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Inventor(s) Tuller; Zachary L

Static friction to dynamic friction spin up modeling and controls for vehicle electric motor in neutral

Abstract

A modeling and control technique for an electric motor of an electrified vehicle includes preparing for reconnection of an electric motor to a driveline, which were temporarily disconnected by a disconnect system therebetween, by commanding the electric motor to generate an open-loop torque in an attempt to overcome a static friction of the electric motor and to begin spinning the electric motor, receiving a set of operating parameters of the electrified vehicle including (i) a speed of the electrified vehicle and (ii) a speed of the electric motor, and in response to detecting that a speed/position of the electric motor increases to the value greater than zero, commanding a feed-forward target speed for open-loop control of the electric motor, wherein the feed-forward target speed ignores static friction dynamics and is offset by a first offset to compensate for delay in actuating the electric motor.

Inventors:	**Tuller; Zachary L (Grand Rapids, MI)**
Applicant:	**FCA US LLC** (Auburn Hills, MI)
Family ID:	**1000007852847**
Assignee:	**FCA US LLC (Auburn Hills, MI)**
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Primary Examiner: Pang; Roger L

Background/Summary

FIELD

(1) The present application generally relates to electrified vehicles and, more particularly, to techniques for static friction to dynamic friction spin up modeling and controls for a vehicle electric motor in neutral.

BACKGROUND

(2) An electrified vehicle includes at least one electric motor, which could be a traction motor configured to provide propulsive torque to propel the electrified vehicle. Some electrified powertrains are capable of temporarily disconnecting an electric motor from the road (also referred to herein as “neutral”). This allows for the electric motor speed to be zero while the electrified

vehicle is moving, thereby reducing or eliminating system losses. Reconnecting the electric motor to the road while the electrified vehicle is moving involves "spin up" control of the electric motor to synchronize the electric motor and electrified vehicle speeds. This is a difficult/complex process that needs to be performed quickly and precisely. Conventional solutions are inadequate because they only attempt to minimize communication delays or have entirely different system dynamics (e.g., the electric motor is connected to an engine). Accordingly, while such conventional electric motor modeling and control systems and methods do work for their intended purpose, there exists an opportunity for improvement in the relevant art.

SUMMARY

(3) According to one example aspect of the invention, a modeling and control system for an electric motor of an electrified vehicle is presented. In one exemplary implementation, the system comprises a set of sensors configured to measure a set of operating parameters of the electrified vehicle, the set of operating parameters including (i) a speed of the electrified vehicle and (ii) a speed of the electric motor, wherein the electric motor is selectively connected to and disconnected from a driveline of the electrified vehicle by a disconnect system and a control system configured to command the disconnect system to disconnect the electric motor from the driveline and prepare for reconnection of the electric motor to the driveline by commanding the electric motor to generate an open-loop torque in an attempt to overcome a static friction of the electric motor and to begin spinning the electric motor and, in response to detecting that a speed/position of the electric motor increases to the value greater than zero, commanding a feed-forward target speed for open-loop control of the electric motor, wherein the feed-forward target speed ignores static friction dynamics and is offset by a first offset to compensate for delay in actuating the electric motor.

(4) In some implementations, the first offset is obtained by integrating products of commanded torques and inertias of the electric motor. In some implementations, the control system is further configured to command a closed-loop target speed for closed-loop control of the electric motor, wherein the closed-loop target speed is set to the feed-forward target speed at a previous time. In some implementations, the previous time corresponds to at least one of a communication delay, an actuation delay, and a processing delay. In some implementations, the control system is further configured to command the disconnect system to reconnect the electric motor to the driveline when their respective speeds are within a threshold amount from each other. In some implementations, the electric motor is connectable to a front axle of the driveline, and wherein the electrified vehicle further comprises another electric motor connected to a rear axle of the driveline. In some implementations, the disconnect system is a splined disconnect clutch. In some implementations, the disconnect system is a front axle disconnect (FAD). In some implementations, the disconnect system is one or more wheel end disconnects (WEDs). In some implementations, the disconnect system is an automatic transmission.

(5) According to another example aspect of the invention, a modeling and control method for an electric motor of an electrified vehicle is presented. In one exemplary implementation, the method comprises commanding, by a control system, a disconnect system to disconnect an electric motor of the electrified vehicle from a driveline of the electrified vehicle and preparing, by the control system, for reconnection of the electric motor to the driveline by commanding the electric motor to generate an open-loop torque in an attempt to overcome a static friction of the electric motor and to begin spinning the electric motor, receiving, by the control system and from a set of sensors of the electrified vehicle, a set of operating parameters of the electrified vehicle including (i) a speed of the electrified vehicle and (ii) a speed of the electric motor, and in response to detecting that a speed/position of the electric motor increases to the value greater than zero, commanding, by the control system, a feed-forward target speed for open-loop control of the electric motor, wherein the feed-forward target speed ignores static friction dynamics and is offset by a first offset to compensate for delay in actuating the electric motor.

(6) In some implementations, the first offset is obtained by integrating products of commanded

torques and inertias of the electric motor. In some implementations, the method further comprises commanding, by the control system, a closed-loop target speed for closed-loop control of the electric motor, wherein the closed-loop target speed is set to the feed-forward target speed at a previous time. In some implementations, the previous time corresponds to at least one of a communication delay, an actuation delay, and a processing delay. In some implementations, the method further comprises commanding, by the control system, the disconnect system to reconnect the electric motor to the driveline when their respective speeds are within a threshold amount from each other. In some implementations, the electric motor is connectable to a front axle of the driveline, and wherein the electrified vehicle further comprises another electric motor connected to a rear axle of the driveline. In some implementations, the disconnect system is a splined disconnect clutch. In some implementations, the disconnect system is an FAD. In some implementations, the disconnect system is one or more WEDs. In some implementations, the disconnect system is an automatic transmission.

(7) Further areas of applicability of the teachings of the present application will become apparent from the detailed description, claims and the drawings provided hereinafter, wherein like reference numerals refer to like features throughout the several views of the drawings. It should be understood that the detailed description, including disclosed embodiments and drawings referenced therein, are merely exemplary in nature intended for purposes of illustration only and are not intended to limit the scope of the present disclosure, its application or uses. Thus, variations that do not depart from the gist of the present application are intended to be within the scope of the present application.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) FIG. **1** is a functional block diagram of an electrified vehicle having an example electric motor modeling and control system according to the principles of the present application;

(2) FIG. **2** is a flow diagram of an example method of modeling and controlling an electric motor of an electrified vehicle according to the principles of the present application; and

(3) FIGS. **3**A-**3**B are example torque and speed plots illustrating the example modeling and control of an electric motor of an electrified vehicle according to the principles of the present application.

DESCRIPTION

(4) As previously discussed, reconnecting an electric motor of an electrified powertrain that is temporarily disconnected (also referred to herein as “neutral”) back to the road involves “spin up” control of the electric motor to synchronize the motor and vehicle speeds. This is a difficult/complex process that involves a plurality of different electronic control units (ECUs) in communication on a controller area network (CAN) and that needs to be performed quickly and precisely. In particular, there are lag times from commanding motor torque to observing motor speed feedback from a sensor, and parameters such as initial motor spin-up static friction losses are difficult to model. Conventional solutions are inadequate because they only attempt to minimize communication delays or have entirely different system dynamics (e.g., the electric motor is connected to an engine). Accordingly, improved spin up modeling and control techniques for an electric motor in neutral are presented herein. Potential benefits of these techniques include faster and/or smoother electric motor spin up and/or reconnection to the road and an improved driver experience.

(5) These techniques begin when the electric motor is temporarily disconnected from the road (i.e., in neutral). When a torque request for the electrified powertrain exceeds a threshold that indicates that the electric motor is needed to satisfy the torque request, the electric motor must be reconnected. Before the electric motor can be reconnected, however, it must first be spun-up and its

speed synchronized with the electrified vehicle's speed. First, a feed-forward (open-loop) torque is commanded with a known communication (CAN) delay. Once a change in motor speed/position is observed, closed-loop feedback control of motor speed is enabled, where static friction modeling can be ignored because the motor is in a dynamic friction regime. The closed-loop speed target is thus recalculated as a sum of torque commands send in the known communication (CAN) delay and the observed motor speed. The feed-forward (open-loop) control then begins dynamic friction speed profiling at this recalculated speed target. In the closed-loop control, the closed-loop speed target is calculated based on the open-loop system's speed target and the torque commands sent to the motor while awaiting the observed speed/position change, factoring in communication (CAN) delay and any other minor corrections.

(6) Referring now to FIG. **1**, a functional block diagram of an electrified vehicle **100** having an example electric motor modeling and control system **104** according to the principles of the present application is illustrated. The electrified vehicle **100** (also "vehicle **100**" herein) includes an electrified powertrain **108** that is configured to generate and transfer propulsive torque to a driveline system **112** for vehicle propulsion. As shown, the electrified powertrain **108** includes a first electric motor **116***a* that is selectively connected to a first portion **112***a* of the driveline system **112** (e.g., a front axle) via a disconnect system **120** and a second electric motor **116***b* that is connected to a second portion **112***b* of the driveline system **112** (e.g., a rear axle). The electrified powertrain **108** includes an energy storage system **124** that provides electrical energy (current) to power the electric motors **116***a*, **116***b* (collectively, "electric motors **116**"). The energy storage system **124** could include a high voltage battery pack or system, a fuel cell system, or some combination thereof. The electrified powertrain **108** could also include one or more other powertrain components **128**, such as, but not limited to, a multi-speed automatic transmission and/or an internal combustion engine.

(7) The disconnect system **120** could be any suitable device or system that is configured to selectively connect the electric motor **116***a* to the first portion **112***a* of the driveline system **112** and to selectively disconnect the electric motor **116***a* from the first portion **112***a* of the driveline system **112**. Non-limiting examples of the disconnect system **120** include a splined disconnect clutch, a conventional automatic transmission, a front axle disconnect (FAD), and one or more wheel end disconnects (WEDs). When disconnected from the first portion **112***a* of the driveline system **112**, the electric motor **116***a* will be in neutral and thus will be able to be fully disabled (e.g., at zero speed) for a period of time during which friction losses are reduced and, in turn, vehicle efficiency is increased. A controller or control system **132** controls operation of the electrified vehicle **100** and, more particularly, controls the electrified powertrain **108** to generate an amount of drive torque in satisfaction of a driver torque request via a driver interface **136** (e.g., an accelerator pedal). The control system **132** also receives measurements from a set of sensors **140**, including, but not limited to, operating parameters of the electrified vehicle **100** such as a speed of the electrified vehicle **100** ("vehicle speed") and a speed of the electric motor **116***a* ("motor speed").

(8) Referring now to FIG. **2**, a flow diagram of an example method **200** of modeling and controlling an electric motor of an electrified vehicle according to the principles of the present application is illustrated. FIGS. **3**A-**3**B, which depict example torque and speed plots illustrating the example modeling and control of an electrified vehicle electric motor (e.g., electric motor **116***a*). While the following description specifically references the electrified vehicle **100** and its components, it will be appreciated that the method **200** could be applicable to any suitably configured electrified vehicle (e.g., any electrified vehicle having an electric motor that is temporarily disconnected from the road). The method **200** begins at **204** where the electric motor **116***a* is disconnected (by disconnect system **120**) from the front portion **112***a* of the driveline system **112**. This could have been previously performed in response to a driver torque request (T.sub.REQ) for the electrified powertrain falling below a threshold that required the electric motor **116***a* in order to satisfy. At **208**, the control system **132** determines the electric motor **116***a* is

required to be connected through the disconnect system **120** to the first portion **112***a* of the driveline system **112**. This could be because the driver torque request (T.sub.REQ) has increased to a level (e.g., greater than the threshold) that now requires the electric motor **116***a* in order to satisfy, because the driver has requested four wheel drive, or other factors. When false, the method **200** ends or returns to **208**. When true, the method **200** proceeds to **212**. At **212**, the control system **132** commands a feed-forward (open-loop) torque command to attempt to spin the electric motor **116***a*.
(9) In FIG. **3**B, the commanded torque **304** begins increasing at time t.sub.1 and the actual torque **308** begins increasing after small delay (e.g., due to actuator and CAN communication delay). This also causes an increase in the speed request **312** for the electric motor **116***a*, which can be seen in FIG. **3**A. In order to cause the electric motor **116***a* to start spinning, a certain amount of torque must be commanded, which is shown and described as a torque to overcome static friction, or T.sub.OSF. At **216**, the control system **132**, at each time step or interval after time t1, stores the commanded feed-forward (open-loop) torque in a memory or buffer (e.g., in control system **132**). At **220**, the control system **132** determines whether the observed speed/position of the electric motor **116***a* (e.g., from sensor(s) **140**) is greater than zero, indicating that the electric motor **116***a* has begin moving/spinning. This can be seen in FIG. **3**A where the actual speed **316** of the electric motor **116***a* increases to a value greater than zero at point **320**, but an observed/sensed speed **340** of the electric motor **116***a* is not recognized until point **324**. When false at **220**, the method **200** proceeds to **224** where the feed-forward (open-loop) torque command is increased and the method **200** returns to **216**. When true at **220**, the method **200** proceeds to **228**.
(10) At **228**, the control system **132** initializes open-loop motor speed profiling with the observed/sensed speed of the electric motor **116***a* plus a first offset **328**. This first offset **328** is obtained from integrating a product of the commanded torques and inertias for the electric motor **116***a* during a previous period **332**. This first offset **328** is utilized to compensate for the initial communication lag time from approximately time t.sub.2 to time t.sub.4. For example only, this lag time between commanding motor torque and observing a change in motor speed/position could be approximately 70 milliseconds (ms). Additionally, for example only, the entire illustrated period in FIGS. **3**A-**3**B, from time t.sub.1 to time t.sub.7, could be approximately 500 ms. After applying the first offset **328**, the open-loop motor speed profiling begins and is shown by curve **336**. At **232**, closed-loop speed control of the electric motor **116***a* is also initialized. This closed-loop control should not be needed if the open-loop speed profiling stays accurately on target, but the closed-loop control allows for minor correction if needed. The target speed for the closed-loop control is illustrated by curve **344** and, as mentioned, it is almost identical to the observed/sensed speed **340** of the electric motor **116***a*.
(11) At **240**, the control system **132** determines whether a communication and actuation lag time has passed. As previously mentioned, this lag time could be approximately 70 ms. When false, the method **200** proceeds to **244** where the closed-loop target speed is set to a previous value plus an offset each iteration and the method **200** returns to **236**. The offset each iteration, also referred to as a “second offset,” is obtained by summing products of commanded torque and motor inertia at every time step across a previous period **332** and creates the closed-loop speed target **344** in time period **348**. When true at **240**, the method **200** proceeds to **248**. At **248**, the control system **132** sets the closed-loop speed target **340** to the open-loop speed target **336** from a communication and actuation lag time ago (e.g., 70 ms earlier). At **252**, the control system **132** determines whether the speeds of the electrified vehicle **100** (the front portion **112***a* of the driveline system **112**) and the electric motor **116***a* are synchronized (e.g., within a threshold amount from each other). When false, the method **200** returns to **248**. When true, the method **200** proceeds to **256** where the control system **132** controls the disconnect system **120** to reconnect the electric motor **116***a* to the first portion **112***a* of the driveline system **112** and the spin up control of the previous steps is disabled. The method **200** then ends at **260** where the electric motor **116***a* is utilized for propulsion of the electrified vehicle **100**, such as until it is subsequently no longer needed for propulsion and can

once again be disconnected from the first portion **112***a* of the driveline system **112** by the disconnect system **120** to save energy.

(12) It will be appreciated that the terms "controller" and "control system" as used herein refer to any suitable control device or set of multiple control devices that is/are configured to perform at least a portion of the techniques of the present application. Non-limiting examples include an application-specific integrated circuit (ASIC), one or more processors and a non-transitory memory having instructions stored thereon that, when executed by the one or more processors, cause the controller to perform a set of operations corresponding to at least a portion of the techniques of the present application. The one or more processors could be either a single processor or two or more processors operating in a parallel or distributed architecture.

(13) It should also be understood that the mixing and matching of features, elements, methodologies and/or functions between various examples may be expressly contemplated herein so that one skilled in the art would appreciate from the present teachings that features, elements and/or functions of one example may be incorporated into another example as appropriate, unless described otherwise above.

Claims

1. A modeling and control system for an electric motor of an electrified vehicle, the system comprising: a set of sensors configured to measure a set of operating parameters of the electrified vehicle, the set of operating parameters including (i) a speed of the electrified vehicle and (ii) a speed of the electric motor, wherein the electric motor is selectively connected to and disconnected from a driveline of the electrified vehicle by a disconnect system; and a control system configured to command the disconnect system to disconnect the electric motor from the driveline and prepare for reconnection of the electric motor to the driveline by: commanding the electric motor to generate an open-loop torque in an attempt to overcome a static friction of the electric motor and to begin spinning the electric motor; and in response to detecting that a speed/position of the electric motor increases to the value greater than zero, commanding a feed-forward target speed for open-loop control of the electric motor, wherein the feed-forward target speed ignores static friction dynamics and is offset by a first offset to compensate for delay in actuating the electric motor.
2. The system of claim 1, wherein the first offset is obtained by integrating products of commanded torques and inertias of the electric motor.
3. The system of claim 2, wherein the control system is further configured to command a closed-loop target speed for closed-loop control of the electric motor, wherein the closed-loop target speed is set to the feed-forward target speed at a previous time.
4. The system of claim 3, wherein the previous time corresponds to at least one of a communication delay, an actuation delay, and a processing delay.
5. The system of claim 1, wherein the control system is further configured to command the disconnect system to reconnect the electric motor to the driveline when their respective speeds are within a threshold amount from each other.
6. The system of claim 5, wherein the electric motor is connectable to a front axle of the driveline, and wherein the electrified vehicle further comprises another electric motor connected to a rear axle of the driveline.
7. The system of claim 1, wherein the disconnect system is a splined disconnect clutch.
8. The system of claim 1, wherein the disconnect system is a front axle disconnect (FAD).
9. The system of claim 1, wherein the disconnect system is one or more wheel end disconnects (WEDs).
10. The system of claim 1, wherein the disconnect system is an automatic transmission.
11. A modeling and control method for an electric motor of an electrified vehicle, the method comprising: commanding, by a control system, a disconnect system to disconnect an electric motor

of the electrified vehicle from a driveline of the electrified vehicle; and preparing, by the control system, for reconnection of the electric motor to the driveline by: commanding the electric motor to generate an open-loop torque in an attempt to overcome a static friction of the electric motor and to begin spinning the electric motor; receiving, by the control system and from a set of sensors of the electrified vehicle, a set of operating parameters of the electrified vehicle including (i) a speed of the electrified vehicle and (ii) a speed of the electric motor; and in response to detecting that a speed/position of the electric motor increases to the value greater than zero, commanding, by the control system, a feed-forward target speed for open-loop control of the electric motor, wherein the feed-forward target speed ignores static friction dynamics and is offset by a first offset to compensate for delay in actuating the electric motor.

12. The method of claim 11, wherein the first offset is obtained by integrating products of commanded torques and inertias of the electric motor.

13. The method of claim 12, further comprising commanding, by the control system, a closed-loop target speed for closed-loop control of the electric motor, wherein the closed-loop target speed is set to the feed-forward target speed at a previous time.

14. The method of claim 13, wherein the previous time corresponds to at least one of a communication delay, an actuation delay, and a processing delay.

15. The method of claim 11, further comprising commanding, by the control system, the disconnect system to reconnect the electric motor to the driveline when their respective speeds are within a threshold amount from each other.

16. The method of claim 15, wherein the electric motor is connectable to a front axle of the driveline, and wherein the electrified vehicle further comprises another electric motor connected to a rear axle of the driveline.

17. The method of claim 11, wherein the disconnect system is a splined disconnect clutch.

18. The method of claim 11, wherein the disconnect system is a front axle disconnect (FAD).

19. The method of claim 11, wherein the disconnect system is one or more wheel end disconnects (WEDs).

20. The method of claim 11, wherein the disconnect system is an automatic transmission.
