fuel return line from the fuel rail and is unable to circulate fuel between the fuel rail and fuel tank, thus eliminating fuel heating and weathering.

A fault in a returnless fuel system may result in replacement of the returnless fuel system during service. Information determined during on-board operation of the returnless fuel system may assist in determining a root cause of such a fault.

SUMMARY

An electric motor is configured to provide mechanical power to a fuel pump. A method for monitoring the fuel pump includes estimating a pump speed and a nominal pump motor current in relation to a pump motor control signal and a fuel pressure. An armature resistance and a back-emf constant for the electric motor are determined corresponding to the estimated pump speed, a monitored pump motor current, and the pump motor control signal. A nominal armature resistance and a nominal back-emf constant for the electric motor are adjusted in relation to a pump motor temperature. A plurality of residuals are calculated based upon the adjusted nominal armature resistance, the adjusted nominal back-emf constant for the electric motor, the estimated armature resistance and the estimated back-emf constant for the electric motor. The residuals are compared with corresponding thresholds. A fault in the electric motor is detected based upon the comparisons of the residuals with the corresponding thresholds.

BRIEF DESCRIPTION OF THE DRAWINGS

One or more embodiments will now be described, by way of example, with reference to the accompanying drawings, in which:

FIG. **1** schematically illustrates a returnless fuel system configured to deliver pressurized fuel to an internal combustion engine via a fuel rail, in accordance with the disclosure;

FIG. **2** illustrates a multi-step process for monitoring, detecting and diagnosing a fault in a returnless fuel system, in accordance with the disclosure;

FIG. **3** illustrates an exemplary process flowchart for adjusting the nominal states for the motor parameters of resistance and back-emf constant to account for pump motor temperature differences, in accordance with the disclosure; and

FIG. **4** illustrates an exemplary process flowchart for identifying a fault location using residuals, in accordance with the disclosure.

DETAILED DESCRIPTION

Referring now to the drawings, wherein the showings are for the purpose of illustrating certain exemplary embodiments only and not for the purpose of limiting the same, FIG. **1** schematically illustrates a returnless fuel system (RFS) **20** configured to deliver pressurized fuel to an internal combustion engine **10** via a fuel rail **30** that is in fluid communication with engine fuel injectors. The RFS **20** is preferably configured to operate at high pressure, which may be in the range of 10-20 MPa in one embodiment. The RFS **20** cooperates with a fuel tank **24** containing a supply of fuel **23** such as gasoline, ethanol, E85, or other combustible fuel. The fuel tank **24** is sealed relative to the surrounding environment and lacks a fuel return line from the fuel rail **30**. The internal combustion engine **10** may be employed on a vehicle to provide torque for tractive power generation or electric power generation.

The RFS **20** includes a fuel pump **28**, an electrically-powered pump motor **25** and a RFS controller **50**, and employs other components, elements and systems as described herein. The fuel pump **28** and pump motor **25** are disposed within the fuel tank **24** and preferably submerged in fuel **23** contained within the fuel tank **24**. The pump motor **25** electrically connects to the RFS controller **50** via control line **42**, with a ground path **44** returning from the pump motor **25** to the RFS controller **50**. The pump motor **25** generates and transfers mechanical power via a rotating pump shaft **26** to the fuel pump **28** in response to a pump motor control signal **56** from the RFS controller **50**. The fuel pump **28** fluidly connects to the fuel rail **30** via a fuel line **29** to provide pressurized fuel to injectors of the engine **10**. The fuel pump **28** is operable to pump fuel **23** to the fuel rail **30** for distribution into the internal combustion engine **10** in response to the pump motor control signal **56**. The fuel pump **28** is preferably a roller vane pump or gerotor pump, and may be any suitable pump element. A fuel pressure sensor **51** is employed to monitor fuel pressure **54** in the fuel line **29**. A current sensor **22** is configured to monitor electrical current **55** supplied to the pump motor **25** via control line **42**. The fuel tank **24** further includes a check valve **46** and a pressure vent valve **48** disposed therein along the fuel line **29**. The fuel pump **28** is electrically grounded via a ground path **44** from the pump motor **25** that includes a grounding shield **40** having a ground shield input **41** to RFS controller **50**.

The RFS controller **50** signally couples to an engine control module (ECM) **5**. The RFS controller **50** operatively connects to the pump motor **25** via control line **42** and signally connects to the fuel pressure sensor **51** and the current sensor **22**. The RFS controller **50** generates the pump motor control signal **56** to control the pump motor **25** to operate the fuel pump **28** to achieve or maintain a desired fuel system pressure in response to commands from the ECM **5**. The RFS controller **50** provides a reference voltage **52** to the pressure sensor **51** and monitors signal outputs from the pressure sensor **51** to determine the fuel pressure **54**. The RFS controller **50** monitors the electrical current **55** and the fuel pressure **54** for feedback control and diagnostics.

The pump motor control signal **56** is a pulsewidth-modulated (PWM) signal in one embodiment that is communicated via control line **42** to operate the fuel pump **28**. The pump motor control signal **56** provides pulsed electrical energy to the pump motor **25** in the form of a rectangular pulse wave. The pump motor control signal **56** is modulated by the RFS controller **50** resulting in a particular variation of an average value of the pulse waveform. Energy for the pump motor control signal **56** can be provided by a battery, e.g., a DC chemical-electrical energy storage system that supplies a battery input **8** to the RFS controller **50**. By modulating the pump motor control signal **56** using the RFS controller **50**, energy flow to the pump motor **25** is regulated to control the fuel pump **28** to achieve a desired fuel system pressure for the fuel supplied to the fuel rail **30**. The RFS **20** described herein is meant to be illustrative, and other embodiments of fuel systems are within the scope of the disclosure.

The pump motor **25** is preferably a brush-type electric motor or another suitable electric motor that provides mechanical power via a rotating pump shaft **26** to the fuel pump **28**. The fuel pump **28** propels fuel into the fuel line **29** to the fuel rail **30**, thereby generating pressurized fuel in the fuel line **29** and the fuel rail **30**, with the fuel pressure **54** monitored by the RFS controller **50** using the pressure sensor **51**.

The RFS controller **50** controls the fuel pump **28** to achieve and/or maintain the desired fuel system pressure by applying closed-loop correction derived from the monitored fuel pressure **54** measured by the pressure sensor **51** and the monitored pump current **55** measured by the current sensor **22** as feedback. Further, the pump motor control signal **56** is monitored by the RFS controller **50**. Thus, monitored pump parameters preferably include the fuel pressure **54**, pump current **55**, and pump motor control signal **56**.

Control module, module, control, controller, control unit, processor and similar terms mean any one or various combinations of one or more of Application Specific Integrated Circuit(s) (ASIC), electronic circuit(s), central processing unit(s) (preferably microprocessor(s)) and associated memory and storage (read only, programmable read only, random access, hard drive, etc.) executing one or more software or firmware programs or routines, combinational logic circuit(s), input/output circuit(s) and devices, appropriate signal conditioning and buffer circuitry, and other components to provide the described functionality. Software, firmware, programs, instructions, routines, code, algorithms and similar terms mean any controller executable instruction sets including calibrations and look-up tables. The control module has a set of control routines executed to provide the desired functions. Routines are executed, such as by a central processing unit, and are operable to monitor inputs from sensing devices and other networked control modules, and execute control and diagnostic routines to control operation of actuators. Routines may be executed at regular intervals, for example each 3.125, 6.25, 12.5, 25 and 100 milliseconds during ongoing engine and vehicle operation. Alternatively, routines may be executed in response to occurrence of an event.

FIG. **2** schematically illustrates a multi-step process for monitoring, detecting and diagnosing a fault in a pump motor, e.g., as applied to a returnless fuel system such as the RFS **20** described with reference to FIG. **1**. The process includes estimating a pump speed ω_m **211** and estimating a nominal pump motor current I_{nom} **213** (**210**) in relation to monitored pump parameters of a pulsewidth-modulated voltage V_m **201** and fuel pressure in the returnless fuel system P_s **205** (**210**). Motor parameters of interest are estimated, including an estimated motor armature resistance **231** and an estimated back-emf constant **233** (**230**). Nominal states for the motor parameters of interest are temperature-adjusted, including a temperature-adjusted armature resistance **251** and a temperature-adjusted back-emf constant **253**, preferably coincident with the estimation of the motor parameters (**250**). Residuals **271** are determined based upon the estimated armature resistance **231**, the estimated back-emf constant **233**, the temperature-adjusted armature resistance **251** and the temperature-adjusted back-emf constant **253** (**270**). The residuals **271** are employed to monitor operation of the pump motor, including generating output signal **291** indicating presence of a pump motor fault and identifying a fault location associated with the pump motor to facilitate a root cause diagnosis of a fault (**290**).

The monitored parameters include pulsewidth-modulated pump motor voltage **201**, fuel pressure **205** and pump motor current **203**, which include monitored pump parameters of pump motor control signal **56**, fuel pressure **54**, and pump current **55** for the embodiment of the RFS **20** described herein. The process includes estimating the pump speed ω_m **211** and estimating a nominal pump motor current I_{nom} **213** in relation to the monitored pump parameters of the pulsewidth-modulated pump motor voltage V_m **201** and fuel pressure P_s **205** employing the following equations (**210**):

$$I_{nom}=a_i(V_m)P_s+b_i(V_m) \quad [1]$$

$$\omega_m=a_\omega(V_m)P_s+b_\omega(V_m) \quad [2]$$

wherein a_i, b_i, a_ω and b_ω are application-specific scalar values.

The estimated pump speed **211** and the nominal pump motor current **213** are used in conjunction with the monitored pump motor current **203** to estimate motor parameters of interest including an estimated armature resistance **231** and an estimated back-emf constant **233**. The armature resistance R_a and the back-emf constant K_e are employed to monitor and detect faults in the pump motor **25**.

A two-stage estimation model is employed to estimate the motor parameters of interest, i.e., the estimated armature resistance **231** and the estimated back-emf constant **233** (**230**). During a first stage it is assumed that a back-emf constant K_e is known, i.e., the back-emf constant K_e has a nominal value. The armature resistance is estimated using a least-square estimation with a forgetting factor. The first stage includes defining a regression model as follows.

$$y_1(t)=\phi_1(t)*\theta_1$$

$$y_1(t)=V_m(t)-K_e*\omega_m,\phi_1(t)=I,\text{ and }\theta_1\pm R_a \quad [3]$$

wherein K_e is the nominal back-emf constant and R_a is the armature resistance, which is estimated as $\hat{R}_a$ employing EQ. 5, below.

During the second stage, the estimated armature resistance determined from the first stage is used and the following regression model is defined.

$$y_2(t)=\phi_2(t)*\theta_2$$

$$y_2(t)=V_m(t)-I*\hat{R}_a(t),\phi_2(t)=\omega_m,\theta_2=K_e \quad [4]$$

wherein $\hat{R}_a$ is the estimated armature resistance determined from the first stage, as described with reference to EQ. 5.

The two-stage estimation model including the least-square estimation with the forgetting factor is executed in accordance with i=1, 2, wherein i is the stage number, i.e., one of the first stage and the second stage. This is depicted in EQ. 5 as follows:

$$\hat{\theta}_i(t)=\hat{\theta}_i(t-1)+\frac{P_i(t-2)\varphi_i(t-1)}{\lambda_i(t-1)+\varphi_i^2(t-1)P_i(t-2)}\varepsilon_i(t) \quad [5]$$

$$P_i(t-1)=\frac{1}{\lambda_i(t-1)}\left[P_i(t-2)-\frac{P_i(t-2)^2\varphi_i(t-1)^2}{\lambda_i(t-1)+\varphi_i^2(t-1)P_i(t-2)}\right]$$

-continued

$$\lambda_i(t) = 1 - \lambda_0 \frac{\varepsilon_i^2(t)}{1 + \varphi_i^2(t-1)P_i(t-2)}$$

$$\epsilon_1 = y_1(t) - I\hat{R}_a(t)$$

wherein

$$\epsilon_2 = y_2(t) - \omega_m \hat{K}_e(t).$$

A first error term ϵ_1 is associated with an error in the armature resistance and a second error term ϵ_2 is associated with an error in the back-emf constant. The term λ_i is a data-dependent weighting factor, and Pi is interpreted as a covariance of the selected parameter having a magnitude that provides a measure of the uncertainty of the parameter values. In the case of a change in motor resistance or back-emf constant from original values ϵ_i increases. This temporarily reduces λ_i but increases P_i quickly, thus permitting a rapid adaptation to the changes in the motor parameters.

The two-stage estimation model shown in EQ. 5 is translated to an algorithm that is periodically executed to determine $\hat{\theta}_i(t)$, with $\hat{\theta}_1(t)=\hat{R}_a(t)$ and $\hat{\theta}_2(t)=\hat{K}_e(t)$. The two-stage estimation model is employed for motor parameter estimation having varying parameter states due to occurrence of a fault or degradation. The use of the forgetting factors allows continuous tracking of time-varying parameters. Execution of the two-stage estimation model using least-square estimation with forgetting factors as described herein results in motor parameters of interest including the estimated armature resistance **231**, i.e., $\hat{R}_a=\hat{\theta}_1$ and the estimated back-emf constant **233**, i.e., $\hat{K}_e=\hat{\theta}_2$.

Nominal states for the motor parameters are temperature-adjusted, preferably coincident with the estimation of the motor parameters (**250**). Inputs include vehicle speed Vss **241** and pump motor temperature T **243**. The nominal states include nominal armature resistance R_0 **245** and nominal back-emf constant K_{e0} **247**. The temperature-dependence of the monitored parameters may be expressed in the following relationships.

$$R_{a\_nom}(T) = R_0(1+\rho(T-T_0)) \qquad [6]$$

$$K_{e\_nom}(T) = K_{e0}(1-\beta(T-T_0)) \qquad [7]$$

The nominal states of the pump motor are determined for a known functional pump motor at nominal pump motor temperature T_0. The terms $R_{a\_nom}(T)$ and $K_{e\_nom}(T)$ are temperature-adjusted nominal states for the armature resistance and back-emf constant, respectively, which are calculated for the known functional pump motor operating at the pump motor temperature T **243**. The change in resistance in relation to temperature is $\rho=0.00393/°$ C. for copper magnet wire, which is employed in one embodiment of the pump motor. The change in back-emf constant in relation to temperature is $\beta=0.002/°$ C. for ferrite material, which is employed in one embodiment of the pump motor.

The nominal states for the motor parameters of armature resistance and back-emf constant are adjusted for changes in pump motor temperature T that varies from the nominal temperature T_0. However, the pump motor temperature T is not directly monitored. Instead, a temperature difference is compensated for using forms of EQS. 6 and 7 and includes adjusting nominal states for the motor parameters of the armature resistance and the back-emf constant to account for pump motor temperature differences between an initial pump motor temperature, the nominal pump motor temperature, and an operating pump motor temperature, which is described with reference to FIG. **3**. The fuel pump and pump motor are immersed in fuel in the fuel tank, which may serve to cool the pump motor. Hence any variation of the pump motor temperature from its initial conditions at the beginning of operation is assumed to be limited to a 3-5° C. change. However, at the beginning of the fuel pump operation, the fuel temperature is not necessarily equal to the nominal temperature T_0, i.e., the temperature at which the nominal values of the pump motor parameters were determined.

A maximum variation of the nominal motor parameters may be determined due to temperature variation based on the initial pump motor temperature. The maximum variations in the motor parameters are employed to determine thresholds at which a fault may be indicated, thus avoiding false fault detection, which is described at a later point.

FIG. **3** schematically shows an exemplary process **300** flowchart for adjusting the nominal states for the motor parameters of the armature resistance and the back-emf constant to account for pump motor temperature differences between an initial pump motor temperature, the nominal pump motor temperature, and an operating pump motor temperature. As described herein, the nominal states for the motor parameters of motor armature resistance and back-emf constant are adjusted to account for differences between ambient temperature and the pump motor temperature. Table 1 is provided as a key to FIG. **3** wherein the numerically labeled blocks and the corresponding functions for the process **300** are set forth as follows.

TABLE 1

BLOCK	BLOCK CONTENTS
302	Set $T_1 = T_{amb}$, Set Timer = 1
304	$R_{init}(T_1) = R_{a\_nom}(T_0)(1 + \rho(T_1 - T_0))$ $K_{init}(T_1) = K_{e\_nom}(T_0)(1 - \beta(T_1 - T_0))$
306	Is Vss > Vth?
308	Increment Timer
310	Is Timer > Time_{thr}?
312	$R_{adj} = R_{a\_nom}(T_0)(1 + \rho(T_1 - T_0))$ $K_{adj} = K_{e\_nom}(T_0)(1 - \beta(T_1 - T_0))$
314	Set $T_2 = T_{amb}$
316	$R_2(T_2) = R_{init}(T_1)(1 + \rho(T_2 - T_1))$
318	$A_1 = \lvert\hat{R}_a - R_2\rvert$, $A_2 = \lvert\hat{R}_a - R_{a\_nom}\rvert$, A_3
320	Select $\min(A_1, A_2, A_3)$
322	Is $\min(A_1, A_2, A_3) < A_{thr}$?
330	$R_{adj} = \begin{cases} \hat{R}_a \text{ if } A_1 \\ R_{a\_nom} \text{ if } A_2 \\ R_2 \text{ if } A_3 \end{cases}$
332	$\Delta T_{corr} = \dfrac{R_{adj} - R_{a\_nom}}{\rho R_{a\_nom}}$
334	$K_{adj} = K_{e\_nom}(T_0)(1 - \beta\Delta T_{corr})$
340	$K_{adj} = K_2(T_2) = K_{init}(T_1)(1 - \beta(T_2 - T_1)$
342	$B_1 = \lvert\hat{K}_e - K_2\rvert$, $B_2 = \lvert\hat{K}_e - K_{e\_nom}\rvert$, B_3
344	Select $\min(B_1, B_2, B_3)$
346	Is $\min(B_1, B_2, B_3) < B_{thr}$?
348	$R_{adj} = R_{a\_nom}(T_0)$ $K_{adj} = K_{a\_nom}(T_0)$
350	$K_{adj} = \begin{cases} \hat{K}_e \text{ if } B_1 \\ K_{e\_nom} \text{ if } B_2 \\ K_2 \text{ if } B_3 \end{cases}$
352	$\Delta T_{corr} = \dfrac{K_{adj} - K_{e\_nom}}{\rho K_{e\_nom}}$

TABLE 1-continued

BLOCK	BLOCK CONTENTS
354	$R_{adj} = R_{a\_nom}(T_0)(1 + \rho\Delta T_{corr})$
360	End

A timer for monitoring operating time is initialized (set Timer=1), and temperature T_1 is set equal to the ambient temperature T_{amb} (**302**). The operating time may provide an indication of engine operating time, vehicle operating time, or another suitable operating time. The selected operating time is dependent upon details of the powertrain system configuration and an overall vehicle propulsion system taking into account whether the powertrain system employs multiple propulsion systems, e.g., a hybrid propulsion system in which engine operation may be intermittent during vehicle operation.

Initial states for the armature resistance $R_{init}(T)$ and back-emf constant $T_{init}(T)$ are determined in relation to temperature T_1 using the following equations.

$$R_{init}(T_1)=R_{a\_nom}(T_0)(1+\rho(T_1-T_0))$$

$$K_{init}(T_1)=K_{e\_nom}(T_0)(1-\beta(T_1-T_0))$$

The above terms are defined as described with reference to EQS. 6 and 7 (**304**).

Operation of the engine system is monitored, including monitoring vehicle speed (Vss) to determine that it is greater than a threshold speed (Vth) (**306**), incrementing the Timer (**308**), and determining whether the Timer is greater than a threshold time Time_{thr} (**310**). The purpose of the monitoring operation of the engine system is to permit the system to operate for a sufficient period of time to achieve homeostasis with regard to temperature in the RFS **20**. During this period, the nominal states for the armature resistance $R_{a\_nom}(T)$ and back-emf constant $K_{e\_nom}(T)$ are adjusted for ambient temperature using the following equations.

$$R_{adj}=R_{a\_nom}(T_0)(1+\rho(T_1-T_0))$$

$$K_{adj}=K_{e\_nom}(T_0)(1-\beta(T_1-T_0))$$

R_{adj} is the armature resistance adjusted for ambient temperature and K_{adj} is the back-emf constant adjusted for ambient temperature. The other terms are defined as described with reference to EQS. 6 and 7 (**312**).

When the Timer is greater than the threshold time Time_{thr} (**310**)(**1**), temperature state T_2 is set equal to the ambient temperature T_{amb} (**314**), which may have changed due to operation of the vehicle including a change in location, such as exiting a garage in which the vehicle is parked.

A second state for the armature resistance $R_2(T_2)$ is calculated in accordance with EQ. 8 (**316**).

$$R_2(T_2)=R_{init}(T_1)(1+\rho(T_2-T_1)) \quad [8]$$

This calculation of armature resistance $R_2(T_2)$ is the adjusted armature resistance based upon the initial state for the armature resistance $R_{init}(T_1)$ and any difference in temperature between the initial ambient temperature T_1 and the present ambient temperature T_2.

Terms A_1, A_2, and A_3 are determined in accordance with the following relationships (**318**):

$$A_1=|\hat{R}_a-R_2|, A_2=|\hat{R}_a-R_{a\_nom}|, A_3=|R_2-R_{a\_nom}|$$

wherein $\hat{R}_a$ is the estimated armature resistance, R_{a_nom} is the temperature-adjusted nominal armature resistance, and R_2 is $R_2(T_2)$ i.e., the armature resistance determined at temperature T_2 as described with reference to EQ. 8.

A minimum state of the terms A_1, A_2, and A_3 is selected (**320**), and compared to a threshold value A_{thr} (**322**). When the minimum state of the terms A_1, A_2, and A_3 is less than a threshold value A_{thr} (**1**), the temperature-adjusted armature resistance R_{adj} is selected in accordance with the following scheme based upon the selected minimum state of the terms A_1, A_2, and A_3 (**330**).

$$R_{adj} = \begin{cases} \hat{R}_a \text{ if } A_1 \\ R_{a\_nom} \text{ if } A_2 \\ R_2 \text{ if } A_3 \end{cases}$$

A temperature correction term ΔT_{corr} is calculated in accordance with EQ. 9 (**332**).

$$\Delta T_{corr} = \frac{R_{adj} - R_{a\_nom}}{\rho R_{a\_nom}} \quad [9]$$

The temperature correction term ΔT_{corr} is employed to calculate a temperature-adjusted back-emf constant K_{adj} in accordance with EQ. 10 (**334**).

$$K_{adj}=K_{e\_nom}(T_0)(1\beta\Delta T_{corr}) \quad [10]$$

Thus the temperature-adjusted armature resistance R_{adj} **251** and the temperature-adjusted back-emf constant K_{adj} **253** are determined, and operation of the control scheme **300** ends (**360**).

Alternatively, when the minimum state of the terms A_1, A_2, and A_3 is greater than the threshold value A_{thr} (O), the temperature-adjusted back-emf constant K_{adj} at temperature T_2 is determined in accordance with EQ. 11 (**340**).

$$K_{adj}=K_2(T_2)=K_{init}(T_1)(1-\beta(T_2-T_1)) \quad [11]$$

Terms B_1, B_2, and B_3 are determined in accordance with the following relationships (**342**).

$$B_1=|\hat{K}_e-K_2|, B_2=|\hat{K}_e-K_{e\_nem}|, B_3=|K_2-K_{e\_nom}|$$

$\hat{K}_e$ is the estimated back-emf constant, K_{e_nom} is the temperature-adjusted nominal state for the back-emf constant, and K_2 is $K_2(T_2)$, i.e., the back-emf constant at temperature T_2 as described with reference to EQ. 11.

A minimum state of the terms B_1, B_2, and B_3 is selected (**344**), and compared to a threshold value B_{thr} (**346**). When the minimum state of the terms B_1, B_2, and B_3 is less than the threshold value B_{thr} (**1**), the temperature-adjusted back-emf constant K_{adj} is selected in accordance with the following scheme based upon the selected minimum state of the terms B_1, B_2, and B_3 (**350**).

$$K_{adj} = \begin{cases} \hat{K}_e \text{ if } B_1 \\ K_{e\_nom} \text{ if } B_2 \\ K_2 \text{ if } B_3 \end{cases}$$

A temperature correction term ΔT_{corr} is calculated in accordance with EQ 12 (**352**).

$$\Delta T_{corr} = \frac{K_{adj} - K_{e\_nom}}{\rho K_{e\_nom}} \quad [12]$$

The temperature correction term ΔT_{corr} is employed to calculate a temperature-adjusted armature resistance R_{adj} in accordance with EQ 13 (**354**).

$$R_{adj}=R_{a\_nom}(T_0)(1+\beta\Delta T_{corr}) \qquad [13]$$

Thus the temperature-adjusted armature resistance R_{adj} **251** and the temperature-adjusted back-emf constant K_{adj} **253** are determined, and operation of the control scheme **300** ends (**360**).

Alternatively, when the minimum state of the terms B_1, B_2, and B_3 is less than the threshold value B_{thr} (O), the temperature-adjusted back-emf constant K_{adj} and the temperature-adjusted armature resistance R_{adj} are determined in accordance with the following relationships (**348**).

$$R_{adj}=R_{a\_nom}(T_0)$$

$$K_{adj}=K_{e\_nom}(T_0)$$

Thus the temperature-adjusted armature resistance R_{adj} **251** and the temperature-adjusted back-emf constant K_{adj} **253** are determined, and operation of the control scheme **300** ends (**360**).

Referring again to FIG. **2**, the residuals **271** are calculated (**270**) in accordance with EQ. 14 using the pulsewidth-modulated pump motor voltage V_m **201**, the estimated pump speed ω_m **211**, the pump motor current I **203**, the temperature-adjusted armature resistance R_{adj} **251**, the temperature-adjusted back-emf constant K_{adj} **253**, the estimated armature resistance $\hat{R}_a$ **231** and the estimated back-emf constant $\hat{K}_e$ **233**.

$$r_1=|V_m-I\hat{R}_a-K_{adj}\omega_m|$$

$$r_2=|V_m-IR_{adj}-\hat{K}_e\omega_m|$$

$$r_3=|V_m-I\hat{R}_a-\hat{K}_e\omega_m|$$

$$r_4=|V_m-IR_{adj}-K_{adj}\omega_m| \qquad [14]$$

The residuals **271**, i.e., r_1, r_2, r_3, and r_4 are calculated to account for any variations occurring between the temperature-adjusted armature resistance R_{adj}, the temperature-adjusted back-emf constant K_{adj}, the estimated armature resistance $\hat{R}_a$ and the estimated back-emf constant $\hat{K}_e$ that may indicate a fault in either the armature windings or magnetic elements of the pump motor **25**.

The residuals **271** are employed to monitor operation of the pump motor, including generating the output signal **291** indicating presence of a fault and identifying a location associated with the pump motor to facilitate root cause diagnosis (**290**). The residuals **271** are preferably evaluated by comparing them to corresponding residual thresholds. The values of each of the residuals **271** will be zero under ideal conditions when the pump motor is functional. Other pump parameters involved in indicating a fault and identifying a fault location include the nominal pump motor current **213** and monitored pump motor current **203**, fuel pressure **205**, and a commanded fuel pressure **215** in the returnless fuel system.

FIG. **4** illustrates an exemplary process **400** flowchart that employs the residuals **271**, i.e., r_1, r_2, r_3, and r_4 to monitor operation of the pump motor, including indicating and identifying a fault location associated with the pump motor. Table 2 is provided as a key to FIG. **4** wherein the numerically labeled blocks and the corresponding functions are set forth as follows.

TABLE 2

BLOCK	BLOCK CONTENTS
402	Determine residuals r_1, r_2, r_3, and r_4, residual thresholds r_{th1}, r_{th2}, r_{th3}, and r_{th4}, ΔI, P
404	Is $r_1 < rth_1$; $r_2 > rth_2$; $r_3 < rth_3$; $r_4 > rth_4$?
406	Indicate fault associated with armature resistance
408	Is $r_1 \geq rth_1$; $r_2 \leq rth_2$; $r_3 < rth_3$; $r_4 > rth_4$? and $\Delta I > I_{th}$?
410	Indicate fault associated with back-emf constant
412	Is $r_1 > rth_1$; $r_2 > rth_2$; $r_3 < rth_3$; $r_4 > rth_4$? and $\Delta I > I_{th}$ and $P < P_{req}$?
414	Indicate fault associated with back-emf constant and with armature resistance
416	No fault detected

The residuals r_1, r_2, r_3, and r_4 are determined as described herein using EQ. 14. A change in pump motor current ΔI from its nominal value I_{nom} is also determined. The residual thresholds r_{th1}, r_{th2}, r_{th3}, and r_{th4} are determined in a manner that accounts for system variations. Such system variations include those resulting from differences between nominal temperatures, initial ambient temperatures, and system temperature during operation to avoid falsely detecting system faults. The residuals r_1, r_2, r_3, and r_4 are compared to corresponding residual thresholds r_{th1}, r_{th2}, r_{th3}, and r_{th4} in accordance with the following relationship (**404**).

$$r_1<rth_1;r_2>rth_2;r_3<rth_3;r_4>rth_4$$

When all of the comparisons are met (1), a fault in the pump motor associated with pump motor resistance is indicated (**406**). When all of the comparisons are not met (O), the residuals r_1, r_2, r_3, and r_4 are compared to corresponding residual thresholds r_{th1}, r_{th2}, r_{th3}, and r_{th4} and the change in pump motor current ΔI is compared to a current threshold I_{th} in accordance with the following relationships (**408**).

$$r_1\geq rth_1;r_2\leq rth_2;r_3<rth_3;r_4>rth_4,\Delta I>I_{th}$$

When all of the comparisons are met (1), including the change in pump motor current exceeding the threshold current, a fault in the pump motor associated with back-emf constant is indicated (**410**). When all of the comparisons are not met (0), the residuals r_1, r_2, r_3, and r_4 are compared to corresponding residual thresholds r_{th1}, r_{th2}, r_{th3}, and r_{th4}, the change in pump motor current ΔI is compared to a current threshold I_{th}, and monitored fuel pressure P **205** is compared to the commanded fuel pressure P_{ref} **215** in accordance with the following relationships (**412**).

$$r_1>rth_1;r_2>rth_2;r_3<rth_3;r_4>rth_4;\Delta I>I_{th};P<P_{req}$$

When all of the comparisons are met (1), including the change in pump motor current exceeding the threshold current and the fuel pressure being less than the commanded fuel pressure, a fault in the pump motor associated with back-emf constant and with armature resistance is indicated (**414**). When all of the comparisons are not met (0), it is an indication that there are no faults associated with operation of the pump motor related to the back-emf constant and with the armature resistance (**416**).

The disclosure has described certain preferred embodiments and modifications thereto. Further modifications and alterations may occur to others upon reading and understanding the specification. Therefore, it is intended that the disclosure not be limited to the particular embodiment(s) disclosed as the best mode contemplated for carrying out this disclosure, but that the disclosure will include all embodiments falling within the scope of the appended claims.

The invention claimed is:

1. Method for monitoring an electric motor configured to transfer mechanical power to a fuel pump, comprising:

estimating a pump speed and a nominal pump motor current in relation to a pump motor control signal and a fuel pressure;

estimating an armature resistance and a back-emf constant for the electric motor corresponding to the estimated pump speed, a monitored pump motor current, and the pump motor control signal;

adjusting a nominal armature resistance and a nominal back-emf constant for the electric motor in relation to a pump motor temperature;

determining a plurality of residuals based upon the adjusted nominal armature resistance, the adjusted nominal back-emf constant, the estimated armature resistance and the estimated back-emf constant;

comparing the residuals with corresponding thresholds; and

detecting a fault in the electric motor based upon the comparisons of the residuals with the corresponding thresholds.

2. The method of claim **1**, wherein estimating the armature resistance and the back-emf constant comprises executing a two-stage estimation model.

3. The method of claim **2**, wherein the estimated pump speed is determined according to the following relationship:

$$\omega_m = a_\omega(V_m)P_s + b_\omega(V_m)$$

wherein ω_m is the pump speed,

V_m is the pump motor control signal,

P_s is the fuel pressure, and

a_ω and b_ω are application-specific scalar values.

4. The method of claim **2**, wherein executing the two-stage estimation model comprises executing a first stage, comprising:

assuming a nominal value for the back-emf constant; and

estimating the armature resistance employing a regression model for the armature resistance comprising a least-square estimation with a forgetting factor.

5. The method of claim **4**, wherein the regression model comprises the following relationship:

$$y_1(t) = \phi_1(t)^* \theta_1$$

$$y_1(t) = V_m(t) - K_e^* \omega_m,\ \phi_1(t) = I, \text{ and } \theta_1 = R_a$$

wherein K_e is the nominal value of the back-emf constant,

V_m(t) is the pump motor control signal,

ω_m is the pump speed, and

R_a is the armature resistance.

6. The method of claim **2**, wherein executing the two-stage estimation model comprises executing a second stage estimation model according to the following relationship:

$$y_2(t) = \phi_2(t)^* \theta_2$$

$$y_2(t) = V_m(t) - I^* \hat{R}_a(t),\ \phi_2(t) = \omega_m, \theta_2 = K_e$$

wherein $\hat{R}_a$ is an estimated armature resistance from a first stage,

V_m is the pump motor control signal, and

I is the monitored pump motor current.

7. The method of claim **1**, wherein adjusting the nominal armature resistance comprises determining an adjusted nominal armature resistance according to the following relationship:

$$R_{a\_nom}(T) = R_0(1 + \rho(T - T_0))$$

wherein R_0 is a nominal armature resistance at nominal temperature T_0,

T is an ambient temperature,

R_{a_nom}(T) is the adjusted nominal armature resistance, and

ρ is a material constant term for the armature resistance.

8. The method of claim **1**, wherein adjusting the nominal back-emf constant comprises determining the nominal back-emf constant according to the following relationship:

$$K_{e\_nom}(T) K_{e0}(1 - \beta(T - T_0))$$

wherein K_{e0} is a nominal back-emf constant at nominal temperature T_0,

T is an ambient temperature,

K_{e_nom}(T) is the adjusted nominal back-emf constant, and

β is a material constant term for the back-emf constant.

9. The method of claim **1**, wherein determining the plurality of residuals comprises determining the plurality of residuals according to the following relationships:

$$r_1 = |V_m - I\hat{R}_a - K_{adj}\omega_m|$$

$$r_2 = |V_m - IR_{adj} - \hat{K}_e\omega_m|$$

$$r_3 = |V_m - I\hat{R}_a - \hat{k}_e\omega_m|$$

$$r_4 = |V_m - IR_{adj} - K_{adj}\omega_m|$$

wherein r**1**, r**2**, r**3**, and r**4** are the residuals,

Radj is the temperature-adjusted armature resistance,

Kadj is the temperature-adjusted back-emf constant,

$\hat{R}_a$ is the estimated armature resistance,

$\hat{K}_e$ is the estimated back-emf constant,

Vm is the pump motor control signal,

I is the pump motor current, and

ωm is a nominal pump motor speed.

10. The method of claim **1**, wherein comparing the residuals with corresponding thresholds comprises determining the corresponding thresholds based upon the nominal pump motor current, the monitored pump motor current, the fuel pressure, and a commanded fuel pressure in the returnless fuel system.

11. Method for monitoring an electric motor configured to provide mechanical power to a fuel pump of a returnless fuel system, comprising:

estimating a pump speed and a nominal pump motor current in relation to a pump motor control signal and a fuel pressure in the returnless fuel system;

estimating an armature resistance and a back-emf constant for the electric motor corresponding to the estimated pump speed, a monitored pump motor current, and the pump motor control signal; and

detecting a fault in the electric motor based upon the estimated armature resistance and the estimated back-emf constant for the electric motor.

12. The method of claim **11**, wherein estimating the armature resistance and the back-emf constant comprises executing a two-stage estimation model.

13. The method of claim **12**, wherein the estimated pump speed is determined according to the following relationship:

$$\omega_m = a_\omega(V_m)P_s + b_\omega(V_m)$$

wherein ω_m is the pump speed,

V_m is the pump motor control signal,

P_s is the fuel pressure, and

a_ω and b_ω are application-specific scalar values.

14. The method of claim **12**, wherein executing the two-stage estimation model comprises executing a first stage, comprising:

assuming a nominal value for the back-emf constant; and

estimating the armature resistance employing a regression model for the armature resistance comprising a least-square estimation with a forgetting factor.

15. The method of claim **14**, wherein the regression model comprises the following relationship:

$$y_1(t)=\phi_1(t)*\theta_1$$

$$y_1(t)=V_m(t)-K_e*\omega_m,\ \phi_1(t)=I,\text{ and }\theta_1=R_a$$

wherein K_e is the nominal value of the back-emf constant,

$V_m(t)$ is the pump motor control signal,

ω_m is the pump speed, and

R_a is the armature resistance.

16. The method of claim **12**, herein executing the two-stage estimation model comprises executing a second stage estimation model according to the following relationship:

$$y_2(t)=\phi_2(t)*\theta_2$$

$$y_2(t)=V_m(t)-I*\hat{R}_a(t),\ \phi_2(t)=\omega_m,\theta_2=K_e$$

wherein $\hat{R}_a$ is an estimated armature resistance from a first stage,

V_m is the pump motor control signal, and

I is the monitored pump motor current.

17. The method of claim **11**, wherein detecting the fault in the electric motor based upon the estimated armature resistance and the estimated back-emf constant comprises:

determining a temperature adjusted nominal armature resistance according to the following relationship:

$$R_{a\_nom}(T)=R_0(1+\rho(T-T_0))$$

wherein R_0 is a nominal armature resistance at nominal temperature T_0,

T is an ambient temperature,

$R_{\_nom}(T)$ is the adjusted nominal armature resistance, and

ρ is a material constant term for the armature resistance;

determining a temperature-adjusted nominal back-emf constant according to the following relationship:

$$K_{e\_nom}(T)=K_{e0}(1-\beta(T-T_0))$$

wherein K_{e0} is a nominal back-emf constant at nominal temperature T_0,

T is an ambient temperature,

$K_{e\_nom}(T)$ is the adjusted nominal back-emf constant, and

β is a material constant term for the back-emf constant; and

detecting presence of a fault in the electric motor based upon the estimated armature resistance, the temperature-adjusted nominal armature resistance, the estimated back-emf constant and the temperature-adjusted nominal armature resistance.

18. The method of claim **17**, wherein detecting the fault in the electric motor based upon the estimated armature resistance, the temperature-adjusted nominal armature resistance, the estimated back-emf constant and the temperature-adjusted nominal armature resistance comprises:

determining a plurality of residuals based upon the estimated armature resistance, the temperature-adjusted nominal armature resistance, the estimated back-emf constant and the temperature-adjusted nominal armature resistance according to the following relationships:

$$r_1=|V_m-I\hat{R}_a-K_{adj}\omega_m|$$

$$r_2=|V_m-IR_{adj}-\hat{K}_e\omega_m|$$

$$r_3=|V_m-I\hat{R}_a-\hat{K}_e\omega_m|$$

$$r_4=|V_m-IR_{adj}-K_{adj}\omega_m|$$

wherein **r1**, **r2**, **r3**, and **r4** are the residuals,

Radj is the temperature-adjusted armature resistance,

Kadj is the temperature-adjusted back-emf constant,

$\hat{R}_a$ is the estimated armature resistance,

$\hat{K}_e$ is the estimated back-emf constant,

Vm is the pump motor control signal,

I is the pump motor current, and

ωm is a nominal pump motor speed; and

comparing the residuals with corresponding thresholds determined based upon the nominal pump motor current, the monitored pump motor current, the fuel pressure, and a commanded fuel pressure in the returnless fuel system;

wherein detecting the fault in the electric motor is based upon the comparisons of the residuals with the corresponding thresholds.

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