United States Patent	12388379
Kind Code	B2
Date of Patent	August 12, 2025
Inventor(s)	Luo; Hai Ming et al.

Sensorless motor assembly and method of controlling the same

Abstract

A method of controlling a sensorless motor (**32**). The method contains the steps of determining a current speed of the motor (**32**); selectively using a first method, a second method, or a third method to determine a position of a rotor of the motor (**32**), depending on the current speed of the motor (**32**); and transmitting a drive signal to the motor (**32**) based on the determined position of the rotor. A sensorless motor assembly is also disclosed. According to the method, multiple rotor position detection methods are provided to the sensorless motor (**32**) which cover a full speed range of the motor (**32**).

Inventors:	**Luo; Hai Ming (Dongguan, CN), Ma; Hai Bo (Hong Kong, CN), Gao; Yong Sheng (Hong Kong, CN)**
Applicant:	**TECHTRONIC CORDLESS GP** (Anderson, SC)
Family ID:	**1000008750123**
Assignee:	**Techtronic Cordless GP (Anderson, SC)**
Appl. No.:	**18/264163**
Filed (or PCT Filed):	**February 25, 2021**
PCT No.:	**PCT/CN2021/077825**
PCT Pub. No.:	**WO2022/178746**
PCT Pub. Date:	September 01, 2022

Prior Publication Data

Document Identifier	Publication Date
US 20240039437 A1	Feb. 01, 2024

Publication Classification

Int. Cl.: **H02P6/185** (20160101); **H02P6/18** (20160101); **H02P6/182** (20160101); **H02P6/20** (20160101)

U.S. Cl.:

CPC   **H02P6/181** (20130101); **H02P6/182** (20130101); **H02P6/20** (20130101);

Field of Classification Search

CPC: H02P (6/185); H02P (6/182); H02P (6/20); H02P (6/181); H02P (2203/03); H02P (2203/05)

USPC: 318/701

References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
5821660	12/1997	Anderson	318/400.11	H02K 3/28
6017354	12/1999	Culp et al.	N/A	N/A
6090123	12/1999	Culp et al.	N/A	N/A
6329778	12/2000	Culp et al.	N/A	N/A
6752816	12/2003	Culp et al.	N/A	N/A
7422582	12/2007	Malackowski et al.	N/A	N/A
7517351	12/2008	Culp et al.	N/A	N/A
7638958	12/2008	Philipp et al.	N/A	N/A
7998157	12/2010	Culp et al.	N/A	N/A
8030867	12/2010	Allison, III	N/A	N/A
8358093	12/2012	Allison, III	N/A	N/A
8616299	12/2012	Ichikawa	N/A	N/A
8653919	12/2013	Culp et al.	N/A	N/A
8657482	12/2013	Malackowski et al.	N/A	N/A
8786233	12/2013	Fair et al.	N/A	N/A
8796964	12/2013	Dietl et al.	N/A	N/A
8847531	12/2013	Allison, III	N/A	N/A
9325264	12/2015	Iwaji et al.	N/A	N/A
9408653	12/2015	Fair et al.	N/A	N/A
9559624	12/2016	Philipp	N/A	N/A
10004517	12/2017	Philipp	N/A	N/A
10076340	12/2017	Belagali et al.	N/A	N/A
10340824	12/2018	Sun et al.	N/A	N/A
10483948	12/2018	Sun et al.	N/A	N/A
10517610	12/2018	Philipp et al.	N/A	N/A
10797629	12/2019	Lakshmi Narasimha et al.	N/A	N/A
10820912	12/2019	Wildgen et al.	N/A	N/A
2002/0101208	12/2001	Yost	318/400.01	H02P 6/12

2006/0038517	12/2005	Mackay	N/A	N/A
2007/0250098	12/2006	Malackowski et al.	N/A	N/A
2010/0090631	12/2009	Yang	318/400.11	H02P 6/20
2011/0084639	12/2010	Brown	318/400.35	H02P 6/182
2011/0198521	12/2010	Hayashi	251/129.13	H02P 7/03
2011/0227523	12/2010	Grantz	N/A	N/A
2012/0062160	12/2011	Yang et al.	N/A	N/A
2014/0077738	12/2013	Iwaji et al.	N/A	N/A
2014/0333241	12/2013	Zhao et al.	N/A	N/A
2015/0130377	12/2014	Hidaka et al.	N/A	N/A
2015/0340980	12/2014	Lovas	318/400.33	H02P 6/183
2016/0287265	12/2015	Macdonald et al.	N/A	N/A
2017/0077851	12/2016	Ma et al.	N/A	N/A
2018/0054148	12/2017	Zhao	N/A	H02P 6/183
2018/0131295	12/2017	Sun et al.	N/A	N/A
2018/0360464	12/2017	Irvine	N/A	N/A
2019/0262977	12/2018	Seith	N/A	N/A
2019/0319562	12/2018	Narumi	N/A	N/A
2020/0113583	12/2019	Philipp et al.	N/A	N/A
2020/0287492	12/2019	Sega	N/A	N/A
2020/0389108	12/2019	Yajurvedi et al.	N/A	N/A
2020/0389109	12/2019	Yajurvedi et al.	N/A	N/A
2020/0389110	12/2019	Yajurvedi et al.	N/A	N/A
2021/0391815	12/2020	Sega	N/A	N/A
2021/0391816	12/2020	Sega	N/A	N/A
2021/0408954	12/2020	Sega	N/A	N/A
2022/0255479	12/2021	Yajurvedi et al.	N/A	N/A

FOREIGN PATENT DOCUMENTS

Patent No.	Application Date	Country	CPC
103501151	12/2013	CN	N/A
104158456	12/2013	CN	N/A
104579040	12/2014	CN	N/A
104601072	12/2014	CN	N/A
108258950	12/2017	CN	N/A
108964531	12/2017	CN	N/A
109450328	12/2018	CN	N/A
102011050101	12/2011	DE	N/A
202013008945	12/2012	DE	N/A
2061147	12/2008	EP	N/A
2535368	12/2015	GB	N/A
2015093056	12/2014	WO	N/A
2015169341	12/2014	WO	N/A
2018214979	12/2017	WO	N/A
2019149675	12/2018	WO	N/A
2020001660	12/2019	WO	N/A
2020214659	12/2019	WO	N/A

OTHER PUBLICATIONS

Extended European Search Report for Application No. 21847918.6 dated Jan. 4, 2023 (7 pages). cited by applicant

International Search Report and Written Opinion for Application No. PCT/CN2021/077825 dated Jul. 27, 2021 (10 pages). cited by applicant

European Patent Office Action for Application No. 21847918.6 dated Dec. 10, 2024 (5 pages). cited by applicant

Background/Summary

FIELD OF INVENTION

(1) This invention relates to brushless motors, and in particular to the control method of brushless motors that have no hall sensors.

BACKGROUND OF INVENTION

(2) Brushless motors are widely used in electrical appliances such as power tools because of their higher power efficiency, larger torque, and longer life term as compared to brushed motors. Most of the brushless motors currently deployed contain built-in sensors for determining the position of the rotor, and in particular hall sensors, because the position of the rotor relative to the stator is essential in determining the control sequence of multi-phase currents by the motor controller when driving the motor. Conventional motors include Hall sensors (or other rotary encoders) that provide rotor magnet position information to the motor controller. The motor controller selectively activates each phase U, V, and W based on the rotor magnet position information. Hall sensors and other external position sensors require additional parts and wiring that add cost, size, and design complexity to the motor drive. The presence of sensors also adds cost to the motor and reduces reliability of operation at high temperatures.

(3) On the other hand, there is another type of brushless motors which are known as sensorless motors, which as its name suggests does not contain any sensor for the rotor's position. Compared to typical brushless motors, sensorless motors are inexpensive, lighter in weight, less complicated and less prone to failure.

(4) However, there are also some disadvantages associated with traditional sensorless motors. When the rotor of a sensorless motor is rotating, its sensorless scheme can work perfectly, but this is not the case when the motor's rotor is stationary, and this leads to one major disadvantage of using conventional sensorless motors. Most traditional sensorless motors employ back EMF (BEMF) for determining the location of the rotor. However, when the motor's rotor is not turning, no back EMF is generated. Without back EMF, the drive circuitry of the sensorless motor lacks the information it needs to properly control the motor.

SUMMARY OF INVENTION

(5) Accordingly, the present invention, in one aspect, is a method of controlling a sensorless motor. The method contains the steps of determining a current speed of the motor; selectively using a first method, a second method, or a third method to determine a position of a rotor of the motor, depending on the current speed of the motor; and transmitting a drive signal to the motor based on the determined position of the rotor.

(6) In some embodiments, the first method is chosen if the motor is at zero speed.

(7) In some embodiments, in case of the first method, the method further contains the steps of sending a plurality of voltage pulses to multiple phases of the motor; in response, detecting a peak value in a total current of the motor; and determining the position of the rotor based on an occurrence time of the peak value.

(8) In some embodiments, the motor is a three-phase motor. The steps of sending a plurality of voltage pulses further contains sending six voltage pulses respectively to each of the three phases, and in both a forward and a reverse direction.

(9) In some embodiments, based on a correlation between the occurrence time of the peak value to one of the six voltage pulses, determining the position of the rotor further includes determining the position of the rotor in one of six angular ranges, each being 60°.

(10) In some embodiments, the second method is chosen if the current speed of the motor is above zero but below a threshold.

(11) In some embodiments, in case of the second method, the method further includes sending a plurality of voltage pulses to multiple phases of the motor; in response; determining self-inductances or mutual-inductances of stator windings of the motor; and determining the position of the rotor based on the self-inductances or the mutual-inductances of the multiple phases.

(12) In some embodiments, the step of determining self-inductances or mutual-inductances further contains the step of determining an air-gap flux density and a leakage flux density, in order to determine the self-inductances or the mutual-inductances.

(13) In some embodiments, the third method is chosen if the current speed of the motor is above the threshold.

(14) In some embodiments, in case of the third method, the method further includes the steps of measuring concurrently voltages of back electromotive force (BEMF) in multiple phases of the motor; and determining the position of the rotor based on the voltages of BEMF of the multiple phases.

(15) In some embodiments, determining the position of the rotor based on the voltages of BEMF of the multiple phases further includes comparing the voltages of BEMF with each other to determine the position of the rotor.

(16) In some embodiments, none of the first, second and third methods involves the detection of a phase current in the motor.

(17) In another aspect of the invention, there is provided a sensorless motor assembly, which contains a motor that includes a stator and a rotor; a switching module adapted to connect the motor to a power supply; and a motor controller connected to the switching module. The motor controller is adapted to determine a position of the rotor using a first method, a second method, or a third method, depending on a current speed of the rotor.

(18) In some embodiments, the motor controller is adapted to determine the position of the rotor using the first method if the motor is at zero speed.

(19) In some embodiments, the motor assembly further contains a current sensor connected to the motor. In case of the first method, the motor controller is adapted to control the switching module to send a plurality of voltage pulses to multiple phases of the motor; in response, read an electromotive force and a peak value in a total current of the motor from the current sensor; and determine the position of the rotor based on the peak value and the electromotive force.

(20) In some embodiments, the motor is a three-phase motor. In case of the first method, the motor controller is adapted to control the switching module to send six pulses respectively to each of the three phases, and in both a forward and a reverse direction.

(21) In some embodiments, based on a correlation between an occurrence time of the peak value to one of the six voltage pulses, the motor controller is further adapted to determine the position of the rotor in one of six angular ranges, each being 60°.

(22) In some embodiments, the motor controller is adapted to determine the position of the rotor using the second method if the current speed of the motor is above zero but below a threshold.

(23) In some embodiments, in case of the second method, the motor controller is adapted to send a plurality of voltage pulses to multiple phases of the motor; in response, determine self-inductances or mutual-inductances of stator windings of the motor; and determine the position of the rotor based on the self-inductances or the mutual-inductances of the multiple phases.

(24) In some embodiments, the motor controller is further adapted to determine an air-gap flux density and a leakage flux density, in order to determine the self-inductances or the mutual-inductances.

(25) In some embodiments, the motor controller is adapted to determine the position of the rotor using the third method if the current speed of the motor is above the threshold.

(26) In some embodiments, in case of the third method, the motor controller is further adapted to measure concurrently voltages of back electromotive force (BEMF) in multiple phases of the motor; and determine the position of the rotor based on the voltages of BEMF of the multiple phases.

(27) In some embodiments, the motor assembly further includes a comparator which is adapted to compare the voltages of BEMF with each other, and send results of comparison to the motor controller.

(28) In some embodiments, none of the first, second and third methods involves the detection of a phase current in the motor.

(29) There are many advantages to the present invention, one being that multiple rotor position detection methods are provided to the sensorless motor which covers a full speed range of the motor. The BEMF detection method is suitable for use when the motor is at relatively high speed, in particular above a threshold. In comparison, when the motor is running in a low-speed region below the threshold, the BEMF method is no longer preferred because of the weak BEMF detected at low or zero speed. Embodiments of the invention then provide an inductance-based detection method that make use of self-inductances or mutual-inductances of stator coils of the motor. This is possible because stator phase inductances are dependent of rotor position, thus an observer could be built to track the variation of the phase inductance over an electrical period, and thus determine the rotor position. Lastly, when the motor is still (i.e. zero speed), the rotor's position can be detected by injecting six pulses to all phases of the motor and in both forward and backward directions, thus to detect the rotor's initial position by finding the occurrence time of the peak value of the motor current. The various detection methods therefore fully cover all possible speed regions of the motor and ensure that a best rotor position detection technique can be applied. The control of the motor based on the detection result is therefore possible without using position sensors like hall sensors.

(30) In addition, the various detection methods according to embodiments of the invention can be conveniently adopted when the motor is started from any speed. For example, the motor may be previously cut power or braked, but if the motor is still running and then the user presses the trigger of the power tool again, then the motor upon energizing is brought back to operation, and depending on the speed at which the motor is re-energized, the motor controller could choose the appropriate detection method to resume operation of the motor.

(31) The foregoing summary is neither intended to define the invention of the application, which is measured by the claims, nor is it intended to be limiting as to the scope of the invention in any way.

Description

BRIEF DESCRIPTION OF FIGURES

(1) The foregoing and further features of the present invention will be apparent from the following description of embodiments which are provided by way of example only in connection with the accompanying figures, of which:

(2) FIG. **1** is a power tool in which the proposed motor assembly/method of controlling the motor is adopted, according to an embodiment of the invention.

(3) FIG. **2** is a schematic diagram of a motor assembly according to another embodiment of the invention.

(4) FIG. **3** shows the switching between three rotor position detection methods when the motor is started from zero speed according to another embodiment of the invention.

(5) FIG. **4** is another chart showing the different speed regions of the motor of FIG. **3** and its rotor position detection methods.

(6) FIG. **5** shows the correspondences between the rotor's position and the comparative magnitude of BEMF at different phases of the motor, when the third method at a high speed is used.

(7) FIG. **6** shows the switching between three rotor position detection methods when the motor of FIG. **3** is started from a low speed.

(8) FIG. **7** shows the switching between three rotor position detection methods when the motor of FIG. **3** is started from a high speed.

DETAILED DESCRIPTION

(9) In the claims which follow and in the preceding description, except where the context requires otherwise due to express language or necessary implication, the word "comprise" or variations such as "comprises" or "comprising" is used in an inclusive sense, i.e. to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

(10) As used herein and in the claims, "couple" or "connect" refers to electrical coupling or connection either directly or indirectly via one or more electrical means unless otherwise stated.

(11) Referring now to FIG. **1**, the first embodiment of the present invention is a power tool **20**, in particular a portable reciprocating saw, to which a sensorless motor assembly can be applied. The power tool **20** is powered by a battery pack (not shown) that can be attached to its handle portion **22**. The power tool **20** contains a housing **24** in which there is incorporated a sensorless motor assembly (not shown in FIG. **1**) that contains a brushless direct-current (BLDC) motor, its driving circuit, and a motor controller. The motor controller and the driving circuit (e.g. a switching module comprising transistors) may be deployed on a same circuit board, or be located on different circuit boards, as those skilled in the art will understand. The power tool **20** further includes an output driver **26** (illustrated as a saw blade clamping member). Although FIG. **1** illustrates a reciprocating saw, it should be understood that the sensorless motor assemblies that will be described in details below may be incorporated into other types of power tools including drill-drivers, impact drivers, impact wrenches, angle grinders, circular saws, reciprocating saws, string trimmers, leaf blowers, vacuums, and the like.

(12) FIG. **2** illustrates one example embodiment of a sensorless motor assembly used to provide a driving force to a power tool. The sensorless motor assembly in FIG. **2** can be applied to the power tool in FIG. **1**, although skilled persons in the art would recognize that the sensorless motor assembly may be used in other types of power tools too as mentioned above. The sensorless motor assembly includes a motor controller **28**, an inverter bridge **30**, and a motor **32**. In some embodiments, the motor controller **28** is implemented as a microprocessor with a separate memory. In other embodiments, the motor controller **28** is implemented as a microcontroller (with memory on the same chip). In other embodiments, the motor controller **28** may be implemented partially or entirely as, for example, a field programmable gate array (FPGA), an application specific integrated circuit (ASIC), hardware implemented state machine, etc., and the memory may not be needed or modified accordingly. The motor controller **28** controls the operation of the motor **32** through the inverter bridge **30**, and the inverter bridge **30** is used as a switching module for electronically commutation of currents through the motor **32**. The motor controller **28** is communicatively coupled to user inputs **34**, and a current sensor **36**. The user inputs **34** may include for example a trigger switch, a mode selector, and the like, all of which are not shown. The

trigger switch may include, for example, a potentiometer, a distance sensor, or the like to determine and provide an indication of the distance the trigger is pulled to the motor controller **28**. The current sensor **36** is coupled between the inverter bridge **30** and a negative DC bus **46** (i.e. in a return path from the motor to a power supply negative terminal) to detect the current flowing through each coil **32***a*, **32***b*, **32***c*, or a total current through the motor **32** (i.e. the DC supply current to the motor **32**). The motor controller **28** performs variable speed control of the motor **32** through the inverter bridge **30** based on one or more of the inputs received from the user input **34** and feedback information including a position of the rotor (not shown) that is received from the motor **32**.

(13) Besides the current sensor **36**, another module connected to the motor **32** is a response detector **48** that is in turn coupled to the motor controller **28**. The response detector **48** is adapted to detect response from the motor **32** other than the line current (i.e. supply current), for example the response detector **48** may be a voltage sensor used to sense a phase voltage, e.g. for measuring the BEMF on each phase in order to determine an air-gap flux density and a leakage flux density in the stator windings of the motor **32**. The response detector **48** is able to detect behaviors of the motor **32** upon the inverter bridge **30** injecting current pulses into the motor **32**. The output of the response detector **48** is supplied to the motor controller **28** so that the latter can conduct computations to obtain a real-time position of the rotor of the motor **32**. Note that the current detector **36** is also a type of response detector.

(14) The motor **32** as shown in FIG. **2** is a three-phase BLDC motor, which contains a stator and a rotor (both not shown). In the motor **32**, there is no position sensors like commonly used Hall sensors found in traditional BLDC motors. Rather, the rotor's position is determined by other feedbacks (e.g. current, BEMF voltage, inductance, flux density) from the motor and calculated by the motor controller **28**, as will be described in more details below. In the example illustrated, stator windings of the motor **32** include six coils **42**A-**42**F connected in a three phase, parallel delta configuration. In alternative embodiments, the coils **42**A-**42**F may be connected in alternative configurations (e.g., series, delta, etc.).

(15) The inverter bridge **30** controls the power supply to the three phases (e.g., U, V, and W) of the motor **32** of the power tool. The inverter bridge **30** includes high-side field effect transistors (FETs) **38** and low-side FETs **40** for each phase of the motor **32**. The high-side FETs **38** and the low-side FETs **40** are controlled by corresponding gate drivers implemented in, for example, the motor controller **28**.

(16) The drain of the high-side FETs **38** is connected to a positive DC bus **44** (e.g., a power supply), and the source of the high-side FETs **38** is connected to the motor **32** (for example, coils **42**A-**42**F of the motor **32**) to provide the power supply to the motor **32** (i.e., the corresponding coil **42**A-**42**F) when the high-side FETs **38** are closed. In other words, the high-side FETs **38** are connected between the positive DC bus **44** and the motor phase coils including the six coils **42**A-**42**F.

(17) The drain of the low-side FETs **40** is connected to the motor **32** (for example, phase coils of the motor **32**) and the source of the low-side FETs **40** is connected to the negative DC bus **46** (e.g., ground). In other words, the low-side FETs **40** are connected between the motor phase coils and negative DC bus **46**. The low-side FETs **40** provide a current path between the motor phase coils and the negative DC bus **46** when closed.

(18) In the example illustrated, to the inverter bridge **30**, the motor **32** appears as coils **42**A-**42**F connected in a DELTA configuration. The below explanation is provided with the DELTA configuration as an example, however, the explanation is equally applicable to other configurations (e.g., a WYE configuration) and the controls for these other configurations are obtained using simple mathematical transforms. The three motor terminals are normally referred to as U, V, and W terminals. The inverter bridge **30** allows the motor **32** to connect each of its terminals to either the positive DC bus **44**, the negative DC bus **46**, or leave the terminal open as explained above. The

motor controller **28** selectively enables the FETs **38**, **40** to activate the coils **42**A-**42**F using pulse-width modulated signals provided to the FETs **38**, **40**. The selective activation of the coils **42**A-**42**F produces a force on the permanent magnets (not shown) of the rotor to rotate the rotor, allowing the motor **32** to provide mechanical driving force.

(19) Turning now to FIGS. **3**-**7**, a sensorless motor control method according to an embodiment of the invention will now be described. The motor control method described herein is applicable to the sensorless motor assembly in FIG. **2**, although skilled persons in the art would recognize that the control method may also be applied to other types of sensorless motor assembly/circuit. FIG. **3** shows the scenario of a sensorless motor being energized when the motor is still (at zero speed). In this method, since the motor is sensorless, an appropriate method has to be chosen to determine a position of the rotor during operation of the motor, and there are three methods that can be selected. In FIG. **3**, as the motor assembly is first turned on when the motor is still, the BEMF method cannot be used because without rotation, it is impossible to detect any BEMF voltage from the stator winding. Instead, for this Initial Position Detection (IPD) mode where the motor is still (as shown by the circle **50** in FIG. **3**), a first method that will be used to detect the initial position of the rotor, which is a six-pulses detection method. In this method, the motor controller sends a plurality of voltage pulses to multiple phases of the motor. In response, the motor controller determines self-inductances or mutual-inductances of stator windings of the motor, and determine the position of the rotor based on the self-inductances or the mutual-inductances of the multiple phases.

(20) The six-pulse detection is conducted multiple times during the IPD mode, so as to minimize the error rate and inaccuracy that may resulted by a single detection, and also any potential, minor movement of the rotor because of the voltage pulses injected. Once these multiple detections have been attempted, the motor controller is aware of the rotor's initial position, and can start to drive the switching module at the moment shown by arrow **58** to drive the motor to rotate. Back to FIG. **3**, the pulses of the three phases of the motor when the motor is in the IPD mode is shown by the waveforms **60**, where one can see that the motor is not rotating as in at least one phase there is no effective current flow.

(21) Once the motor is driven to start rotating after the IPD mode, the motor then enters the DRIVE mode until the speed of the motor arrives at a first threshold shown by arrow **62**. As one can see, the DRIVE mode of the motor covers a substantial range of the motor speed, from near zero (but not at zero) to the threshold. In one example, the first threshold is set to be 3,000 RPM. If the motor speed is above the threshold, then the motor enters a BEMF mode. Both the DRIVE mode and the BEMF mode will be described in further details later. As shown in FIG. **3**, when the motor speed is dropping from a high level, for example because of a braking action and/or de-energizing of the motor, then when the motor speed drops to a second threshold indicated by the arrow **64**, the motor will return from the BEMF mode to the DRIVE mode. The second threshold can be equal to or different from the first threshold, and in an example the second threshold is 2,500 RPM.

(22) FIG. **6** is a simplified diagram showing the various speed regions of the motor from zero to full speed, and the corresponding rotor position detection modes for each speed region. In FIG. **6**, the difference between the time of mode change in an uprising speed curve and that in a lowering speed curve is ignored.

(23) In the inductance detection method, the motor controller sends signals to the switching module to drive the motor with two types of pulses. One of them is the driver pulse which is similar to typical drive currents used to drive a BLDC motor and speed it up. Another type of the pulses is the detection pulses, which are discrete from one other and the detection pulses are superimposed to the drive signals. The current detector and/or the response detector mentioned above is able to detect the behavior of the motor caused by the detection pulses to determine the various inductances mentioned above. Back to FIG. **3**, the change of currents in the three phases of the motor when the motor is changed from the DRIVE mode to the BEMF mode is shown by the waveforms **66**. Likewise, the change of currents in the three phases of the motor when the motor is

changed from the BEMF mode back to the DRIVE mode is shown by the waveforms **68**.

(24) In the third detection method of rotor's position, i.e. the BEMF mode, there is no specific signals (e.g. pulses) injected to the motor by the motor controller. Rather, as the motor is running at a high speed sufficient for its BEMF voltage to be detected, the rotor's position can be determined from the BEMF voltages. When a rotor magnet passes by a phase coil, the rotor magnet generates a current or BEMF in the phase coil. The current and/or EMF can be detected in sensorless motors to determine the rotor position and drive the motor accordingly, as will be described in more details below.

(25) In one implementation as shown in FIG. **5**, there is no zero-crossing or neutral point of the BEMF voltages determined. Rather, the BEMF voltages from the three phases of the motor are compared with a reference value to determine the rotor's position. In this method, the response detector of the sensorless motor assembly therefore includes a voltage detector (e.g. a voltage divider network), and there is also a comparator either built-in in the motor controller or being part of the response detector. As shown in FIG. **5**, for each of the six angular ranges of the motor as described above, the detected BEMF voltage will be different with respect to a reference value **70**. For example, in case the motor's rotor is located in the region of 60°~120°, then Phase A BEMF is substantially constant and above the reference value, while Phase C BEMF is substantially constant and below the reference value, and in addition Phase B BEMF is varying from below the reference value to above the reference value. As shown in FIG. **5**, in the BEMF detection method, there is no particular detection pulse injected to the motor, but the BEMF voltages are detected as the motor rotates.

(26) FIGS. **6** and **7** show respectively how the motor controller apply different detection methods if the motor is not energized from still. In FIG. **6**, if the motor is started from a low speed (e.g. before it reaches any of the first and second thresholds mentioned above), then the motor controller will apply the DRIVE mode and uses the inductance detection method directly. The change of currents in the three phases of the motor when the motor is energized at a low speed and enters the DRIVE mode is shown by the waveforms **72**. In FIG. **7**, if the motor is started from a high speed (e.g. before it reaches the second, lower threshold mentioned above), then the motor controller will apply the BEMF mode and uses the BEMF detection method directly. The change of currents in the three phases of the motor when the motor is energized at a low speed and enters the DRIVE mode is shown by the waveforms **74**.

(27) The scenarios shown in FIGS. **6-7** happen when the motor was previously de-energized, or braked (either passively or actively), but before the motor comes to a completely stop, the motor controller receives a user input to start the motor again (e.g. by the user pressing the trigger switch of the power tool). Then, the motor will start at a rotating status.

(28) The exemplary embodiments are thus fully described. Although the description referred to particular embodiments, it will be clear to one skilled in the art that the invention may be practiced with variation of these specific details. Hence this invention should not be construed as limited to the embodiments set forth herein.

(29) While the embodiments have been illustrated and described in detail in the drawings and foregoing description, the same is to be considered as illustrative and not restrictive in character, it being understood that only exemplary embodiments have been shown and described and do not limit the scope of the invention in any manner. It can be appreciated that any of the features described herein may be used with any embodiment. The illustrative embodiments are not exclusive of each other or of other embodiments not recited herein. Accordingly, the invention also provides embodiments that comprise combinations of one or more of the illustrative embodiments described above. Modifications and variations of the invention as herein set forth can be made without departing from the spirit and scope thereof, and, therefore, only such limitations should be imposed as are indicated by the appended claims.

(30) It is to be understood that, if any prior art publication is referred to herein, such reference does

not constitute an admission that the publication forms a part of the common general knowledge in the art, in Australia or any other country.

Claims

1. A method of controlling a sensorless motor, the method comprising: a) determining a current speed of the motor; b) selectively using a first method, a second method, or a third method to determine a position of a rotor of the motor, depending on the current speed of the motor; and c) transmitting a drive signal to the motor based on the determined position of the rotor; wherein the first method is chosen in step b) if the motor is at zero speed, wherein the second method is chosen in step b) if the current speed of the motor is above zero but below a threshold, and wherein the third method is chosen in step b) if the current speed of the motor is above the threshold; and wherein in case of the first method, step b) further includes: d) sending a plurality of voltage pulses to multiple phases of the motor, e) in response, detecting a peak value in a total current of the motor, and f) determining the position of the rotor based on an occurrence time of the peak value.

2. The method of claim 1, wherein the motor is a three-phase motor; step d) further comprising sending six voltage pulses respectively to each of the three phases, and in both a forward and a reverse direction, and wherein based on a correlation between the occurrence time of the peak value to one of the six voltage pulses, step f) further comprises determining the position of the rotor in one of six angular ranges, each being 60°.

3. The method of claim 1, wherein in case of the second method, step b) further comprises: g) sending a plurality of voltage pulses to multiple phases of the motor; h) in response, determining self-inductances or mutual-inductances of stator windings of the motor; and i) determining the position of the rotor based on the self-inductances or the mutual-inductances of the multiple phases.

4. The method of claim 3, wherein step h) further comprises determining an air-gap flux density and a leakage flux density, in order to determine the self-inductances or the mutual-inductances.

5. The method of claim 1, wherein in case of the third method, step b) further comprises: j) measuring concurrently voltages of back electromotive force (BEMF) in multiple phases of the motor; k) determining the position of the rotor based on the voltages of BEMF of the multiple phases.

6. The method of claim 5, wherein step k) further comprises comparing the voltages of BEMF with each other to determine the position of the rotor.

7. The method of claim 1, wherein none of the first, second and third methods involves the detection of a phase current in the motor.

8. A sensorless motor assembly, comprising a) a motor that comprises a stator and a rotor; b) a switching module adapted to connect the motor to a power supply; and c) a motor controller connected to the switching module; wherein the motor controller is adapted to determine a position of the rotor using a first method, a second method, or a third method, depending on a current speed of the rotor; wherein the motor controller is adapted to determine the position of the rotor using the first method if the motor is at zero speed; and wherein a current sensor is connected to the motor, and wherein in a case of the first method, the motor controller is configured to: d) control the switching module to send a plurality of voltage pulses to multiple phases of the motor, e) in response, read an electromotive force and a peak value in a total current of the motor from the current sensor, and f) determine the position of the rotor based on the peak value and the electromotive force.

9. The motor assembly of claim 8, wherein the motor is a three-phase motor; in case of the first method, the motor controller is adapted to control the switching module to send six voltage pulses respectively to each of the three phases, and in both a forward and a reverse direction, and wherein based on a correlation between the peak value to one of the six pulses, the motor controller is further adapted to determine the position of the rotor in one of six angular ranges, each being 60°.

10. The motor assembly of claim 8, wherein the motor controller is adapted to determine the position of the rotor using the second method if the current speed of the motor is above zero but below a threshold.

11. The motor assembly of claim 10, wherein in the case of the second method, the motor controller is adapted to: g) send a plurality of voltage pulses to multiple phases of the motor; h) in response, determine self-inductances or mutual-inductances of stator windings of the motor; and i) determine the position of the rotor based on the self-inductances or the mutual-inductances of the multiple phases.

12. The motor assembly of claim 11, wherein the motor controller is further adapted to determine an air-gap flux density and a leakage flux density, in order to determine the self-inductances or the mutual-inductances.

13. The motor assembly of claim 8, wherein none of the first, second and third methods involves a detection of a phase current in the motor.

14. The motor assembly of claim 8, wherein the motor controller is adapted to determine the position of the rotor using the third method if the current speed of the motor is above a threshold.

15. The motor assembly of claim 14, wherein in case of the third method, the motor controller is further adapted to: j) measure concurrently voltages of back electromotive force (BEMF) in multiple phases of the motor; and k) determine the position of the rotor based on the voltages of BEMF of the multiple phases.

16. The motor assembly of claim 15, further comprises a comparator which is adapted to compare the voltages of BEMF with each other, and send results of comparison to the motor controller.