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(54) **ELECTRIC MOTOR CONTROLLER AND RELATED METHODS**

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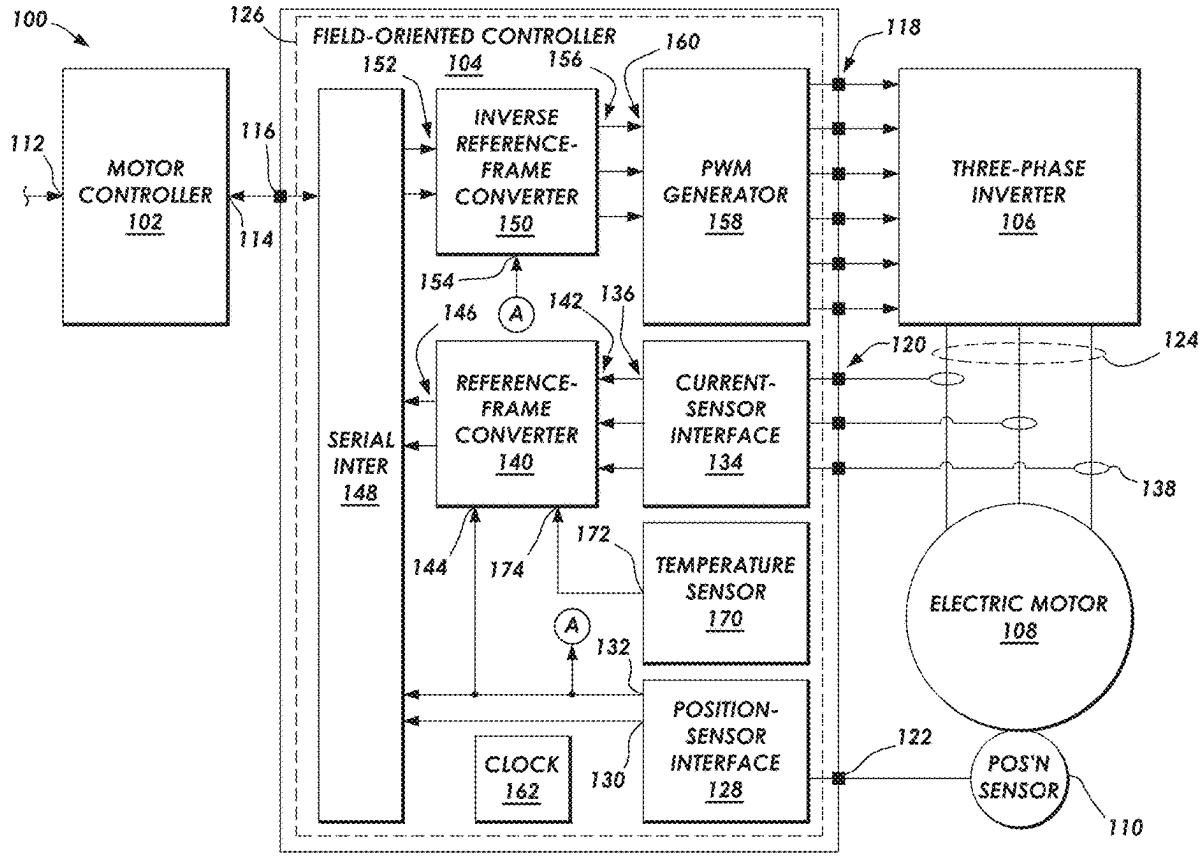
(57) **ABSTRACT**

Electric motor controller and related methods. One example is method of controlling an electric motor, the method comprising: calculating, by a motor controller, setpoint Q-D signals based on a setpoint speed signal, the setpoint Q-D signals represent setpoint position of a magnetic field relative to a rotor of the electric motor; serially sending, by the motor controller, the setpoint Q-D signals to a field-oriented controller disposed within a distinct packaging from the motor controller; converting, by the field-oriented controller, the setpoint Q-D signals to setpoint α-β signals that represent setpoint position of the magnetic field relative to A stator of the electric motor; transforming, by the field-oriented controller, the setpoint α-β signals into setpoint voltage signals; and gating, by the field-oriented controller, an inverter based on the setpoint voltage signals.



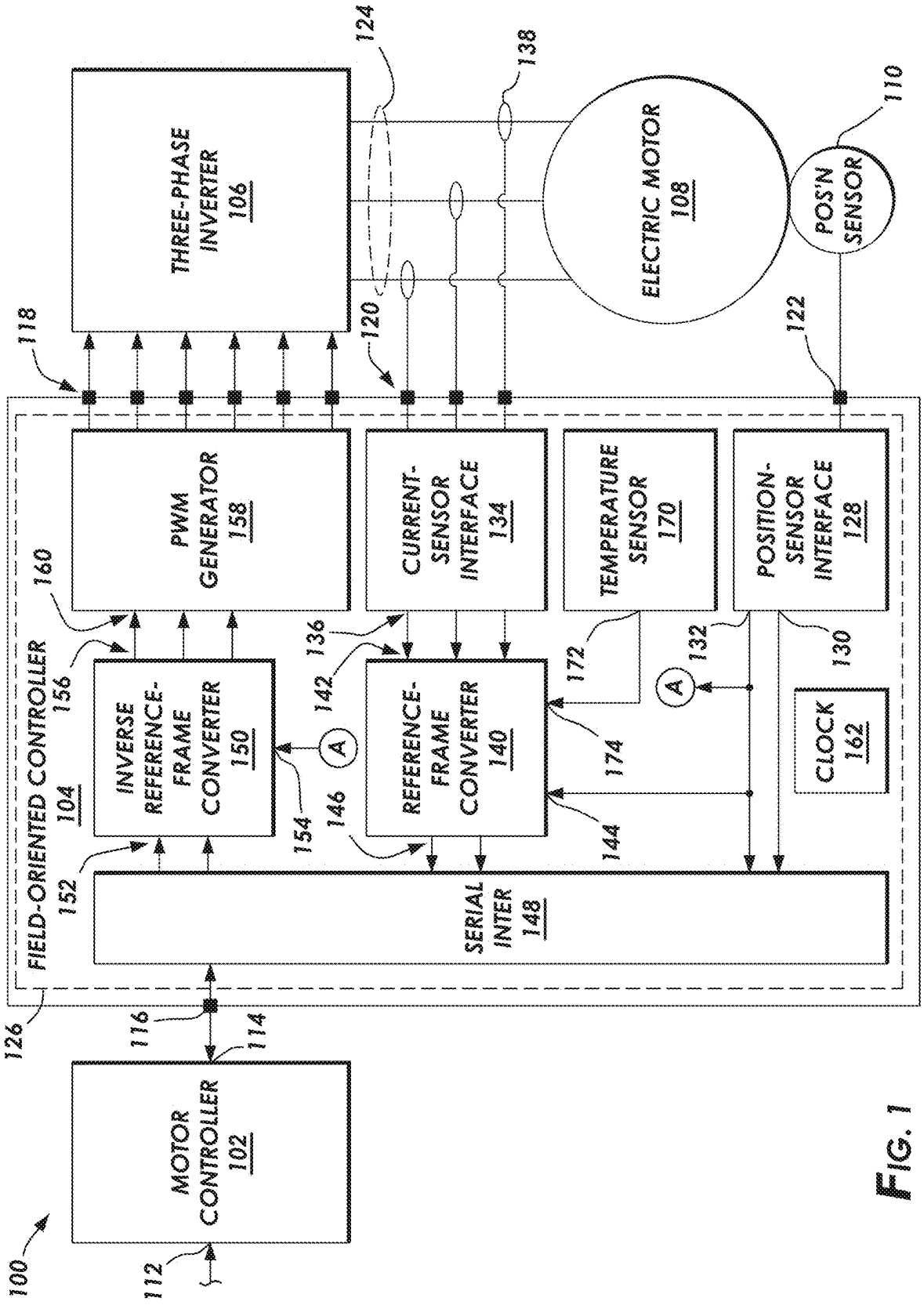

100
MOTOR CONTROLLER 102
112
126
FIELD-ORIENTED CONTROLLER 104
116
114
118
120
122
124
138
110
THREE-PHASE INVERTER 106
ELECTRIC MOTOR 108
POS'N SENSOR
PWM GENERATOR 158
CURRENT-SENSOR INTERFACE 134
TEMPERATURE SENSOR 170
POSITION-SENSOR INTERFACE 128
160
156
136
142
172
132
130
INVERSE REFERENCE-FRAME CONVERTER 150
154
146
REFERENCE-FRAME CONVERTER 140
174
144
CLOCK 162
152
SERIAL INTER 148
A
A

FIG. 1

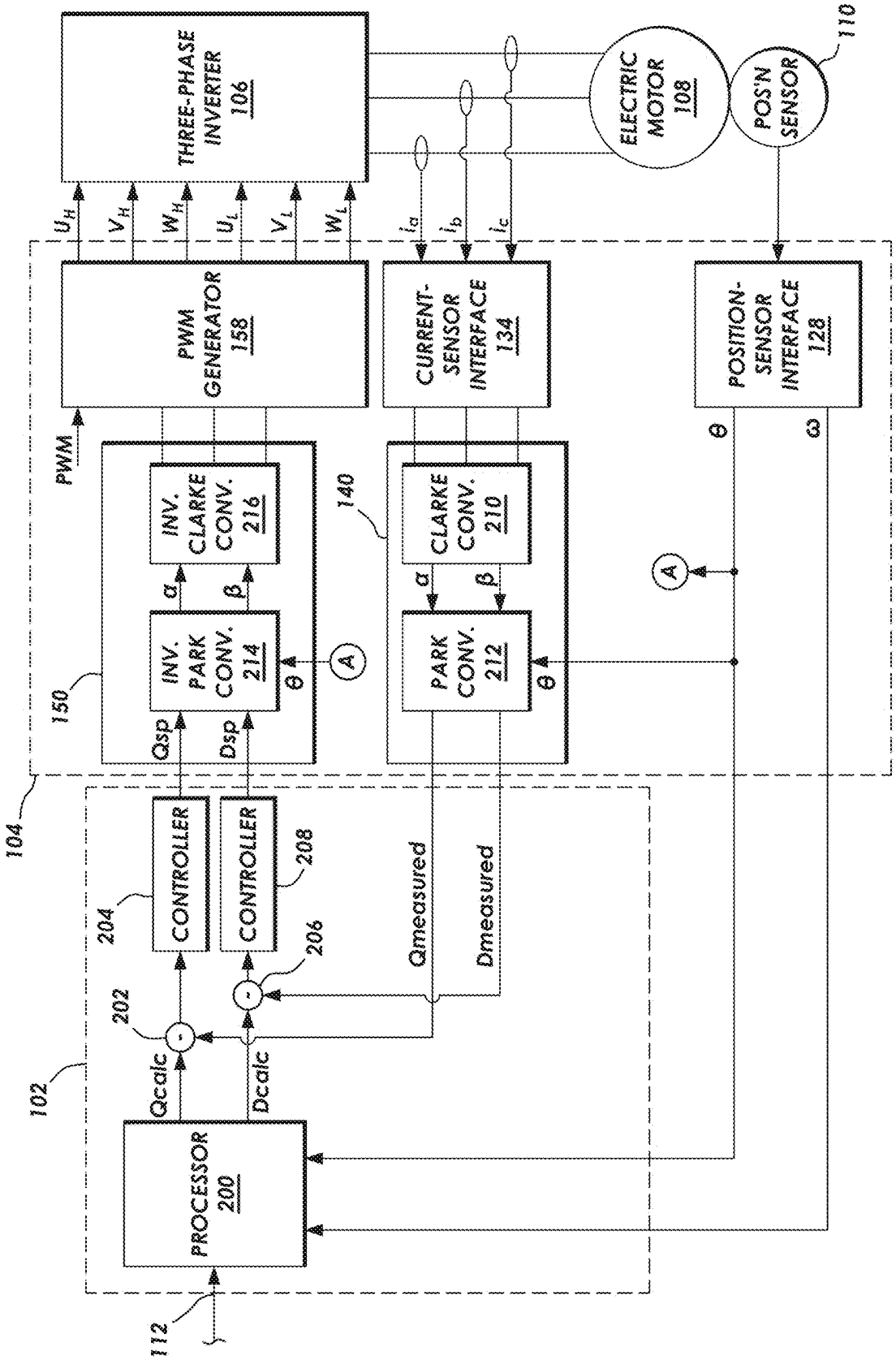

THREE-PHASE INVERTER 106
ELECTRIC MOTOR 108
POS'N SENSOR 110
U_H
V_H
W_H
U_L
V_L
W_L
i_a
i_b
i_c
PWM GENERATOR 158
CURRENT-SENSOR INTERFACE 134
POSITION-SENSOR INTERFACE 128
PWM
θ
ω
INV. CLARKE CONV. 216
INV. PARK CONV. 214
CLARKE CONV. 210
PARK CONV. 212
140
150
α
β
A
Qsp
Dsp
104
CONTROLLER
CONTROLLER
204
208
206
202
Qmeasured
Dmeasured
Qcalc
Dcalc
102
PROCESSOR 200
112

FIG. 2

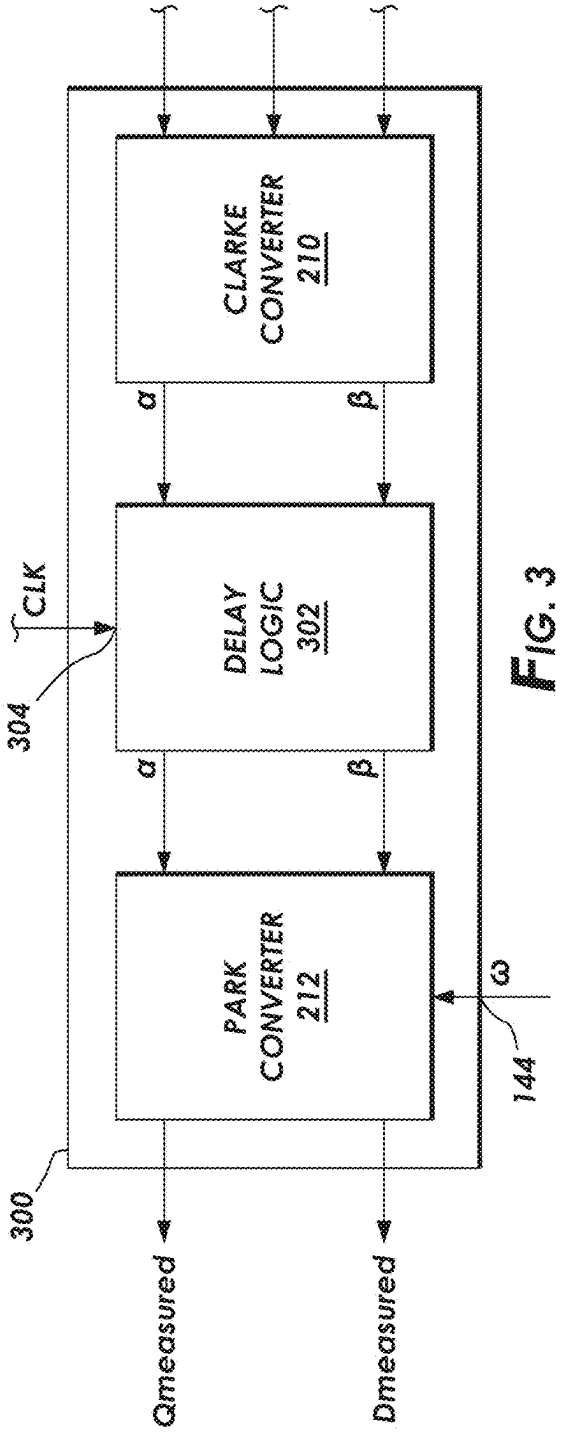
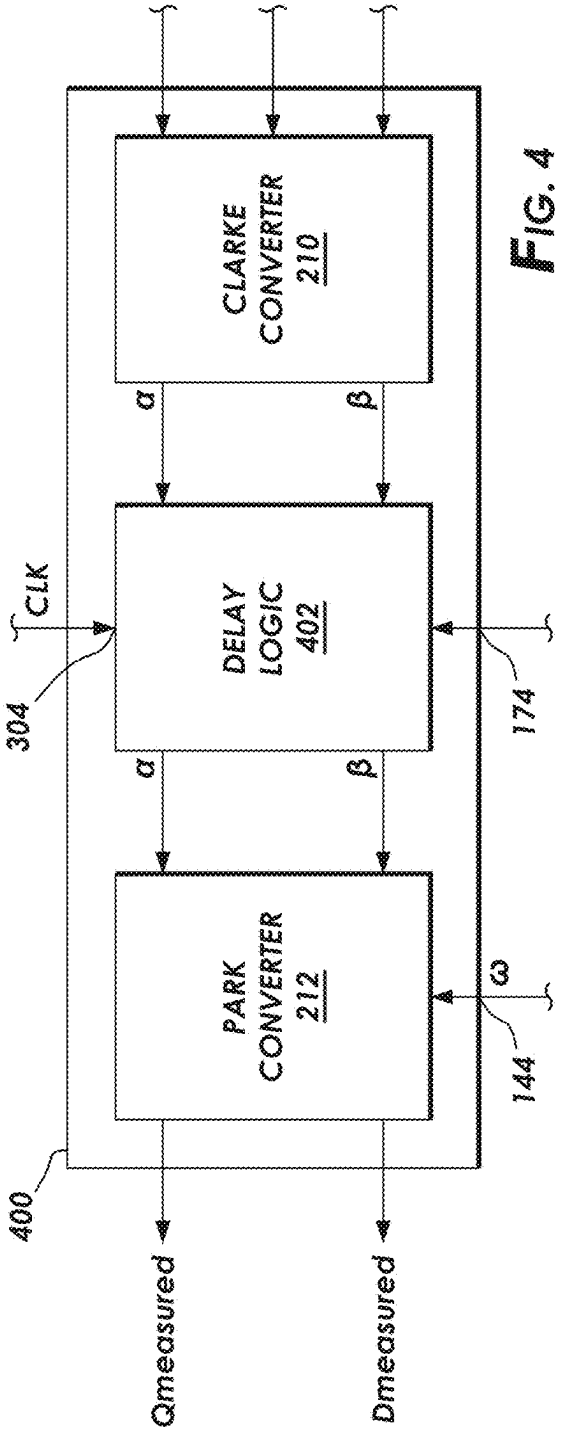

CLARKE CONVERTER 210
DELAY LOGIC 302
PARK CONVERTER 212
CLK
304
α
β
ω
144
300
Qmeasured
Dmeasured

FIG. 3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PARK CONVERTER 212
CLK
304
α
β
ω
174
144
400
Qmeasured
Dmeasured

FIG. 4

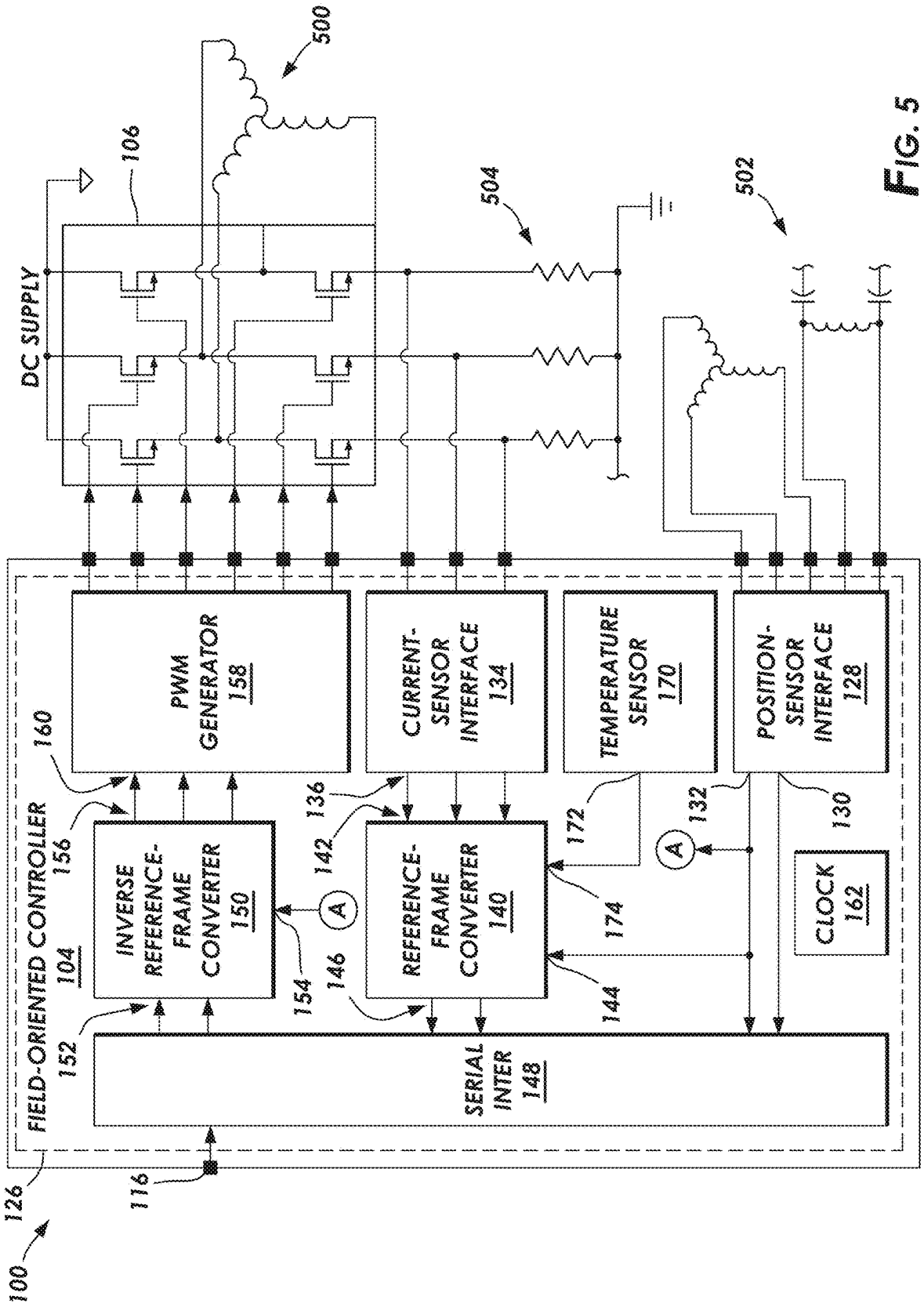
500
106
DC SUPPLY
504
502
FIELD-ORIENTED CONTROLLER
104
PWM GENERATOR
158
CURRENT-SENSOR INTERFACE
134
TEMPERATURE SENSOR
170
POSITION-SENSOR INTERFACE
128
INVERSE REFERENCE-FRAME CONVERTER
150
REFERENCE-FRAME CONVERTER
140
SERIAL INTER
148
CLOCK
162
160
156
136
142
172
132
130
154
146
174
144
152
126
116
100

FIG. 5

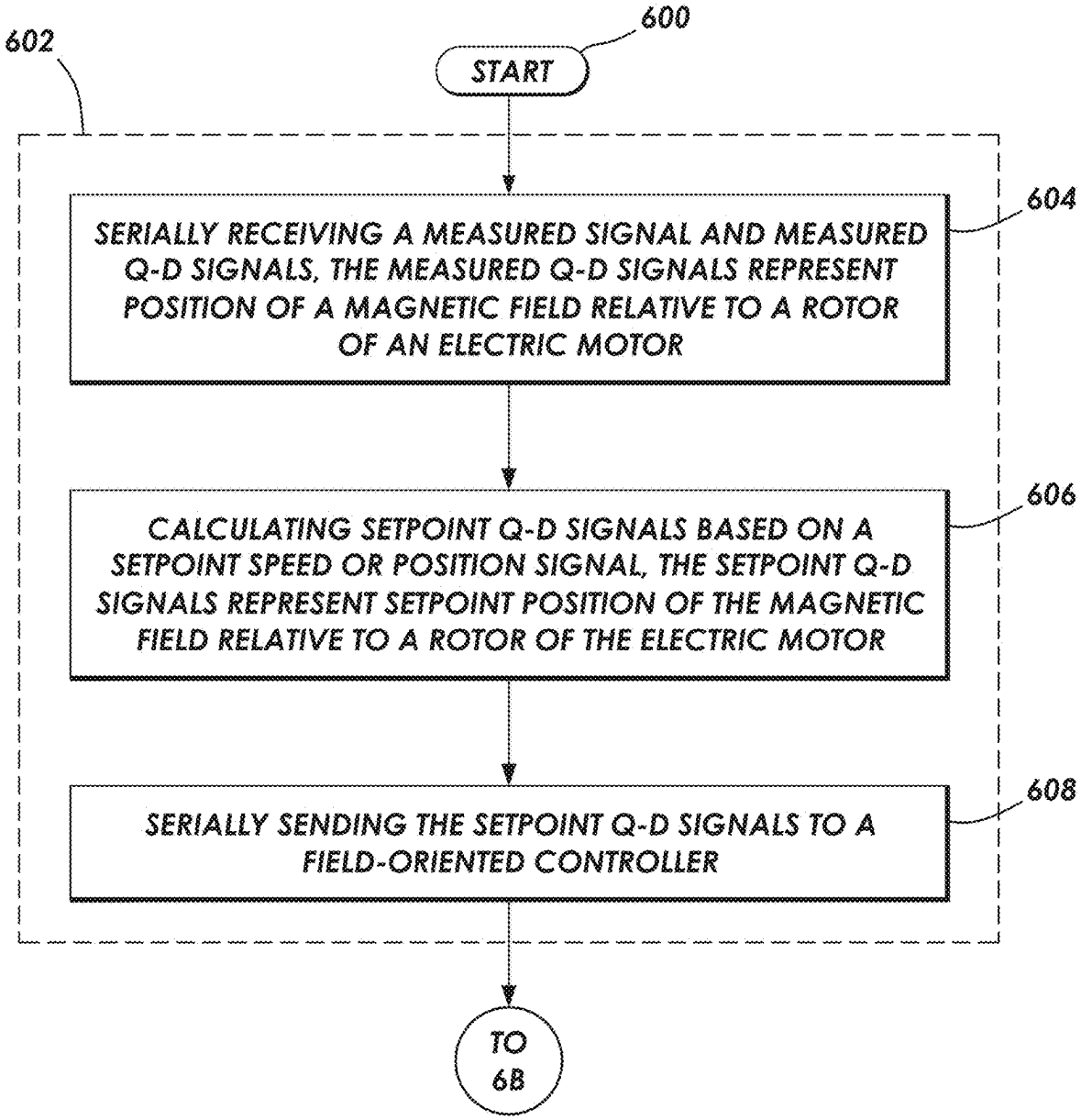
600
START
602
SERIALLY RECEIVING A MEASURED SIGNAL AND MEASURED Q-D SIGNALS, THE MEASURED Q-D SIGNALS REPRESENT POSITION OF A MAGNETIC FIELD RELATIVE TO A ROTOR OF AN ELECTRIC MOTOR
604
CALCULATING SETPOINT Q-D SIGNALS BASED ON A SETPOINT SPEED OR POSITION SIGNAL, THE SETPOINT Q-D SIGNALS REPRESENT SETPOINT POSITION OF THE MAGNETIC FIELD RELATIVE TO A ROTOR OF THE ELECTRIC MOTOR
606
SERIALLY SENDING THE SETPOINT Q-D SIGNALS TO A FIELD-ORIENTED CONTROLLER
608
TO 6B

FIG. 6A

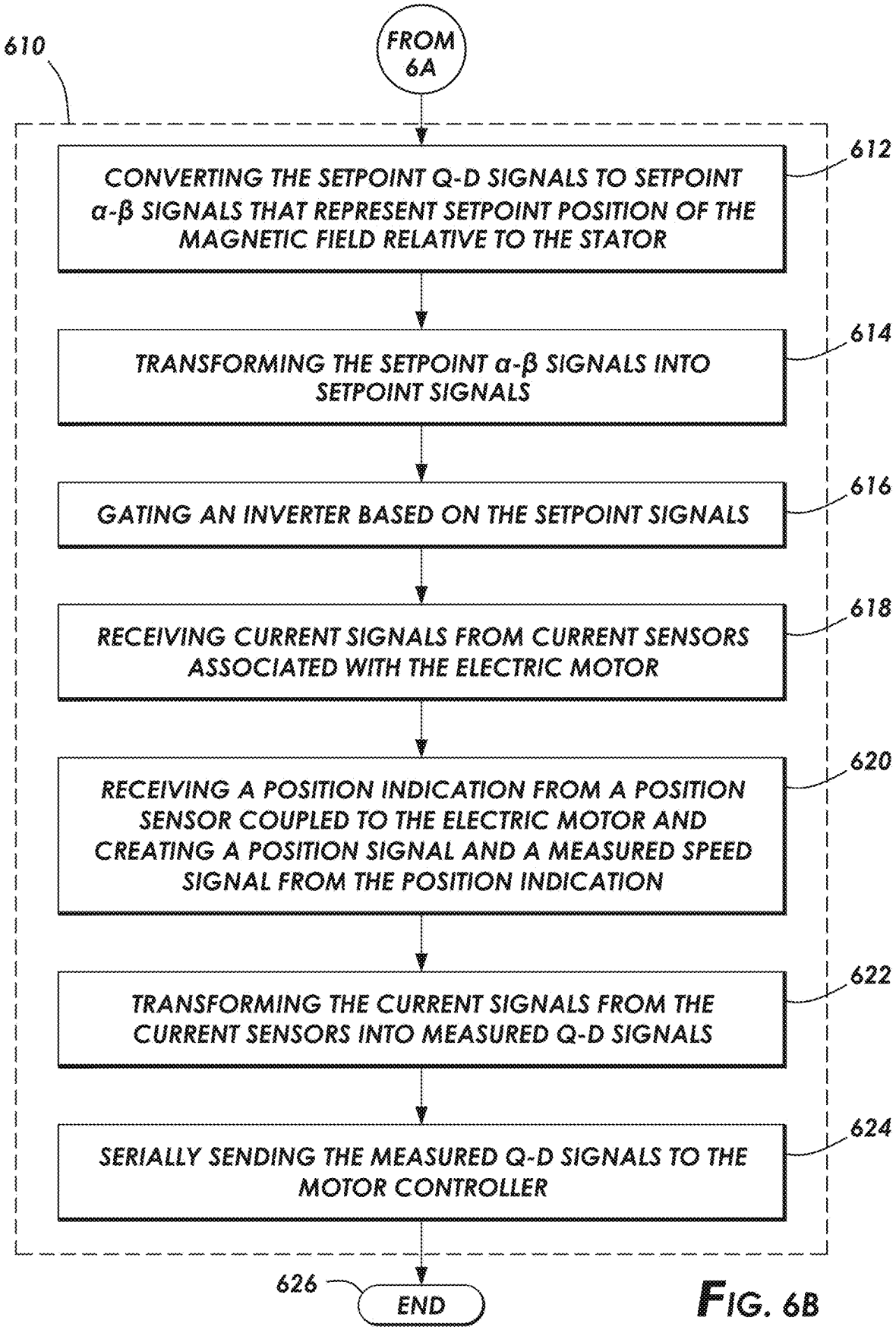
610
FROM 6A
CONVERTING THE SETPOINT Q-D SIGNALS TO SETPOINT α-β SIGNALS THAT REPRESENT SETPOINT POSITION OF THE MAGNETIC FIELD RELATIVE TO THE STATOR
612
TRANSFORMING THE SETPOINT α-β SIGNALS INTO SETPOINT SIGNALS
614
GATING AN INVERTER BASED ON THE SETPOINT SIGNALS
616
RECEIVING CURRENT SIGNALS FROM CURRENT SENSORS ASSOCIATED WITH THE ELECTRIC MOTOR
618
RECEIVING A POSITION INDICATION FROM A POSITION SENSOR COUPLED TO THE ELECTRIC MOTOR AND CREATING A POSITION SIGNAL AND A MEASURED SPEED SIGNAL FROM THE POSITION INDICATION
620
TRANSFORMING THE CURRENT SIGNALS FROM THE CURRENT SENSORS INTO MEASURED Q-D SIGNALS
622
SERIALLY SENDING THE MEASURED Q-D SIGNALS TO THE MOTOR CONTROLLER
624
626
END

FIG. 6B

ELECTRIC MOTOR CONTROLLER AND RELATED METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 63/556,246 filed Feb. 21, 2024 and titled, "Sensored Field Oriented Control Signal Processing." The provisional application is incorporated by reference herein as if reproduced in full below.

BACKGROUND

[0002] Electric motor speed control plays an ever-increasing role in various industrial and consumer applications, ranging from household appliances to complex manufacturing systems. With the advent of electronic control systems, there has been a significant shift towards more sophisticated methods that utilize microcontrollers, sensors, and advanced algorithms to achieve precise and efficient speed regulation. The electronic systems not only enhance performance and reliability, but also offer greater flexibility in terms of speed adjustment and energy efficiency.

SUMMARY

[0003] One example is a method of controlling an electric motor, the method comprising: calculating, by a motor controller, setpoint Q-D signals based on a setpoint speed signal, the setpoint Q-D signals represent setpoint position of a magnetic field relative to a rotor of the electric motor; serially sending, by the motor controller, the setpoint Q-D signals to a field-oriented controller disposed within a distinct packaging from the motor controller; converting, by the field-oriented controller, the setpoint Q-D signals to setpoint α-β signals that represent setpoint position of the magnetic field relative to A stator of the electric motor; transforming, by the field-oriented controller, the setpoint α-β signals into setpoint voltage signals; and gating, by the field-oriented controller, an inverter based on the setpoint voltage signals.

[0004] In the example method, serially communicating the setpoint Q-D signals may comprise sending at one megabit per second or less.

[0005] The example method may further comprise: serially receiving, by the motor controller, a measured speed signal and measured Q-D signals, the measured Q-D signals represent position of a magnetic field relative to a rotor of the electric motor; wherein calculating the setpoint Q-D signals further comprises calculating based on the setpoint speed signal, the measured speed signal, and the measured Q-D signals. Serially sending the setpoint Q-D signals may comprise sending at one megabit per second or less, and wherein serially receiving the measured speed signal and measured Q-D signals may comprise receiving at one megabit per second or less. Serially receiving may comprise receiving the setpoint speed signal, the measured speed signal, and the measured Q-D signals by serial communication at one megabit per second or less.

[0006] The example method may further comprise, by the field-oriented controller: receiving current signals from current sensors associated with the electric motor; converting the current signals into measured α-β signals that represent position of the magnetic field relative to the stator of the electric motor; receiving a position indication from a position sensor coupled to the electric motor, and creating a position signal and a measured speed signal from the position indication; converting the measured α-β signals and the position signal into measured Q-D signals that represent measured position of the magnetic field relative to the rotor of the electric motor; and serially sending the measured Q-D signals and the measured speed signal to the motor controller. Calculating the setpoint Q-D signals may further comprise calculating based on the setpoint speed signal, the measured speed signal, and the measured Q-D signals. The example method may further comprise providing measured α-β signals and position signal synchronously with the position signal to the converting into the measured Q-D signals. The example method may further comprise, by the field-oriented controller: measuring temperature of a semiconductor substrate to create a measured temperature; and delaying propagation of the measured α-β signals based on the measured temperature to compensate for processing delay in creating the position signal.

[0007] Another example is a packaged semiconductor product, comprising: a position-sense terminal, current-sense terminals, a serial-bus terminal, and gate terminals; a position-sensor interface coupled to the position-sense terminal, the position-sensor interface configured to generate a position signal and a speed signal; a current-sensor interface coupled to the current-sense terminals, the current-sensor interface configured to generate current-sense signals; a reference-frame converter coupled to the current-sense signals and the position signal, the reference-frame converter configured to transform a multiphase current reference frame of an electric motor to measured Q-D signals that represent position of a magnetic field relative to a rotor of the electric motor; a communications interface coupled to the serial-bus terminal, the speed signal, and the measured Q-D signals, the communications interface configured to serially transmit the speed signal and the measured Q-D signals to a motor controller by way of the serial-bus terminal; the communications interface may be further configured to receive, by way of the serial-bus terminal, setpoint Q-D signals; an inverse reference-frame converter coupled to the setpoint Q-D signals, the inverse reference-frame converter configured to transform the setpoint Q-D signals into setpoint signals for a plurality of phases of the electric motor; and a PWM generator coupled to the setpoint signals and configured to drive gate signals to the gate terminals.

[0008] In the example packaged semiconductor product, the communications interface may be configured to serially transmit the speed signal and the measured Q-D signals at one megabit per second or less.

[0009] In the example packaged semiconductor product, the communications interface may be configured to serially receive the setpoint Q-D signals at one megabit per second or less.

[0010] In the example packaged semiconductor product, the reference-frame converter may comprise: a Clarke converter coupled to the current-sense signals and configured to generate measured α-β signals that represent position of a magnetic field relative to a stator of the electric motor; and a Park converter coupled to the position signal and the measured α-β signals, the Park converter configured to generate the measured Q-D signals. The inverse reference-frame converter may comprise: an inverse Park converter coupled to the setpoint Q-D signals, the inverse Park converter configured to generate setpoint α-β signals that represent setpoint position of the electric field relative to the

stator; and an inverse Clarke converter coupled to the setpoint α-β signals and configured to generate the setpoint signals. The example packaged semiconductor product may further comprise a delay logic communicatively disposed between the Clarke converter and the Park converter, the delay logic configured to compensate for computational delay of the position-sensor interface. The example packaged semiconductor product may further comprise: a temperature sensor disposed within the packaged semiconductor product; a controllable delay logic coupled to the temperature sensor and communicatively disposed between the Clarke converter and the Park converter, the controllable delay logic configured to compensate for both static computational delay and temperature dependent computational delay of the of the position-sensor interface. The example packaged semiconductor product may further comprise a controllable delay logic communicatively disposed between the Clarke converter and the Park converter, the controllable delay logic configured to sense clocking frequency, and compensate for frequency-dependent computational delay of the of the position-sensor interface. The example packaged semiconductor product may further comprise: a temperature sensor disposed within the packaged semiconductor product; and a controllable delay logic coupled to the temperature sensor. The controllable delay logic communicatively disposed between the Clarke converter and the Park converter, the controllable delay logic may be configured to: compensate for static computational delay of the position-sensor interface; and compensate for temperature-dependent computation delay of the position-sensor interface.

[0011] In the example packaged semiconductor product the current-sensor interface may be configured to receive analog signals from the current-sense terminal, and generate the current-sense signals in digital format.

[0012] In the example packaged semiconductor product the position-sensor interface may be configured to receive analog signals from the position-sense terminal, and generate the position signals in digital format.

[0013] The example packaged semiconductor product may comprise a semiconductor substrate, and wherein the position-sensor interface, the current sensor, the reference-frame converter, the communications interface, the inverse reference-frame converter, and the PWM generator are all implemented on the semiconductor substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] For a detailed description of example embodiments, reference will now be made to the accompanying drawings in which:

[0015] FIG. **1** shows a block diagram of an example motor control system.

[0016] FIG. **2** shows a functional block diagram of the motor control system.

[0017] FIG. **3** shows a block diagram of an example a reference-frame converter.

[0018] FIG. **4** shows a block diagram of an example a reference-frame converter that implements controllable delay.

[0019] FIG. **5** shows a block diagram of an example motor control system.

[0020] FIGS. **6**A and **6**B show a method in accordance with at least some embodiments.

DEFINITIONS

[0021] Various terms are used to refer to particular system components. Different companies may refer to a component by different names-this document does not intend to distinguish between components that differ in name but not function. In the following discussion and in the claims, the terms "including" and "comprising" are used in an open-ended fashion, and thus should be interpreted to mean "including, but not limited to . . . " Also, the term "couple" or "couples" is intended to mean either an indirect or direct connection. Thus, if a first device couples to a second device, that connection may be through a direct connection or through an indirect connection via other devices and connections.

[0022] "A", "an", and "the" as used herein refers to both singular and plural referents unless the context clearly dictates otherwise. By way of example, "a processor" programmed to perform various functions refers to one processor programmed to perform each and every function, or more than one processor collectively programmed to perform each of the various functions. To be clear, an initial reference to "a [referent]", and then a later reference for antecedent basis purposes to "the [referent]", shall not obviate the fact the recited referent may be plural.

[0023] The terms "input" and "output," when used as nouns, refer to connections and shall not be read as verbs requiring action. For example, a position-sensor circuit may define a position output. The position output may be multi-bit digital word that represents positon of a rotor an electric motor. In systems implemented directly in hardware (e.g., on a semiconductor substrate), these "inputs" and "outputs" define electrical connections.

[0024] "Signal" or "signals" shall mean any form of transmitted or received data that conveys information. "Signal" thus encompasses both analog signals, which are continuous waveforms that vary over time, and multi-bit digital words that are discrete, quantized representations of data composed of multiple binary digits (bits) that encode information in a structured format.

DETAILED DESCRIPTION

[0025] The following discussion is directed to various embodiments of the invention. Although one or more of these embodiments may be preferred, the embodiments disclosed should not be interpreted, or otherwise used, as limiting the scope of the disclosure, including the claims. In addition, one skilled in the art will understand that the following description has broad application, and the discussion of any embodiment is meant only to be exemplary of that embodiment, and not intended to intimate that the scope of the disclosure, including the claims, is limited to that embodiment.

[0026] Various examples are directed to electric motor controllers and related methods. More particularly, various examples are directed to a field-oriented controller as a packaged semiconductor product. The field-oriented controller implements the "high speed" aspects of motor control, such Clarke Transforms and Park Transforms, and leaves to other, external devices to implement user-programmable and/or "low speed" aspects of motor control, such as the proportional-integral-differential (PID) control loops. In this way, the field-oriented controller is usable with multiple different front-end control preferences, usable with different

controlled parameter implementations (e.g., speed, position, torque), and also usable with a range of electric motors types, such as brushless DC and three-phase AC motors (e.g., induction motors and synchronous motors). The specification now turns to an example implementation.

[0027] FIG. **1** shows, in block diagram form, an example motor control system **100**. In particular, the example motor control system **100** comprises a motor controller **102**, a field-oriented controller **104**, a three-phase inverter **106**, an electric motor **108**, and a position sensor **110**. The example motor controller **102** defines a setpoint input **112** and a serial bus connection **114**. The example motor controller **102** receives a setpoint signal by way the setpoint input **112**, and also receives a measured signal by way of the serial bus connection **114**. The motor controller **102** makes various user-specific calculations, such as user-specific proportional-integral-differential control loop(s), and communicates control values to the field-oriented controller **104** by way of the serial bus connection **114**. The various control values communicated are discussed in greater detail below after introduction of reference frame converters in the field-oriented controller **104**. The serial bus protocol, and thus the precise electrical arrangement of the serial bus, may implement any suitable bidirectional serial bus communication scheme, such as an Inter-Integrated Circuit (I2C) protocol or a Serial Peripheral Interface (SPI) protocol. The motor controller **102** may control based on any controllable parameter of the motor, such as speed, motor position, or torque, and combinations. Thus, the setpoint input may be a speed setpoint, a position setpoint, or a torque setpoint. Similarly, the measured signal may be speed, motor position, or torque. The various embodiments were developed in the context of a system controlling motor speed, and the specification that follows is based on the developmental context; however, the developmental context of speed control shall not be read as a limitation of the applicability of the various examples.

[0028] The example field-oriented controller **104** is a packaged semiconductor product with various pins or terminals electrically accessible on the outside of the packaging. The example field-oriented controller **104** defines a serial-bus terminal **116**, a set of gate terminals **118** (e.g., six), a set of current-sense terminals **120** (e.g., three), and a set of position-sense terminals **122** (e.g., five). Additional terminals will be present, such as power and ground terminals, but the additional terminals are not shown so as not to unduly complication the discussion. While only one serial-bus terminal **116** is shown, two or more may be present depending upon the serial communication protocol implemented between the motor controller **102** and the field-oriented controller **104**. Similarly for the set of position-sense terminals **122**, while only one position-sense terminal is shown, two or more position sense terminals may be implemented to accommodate multiple types of position sensors **110**.

[0029] The set of gate terminals **118** is coupled to the three-phase inverter **106**. In particular, the three-phase inverter **106** is provided gate signals from the field-oriented controller **104**, and the three-phase inverter **106** uses the gate signals to provide voltage and current to the electric motor **108** through motor leads **124**. Stated otherwise, the three-phase inverter **106** receives the on/off signals and turns on or off the high side and low side electrically-controlled switches, such as field-effect transistors (FETs). Thus, the gate signals provided from the field-oriented controller **104** control the conductive state of the FETs to provide three-phase voltage and current to the electric motor **108**. Though the example motor control system **100** of FIG. **1** shows the field-oriented controller **104** directly coupled to the three-phase inverter **106**, in other cases one or more gate driver circuits may reside between the field-oriented controller **104** and the three-phase inverter **106**. That is, the field-oriented controller **104** may provide gate signals that are Boolean, but the field-oriented controller **104** may not be designed and constructed to drive sufficient voltage and current to control the gate of the power semiconductor FETs within the three-phase inverter **106**. The gate driver circuits may be selected based on the voltage and current requirements of the electrically-controlled switches.

[0030] Still referring to FIG. **1**, the example motor control system **100** comprises the electric motor **108** and attached position sensor **110**. The electrical motor **108** may take any suitable form, such as an AC synchronous motor, an AC induction motor, or a brushless DC motor (which is driven similarly to its AC counterparts). The various embodiments were developed in the context of the electric motor **108** being a brushless DC motor, and the description that follows is based on the developmental context. However, one having ordinary skill, and with the benefit of this disclosure, could apply the teachings of the field-oriented controller **104** to many different types of electrical motors. Though not specifically shown in FIG. **1**, the electric motor **108** has a rotating portion or rotor, and a stationary portion or stator. The voltage and current applied by way of the motor leads **124** to the stator creates a rotating magnetic field. A magnetic field of the rotor is attracted to the rotating magnetic field of the stator, causing the rotor to turn.

[0031] The position sensor **110** measures or senses the physical position of the rotor. Any suitable position sensor **110** technology may be used, such as Hall Effect Sensors, an optical or magnetic encoder, or a resolver that uses a rotating transformer. Regardless, data related to the instantaneous rotational position of the rotor is provided to the field-oriented controller **104** by way of the set of position-sense terminals **122**.

[0032] Still referring to FIG. **1**, and now specifically to the internal components of the field-oriented controller **104**. In example cases, the functionality of the field-oriented controller **104** is implemented on a single semiconductor die or semiconductor substrate **126**. That is, at the semiconductor processing stage, many such field-oriented controllers may be simultaneously constructed on a semiconductor wafer. After fabrication is complete, the various device are cut or singulated. Each singulated die is then packaged as a semiconductor product, with the various electrical connections on the die (e.g., bond pads) electrically coupled to the externally accessible terminals.

[0033] Starting at the bottom-right, the example field-oriented controller **104** comprises a position-sensor interface **128** coupled to the set of position-sense terminals **122**. The position-sensor interface **128** defines a speed output **130** and a position output **132**. The position-sensor interface **128** is designed and constructed to generate speed signals driven to the speed output **130**, and to generate position signals driven to the position output **132**. In some implementations, the rotor of the electric motor **108** may be turning at 10,000 revolutions per minute (RPM) or more. In order for the other components of the field-oriented controller **104** to correctly utilize the position signals, the position-sensor interface **128** may sample and drive an updated position signals at the

Nyquist rate or faster taking into account the speed of the rotor. In one example implementation, the position-sensor interface **128** samples the position at a frequency of about one mega-Hertz, and each sample produces a multibit word of 20 bits representing position.

[0034] The example field-oriented controller **104** further defines a current-sensor interface **134** coupled to the set of current-sense terminals **120**, and the current-sensor interface defines a set of current-sense outputs **136**. The current-sensor interface **134** is designed and constructed to read indications of the phase currents on the motor leads **124**, and to generate a set of current-sense signals, one signal each for each of the motor leads **124**. In the example of FIG. **1**, the individual phase currents of the motor leads **124** are sampled by current transformers, such as current transformer **138**. However, any suitable current sensing technology may be used, such as Hall Effect sensing and current sense resistors. In order for the other components of the field-oriented controller **104** to correctly utilize the set of current-sense signals, the current-sensor interface **134** may sample and drive an updated position signals at the Nyquist rate or faster relative to the frequency of the signals applied to the electric motor **108**. In one example implementation, the current-sensor interface **134** samples the phase currents at 100,000 samples per second, and each sample produces a multibit word of 16 bits representing instantaneous current.

[0035] Still referring to FIG. **1**, the example field-oriented controller **104** further comprises a reference-frame converter **140**. The reference-frame converter **140** defines a set of current-sense inputs **142** coupled to the set of current-sense outputs **136**, a position input **144** coupled to the position output **132**, and Q-D outputs **146**. The reference-frame converter **140** receives the position signals from the position-sensor interface **128**, and receives current-sense signals from the current-sensor interface **134**. The reference-frame converter **140** is designed and constructed to transform the multiphase current reference frame of the electric motor **108** to measured Q-D signals that represent position of the magnetic field of the stator relative to the rotor of the electric motor. The reference-frame converter **140** is explained in greater detail below in reference to FIG. **2**.

[0036] The example field-oriented controller **104** further includes a communications interface **148** (labeled "Serial Inter" in the figure) coupled to the serial-bus terminal **116**, the Q-D outputs **146**, the speed output **130**, and the position output **132**. Thus, the communications interface **148** receives the speed signals and/or the position signals from the position-sensor interface **128**, and receives the measured Q-D signals from the reference-frame converter **140**. The communications interface **148** is designed and constructed to serially transmit the speed signals and/or the position signals, along with the measured Q-D signals, to the motor controller **102** by way of the serial-bus terminal **116**. The communications interface **148** is further configured to receive, by way of the serial-bus terminal **116**, setpoint Q-D signals from the motor controller **102**. In the example method, serially communicating the setpoint Q-D signals may comprise sending at one megabit per second or less.

[0037] The example communications interface **148** communicates at relatively low speed compared to the "high speed" calculations within the field-orientated controller **104**. For example, the communications interface **148** may send data, such as the measured speed signal, the measured position signal, and the measured Q-D signals, at one megabit per second or less. Similarly, the communications interface **148** may receive data from the motor controller **102**, such as the setpoint Q-D signals, at one megabit per second or less. Given that the position-sensor interface **128** samples the position at a frequency of about one mega-Hertz, and each sample produces a multibit word of 20 bits representing position, not all of the position signals can be communicated across the communications interface **148**.

[0038] The example field-oriented controller **104** further comprises an inverse reference-frame converter **150**. The inverse reference-frame converter **150** defines setpoint Q-D inputs **152** coupled to the communications interface **148**, a position input **154** coupled to the position output **132** (as shown by bubble "A"), and a set of setpoint-voltage outputs **156**. The inverse reference-frame converter **150** receives setpoint Q-D signals from the motor controller **102** (by way of the communications interface **148**), and position signals from the position-sensor interface **128**. The inverse reference-frame converter **150** is designed and constructed to transform the setpoint Q-D signals into setpoint-voltage signals for a plurality of phases of the electric motor **108**. The inverse reference-frame converter **150** is explained in greater detail below in reference to FIG. **2**.

[0039] Still referring to FIG. **1**, the example field-oriented controller **104** further comprises a pulse-width modulation generator, hereafter just PWM generator **158**. The PWM generator **158** defines a set of setpoint-voltage inputs **160**, and the PWM generator **158** is coupled to the set of gate terminals **118**. The PWM generator **158** is designed and constructed to drive gate signals to the set of gate terminals **118**, which in turn cause the three-phase inverter **106** to drive currents to the electric motor **108**.

[0040] The field-oriented controller **104** further comprises a clock circuit **162**. The clock circuit **162** is shown unconnected; however, the clock circuit **162** may be connected to all the various functional blocks of the field-oriented controller **104**, but those connections are not shown so as not to unduly complicate the figure. The clock signal provided by the clock circuit **162** may have a frequency of between and including 30 and 60 MHz. The functions of the reference-frame converter **140** and inverse reference-frame converter **150** are implemented digitally as a hardware-based system or hardware logic. That is, the calculations are performed based on digital words, such as in combination logic and/or sequential logic. With the exception of the analog aspects of the position-sensor interface **128** and the current-sensor interface **134**, those functions too are implemented as hardware logic. Thus, the field-oriented controller **104** may be an application-specific integrated circuit that does not include a processor or micro-processor executing software.

[0041] FIG. **2** shows a functional block diagram of the motor control system **100**. In particular, FIG. **2** shows in more detail the motor controller **102** and the field-oriented controller **104**. Turning first to the motor controller **102**, the example motor controller **102** comprises a processor **200**, a Q-error block **202**, a Q controller **204**, a D-error block **206**, and a D controller **208**. The processor **200** is communicatively coupled to the setpoint input **112**. The processor **200** may be communicatively coupled to the speed signals from the position-sensor interface **128** and/or the position signals from the position-sensor interface **128**. The processor **200** may implement user-specific calculations in generating calculated Q-D signals, labeled as Qcalc and Dcalc, respectively, in the figure. Each set of Qcalc and Dcalc signals are

digital words; however, the Qcalc and Dcalc represent setpoint voltage values. While the processor **200** is shown directly coupled to the position-sensor interface **128**, in practice the speed signals and/or position signals are provided to the processor **200** by way of the communications interface **148** (FIG. **1**), but the communications interface is not shown in FIG. **2** so as not to further complicate the figure.

[0042] The Q-error block **202** is coupled to the Qcalc signal from the processor **200**, and is coupled to measured Q signal (labeled Qmeasured in the figure) from the field-oriented controller **104**. The Q-error block **202** is designed and constructed to calculate a Q-error signal applied to the Q controller **204**. The Q controller **204**, in turn, may implement any suitable closed loop control, such as a PID controller, and the Q controller **204** is designed and constructed to generate a setpoint Q value, labeled Qsp in the figure. While the Qmeasured signal is shown directly coupled to the Q-error block **202**, and the Qsp signal is shown directly coupled to the field-oriented controller **104**, in practice the signals are provided by way of the communications interface **148** (FIG. **1**), but the communications interface is not shown in FIG. **2** so as not to further complicate the figure.

[0043] Similarly, the D-error block **206** is coupled to the Dcalc signal from the processor **200**, and is coupled to measured D signal (labeled Dmeasured in the figure) from the field-oriented controller **104**. The D-error block **206** is designed and constructed to calculate a D-error signal applied to the D controller **208**. The D controller **208**, in turn, may implement any suitable closed loop control, such as a PID controller, and the D controller **208** is designed and constructed to generate a setpoint D value, labeled Dsp in the figure. While the Dmeasured signal is shown directly coupled to the D-error block **206**, and the Dsp signal is shown directly coupled to the field-oriented controller **104**, in practice the signals are provided by way of the communications interface **148** (FIG. **1**).

[0044] Still referring to FIG. **2**, and turning now to the field-oriented controller **104**. The field-oriented controller **104** comprises the position-sensor interface **128**, the current-sensor interface **134**, the reference-frame converter **140**, the inverse reference-frame converter **150**, and the PWM generator **158**. The example reference-frame converter **140** comprises a Clarke converter **210** and a Park converter **212**. The Clarke converter **210** is coupled to the current-sense signals from the current-sensor interface **134**. The Clarke converter **210** is designed and constructed to generate measured α-β signals that represent position of the magnetic field of the stator relative to the stator **108**. Stated otherwise, the Clarke converter **210** is designed and constructed to transform a multiphase current reference frame of the phase currents i_a, i_b, and i_c into measured α-β signals having a stationary reference of the stator.

[0045] In the example of FIG. **2**, the Park converter **212** is coupled to the position signal from the position-sensor interface **128** and the measured α-β signals from the Clarke converter **210**. The example Park converter **212** is designed and constructed to generate the measured Q-D signals based on the position signals and the measured α-β signals. Stated otherwise, the Park converter **212** is designed and constructed to transform the measured α-β signals, expressed in the stationary reference of the stator, to the measured Q-D signals that represent position of the magnetic field of the stator relative to the magnetic field of the rotor. Each Qmeasured signal can be thought of as an indication of the amount of instantaneous torque provided by the electrical motor **108**, and Qmeasured is sometimes referred to as "quadrature current." The Dmeasured signal can be thought of as an indication of the amount of instantaneous magnetization current, and Dmeasured is sometimes referred to as "direct current" or "magnetization current." For brushless DC motors, the magnetization current is controlled to be near zero, but for other electric motors, such as induction motors, non-zero magnetization current may be used.

[0046] Still referring to FIG. **2**, and now turning to the inverse reference-frame converter **150**. The example inverse reference-frame converter **150** comprises an inverse Park converter **214** and an inverse Clarke converter **216**. The inverse Park converter **214** is coupled to the position signals from the position-sensor interface **128** and the setpoint Q-D signals from the motor controller **102**. The inverse Park converter **214** is designed and constructed to generate setpoint α-β signals that represent setpoint position of the voltages applied to the stator relative to the stator. Stated otherwise, the inverse Park converter **214** is designed and constructed to transform the setpoint Q-D signals, expressed in the rotating reference of the rotor, to the setpoint α-β signals that represent position of the magnetic field relative to the stator.

[0047] The inverse Clarke converter **216** is coupled to the setpoint α-β signals. The inverse Clarke converter **216** is designed and constructed to generate the setpoint voltage signals applied to the PWM generator **158**. Stated otherwise, the inverse Clarke converter **216** is designed and constructed to transform the setpoint α-β signals, expressed in the stationary reference frame of the rotor, into setpoint phase voltages to be applied to the stator.

[0048] In various examples, the functions of the Clarke converter **210**, the Park converter **212**, the inverse Park converter **214**, and the inverse Clark converter **216** are implemented digitally as a hardware-based system or hardware logic. That is, the calculations are performed based on digital words, such as in combination logic and/or sequential logic. With the exception of the analog aspects of the position-sensor interface **128** and the current-sensor interface **134**, those functions too are implemented as hardware logic. Having the various functions implemented as hardware logic enables characterization of the field-oriented controller **104**, and direct hardware compensation for the delays and/or differences in processing speed for each of the functions. For example, the Park converter **212** provides higher accuracy measured Q-D signals when the instantaneous position signal provided from the position-sensor interface **128** is aligned in time with the measured α-β signals provided from the Clarke converter **210**. Stated otherwise, higher accuracy measured Q-D signals are created when the position signal from the position-sensor interface **128** is synchronous with the corresponding measured α-β signal. However, the position-sensor interface **128** may have a longer computation time (e.g., takes more clock cycles) than the computation time of the combined current-sensor interface **134** and Clarke converter **210**. Some example field-oriented controllers **104** compensate differences in computational time by slowing down or delaying delivery of the measured α-β signals to the Park converter **212**.

[0049] FIG. **3** shows a block diagram of an example of reference frame converter **300**. In particular, the reference frame converter **300** comprises the Clarke converter **210** and the Park converter **212**, and also comprises a delay logic **302** communicatively disposed between the Clarke converter **210** and the Park converter **212**. The delay logic **302** receives the measured α-β signals from the Clarke converter **210**, and implements a propagation delay for each set of values. Stated otherwise, the example delay logic **302** provides a fixed and predetermined delay in communicating the measured α-β signals to the Park converter **212**. The delay at least partially compensates for computational delay of the position-sensor interface **128** (FIG. **1**). The delay logic **302** may take any suitable form, such as shift register-based delay circuits or a fixed set of first-in first-out buffers.

[0050] The amount of delay implemented by the delay logic **302** may be determined in many ways. In one example, at the design stage the expected computational delay of the position-sensor interface **128** may be compared to the expected computational delay of the current-sensor interface **134** and the Clarke converter **210**. Based on the differences in computational delay, the delay logic **302** may be designed to provide the predetermined delay.

[0051] However, the computational delay of the position-sensor interface **128** (FIG. **1**) may vary from die-to-die even on the same semiconductor wafer. Thus, in other cases the computational delay may be measured on the semiconductor wafer after the construction (e.g., at the "probe" stage), and then a more precise delay may be implemented within the delay logic **302**, such as by laser removal of delay elements to more precisely control the delay on each die. In other examples, the delay logic **302** may implement a controllable delay based on operating parameters of the field-oriented controller **104**. For example, the delay logic **302** may sense the clock frequency by way of a clock input **304**, and compensate for frequency-dependent computational delay of the position-sensor interface **128**. Stated otherwise, the example delay logic **302** may implement a delay comprising a "static" computational delay and a frequency-dependent computational delay.

[0052] Returning briefly to FIG. **1**, the example field-oriented controller **104** may comprise a temperature sensor **170** disposed within the packaging, and in some cases disposed on the semiconductor substrate **126**. The temperature sensor **170** may be designed and constructed to determine a temperature of the semiconductor substrate **126**, and produce a temperature signal driven to a temperature output **172**. Creating the temperature signal may take any suitable form. In one example, analog-based measurements (e.g., resistive temperature measurement) are converted into digital form and driven to the temperature output **172**. In other cases, the temperature signal may be calculated digitally, such as based on an amount of time for a signal to propagate along a logic chain whose speed of propagation is temperature dependent. The example reference-frame converter **140** further includes a temperature input **174**. In various examples, the reference-frame converter **140** uses the temperature signals to implement variable delay.

[0053] FIG. **4** shows a block diagram of an example reference-frame converter **400** that implements controllable delay based on temperature. In particular, the reference-frame converter **400** comprises the Clarke converter **210** and the Park converter **212**, and also comprises a delay logic **402** communicatively disposed between the Clarke converter **210** and the Park converter **212**. The delay logic **402** receives the measured α-β signals from the Clarke converter **210**, and implements a propagation delay for each set of values. More particularly, the example delay logic **402** receives temperature signals by way of the temperature input **174**, and the example delay logic **402** implements a controllable delay based on the temperature signals to compensate for temperature-dependent computation delay of the position-sensor interface **128** (FIG. **1**). Stated otherwise, the example delay logic **402** may compensate for both the "static" computational delay of the position-sensor interface **128** and temperature-dependent computation delay of the position-sensor interface **128**. In yet still further cases, the example delay logic **402** may compensate for static computational delay of the position-sensor interface **128**, temperature-dependent computation delay of the position-sensor interface **128**, and frequency-dependent computational delay of the of the position-sensor interface **128**.

[0054] FIG. **5** shows a block diagram of an example motor control system **100**. In particular, FIG. **5** shows the field-oriented controller **104** from FIG. **1**, along with a three-phase inverter **106**, stator windings **500**, and an inductive rotor-position sensor **502**. The example three-phase inverter **106** comprises six FETs. The upper FETS have their drains coupled to a DC supply, while the lower FETs have their sources coupled to a reference voltage, such as ground. The sources of the upper FETS and the drains of the lower FETs define respective switch nodes coupled to respected leads of the stator windings **500**. More particularly, the example stator **500** is a three-phase stator connected in a "Y" configuration, thus defining three stator leads. Each stator lead is associated with a set of FETs comprising an upper FET and a lower FET within the three-phase inverter **106**. Thus, the field-oriented controller **104** gates (e.g., PWM) the three-phase inverter **106** and thereby supplies voltage and current to the stator windings **500** to create a magnetic field that rotates with respect to the stator windings.

[0055] In the example of FIG. **5**, the current sensors used to sense phase currents are current-sense resistors **504** associated one each with motor lead. The example current-sensor interface **134** is thus designed and constructed to sense voltage across each of the current-sense resistors, and convert the sensed voltages into the sensed current signals discussed above. Again, the field-effect controller **104** may interface with other, different types of current sensors, such as Hall Effect sensors.

[0056] Finally, the example field-oriented controller **104**, and specifically the position-sensor interface **128**, is shown coupled to a position sensor in the form of an inductive rotor-position sensor **502**. In this example, the field-oriented controller thus implements five terminals coupled to the position-sensor interface **128**. In particular, the example position-sensor interface **128** may sense rotor position based on analog signals from the inductive rotor-position sensor **502**, and create the position signals and speed signals based thereon.

[0057] FIGS. **6**A and **6**B show a method in accordance with at least some embodiments. In particular, the method starts (block **600**) and comprises steps implemented within the motor controller, as shown by dashed box **602**. The example motor controller serially receives a measured signal and measured Q-D signals, with the measured Q-D signals representing position of a magnetic field relative to a rotor of an electric motor (block **604**). The measured signal could

be the measured speed signal, the measured position signal, or both. The motor controller calculates setpoint Q-D signals based on a setpoint speed or position signal, with the setpoint Q-D signals representing setpoint position of a magnetic field of a stator relative to a rotor of the electric motor (block **606**). The motor controller may then serially send the setpoint Q-D signals to a field-oriented controller disposed within a distinct packaging from the motor controller (block **608**).

[0058] Turning now to the method steps associated with the field-oriented controller, as shown in FIG. **6**B within dashed box **610**. The method may further comprise the field-oriented controller converting the setpoint Q-D signals to setpoint α-β signals that represent setpoint position of the magnetic field of the stator relative to the stator (block **612**). The field-oriented controller may thereafter transform the setpoint α-β signals into setpoint signals (block **614**). The field-oriented controller then gates the inverter based on the setpoint current signals (block **616**). The field-oriented controller receives current signals from current sensors associated with the electric motor (block **618**). The field-oriented controller receives a position indication from a position sensor coupled to the electric motor, and creates a position signal and a measured speed signal from the position indications (block **620**). The field-oriented controller may then transform the current signals from the current sensors into measured Q-D signals (block **622**), and serially send the measured Q-D signals to the motor controller (block **624**). Thereafter, the method ends (block **626**) to be repeated continually during operation of the electric motor.

[0059] The example field-oriented controller **104** thus implements the "high speed" aspects of motor control, such Clarke Transforms and Park Transforms, and leaves to other, external devices to implement user-programmable and "low speed" aspects of motor control, such as the proportional-integral-differential (PID) control loops. In this way, the field-oriented controller is usable with multiple different front-end control preferences, and is also usable with a range of electric motors types, such as brushless DC and three-phase AC motors (e.g., induction motors and synchronous motors).

[0060] Many of the electrical connections in the drawings are shown as direct couplings having no intervening devices, but not expressly stated as such in the description above. Nevertheless, this paragraph shall serve as antecedent basis in the claims for referencing any electrical connection as "directly coupled" for electrical connections shown in the drawing with no intervening device(s).

[0061] The above discussion is meant to be illustrative of the principles and various embodiments of the present invention. Numerous variations and modifications will become apparent to those skilled in the art once the above disclosure is fully appreciated. It is intended that the following claims be interpreted to embrace all such variations and modifications.

1. A method of controlling an electric motor, the method comprising:

calculating, by a motor controller, setpoint Q-D signals based on a setpoint speed signal, the setpoint Q-D signals represent setpoint position of a magnetic field relative to a rotor of the electric motor;

serially sending, by the motor controller, the setpoint Q-D signals to a field-oriented controller disposed within a distinct packaging from the motor controller;

converting, by the field-oriented controller, the setpoint Q-D signals to setpoint α-β signals that represent setpoint position of the magnetic field relative to a stator of the electric motor;

transforming, by the field-oriented controller, the setpoint α-β signals into setpoint voltage signals; and

gating, by the field-oriented controller, an inverter based on the setpoint voltage signals.

2. The method of claim **1** wherein serially communicating the setpoint Q-D signals comprises sending at one megabit per second or less.

3. The method of claim **1** further comprising:

serially receiving, by the motor controller, a measured speed signal and measured Q-D signals, the measured Q-D signals represent position of a magnetic field relative to a rotor of the electric motor;

wherein calculating the setpoint Q-D signals further comprises calculating based on the setpoint speed signal, the measured speed signal, and the measured Q-D signals.

4. The method of claim **3** wherein serially sending the setpoint Q-D signals comprises sending at one megabit per second or less, and wherein serially receiving the measured speed signal and measured Q-D signals comprises receiving at one megabit per second or less

5. The method of claim **3** wherein serially receiving comprises receiving the setpoint speed signal, the measured speed signal, and the measured Q-D signals by serial communication at one megabit per second or less.

6. The method of claim **1** further comprising, by the field-oriented controller:

receiving current signals from current sensors associated with the electric motor;

converting the current signals into measured α-β signals that represent position of the magnetic field relative to the stator of the electric motor;

receiving a position indication from a position sensor coupled to the electric motor, and creating a position signal and a measured speed signal from the position indication;

converting the measured α-β signals and the position signal into measured Q-D signals that represent measured position of the magnetic field relative to the rotor of the electric motor; and

serially sending the measured Q-D signals and the measured speed signal to the motor controller.

7. The method of claim **6** further comprising wherein calculating the setpoint Q-D signals further comprises calculating based on the setpoint speed signal, the measured speed signal, and the measured Q-D signals.

8. The method of claim **6** further comprising providing measured α-β signals and position signal synchronously with the position signal to the converting into the measured Q-D signals.

9. The method of claim **6** further comprising, by the field-oriented controller:

measuring temperature of a semiconductor substrate to create a measured temperature; and

delaying propagation of the measured α-β signals based on the measured temperature to compensate for processing delay in creating the position signal.

10. A packaged semiconductor product, comprising:

a position-sense terminal, current-sense terminals, a serial-bus terminal, and gate terminals;

a position-sensor interface coupled to the position-sense terminal, the position-sensor interface configured to generate a position signal and a speed signal;

a current-sensor interface coupled to the current-sense terminals, the current-sensor interface configured to generate current-sense signals;

a reference-frame converter coupled to the current-sense signals and the position signal, the reference-frame converter configured to transform a multiphase current reference frame of an electric motor to measured Q-D signals that represent position of a magnetic field relative to a rotor of the electric motor;

a communications interface coupled to the serial-bus terminal, the speed signal, and the measured Q-D signals, the communications interface configured to serially transmit the speed signal and the measured Q-D signals to a motor controller by way of the serial-bus terminal;

the communications interface further configured to receive, by way of the serial-bus terminal, setpoint Q-D signals;

an inverse reference-frame converter coupled to the setpoint Q-D signals, the inverse reference-frame converter configured to transform the setpoint Q-D signals into setpoint signals for a plurality of phases of the electric motor; and

a PWM generator coupled to the setpoint signals and configured to drive gate signals to the gate terminals.

11. The packaged semiconductor product of claim **10** wherein the communications interface is configured to serially transmit the speed signal and the measured Q-D signals at one megabit per second or less.

12. The packaged semiconductor product of claim **10** wherein the communications interface is configured to serially receive the setpoint Q-D signals at one megabit per second or less.

13. The packaged semiconductor product of claim **10**:

wherein the reference-frame converter comprises:

a Clarke converter coupled to the current-sense signals and configured to generate measured α-β signals that represent position of a magnetic field relative to a stator of the electric motor; and

a Park converter coupled to the position signal and the measured α-β signals, the Park converter configured to generate the measured Q-D signals;

wherein the inverse reference-frame converter comprises:

an inverse Park converter coupled to the setpoint Q-D signals, the inverse Park converter configured to generate setpoint α-β signals that represent setpoint position of the magnetic field relative to the stator; and

an inverse Clarke converter coupled to the setpoint α-β signals and configured to generate the setpoint signals.

14. The packaged semiconductor product of claim **13** further comprising a delay logic communicatively disposed between the Clarke converter and the Park converter, the delay logic configured to compensate for computational delay of the position-sensor interface.

15. The packaged semiconductor product of claim **13** further comprising:

a temperature sensor disposed within the packaged semiconductor product;

a controllable delay logic coupled to the temperature sensor and communicatively disposed between the Clarke converter and the Park converter, the controllable delay logic configured to compensate for both static computational delay and temperature dependent computational delay of the of the position-sensor interface.

16. The packaged semiconductor product of claim **13** further comprising a controllable delay logic communicatively disposed between the Clarke converter and the Park converter, the controllable delay logic configured to sense clocking frequency, and compensate for frequency-dependent computational delay of the of the position-sensor interface.

17. The packaged semiconductor product of claim **13** further comprising:

a temperature sensor disposed within the packaged semiconductor product;

a controllable delay logic coupled to the temperature sensor, and the controllable delay logic communicatively disposed between the Clarke converter and the Park converter, the controllable delay logic configured to:

compensate for static computational delay of the position-sensor interface; and

compensate for temperature-dependent computation delay of the position-sensor interface.

18. The packaged semiconductor product of claim **10** wherein the current-sensor interface is configured to receive analog signals from the current-sense terminal, and generate the current-sense signals in digital format.

19. The packaged semiconductor product of claim **10** wherein the position-sensor interface is configured to receive analog signals from the position-sense terminal, and generate the position signals in digital format.

20. The packaged semiconductor product of claim **10** comprising a semiconductor substrate, and wherein the position-sensor interface, the current sensor, the reference-frame converter, the communications interface, the inverse reference-frame converter, and the PWM generator are all implemented on the semiconductor substrate.

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