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(54) **METHOD FOR MOTOR AND INVERTER TEMPERATURE CONTROL**

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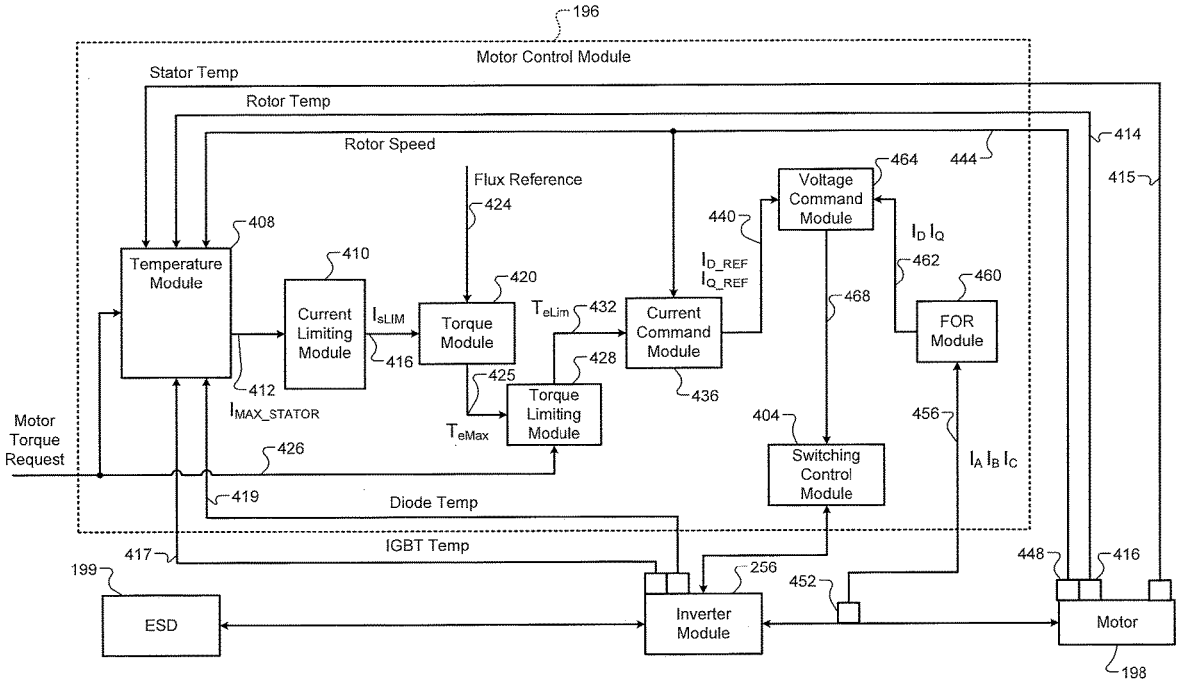
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(57) **ABSTRACT**

An electric motor control system of a vehicle includes a temperature module configured to, based on a motor torque request, (i) determine a plurality of stator current values based on a plurality of temperatures and (ii) generate a maximum stator current based on a lowest value of the plurality of stator current values. A torque module configured to, based on the maximum stator current, the motor torque request, and a maximum allowable flux, generate a maximum torque output. A current command module configured to, based on a speed of a rotor of the electric motor and the maximum torque output, generate a d-axis current adjustment and a q-axis current adjustment. A switching control module configured to, based on the d- and q-axis current adjustments, control switching of an inverter module and apply power to stator windings of the electric motor from an energy storage device.



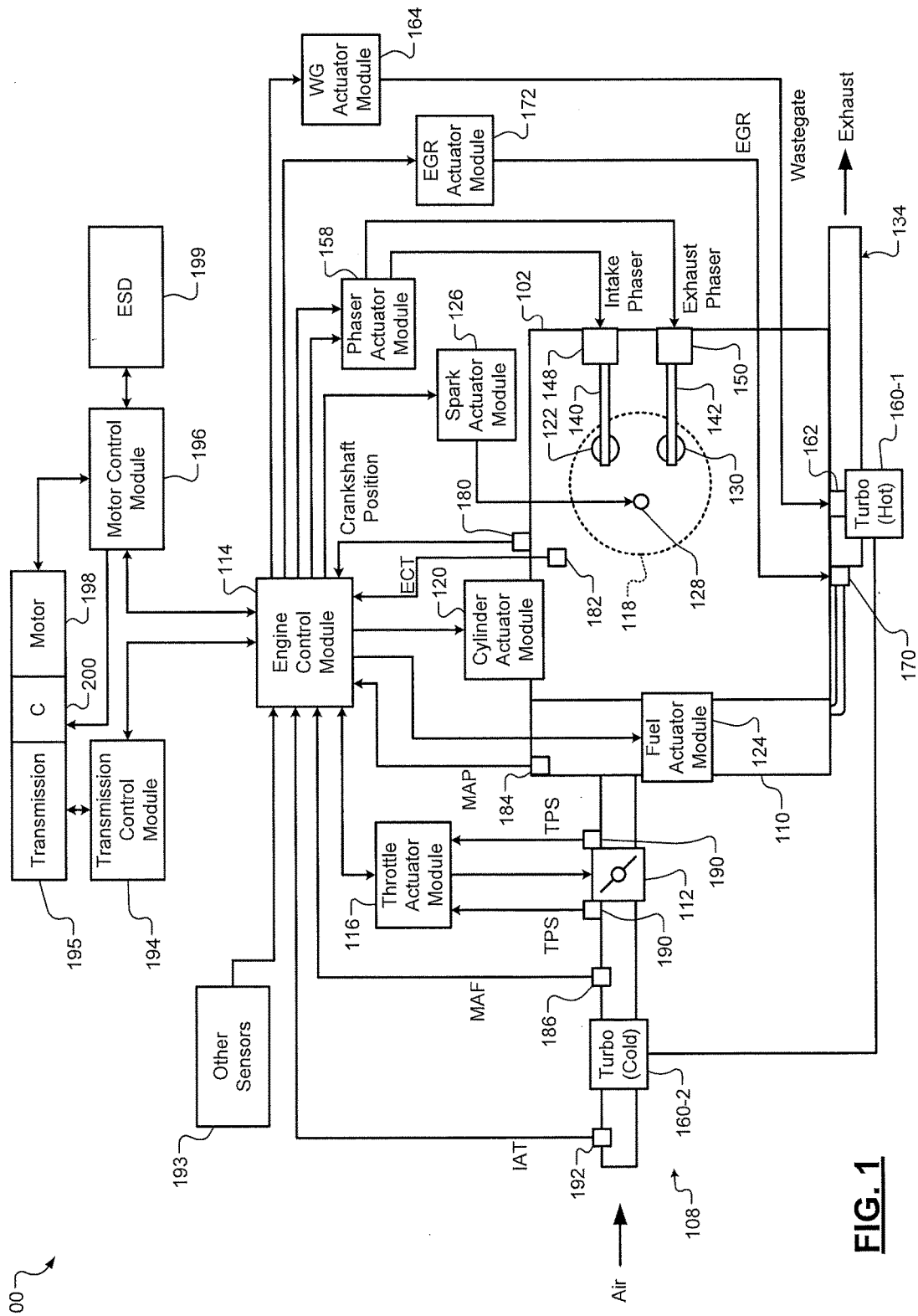

100
Air
108
Exhaust
Wastegate
EGR
Intake Phaser
Exhaust Phaser
Crankshaft Position
ECT
MAP
TPS
TPS
MAF
IAT
Engine Control Module
Motor Control Module
Transmission Control Module
Motor
C
Transmission
ESD
WG Actuator Module
EGR Actuator Module
Phaser Actuator Module
Spark Actuator Module
Cylinder Actuator Module
Fuel Actuator Module
Throttle Actuator Module
Other Sensors
Turbo (Hot)
Turbo (Cold)
110
112
114
116
118
120
122
124
126
128
130
134
140
142
148
150
158
160-1
160-2
162
164
170
172
180
182
184
186
190
192
193
194
195
196
198
199
200

FIG. 1

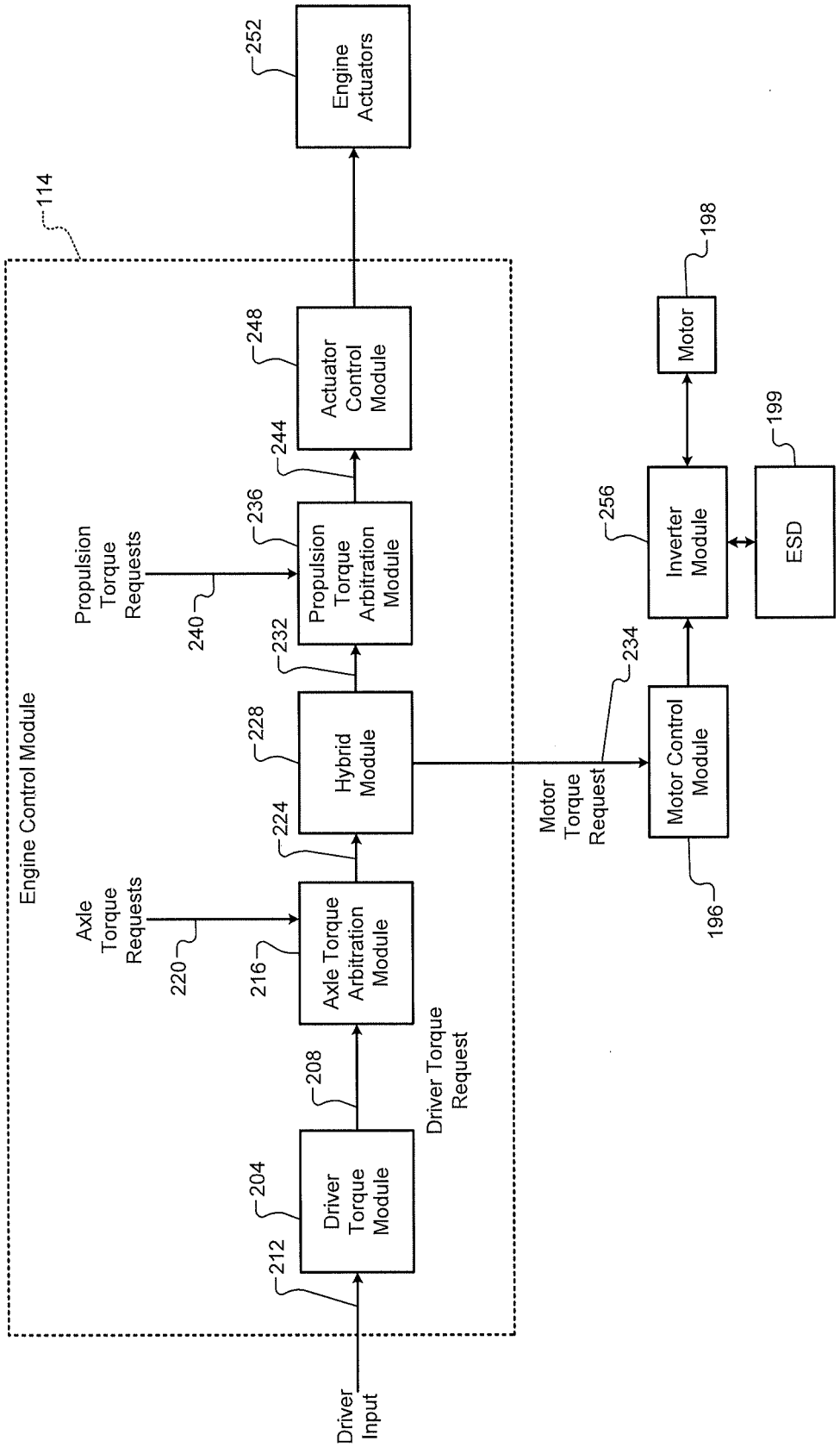

Engine Actuators
252
114
Engine Control Module
Actuator Control Module
248
244
Propulsion Torque Arbitration Module
236
Propulsion Torque Requests
240
232
Hybrid Module
228
224
Axle Torque Arbitration Module
216
Axle Torque Requests
220
208
Driver Torque Module
204
212
Driver Input
Driver Torque Request
Motor Torque Request
234
Motor Control Module
196
Inverter Module
256
Motor
198
ESD
199

FIG. 2

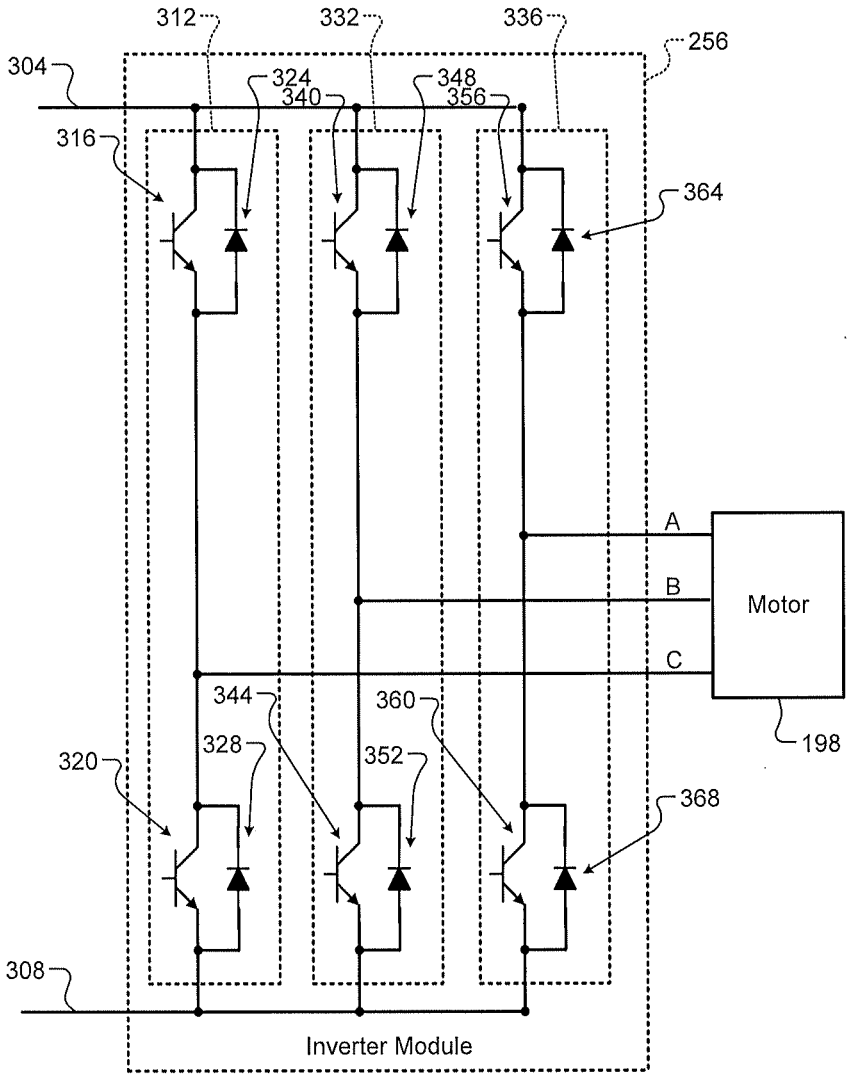

312
332
336
256
304
324
340
348
356
316
364
A
B
C
Motor
198
344
360
328
352
320
368
308
Inverter Module

FIG. 3

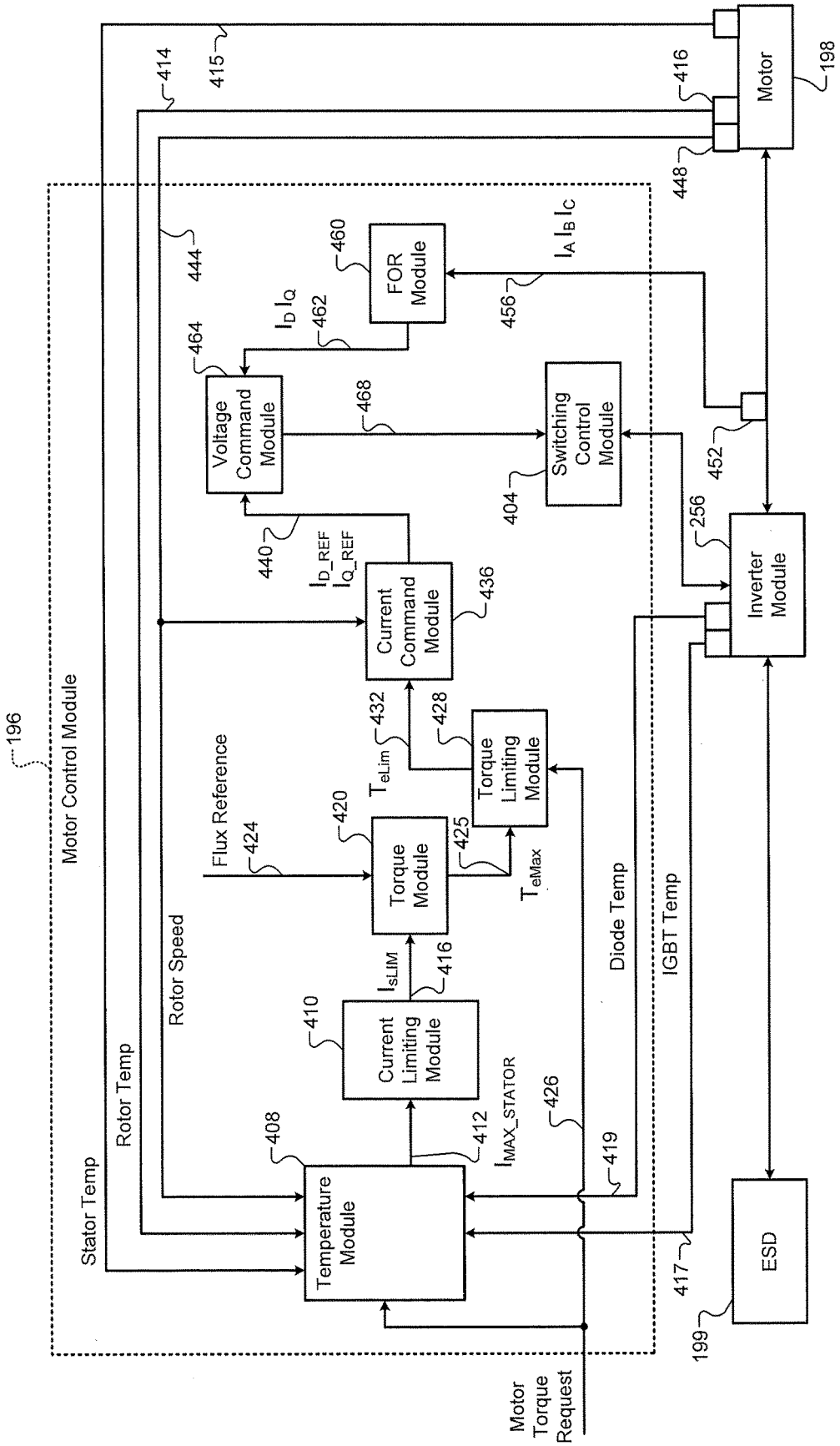

Motor Control Module
196
Motor
198
414
415
416
448
444
460
FOR Module
$I_A I_B I_C$
456
462
$I_D I_Q$
464
Voltage Command Module
468
Switching Control Module
404
452
256
Inverter Module
440
I_{D_REF}
I_{Q_REF}
Current Command Module
436
Flux Reference
424
420
Torque Module
T_{eLim}
432
428
Torque Limiting Module
425
T_{eMax}
Rotor Speed
Rotor Temp
Stator Temp
I_{sLIM}
416
410
Current Limiting Module
408
Temperature Module
412
I_{MAX_STATOR}
426
419
Diode Temp
IGBT Temp
417
ESD
199
Motor Torque Request

FIG. 4

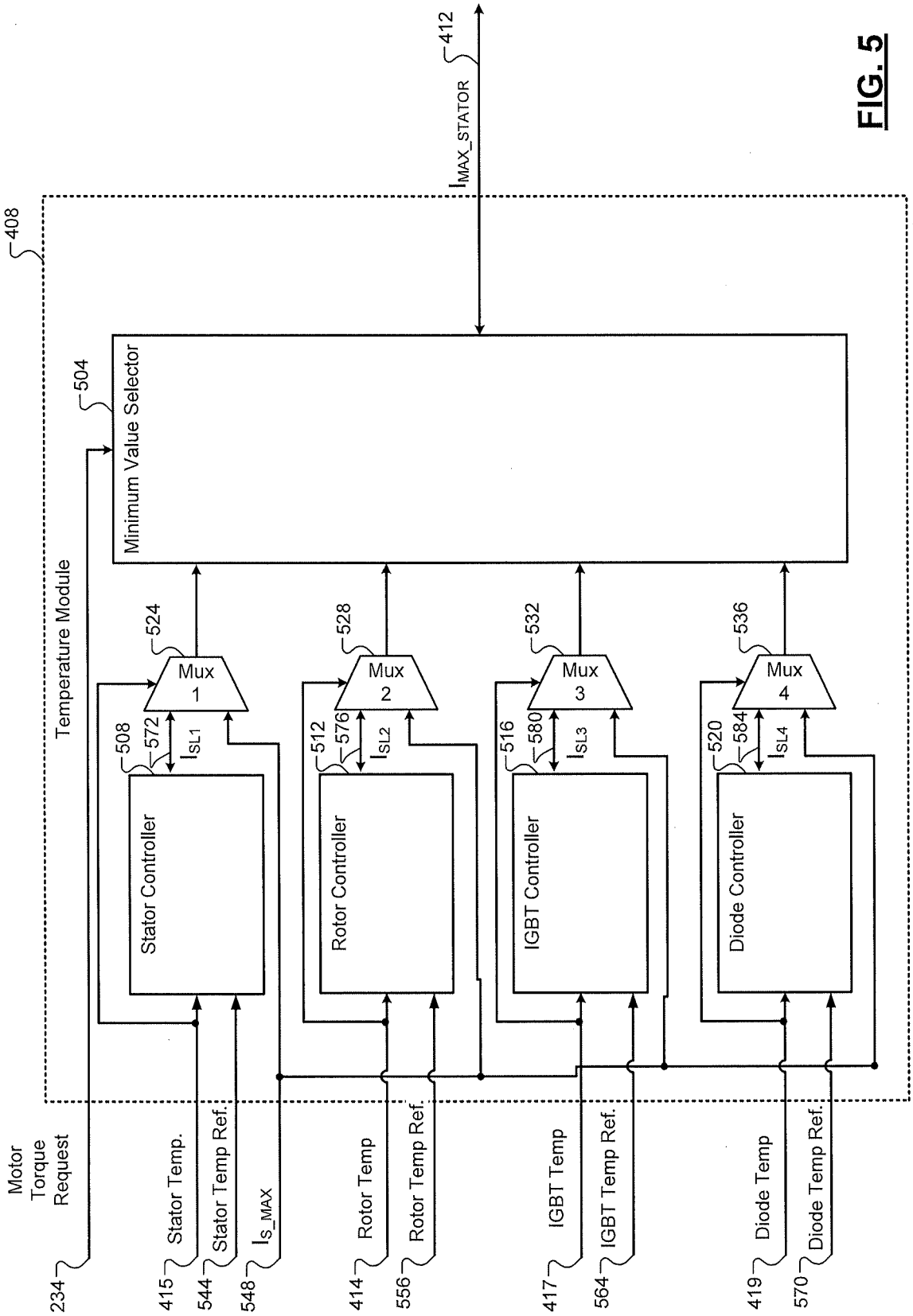

408
Temperature Module
504
Minimum Value Selector
412
I_{MAX_STATOR}
524
Mux 1
528
Mux 2
532
Mux 3
536
Mux 4
508
572
I_{SL1}
Stator Controller
512
576
I_{SL2}
Rotor Controller
516
580
I_{SL3}
IGBT Controller
520
584
I_{SL4}
Diode Controller
Motor Torque Request
234
Stator Temp.
415
Stator Temp Ref.
544
I_{S_MAX}
548
Rotor Temp
414
Rotor Temp Ref.
556
IGBT Temp
417
IGBT Temp Ref.
564
Diode Temp
419
Diode Temp Ref.
570

FIG. 5

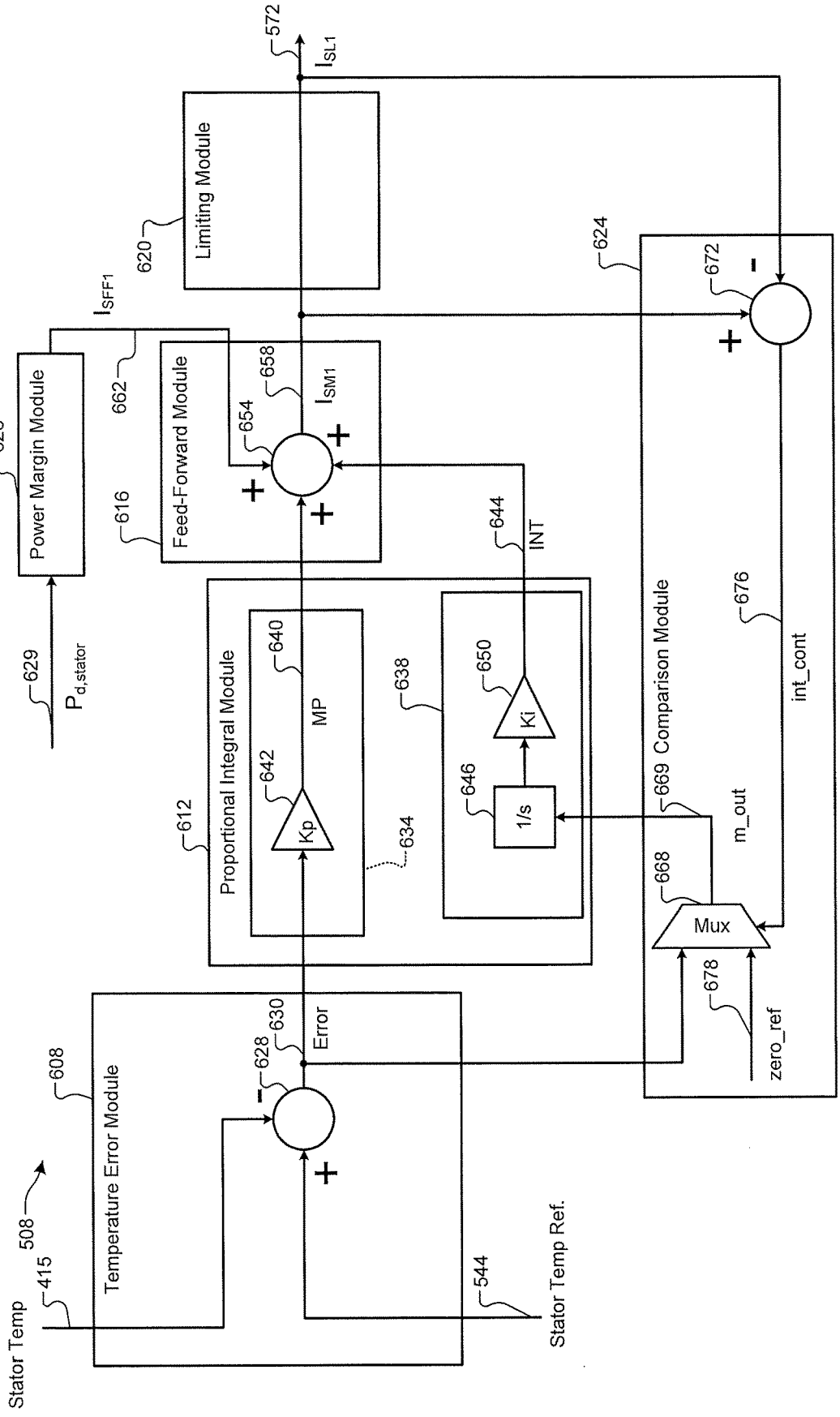

572
I_{SL1}
Limiting Module
620
624
672
-
+
I_{SFF1}
662
658
654
I_{SM1}
Power Margin Module
626
Feed-Forward Module
616
644
INT
629
$P_{d,stator}$
Proportional Integral Module
612
640
MP
Kp
642
634
638
650
Ki
646
1/s
669 Comparison Module
676
int_cont
m_out
668
Mux
678
zero_ref
608
Temperature Error Module
628
630
Error
508
415
Stator Temp
544
Stator Temp Ref.

FIG. 6

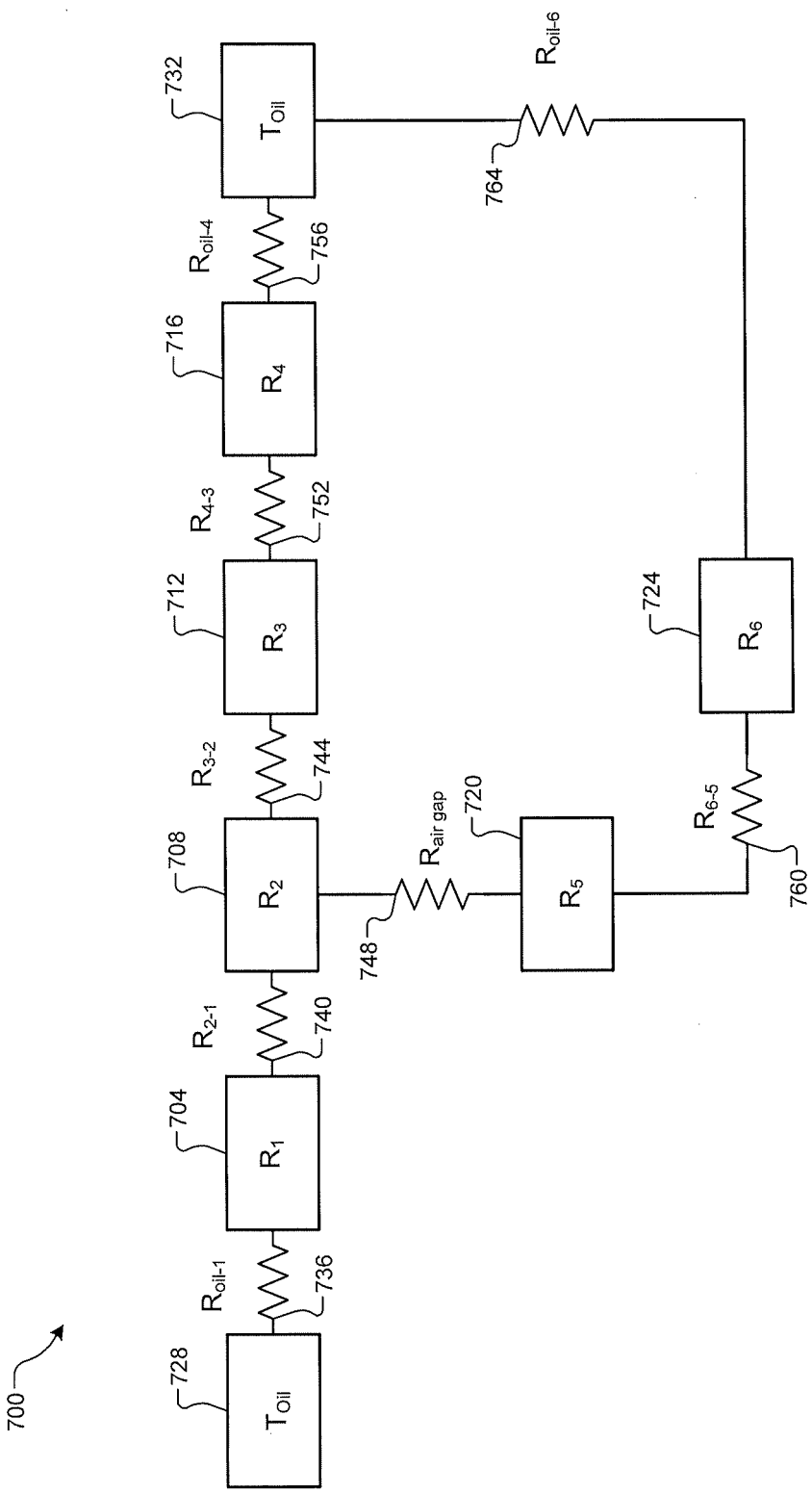

700
728
T_{Oil}
R_{oil-1}
736
704
R_1
R_{2-1}
740
708
R_2
R_{3-2}
744
712
R_3
R_{4-3}
752
716
R_4
R_{oil-4}
756
732
T_{Oil}
R_{oil-6}
764
$R_{air\ gap}$
720
748
R_5
R_{6-5}
760
724
R_6

FIG. 7

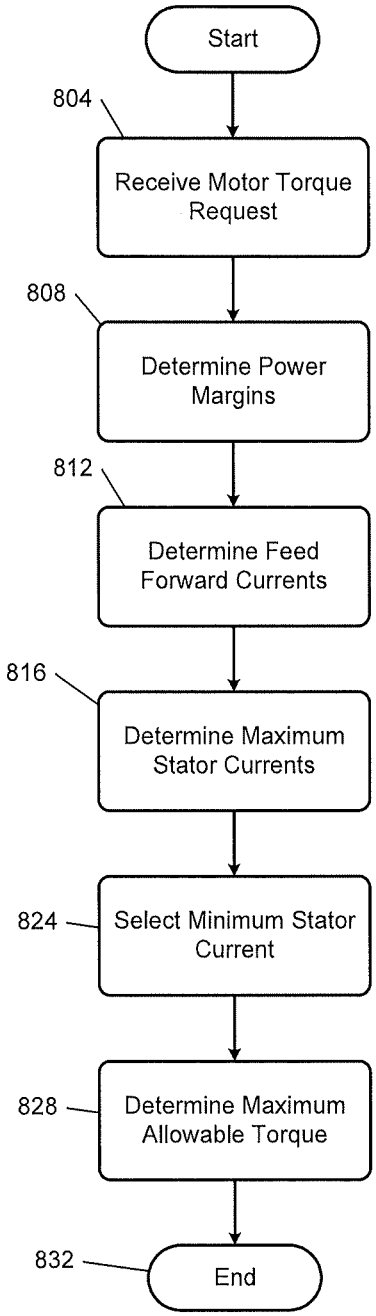

Start
804
Receive Motor Torque Request
808
Determine Power Margins
812
Determine Feed Forward Currents
816
Determine Maximum Stator Currents
824
Select Minimum Stator Current
828
Determine Maximum Allowable Torque
832
End

FIG. 8

METHOD FOR MOTOR AND INVERTER TEMPERATURE CONTROL

INTRODUCTION

[0001] The information provided in this section is for the purpose of generally presenting the context of the disclosure. Work of the presently named inventors, to the extent it is described in this section, as well as aspects of the description that may not otherwise qualify as prior art at the time of filing, are neither expressly nor impliedly admitted as prior art against the present disclosure.

[0002] The present disclosure relates to systems and methods for controlling an electric motor of a vehicle based on temperatures of one or more components of the electric motor.

[0003] Some types of vehicles include only an internal combustion engine that generates propulsion torque. Non-hybrid electric vehicles may include one or more electric motors. Hybrid vehicles include both an internal combustion engine and one or more electric motors. Some types of hybrid vehicles utilize the electric motor and the internal combustion engine in an effort to achieve greater fuel efficiency than if only the internal combustion engine was used. Some types of hybrid vehicles utilize the electric motor and the internal combustion engine to achieve greater torque output than the internal combustion could achieve by itself.

[0004] Some example types of hybrid vehicles include parallel hybrid vehicles, series hybrid vehicles, and other types of hybrid vehicles. In a parallel hybrid vehicle, the electric motor works in parallel with the engine to combine power and range advantages of the engine with efficiency and regenerative braking advantages of electric motors. In a series hybrid vehicle, the engine drives a generator to produce electricity for the electric motor, and the electric motor drives a transmission. This allows the electric motor to assume some of the power responsibilities of the engine, which may permit the use of a smaller and possibly more efficient engine.

SUMMARY

[0005] In an electric motor control system of a vehicle is described. A temperature module is configured to, based on a motor torque request for an electric motor of the vehicle, (i) determine a plurality of stator current values based on a plurality of temperatures and (ii) generate a maximum stator current based on a lowest value of the plurality of stator current values. A torque module is configured to, based on the maximum stator current, the motor torque request, and a maximum allowable flux, generate a maximum torque output. A current command module is configured to, based on a speed of a rotor of the electric motor and the maximum torque output, generate a d-axis current adjustment and a q-axis current adjustment. A switching control module is configured to, based on the d-axis current adjustment and the q-axis current adjustment, control switching of an inverter module and apply power to stator windings of the electric motor from an energy storage device. The plurality of temperatures correspond to at least one temperature associated with the electric motor and at least one temperature associated with the inverter module.

[0006] In further features, the temperature module includes a plurality of controllers; and each of the plurality of controllers includes: a temperature error module that is configured to output an error signal corresponding to a difference between a temperature reference and a measured temperature; and a proportional integral module, is connected to the temperature error module, that is configured to output a first signal and a second signal, where the first signal is a first multiplication product of the error signal and the second signal is based on at least one of an integral of the error signal and a second multiplication product of the error signal.

[0007] In further features, each of the plurality of controllers further includes a feed-forward module, is connected to the proportional integral module, and outputs the maximum stator current based on the first signal, the second signal, and a feed-forward current value.

[0008] In further features, each of the plurality of controllers includes a limiting module, to which an output of the feed-forward module is input, configured to: in response to the maximum stator current being greater than a first predetermined current, output the first predetermined current; and in response to the maximum stator current being less than the first predetermined current, output the maximum stator current, where the first predetermined current is less than the maximum stator current.

[0009] In further features, the proportional integral module includes a proportional portion and an integral portion; each of the plurality of controllers includes a comparison module that is configured to determine a difference between an output of the limiting module and an input of the limiting module; in response to the difference not being equal to a first predetermined value, setting an input to the integral portion to a second predetermined value; and in response to the difference being equal to the first predetermined value, setting the input to the integral portion to the difference between the temperature reference and the measured temperature.

[0010] In further features, the at least one temperature associated with the electric motor is at least one of a temperature of the rotor and a temperature of the stator windings of the electric motor; and the plurality of controllers includes a stator controller, a rotor controller, a diode controller, and an IGBT controller.

[0011] In further features, the feed-forward current value is set by a power margin module that determines the feed-forward current value based on a thermal model of the electric motor.

[0012] In further features, the inverter module includes at least one diode and at least one insulated gate bipolar transistor; and the at least one temperature associated with the inverter module is associated with the at least one diode.

[0013] In further features, the feed-forward current term is based on a switching loss of the at least one diode and a conduction loss of the at least one diode.

[0014] In further features, the at least one temperature associated with the inverter module is associated with the at least one insulated gate bipolar transistor; and the feed-forward current value is based on a switching loss of the at least one insulated gate bipolar transistor and a conduction loss of the at least one insulated gate bipolar transistor.

[0015] In a feature, an electric motor control method for a vehicle includes: in response to receiving a motor torque request for an electric motor of the vehicle: determining, with a temperature module, a plurality of stator current values based on a plurality of temperatures; and generating,

with the temperature module, a maximum stator current based on a lowest value of the plurality of stator current values. The method further includes generating, with a torque module, a maximum torque output based on the maximum stator current, the motor torque request, and a maximum allowable flux. The method further includes generating, with a current command module, a d-axis current adjustment and a q-axis current adjustment based on a speed of a rotor of the electric motor and the maximum torque output. The method further includes controlling, with a switching control module, switching of an inverter module and applying power to stator windings of the electric motor from an energy storage device, where the plurality of temperatures correspond to at least one temperature associated with the electric motor and at least one temperature associated with the inverter module.

[0016] In further features, the temperature module includes a plurality of controllers and determining the plurality of stator current values includes: generating, for each of the plurality of controllers, an error signal corresponding to a difference between a temperature reference and a measured temperature; and generating, for each of the plurality of controllers, a first signal and a second signal, where the first signal is a first multiplication product of the error signal and the second signal is based on at least one of an integral of the error signal and a second multiplication product of the error signal.

[0017] In further features, determining the plurality of stator current values includes: generating, for each of the plurality of controllers, a feed-forward current value; and generating, for each of the plurality of controllers, the maximum stator current based on the first signal, the second signal, and the feed-forward current value.

[0018] In further features, each of the plurality of controllers includes a limiting module and determining the plurality of stator current values includes: outputting, for each of the plurality of controllers, a first predetermined current in response to the maximum stator current being greater than the first predetermined current; and outputting, for each of the plurality of controllers, the maximum stator current in response to the maximum stator current being less than the first predetermined current, where the first predetermined current is less than the maximum stator current.

[0019] In further features, determining the plurality of stator current values includes: determining, for each of the plurality of controllers, a difference between an output of the controller and the maximum stator current; in response to the difference not being equal to a first predetermined value, setting an input to an integral portion of each of the plurality of controllers to a second predetermined value; and in response to the difference being equal to the first predetermined value, setting the input to the integral portion of each of the plurality of controllers to the difference between the temperature reference and the measured temperature.

[0020] In further features, the at least one temperature associated with the electric motor is at least one of a temperature of the rotor and a temperature of the stator windings of the electric motor.

[0021] In further features, the feed-forward current value is based on a thermal model of the electric motor.

[0022] In further features, the inverter module includes at least one diode and at least one insulated gate bipolar transistor; and the at least one temperature associated with the inverter module is associated with the at least one diode.

[0023] In further features, the feed-forward current value is based on a switching loss of the at least one diode and a conduction loss of the at least one diode.

[0024] In further features, the at least one temperature associated with the inverter module is associated with the at least one insulated gate bipolar transistor; and the feed-forward current value is based on a switching loss of the at least one insulated gate bipolar transistor and a conduction loss of the at least one insulated gate bipolar transistor.

[0025] Further areas of applicability of the present disclosure will become apparent from the detailed description, the claims and the drawings. The detailed description and specific examples are intended for purposes of illustration only and are not intended to limit the scope of the disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] The present disclosure will become more fully understood from the detailed description and the accompanying drawings, wherein:

[0027] FIG. **1** is a functional block diagram of an example engine control system;

[0028] FIG. **2** is a functional block diagram of an example engine and motor control system;

[0029] FIG. **3** is a schematic including an example implementation of an inverter module;

[0030] FIG. **4** is a functional block diagram including an example implementation of a motor control module;

[0031] FIG. **5** is an example implementation of a temperature module;

[0032] FIG. **6** is a functional block diagram including an example implementation of a stator controller;

[0033] FIG. **7** is a schematic diagram of an example thermal model of a motor; and

[0034] FIG. **8** is a flowchart of an example method of determining a maximum allowable torque.

[0035] In the drawings, reference numbers may be reused to identify similar and/or identical elements.

DETAILED DESCRIPTION

[0036] An internal combustion engine of a vehicle combusts air and fuel within cylinders to generate propulsion torque. The engine outputs torque to wheels of the vehicle via a transmission. Some types of vehicles may not include an internal combustion engine or the internal combustion engine may not be mechanically coupled to a driveline of the vehicle.

[0037] In a hybrid or non-hybrid electric vehicle, an electric motor is mechanically coupled to a shaft of the transmission. A motor control module may apply power to the electric motor from a battery to cause the electric motor to output torque for vehicle propulsion. In a hybrid vehicle, under some circumstances, the motor control module may disable power flow to the electric motor and allow the transmission to drive rotation of the electric motor. The electric motor generates power when driven by the transmission. Power generated by the electric motor can be used to recharge the battery when a voltage generated via the electric motor is greater than a voltage of the battery.

[0038] The motor control module determines a d-axis current command and a q-axis current command for the electric motor based on a requested torque output of the electric motor. Torque output of the electric motor, however, may vary with temperatures of components of the electric

motor (e.g., a rotor and stator) and an inverter (e.g., an insulated gate bipolar transistor (IGBT) and an inverter diode). For example, torque output of the electric motor may decrease as respective temperatures of the rotor, the stator, the IGBT, and the inverter diode increase and vice versa.

[0039] According to the present disclosure, the motor control module selectively adjusts at least one of the d-axis current command and the q-axis current command based on electric motor and inverter temperatures. For example, a maximum allowable torque may vary due to temperature derating to prevent motor or inverter overheating, and the motor control module adjusts the current commands in accordance with the maximum allowable torque. The motor control module maximizes torque output by calculating and adjusting the maximum allowable torque based on the temperatures of the rotor, stator, IGBT, and inverter diode and a flux magnitude (e.g., corresponding to a voltage limit).

[0040] Referring now to FIG. **1**, a functional block diagram of an example powertrain system **100** is presented. The powertrain system **100** of a vehicle includes an engine **102** that combusts an air/fuel mixture to produce torque. The vehicle may be non-autonomous or autonomous.

[0041] Air is drawn into the engine **102** through an intake system **108**. The intake system **108** may include an intake manifold **110** and a throttle valve **112**. For example only, the throttle valve **112** may include a butterfly valve having a rotatable blade. An engine control module (ECM) **114** controls a throttle actuator module **116**, and the throttle actuator module **116** regulates opening of the throttle valve **112** to control airflow into the intake manifold **110**.

[0042] Air from the intake manifold **110** is drawn into cylinders of the engine **102**. While the engine **102** includes multiple cylinders, for illustration purposes a single representative cylinder **118** is shown. For example only, the engine **102** may include 2, 3, 4, 5, 6, 8, 10, and/or 12 cylinders. The ECM **114** may instruct a cylinder actuator module **120** to selectively deactivate some of the cylinders under some circumstances, as discussed further below, which may improve fuel efficiency.

[0043] The engine **102** may operate using a four-stroke cycle or another suitable engine cycle. The four strokes of a four-stroke cycle, described below, will be referred to as the intake stroke, the compression stroke, the combustion stroke, and the exhaust stroke. During each revolution of a crankshaft (not shown), two of the four strokes occur within the cylinder **118**. Therefore, two crankshaft revolutions are necessary for the cylinder **118** to experience all four of the strokes. For four-stroke engines, one engine cycle may correspond to two crankshaft revolutions.

[0044] When the cylinder **118** is activated, air from the intake manifold **110** is drawn into the cylinder **118** through an intake valve **122** curing the intake stroke. The ECM **114** controls a fuel actuator module **124**, which regulates fuel injection to achieve a desired air/fuel ratio. Fuel may be injected into the intake manifold **110** at a central location or at multiple locations, such as near the intake valve **122** of each of the cylinders. In various implementations (not shown), fuel may be injected directly into the cylinders or into mixing chambers/ports associated with the cylinders. The fuel actuator module **124** may halt injection of fuel to cylinders that are deactivated.

[0045] The injected fuel mixes with air and creates an air/fuel mixture in the cylinder **118**. During the compression stroke, a piston (not shown) within the cylinder **118** compresses the air/fuel mixture. The engine **102** may be a compression-ignition engine, in which case compression causes ignition of the air/fuel mixture. Alternatively, the engine **102** may be a spark-ignition engine, in which case a spark actuator module **126** energizes a spark plug **128** in the cylinder **118** based on a signal from the ECM **114**, which ignites the air/fuel mixture. Some types of engines, such as homogeneous charge compression ignition (HCCI) engines may perform both compression ignition and spark ignition. The timing of the spark may be specified relative to the time when the piston is at its topmost position, which will be referred to as top dead center (TDC).

[0046] The spark actuator module **126** may be controlled by a timing signal specifying how far before or after TDC to generate the spark. Because piston position is directly related to crankshaft rotation, operation of the spark actuator module **126** may be synchronized with the position of the crankshaft. The spark actuator module **126** may disable provision of spark to deactivated cylinders or provide spark to deactivated cylinders.

[0047] During the combustion stroke, the combustion of the air/fuel mixture drives the piston down, thereby driving the crankshaft. The combustion stroke may be defined as the time between the piston reaching TDC and the time when the piston returns to a bottommost position, which will be referred to as bottom dead center (BDC).

[0048] During the exhaust stroke, the piston begins moving up from BDC and expels the byproducts of combustion through an exhaust valve **130**. The byproducts of combustion are exhausted from the vehicle via an exhaust system **134**.

[0049] The intake valve **122** may be controlled by an intake camshaft **140**, while the exhaust valve **130** may be controlled by an exhaust camshaft **142**. In various implementations, multiple intake camshafts (including the intake camshaft **140**) may control multiple intake valves (including the intake valve **122**) for the cylinder **118** and/or may control the intake valves (including the intake valve **122**) of multiple banks of cylinders (including the cylinder **118**). Similarly, multiple exhaust camshafts (including the exhaust camshaft **142**) may control multiple exhaust valves for the cylinder **118** and/or may control exhaust valves (including the exhaust valve **130**) for multiple banks of cylinders (including the cylinder **118**). While camshaft based valve actuation is shown and has been discussed, camless valve actuators may be implemented. While separate intake and exhaust camshafts are shown, one camshaft having lobes for both the intake and exhaust valves may be used.

[0050] The cylinder actuator module **120** may deactivate the cylinder **118** by disabling opening of the intake valve **122** and/or the exhaust valve **130**. The time when the intake valve **122** is opened may be varied with respect to piston TDC by an intake cam phaser **148**. The time when the exhaust valve **130** is opened may be varied with respect to piston TDC by an exhaust cam phaser **150**. A phaser actuator module **158** may control the intake cam phaser **148** and the exhaust cam phaser **150** based on signals from the ECM **114**. In various implementations, cam phasing may be omitted. Variable valve lift (not shown) may also be controlled by the phaser actuator module **158**. In various other implementations, the intake valve **122** and/or the exhaust valve **130** may be controlled by actuators other than a camshaft, such as electromechanical actuators, electrohydraulic actuators, electromagnetic actuators, etc.

[0051] The engine **102** may include zero, one, or more than one boost device that provides pressurized air to the intake manifold **110**. For example, FIG. **1** shows a turbocharger including a turbocharger turbine **160-1** that is driven by exhaust gases flowing through the exhaust system **134**. A supercharger is another type of boost device.

[0052] The turbocharger also includes a turbocharger compressor **160-2** that is driven by the turbocharger turbine **160-1** and that compresses air leading into the throttle valve **112**. A wastegate **162** controls exhaust flow through and bypassing the turbocharger turbine **160-1**. Wastegates can also be referred to as (turbocharger) turbine bypass valves. The wastegate **162** may allow exhaust to bypass the turbocharger turbine **160-1** to reduce intake air compression provided by the turbocharger. The ECM **114** may control the turbocharger via a wastegate actuator module **164**. The wastegate actuator module **164** may modulate the boost of the turbocharger by controlling an opening of the wastegate **162**.

[0053] A cooler (e.g., a charge air cooler or an intercooler) may dissipate some of the heat contained in the compressed air charge, which may be generated as the air is compressed. Although shown separated for purposes of illustration, the turbocharger turbine **160-1** and the turbocharger compressor **160-2** may be mechanically linked to each other, placing intake air in close proximity to hot exhaust. The compressed air charge may absorb heat from components of the exhaust system **134**.

[0054] The engine **102** may include an exhaust gas recirculation (EGR) valve **170**, which selectively redirects exhaust gas back to the intake manifold **110**. The EGR valve **170** may receive exhaust gas from upstream of the turbocharger turbine **160-1** in the exhaust system **134**. The EGR valve **170** may be controlled by an EGR actuator module **172**.

[0055] Crankshaft position may be measured using a crankshaft position sensor **180**. Engine speed may be determined based on the crankshaft position measured using the crankshaft position sensor **180**. A temperature of engine coolant may be measured using an engine coolant temperature (ECT) sensor **182**. The ECT sensor **182** may be located within the engine **102** or at other locations where the coolant is circulated, such as a radiator (not shown).

[0056] A pressure within the intake manifold **110** may be measured using a manifold absolute pressure (MAP) sensor **184**. In various implementations, engine vacuum, which is the difference between ambient air pressure and the pressure within the intake manifold **110**, may be measured. A mass flow rate of air flowing into the intake manifold **110** may be measured using a mass air flow (MAF) sensor **186**. In various implementations, the MAF sensor **186** may be located in a housing that also includes the throttle valve **112**.

[0057] Position of the throttle valve **112** may be measured using one or more throttle position sensors (TPS) **190**. Temperature of air being drawn into the engine **102** may be measured using an intake air temperature (IAT) sensor **192**. One or more other sensors **193** may also be implemented. The other sensors **193** include an accelerator pedal position (APP) sensor, a brake pedal position (BPP) sensor, may include a clutch pedal position (CPP) sensor (e.g., in the case of a manual transmission), and may include one or more other types of sensors. An APP sensor measures a position of an accelerator pedal within a passenger cabin of the vehicle. A BPP sensor measures a position of a brake pedal within a passenger cabin of the vehicle. A CPP sensor measures a position of a clutch pedal within the passenger cabin of the vehicle. The other sensors **193** may also include one or more acceleration sensors that measure longitudinal (e.g., fore/aft) acceleration of the vehicle and latitudinal acceleration of the vehicle. An accelerometer is an example type of acceleration sensor, although other types of acceleration sensors may be used. The ECM **114** may use signals from the sensors to make control decisions for the engine **102**.

[0058] The ECM **114** may communicate with a transmission control module **194**, for example, to coordinate engine operation with gear shifts in a transmission **195**. The ECM **114** may communicate with a motor control module **196**, for example, to coordinate operation of the engine **102** and an electric motor **198**. While the example of one electric motor is provided, multiple electric motors may be implemented. The electric motor **198** may be a permanent magnet electric motor or another suitable type of electric motor that outputs voltage based on back electromagnetic force (EMF) when free spinning, such as a direct current (DC) electric motor or a synchronous electric motor. In various implementations, various functions of the ECM **114**, the transmission control module **194**, and the motor control module **196** may be integrated into one or more modules.

[0059] Each system that varies an engine parameter may be referred to as an engine actuator. Each engine actuator has an associated actuator value. For example, the throttle actuator module **116** may be referred to as an engine actuator, and the throttle opening area may be referred to as the actuator value. In the example of FIG. **1**, the throttle actuator module **116** achieves the throttle opening area by adjusting an angle of the blade of the throttle valve **112**.

[0060] The spark actuator module **126** may also be referred to as an engine actuator, while the corresponding actuator value may be the amount of spark advance relative to cylinder TDC. Other engine actuators may include the cylinder actuator module **120**, the fuel actuator module **124**, the phaser actuator module **158**, the wastegate actuator module **164**, and the EGR actuator module **172**. For these engine actuators, the actuator values may correspond to a cylinder activation/deactivation sequence, fueling rate, intake and exhaust cam phaser angles, target wastegate opening, and EGR valve opening, respectively.

[0061] The ECM **114** may control the actuator values in order to cause the engine **102** to output torque based on a torque request. The ECM **114** may determine the torque request, for example, based on one or more driver inputs, such as an APP, a BPP, a CPP, and/or one or more other suitable driver inputs. The ECM **114** may determine the torque request, for example, using one or more functions or lookup tables that relate the driver input(s) to torque requests.

[0062] Under some circumstances, the motor control module **196** controls the electric motor **198** to output torque, for example, to supplement engine torque output. The motor control module **196** may also control the electric motor **198** to output torque for vehicle propulsion at times when the engine **102** is shut down.

[0063] The motor control module **196** applies electrical power from an energy storage device (ESD) **199** to the electric motor **198** to cause the electric motor **198** to output positive torque. The ESD **199** may include, for example, one or more batteries. The ESD **199** may be dedicated for power

flow to and from the electric motor **198**, and one or more other batteries or energy storage devices may supply power for other vehicle functions.

[0064] The electric motor **198** may output torque, for example, to an input shaft of the transmission **195** or to an output shaft of the transmission **195**. A clutch **200** is engaged to couple the electric motor **198** to the transmission **195** and disengaged to decouple the electric motor **198** from the transmission **195**. One or more gearing devices may be implemented between an output of the clutch **200** and an input of the transmission **195** to provide a predetermined ratio between rotation of the electric motor **198** and rotation of the input of the transmission **195**.

[0065] The motor control module **196** may also selectively convert mechanical energy of the vehicle into electrical energy. More specifically, the electric motor **198** generates and outputs power via back EMF when the electric motor **198** is being driven by the transmission **195** and the motor control module **196** is not applying power to the electric motor **198** from the ESD **199**. The motor control module **196** may charge the ESD **199** via the power output by the electric motor **198**. This may be referred to as regeneration.

[0066] Referring now to FIG. **2**, a functional block diagram of an example engine control system is presented. The ECM **114** includes a driver torque module **204** that determines a driver torque request **208** based on driver input **212**. The driver input **212** may include, for example, an accelerator pedal position (APP), a brake pedal position (BPP), and/or cruise control input. In various implementations, the cruise control input may be provided by an adaptive cruise control system that attempts to maintain at least a predetermined distance between the vehicle and objects in a path of the vehicle. The driver torque module **204** determines the driver torque request **208** based on one or more lookup tables that relate the driver inputs to driver torque requests. The APP and BPP may be measured using one or more APP sensors and BPP sensors, respectively.

[0067] The driver torque request **208** is an axle torque request. Axle torques (including axle torque requests) refer to torque at the wheels. As discussed further below, propulsion torques (including propulsion torque requests) are different than axle torques in that propulsion torques may refer to torque at a transmission input shaft.

[0068] An axle torque arbitration module **216** arbitrates between the driver torque request **208** and other axle torque requests **220**. Axle torque (torque at the wheels) may be produced by various sources including the engine **102** and/or one or more electric motors, such as the electric motor **198**. Examples of the other axle torque requests **220** include, but are not limited to, a torque reduction requested by a traction control system when positive wheel slip is detected, a torque increase request to counteract negative wheel slip, brake management requests to reduce axle torque to ensure that the axle torque does not exceed the ability of the brakes to hold the vehicle when the vehicle is stopped, and vehicle overspeed torque requests to reduce the axle torque to prevent the vehicle from exceeding a predetermined speed. The axle torque arbitration module **216** outputs one or more axle torque requests **224** based on the results of arbitrating between the received axle torque requests **220** and **224**.

[0069] In examples where the vehicle is a hybrid vehicle, a hybrid module **228** may determine how much of the one or more axle torque requests **224** should be produced by the engine **102** and how much of the one or more axle torque requests **224** should be produced by the electric motor **198**. The example of the electric motor **198** will be continued for simplicity, but multiple electric motors may be used. The hybrid module **228** outputs one or more engine torque requests **232** to a propulsion torque arbitration module **236**. The engine torque requests **232** indicate a requested torque output of the engine **102**. The hybrid module **228** also outputs a motor torque request **234** to the motor control module **196**. The motor torque request **234** indicates a requested torque output (positive or negative) of the electric motor **198**. In vehicles where the engine **102** is omitted or is not connected to output propulsion torque for the vehicle, the axle torque arbitration module **216** may output one axle torque request and the motor torque request **234** may be equal to that axle torque request.

[0070] The propulsion torque arbitration module **236** converts the engine torque requests **232** from an axle torque domain (torque at the wheels) into a propulsion torque domain (e.g., torque at an input shaft of the transmission). The propulsion torque arbitration module **236** arbitrates the converted torque requests with other propulsion torque requests **240**. Examples of the other propulsion torque requests **240** include, but are not limited to, torque reductions requested for engine over-speed protection and torque increases requested for stall prevention. The propulsion torque arbitration module **236** may output one or more propulsion torque requests **244** as a result of the arbitration.

[0071] An actuator control module **248** controls actuators **252** of the engine **102** based on the propulsion torque requests **244**. Based on the propulsion torque requests **244**, the actuator control module **248** may control opening of the throttle valve **112**, timing of spark provided by spark plugs, timing and amount of fuel injected by fuel injectors, cylinder actuation/deactivation, intake and exhaust valve phasing, output of one or more boost devices (e.g., turbochargers, superchargers, etc.), opening of the EGR valve **170**, and/or one or more other engine actuators. In various implementations, the propulsion torque requests **244** may be adjusted or modified before use by the actuator control module **248**, such as to create a torque reserve.

[0072] The motor control module **196** controls switching of an inverter module **256** based on the motor torque request **234**. Switching of the inverter module **256** controls power flow from the ESD **199** to the electric motor **198**. As such, switching of the inverter module **256** controls torque of the electric motor **198**. The inverter module **256** also converts power generated by the electric motor **198** and outputs power to the ESD **199**, for example, to charge the ESD **199**.

[0073] The inverter module **256** includes a plurality of switches. The switches are switched to convert DC power from the ESD **199** into alternating current (AC) power and apply the AC power to the electric motor **198** to drive the electric motor **198**. For example, the inverter module **256** may convert the DC power from the ESD **199** into 3-phase AC power and apply the 3-phase AC power to (e.g., a, b, and c or u, v, and w) stator windings of the electric motor **198**. Magnetic flux produced via current flow through the stator windings drives a rotor of the electric motor **198**. The rotor is connected to and drives rotation of an output shaft of the electric motor **198**.

[0074] In various implementations, one or more filters may be electrically connected between the inverter module **256** and the ESD **199**. The one or more filters may be implemented, for example, to filter power flow to and from

the ESD **199**. As an example, a filter including one or more capacitors and resistors may be electrically connected in parallel with the inverter module **256** and the ESD **199**.

[0075] FIG. **3** shows a schematic including an example implementation of the inverter module **256**. High (positive) and low (negative) sides **304** and **308** are connected to positive and negative terminals, respectively, of the ESD **199**. The inverter module **256** is also connected between the high and low sides **304** and **308**.

[0076] The inverter module **256** includes three legs (one leg connected to each phase of the electric motor **198**). A first leg **312** includes first and second switches **316** and **320**. The switches **316** and **320** each include a first terminal, a second terminal, and a control terminal. Each of the switches **316** and **320** may be an insulated gate bipolar transistor (IGBT), a field effect transistor (FET), such as a metal oxide semiconductor FET (MOSFET), or another suitable type of switch. In the example of IGBTs and FETs, the control terminal is referred to as a gate.

[0077] The first terminal of the first switch **316** is connected to the high side **304**. The second terminal of the first switch **316** is connected to the first terminal of the second switch **320**. The second terminal of the second switch **320** may be connected to the low side **308**. A node connected to the second terminal of the first switch **316** and the first terminal of the second switch **320** is connected to a first phase (e.g., a) of the electric motor **198**.

[0078] The first leg **312** also includes first and second diodes **324** and **328** connected anti-parallel to the switches **316** and **320**, respectively. In other words, an anode of the first diode **324** is connected to the second terminal of the first switch **316**, and a cathode of the first diode **324** is connected to the first terminal of the first switch **316**. An anode of the second diode **328** is connected to the second terminal of the second switch **320**, and a cathode of the second diode **328** is connected to the first terminal of the second switch **320**. When the switches **316** and **320** are off (and open), power generated by the electric motor **198** is transferred through the diodes **324** and **328** when the output voltage of the electric motor **198** is greater than the voltage of the ESD **199**. This charges the ESD **199**. The diodes **324** and **328** form one phase of a three-phase rectifier.

[0079] The inverter module **256** also includes second and third legs **332** and **336**. The second and third legs **332** and **336** may be (circuitry wise) similar or identical to the first leg **312**. In other words, the second and third legs **332** and **336** may each include respective switches and diodes like the switches **316** and **320** and the diodes **324** and **328**, connected in the same manner as the first leg **312**. For example, the second leg **332** includes switches **340** and **344** and anti-parallel diodes **348** and **352**. A node connected to the second terminal of the switch **340** and the first terminal of the switch **344** is connected to a second stator winding (e.g., b) of the electric motor **198**. The third leg **336** includes switches **356** and **360** and anti-parallel diodes **364** and **368**. A node connected to the second terminal of the switch **356** and the first terminal of the switch **360** is connected to a third stator winding (e.g., c) of the electric motor **198**.

[0080] FIG. **4** is a functional block diagram including an example implementation of the motor control module **196**. A switching control module **404** controls switching of the switches **316** and **320** using pulse width modulation (PWM) signals. For example, the switching control module **404** may apply PWM signals to the control terminals of the switches **316**, **320**, **340**, **344**, **356**, and **360**. When on, power flows from the ESD **199** to the electric motor **198** to drive the electric motor **198**.

[0081] For example, the switching control module **404** may apply generally complementary PWM signals to the control terminals of the switches **316** and **320** when applying power from the ESD **199** to the electric motor **198**. In other words, the PWM signal applied to the control terminal of the first switch **316** is opposite in polarity to the PWM signal applied to the control terminal of the second switch **320**. Short circuit current may flow, however, when the turning on of one of the switches **316** and **320** overlaps with the turning off of the other of the switches **316** and **320**. As such, the switching control module **404** may generate the PWM signals to turn both of the switches **316** and **320** off during a dead time period before turning either one of the switches **316** and **320** on. With this in mind, generally complementary may mean that two signals have opposite polarities for a majority of their periods when power is being output to the electric motor **198**. Around transitions, however, both PWM signals may have the same polarity (off) for some overlap dead time period.

[0082] The PWM signals provided to the switches of the second and third legs **332** and **336** may also be generally complementary per leg. The PWM signals provided to the second and third legs **332** and **336** may be phase shifted from each other and from the PWM signals provided to the switches **316** and **320** of the first leg **312**. For example, the PWM signals for each leg may be phase shifted from each other leg by 120° (360°/3 legs=120° shift per leg). In this way, the currents through the stator windings (phases) of the electric motor **198** are phase shifted by 120° from each other.

[0083] A temperature module **408** determines a maximum stator current (I_{MAX_STATOR}) **412** based on one or more components of the electric motor **198** or the inverter module **256**. For example, a stator temperature **415**, a rotor temperature **414**, an IGBT temperature **417**, and a diode temperature **419** are provided to the temperature module **408**. The stator temperature **415** and the rotor temperature **414** may be estimated based on a motor temperature estimation model such as described in greater detail in FIG. **7**. Alternately, the stator temperature **415**, the rotor temperature **414**, the IGBT temperature **417**, and the diode temperature **419** may be measured by one or more sensors such as a rotor temperature sensor **416**.

[0084] A current limiting module **410** limits the maximum stator current (I_{MAX_STATOR}) **412** to a limited maximum stator current (I_{sLIM}) **416**. The limited maximum stator current (I_{sLIM}) **416** may be limited to within a predetermined maximum current range bounded by a predetermined minimum current (e.g., 0). A torque module **420** determines a maximum allowable torque (T_{eMAX}). For example, the torque module **420** may determine a maximum torque (T_{eMAX}) **425** from a look-up table based on the limited maximum stator current (I_{sLIM}) **416** and a flux reference **424**. The flux reference **424** may be a predetermined flux reference or calibrated flux value that is based on a ratio between the DC bus voltage (V_{DC}) and the operating speed of the motor.

[0085] A torque limiting module **428** compares the maximum torque (T_{eMAX}) **425** to a motor torque request **234**. If the motor torque request **234** is greater than the maximum torque (T_{eMAX}) **425**, the torque limiting module **428** outputs the maximum torque (T_{eMAX}) **425** as a limited maximum

torque (T_{eLIM}) **432**. If the motor torque request **234** is less than the maximum torque (T_{eMAX}) **425**, the torque limiting module **428** outputs the motor torque request **234** as the limited maximum torque (T_{eLIM}) **432**.

[0086] A current command module **436** determines a d-axis current command (I_{D_REF}) and a q-axis current command (I_{Q_REF}) for the electric motor **198**. The d-axis current command (I_{D_REF}) and the q-axis current command (I_{Q_REF}) are collectively illustrated by **440**. The current command module **436** determines the d-axis current command (I_{D_REF}) and the q-axis current command (I_{Q_REF}) using one or more equations and/or lookup tables that relate torques (e.g., torque requests or commands), the rotor speed **444**, to the d-axis current command (I_{D_REF}) and the q-axis current command (I_{Q_REF}).

[0087] The rotor speed **444** is a rotational speed of the rotor of the electric motor **198**. The rotor speed **444** may be measured, for example, using a rotor speed sensor **448**. In various implementations, the rotor speed **444** may be determined by a rotor speed module based on one or more other parameters, such change in position of the rotor over time where position is determined based on currents (e.g., I_A, I_C, I_C) **456** flow through the stator windings of the electric motor **198**. Current sensors **452** may measure the currents **456**.

[0088] A frame of reference (FOR) module **460** receives the currents (e.g., I_A, I_C, I_C) **456** from the current sensors **452**. The FOR module **460** may transform the currents (e.g., I_A, I_C, I_C) **456** into the d and q-axis currents by applying a Clarke transform and a Park transform. A voltage command module **464** determines voltage commands **468** for voltages to apply to the stator windings based on the d-axis and q-axis current commands (I_{D_REF} and I_{Q_REF}) **440** and the d and q-axis currents (I_D and I_Q) **462**. The voltage command module **464** may determine the voltage commands **468** using one or more equations and/or lookup tables that relate d and q axis current commands (I_{D_REF} and I_{Q_REF}) **440** and d and q-axis currents (I_D and I_Q) **462** to the voltage commands **468**. In various implementations, the voltage command module **464** may generate the voltage commands **468** using closed-loop control to adjust the d and q-axis currents (I_D and I_Q) **462** toward the d and q-axis current commands (I_{D_REF} and I_{Q_REF}) **440**.

[0089] The switching control module **404** determines duty cycles of the PWM signals to apply to the stator windings based on the respective voltage commands **468** for the stator windings. For example, the switching control module **404** may determine the duty cycles using one or more equations or lookup tables that relate voltage commands to PWM duty cycles.

[0090] Torque output of the electric motor **198**, however, varies as a temperature of one or more components of the electric motor **198** or one or more components of the inverter module **256** varies. For example, under the same conditions, torque output of the electric motor **198** may decrease as the temperature of the rotor increases and vice versa. The relationship between the rotor temperature **414** and torque output may be linear or non-linear.

[0091] FIG. **5** is an example implementation of the temperature module **408**. The temperature module **408** includes a plurality of controllers, a plurality of multiplexors, and a minimum value selector **504**. The plurality of controllers includes a stator controller **508**, a rotor controller **512**, an IGBT controller **516**, and a diode controller **520**. The plurality of multiplexors includes a first multiplexor **524**, a second multiplexor **528**, a third multiplexor **532**, and a fourth multiplexor **536**.

[0092] The first multiplexor **524** determines whether to input the first limited maximum stator current (I_{SL1}) **572** or a predetermined maximum stator current (I_{S_MAX}) **548** to the minimum value selector **504** based on the stator temperature **415**. The predetermined maximum stator current (I_{S_MAX}) **548** may be a predetermined value or a calibrated value. For example, when the stator temperature **415** is not available, the first multiplexor **524** may select the predetermined maximum stator current (I_{S_MAX}) **548** as an input to the minimum value selector **504**. When the stator temperature **415** is available, the first multiplexor **524** may select the first limited maximum stator current (I_{SL1}) **572** as an input to the minimum value selector **504** (I_{S_MAX} is only used when the stator temperature is not available).

[0093] FIG. **6** is a functional block diagram including an example implementation of the stator controller **508**. The stator controller **508** outputs the first limited maximum stator current (I_{SL1}) **572** to the first multiplexor **524** based on the stator temperature **415**. The stator controller **508** includes a temperature error module **608**, a proportional integral (PI) module **612**, a feed-forward module **616**, a limiting module **620**, a comparison module **624**, and a power margin module **626**. The temperature error module **608** includes a summation junction **628** that outputs an error signal **630** corresponding to the difference between the stator temperature **415** and the stator temperature reference signal **544**.

[0094] The PI module **612** includes a proportional portion **634** and an integral portion **638**. The proportional portion **634** includes a gain module **642** that outputs a multiplication product (MP) **640** of the error signal **630**. The integral portion **638** outputs an integral signal (INT) **644** based on an integral module **646**, a gain module **650**, and the error signal **630**. The feed-forward module **616** includes a summation junction **654** that outputs a first maximum stator current (I_{SM1}) **658** based on the outputs of the PI module **612** and a first feed-forward stator current (I_{SFF1}) **662**. The first feed-forward stator current (I_{SFF1}) **662** is set by the power margin module **626** (described in greater detail with respect to FIG. **7**).

[0095] The limiting module **620** limits the first maximum stator current (I_{SM1}) **658** to the first limited maximum stator current (I_{SL1}) **572**. The first limited maximum stator current (I_{SL1}) **572** may be limited between an upper predetermined current limit and a lower predetermined current limit. The comparison module **624** includes a multiplexor **668** and a summation junction **672** that outputs an integral control signal (int_cont) **676** based on the absolute value of the difference between the limited maximum stator current (I_{SL1}) **572** and the first maximum stator current (I_{SM1}) **658**.

[0096] Based on the integral control signal (int_cont) **676**, the multiplexor **668** will either set the input to the integral portion **638** to a zero reference signal (zero_ref) **678** or to the error signal **630**. In this manner, integral windup and temperature overshoot can be prevented. For example, when the integral control signal (int_cont) **676** is greater than zero, the multiplexor **668** may set the input to the integral portion **638** to zero (i.e., the first maximum stator current (I_{SM1}) **658** is not equal to the first limited maximum stator current (I_{SL1}) **572**) with a multiplexor output signal (m_out) **669**. If the error signal **630** is equal to zero (i.e., the first maximum

stator current (I_{SM1}) **658** is equal the first limited maximum stator current (I_{SL1}) **572**), the multiplexor may set, with the mux output signal (m_out) **669**, the error signal **630** as an input to the integral portion **638**.

[0097] With reference back to FIG. **5**, the rotor controller **512** outputs a second limited maximum stator current (I_{SL2}) **576** based on the rotor temperature **414** and a rotor temperature reference signal **556**. The IGBT controller **516** outputs a third limited maximum stator current (I_{SL3}) **580** based on the IGBT temperature **417** and an IGBT temperature reference signal **564**. The diode controller **520** outputs a fourth limited maximum stator current (I_{SL4}) **584** based on the diode temperature **419** and a diode temperature reference signal **570**. The rotor controller **512**, the IGBT controller **516**, and the diode controller **520** function substantially similar to the stator controller **508**. The IGBT temperature **417** and the IGBT temperature reference signal **564** may be associated with one or more IGBTs of the inverter module **256** such as the IGBTs of the first leg, the second leg, or the third leg. Likewise, the diode temperature **419** and the diode temperature reference signal **570** may be associated with one or more diodes of the inverter module **256** such as the diodes of the first leg, the second leg, or the third leg.

[0098] The second multiplexor **528** determines, based on the rotor temperature **414**, whether to input the second limited maximum stator current (I_{SL2}) **576** or the predetermined maximum stator current (I_{S_MAX}) **548** to the minimum value selector **504**. The third multiplexor **532** determines, based on the IGBT temperature **417**, whether to input the third limited maximum stator current (I_{SL3}) **580** or the predetermined maximum stator current (I_{S_MAX}) **548** to the minimum value selector **504**. The fourth multiplexor **536** determines, based on the diode temperature **419**, whether to input the fourth limited maximum stator current (I_{SL4}) **584** or the predetermined maximum stator current (I_{S_MAX}) **548** to the minimum value selector **504**.

[0099] The minimum value selector **504** outputs a maximum stator current (I_{MAX_STATOR}) **412** corresponding to the minimum value of the first multiplexor **524**, the second multiplexor **528**, the third multiplexor **532**, and the fourth multiplexor **536**. In this manner, the minimum value selector **504** is able to minimize the effects of temperate derating.

[0100] FIG. **7** is a schematic diagram of an example thermal model of the motor **198**. An example of such thermal model may be found in commonly assigned U.S. Pat. No. 8,482,237, which is incorporated herein in its entirety. The power margin module **626** calculates the first feed-forward stator current (I_{SFF1}) **662** and a second feed-forward stator current based on a thermal model. As illustrated, a thermal model **700** includes eight nodes representing the temperature of various regions of the motor **198** given certain operating conditions and boundary conditions of one or more components of the vehicle. However, more or fewer regions of the motor **198** and/or boundary conditions may be considered to estimate the temperature of the motor **198**.

[0101] Some of the nodes in the thermal model **700** may represent regions of the stator and other nodes may represent regions of the rotor, and a temperature may be assigned to each node. That is, a first stator node **704** may represent the temperature at a non-flux producing region of the stator (e.g., a stator iron). A second stator node **708** may represent the temperature at a flux producing region of the stator.

[0102] A third stator node **712** may represent the temperature of the copper used in the windings of the stator, such as the copper disposed between slots defined by the stator. A fourth stator node **716** may represent the temperature of the end turns of the copper used in the windings of the stator. A first rotor node **720** may represent the temperature from the permanent magnets used by the rotor. A second rotor node **724** may represent the temperature from a non-flux producing region of the rotor (e.g., a rotor iron).

[0103] The thermal model **700** may further include additional nodes that represent various other regions of interest of the motor **198** independent of the stator **1** and the rotor. For instance, some nodes may represent the temperature of the oil used in the motor **198**. In one example implementation, a first oil node **728** may represent the temperature of the oil in one region of the motor **198** and a second oil node **732** may represent the temperature of the oil in another region of the motor **198**.

[0104] Each of the nodes in the thermal model **700** may be connected to at least one other node by one or more heat transfer paths. The thermal model **700** may, therefore, include thermal resistances representing the heat transfer paths between the nodes. For instance, a first thermal resistance ($R_{oil\text{-}1}$) **736** may represent convective external heat transfer between the regions represented by the first oil node **728** and the first stator node **704**.

[0105] A second thermal resistance ($R_{2\text{-}1}$) **740** may represent conduction between the regions represented by the first stator node **704** and the second stator node **708** via, e.g., the stator stack. A third thermal resistance ($R_{3\text{-}2}$) **744** may represent conduction between the regions represented by the second stator node **708** and the third stator node **712** via, e.g., the stator stack, copper windings, and an insulation system. A fourth thermal resistance ($R_{air\ gap}$) **748** may represent heat transfer through, e.g., an air gap between the regions represented by the second stator node **708** and the first rotor node **720**.

[0106] A fifth thermal resistance ($R_{4\text{-}3}$) **752** may represent conduction through copper windings between the regions represented by the third stator node **712** and the fourth stator node **716**. A sixth thermal resistance ($R_{oil\text{-}4}$) **756** may represent convection between the regions represented by the fourth stator node **716** and the second oil node **732**, e.g., from the oil to the end turns of the stator. A seventh thermal resistance ($R_{6\text{-}5}$) **760** may represent conduction through the rotor core between the regions represented by the first rotor node **720** and the second rotor node **724**. An eighth thermal resistance **764** may represent the heat transfer path between the second rotor node **724** and the second oil node **732** caused by convection from the oil to the hub of the rotor ($R_{oil\text{-}6}$).

[0107] Based on the thermal model described above, the thermal resistances for R_1,R_2,R_3,R_4 and R_5 can be determined as follows:

$$R_1=R_{oil\text{-}1}+R_{2\text{-}1}$$

$$R_2=R_{oil\text{-}4}+R_{4\text{-}3}$$

$$R_3=R_{3\text{-}2}$$

$$R_4=R_{air\ gap}+R_{6\text{-}5}$$

$$R_5=R_{oil\text{-}6}$$

[0108] The power margin module **626** uses R_1,R_2,R_3,R_4 and R_5 to determine the first feed-forward stator current (I_{SFF1}) **662** and the second feed-forward stator current. For example, the first feed-forward stator current (I_{SFF1}) **662** may be determined based on or equal to:

$$\sqrt{\frac{P_{d,stator}}{1.5R_s}}$$

where $P_{d,stator}$ **629** is equal to:

$$\frac{T_{ref_stator} - T_{Oil}}{R_{\theta_Stator}}$$

where T_{Oil} represents the temperature of the oil in one region of the motor **198** such as at the first oil node or the second oil node, and T_{ref_stator} is a predetermined temperature reference of the stator and $R_{\theta_{Stator}}$ is equal to:

$$R_2 \| \{[(R_4+R_5) \| R_1]+R_3\}$$

[0109] A power module of the rotor controller **512** determines the second feed-forward current based on one or more equations and look-up tables that relate power dissipated by the rotor ($P_{d,rotor}$) and a speed of the rotor (ω_r) to the second feed-forward current. The power module may determine the power dissipated by the rotor ($P_{d,rotor}$) based on or equal to:

$$\frac{T_{ref_rotor} - T_{Oil}}{R_{\theta_rotor}}$$

where T_{Oil} represents the temperature of the oil in one region of the motor **198** such as at the first oil node or the second oil node **732**, and T_{ref_rotor} predetermined temperature reference of the rotor and R_{θ_rotor} is equal to:

$$R_5 \| \{R_4+[R_1) \| (R_2+R_3)\}$$

[0110] Referring to back to FIG. **5**, a power margin module of the IGBT controller **516** and a power margin module of the diode controller **520** calculate a third feed-forward current and a fourth feed-forward current based on an IGBT conduction and switching loss and a diode conduction and switching loss, respectively. An example of such model of determining an IGBT/diode conduction and switching loss may be found in commonly assigned U.S. Pat. No. 7,755,313, which is incorporated herein in its entirety. For example, the third feed-forward current may be based on the following second-degree polynomial equation:

$$\alpha_{igbt}I^2+\beta_{igbt}I+\gamma_{igbt}=0$$

where I is solved for using a quadratic equation, γ_{igbt} is equal to the power dissipated by the IGBT, α_{igbt} is based on or set equal to:

$$\frac{R_{Ton}I^2}{8}\left(1+\frac{8}{3\pi}M_1\cos\varphi\right)$$

β is based on or set equal to:

$$\frac{V_{ce}I}{2\pi}\left(1+\frac{\pi}{4}M_1\cos\varphi\right)+\frac{E_{SW}f_{sw}}{\pi}SLF$$

where R_{Ton} is the turn-on resistance of the IGBT, I is the peak amplitude of the current flowing through the inverter, M_1 represents the modulation index normalized by half of the DC voltage supply, V_{ce} represents the common to emitter voltage, $E_{sw}f_{sw}$ is the switching energy and SLF is the switching load function.

[0111] The power margin module **626** of the diode controller **520** calculates the fourth feed-forward current based on diode conduction and switching loss. For example, the fourth feed-forward current may be based on the following second-degree polynomial equation:

$$\alpha_{diode}I^2+\beta_{diode}I+\gamma_{diode}=0$$

where I is solved for using a quadratic equation, γ_{diode} is equal to the power dissipated by the diode, α_{diode} is based on or set equal to:

$$\frac{R_{Don}I^2}{8}\left(1-\frac{8}{3\pi}M_1\cos\varphi\right)$$

β is based on or set equal to:

$$\frac{V_{DO}}{2\pi}\left(1-\frac{\pi}{4}M_1\cos\varphi\right)+\frac{E_{rr}f_{sw}}{\pi}SLF$$

where R_{Don} is the turn-on voltage of the diode, I is the peak amplitude of the current flowing through the inverter, M_1 represents the modulation index normalized by half of the DC voltage supply, $E_{rr}f_{sw}$ is the reverse recovery energy of the diode, and SLF is the switching load function.

[0112] FIG. **8** is a flowchart depicting an example method of determining the maximum allowable torque based on the stator temperature **415**, the rotor temperature **414**, the IGBT temperature **417**, and the diode temperature **419**. At **804**, control receives the motor torque request **234** and control continues at **808**. At **808**, control determines a power margin for each of the stator controller **508**, the rotor controller **512**, the IGBT controller **516**, and the diode controller **520**. At **812**, control determines a feed-forward current for each controller and control continues at **816**.

[0113] At **816**, control determines the limited maximum stator currents (I_{SL1}, I_{SL2}, I_{SL3}, I_{SL4}) **572**, **576**, **580**, and **584** based on the feed-forward currents. At **824**, control selects a lowest value of the limited maximum stator currents (I_{SL1}, I_{SL2}, I_{SL3}, and I_{SL4}) **572**, **576**, **580**, and **584** as the maximum stator current (I_{MAX_STATOR}) **412** and control continues at **828**. At **828**, control determines the maximum torque based on the maximum stator current (I_{MAX_STATOR}) **412** and control ends at **832**.

[0114] The foregoing description is merely illustrative in nature and is in no way intended to limit the disclosure, its application, or uses. The broad teachings of the disclosure can be implemented in a variety of forms. Therefore, while this disclosure includes particular examples, the true scope of the disclosure should not be so limited since other modifications will become apparent upon a study of the drawings, the specification, and the following claims. It

should be understood that one or more steps within a method may be executed in different order (or concurrently) without altering the principles of the present disclosure. Further, although each of the embodiments is described above as having certain features, any one or more of those features described with respect to any embodiment of the disclosure can be implemented in and/or combined with features of any of the other embodiments, even if that combination is not explicitly described. In other words, the described embodiments are not mutually exclusive, and permutations of one or more embodiments with one another remain within the scope of this disclosure.

[0115] Spatial and functional relationships between elements (for example, between modules, circuit elements, semiconductor layers, etc.) are described using various terms, including "connected," "engaged," "coupled," "adjacent," "next to," "on top of," "above," "below," and "disposed." Unless explicitly described as being "direct," when a relationship between first and second elements is described in the above disclosure, that relationship can be a direct relationship where no other intervening elements are present between the first and second elements, but can also be an indirect relationship where one or more intervening elements are present (either spatially or functionally) between the first and second elements. As used herein, the phrase at least one of A, B, and C should be construed to mean a logical (A OR B OR C), using a non-exclusive logical OR, and should not be construed to mean "at least one of A, at least one of B, and at least one of C."

[0116] In the figures, the direction of an arrow, as indicated by the arrowhead, generally demonstrates the flow of information (such as data or instructions) that is of interest to the illustration. For example, when element A and element B exchange a variety of information but information transmitted from element A to element B is relevant to the illustration, the arrow may point from element A to element B. This unidirectional arrow does not imply that no other information is transmitted from element B to element A. Further, for information sent from element A to element B, element B may send requests for, or receipt acknowledgements of, the information to element A.

[0117] In this application, including the definitions below, the term "module" or the term "controller" may be replaced with the term "circuit." The term "module" may refer to, be part of, or include: an Application Specific Integrated Circuit (ASIC); a digital, analog, or mixed analog/digital discrete circuit; a digital, analog, or mixed analog/digital integrated circuit; a combinational logic circuit; a field programmable gate array (FPGA); a processor circuit (shared, dedicated, or group) that executes code; a memory circuit (shared, dedicated, or group) that stores code executed by the processor circuit; other suitable hardware components that provide the described functionality; or a combination of some or all of the above, such as in a system-on-chip.

[0118] The module may include one or more interface circuits. In some examples, the interface circuits may include wired or wireless interfaces that are connected to a local area network (LAN), the Internet, a wide area network (WAN), or combinations thereof. The functionality of any given module of the present disclosure may be distributed among multiple modules that are connected via interface circuits. For example, multiple modules may allow load balancing. In a further example, a server (also known as remote, or cloud) module may accomplish some functionality on behalf of a client module.

[0119] The term code, as used above, may include software, firmware, and/or microcode, and may refer to programs, routines, functions, classes, data structures, and/or objects. The term shared processor circuit encompasses a single processor circuit that executes some or all code from multiple modules. The term group processor circuit encompasses a processor circuit that, in combination with additional processor circuits, executes some or all code from one or more modules. References to multiple processor circuits encompass multiple processor circuits on discrete dies, multiple processor circuits on a single die, multiple cores of a single processor circuit, multiple threads of a single processor circuit, or a combination of the above. The term shared memory circuit encompasses a single memory circuit that stores some or all code from multiple modules. The term group memory circuit encompasses a memory circuit that, in combination with additional memories, stores some or all code from one or more modules.

[0120] The term memory circuit is a subset of the term computer-readable medium. The term computer-readable medium, as used herein, does not encompass transitory electrical or electromagnetic signals propagating through a medium (such as on a carrier wave); the term computer-readable medium may therefore be considered tangible and non-transitory. Non-limiting examples of a non-transitory, tangible computer-readable medium are nonvolatile memory circuits (such as a flash memory circuit, an erasable programmable read-only memory circuit, or a mask read-only memory circuit), volatile memory circuits (such as a static random access memory circuit or a dynamic random access memory circuit), magnetic storage media (such as an analog or digital magnetic tape or a hard disk drive), and optical storage media (such as a CD, a DVD, or a Blu-ray Disc).

[0121] The apparatuses and methods described in this application may be partially or fully implemented by a special purpose computer created by configuring a general purpose computer to execute one or more particular functions embodied in computer programs. The functional circuits, flowchart components, and other elements described above serve as software specifications, which can be translated into the computer programs by the routine work of a skilled technician or programmer.

[0122] The computer programs include processor-executable instructions that are stored on at least one non-transitory, tangible computer-readable medium. The computer programs may also include or rely on stored data. The computer programs may encompass a basic input/output system (BIOS) that interacts with hardware of the special purpose computer, device drivers that interact with particular devices of the special purpose computer, one or more operating systems, user applications, background services, background applications, etc.

[0123] The computer programs may include: (i) descriptive text to be parsed, such as HTML (hypertext markup language), XML (extensible markup language), or JSON (JavaScript Object Notation) (ii) assembly code, (iii) object code generated from source code by a compiler, (iv) source code for execution by an interpreter, (v) source code for compilation and execution by a just-in-time compiler, etc. As examples only, source code may be written using syntax from languages including C, C++, C#, Objective-C, Swift,

Haskell, Go, SQL, R, Lisp, Java®, Fortran, Perl, Pascal, Curl, OCaml, Javascript®, HTML5 (Hypertext Markup Language 5th revision), Ada, ASP (Active Server Pages), PHP (PHP: Hypertext Preprocessor), Scala, Eiffel, Smalltalk, Erlang, Ruby, Flash®, Visual Basic®, Lua, MATLAB, SIMULINK, and Python®.

1. An electric motor control system of a vehicle, comprising:

a temperature module configured to, based on a motor torque request for an electric motor of the vehicle, (i) determine a plurality of stator current values based on a plurality of temperatures and (ii) generate a maximum stator current based on a lowest value of the plurality of stator current values;

a torque module configured to, based on the maximum stator current, the motor torque request, and a maximum allowable flux, generate a maximum torque output;

a current command module configured to, based on a speed of a rotor of the electric motor and the maximum torque output, generate a d-axis current adjustment and a q-axis current adjustment; and

a switching control module configured to, based on the d-axis current adjustment and the q-axis current adjustment, control switching of an inverter module and apply power to stator windings of the electric motor from an energy storage device,

wherein the plurality of temperatures correspond to at least one temperature associated with the electric motor and at least one temperature associated with the inverter module.

2. The electric motor control system of claim **1** wherein:

the temperature module includes a plurality of controllers; and

each of the plurality of controllers includes:

a temperature error module configured to output an error signal corresponding to a difference between a temperature reference and a measured temperature; and

a proportional integral module, connected to the temperature error module, configured to output a first signal and a second signal,

wherein the first signal is a first multiplication product of the error signal and the second signal is based on at least one of an integral of the error signal and a second multiplication product of the error signal.

3. The electric motor control system of claim **2** wherein each of the plurality of controllers further includes a feed-forward module, connected to the proportional integral module, that outputs the maximum stator current based on the first signal, the second signal, and a feed-forward current value.

4. The electric motor control system of claim **3** wherein each of the plurality of controllers includes a limiting module, to which an output of the feed-forward module is input, configured to:

in response to the maximum stator current being greater than a first predetermined current, output the first predetermined current; and

in response to the maximum stator current being less than the first predetermined current, output the maximum stator current,

wherein the first predetermined current is less than the maximum stator current.

5. The electric motor control system of claim **4** wherein:

the proportional integral module includes a proportional portion and an integral portion;

each of the plurality of controllers includes a comparison module configured to determine a difference between an output of the limiting module and an input of the limiting module;

in response to the difference not being equal to a first predetermined value, setting an input to the integral portion to a second predetermined value; and

in response to the difference being equal to the first predetermined value, setting the input to the integral portion to the difference between the temperature reference and the measured temperature.

6. The electric motor control system of claim **5** wherein:

the at least one temperature associated with the electric motor is at least one of a temperature of the rotor and a temperature of the stator windings of the electric motor; and

the plurality of controllers includes a stator controller, a rotor controller, a diode controller, and an IGBT controller.

7. The electric motor control system of claim **6** wherein the feed-forward current value is set by a power margin module that determines the feed-forward current value based on a thermal model of the electric motor.

8. The electric motor control system of claim **6** wherein:

the inverter module includes at least one diode and at least one insulated gate bipolar transistor; and

the at least one temperature associated with the inverter module is associated with the at least one diode.

9. The electric motor control system of claim **8** the feed-forward current value is based on a switching loss of the at least one diode and a conduction loss of the at least one diode.

10. The electric motor control system of claim **8** wherein:

the at least one temperature associated with the inverter module is associated with the at least one insulated gate bipolar transistor; and

the feed-forward current value is based on a switching loss of the at least one insulated gate bipolar transistor and a conduction loss of the at least one insulated gate bipolar transistor.

11. An electric motor control method for a vehicle, the method comprising:

in response to receiving a motor torque request for an electric motor of the vehicle:

determining, with a temperature module, a plurality of stator current values based on a plurality of temperatures; and

generating, with the temperature module, a maximum stator current based on a lowest value of the plurality of stator current values;

generating, with a torque module, a maximum torque output based on the maximum stator current, the motor torque request, and a maximum allowable flux;

generating, with a current command module, a d-axis current adjustment and a q-axis current adjustment based on a speed of a rotor of the electric motor and the maximum torque output; and

controlling, with a switching control module, switching of an inverter module and applying power to stator windings of the electric motor from an energy storage device,

wherein the plurality of temperatures correspond to at least one temperature associated with the electric motor and at least one temperature associated with the inverter module.

12. The electric motor control method of claim **11** wherein the temperature module includes a plurality of controllers and determining the plurality of stator current values includes:

generating, for each of the plurality of controllers, an error signal corresponding to a difference between a temperature reference and a measured temperature; and

generating, for each of the plurality of controllers, a first signal and a second signal,

wherein the first signal is a first multiplication product of the error signal and the second signal is based on at least one of an integral of the error signal and a second multiplication product of the error signal.

13. The electric motor control method of claim **12** wherein determining the plurality of stator current values includes:

generating, for each of the plurality of controllers, a feed-forward current value; and

generating, for each of the plurality of controllers, the maximum stator current based on the first signal, the second signal, and the feed-forward current value.

14. The electric motor control method of claim **13** wherein each of the plurality of controllers includes a limiting module and determining the plurality of stator current values includes:

outputting, for each of the plurality of controllers, a first predetermined current in response to the maximum stator current being greater than the first predetermined current; and

outputting, for each of the plurality of controllers, the maximum stator current in response to the maximum stator current being less than the first predetermined current,

wherein the first predetermined current is less than the maximum stator current.

15. The electric motor control method of claim **14** wherein determining the plurality of stator current values includes:

determining, for each of the plurality of controllers, a difference between an output of the controller and the maximum stator current;

in response to the difference not being equal to a first predetermined value, setting an input to an integral portion of each of the plurality of controllers to a second predetermined value; and

in response to the difference being equal to the first predetermined value, setting the input to the integral portion of each of the plurality of controllers to the difference between the temperature reference and the measured temperature.

16. The electric motor control method of claim **15** wherein the at least one temperature associated with the electric motor is at least one of a temperature of the rotor and a temperature of the stator windings of the electric motor.

17. The electric motor control method of claim **16** wherein the feed-forward current value is based on a thermal model of the electric motor.

18. The electric motor control method of claim **16** wherein:

the inverter module includes at least one diode and at least one insulated gate bipolar transistor; and

the at least one temperature associated with the inverter module is associated with the at least one diode.

19. The electric motor control method of claim **18** the feed-forward current value is based on a switching loss of the at least one diode and a conduction loss of the at least one diode.

20. The electric motor control method of claim **18** wherein:

the at least one temperature associated with the inverter module is associated with the at least one insulated gate bipolar transistor; and

the feed-forward current value is based on a switching loss of the at least one insulated gate bipolar transistor and a conduction loss of the at least one insulated gate bipolar transistor.

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