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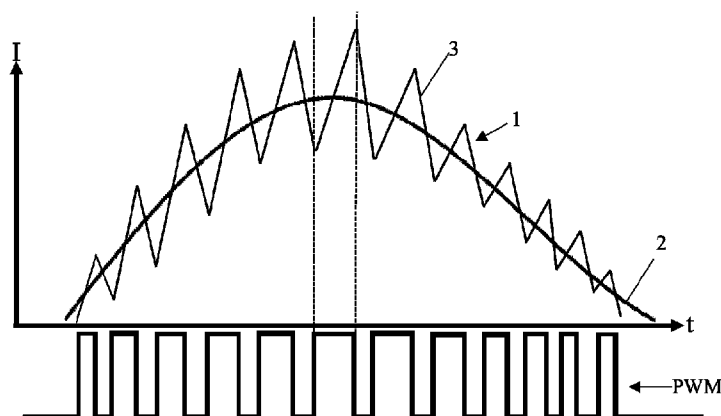


Figure 2A

(57) Abstract: The present invention provides systems and methods for controlling an electric motor. The system comprises a sensor arrangement (110) comprising a first sensor (117) configured to measure the current in a phase (U, V, W) of the motor, and a second sensor (115) configured to measure the rate of change of current (di/dt) in the phase of the motor. A controller (120) is configured to drive the electric motor based on feedback received from the sensor arrangement (110). The controller (120) does not have to apply test signals or injection pulses to the motor phase to determine the angle of the rotor.



ELECTRIC MOTOR CONTROL

Field of the Invention

- 5 This invention relates to an apparatus and method for controlling or driving a motor, in particular a brushless sensorless motor.

Background

- 10 Electric motors are machines that convert electrical energy into mechanical energy. Brushed DC motors are well known, as they have been in use for over 100 years. A brushed DC motor comprises a stator which generates a permanent magnetic field and a rotor placed inside the magnetic field. The rotor comprises one or more wire windings which are connected to a power supply to generate a magnetic field. The poles of the rotor field are attracted to the
15 opposing pole of the stator field, causing the rotor to move.

- To keep the rotor turning the magnetic poles of the rotor field need to be switched. In a brushed DC motor this switching is done using a split-ring commutator mounted on the axle of the rotor and two brushes connected to the terminals of the power supply. When the
20 brushes contact a different segment of the commutator the polarity of the rotor field is reversed.

- Brushed DC motors are still used today, for example in many stairlifts, as they are a cheap and relatively simple motor system. However, there are disadvantages to this system. The
25 friction generated between the brushes and the commutator causes wear, which limits the life of the motor. The motors are also relatively loud, large and 'clunky'.

- In an attempt to address these issues, the more modern brushless DC motor (BLDC) and brushless AC motor (BLAC) were invented. As the name suggests, there are no brushes or
30 split-ring commutators in these motors. In a BLDC motor the rotor comprises at least one permanent magnet and it is the magnetic fields of the surrounding stator windings which are switched. An 'electronic commutator' (drive electronics) sequentially energises the stator

-2-

windings to generate a rotating magnetic field that causes the rotor to spin. Specifically, Pulse Width Modulation (PWM) voltage signals are applied to the stator windings. Typically, a three-phase motor is used which comprises three stator windings surrounding the rotor, each winding being powered by a different PWM signal (see Figure 1).

5

In order to power the stator windings in the correct sequence to rotate the rotor at the desired speed, the position (or angle) of the rotor must be known at all times. In a standard BLDC motor the position of the rotor is measured using Hall-effect sensors. A Hall-effect sensor generates an output voltage which is a function of the magnetic field density at the sensor.

10 If a Hall-effect sensor is provided proximate to each stator winding, then the position of the rotor relative to each sensor will determine the strength of the output voltage signal, thereby allowing the position of the rotor to be determined.

Brushless motors do address the problem of mechanical wear in the motor, thereby
15 improving reliability. They are also generally quieter and more powerful than a brushed motor. However, BLDC motors are more expensive due to the cost of the sensors and the complex electronic commutator system.

In addition, there are a lot of electric cables and connections in a brushless motor compared
20 to a brushed motor. Any dust, dirt or moisture which gets into these cables, particularly those connected to the Hall-effect sensors, affects the performance of the motor. Therefore, an increased amount of cabling is a disadvantage, particularly for motors used in potentially dusty or dirty environments, such as in vehicles.

25 An alternative solution is the brushless sensorless motor (or sensorless BLDC). Sensorless brushless motor systems do not use Hall-effect sensors built-in to the motor to determine the position of the rotor. Advantageously, removing these sensors from the motor can potentially decrease the complexity, size and weight of the motor system.

30 Instead, one option used is to measure the back EMF generated by the movement of the rotor. As the stator windings cut through the rotating magnetic field of the rotor, a potential

-3-

is generated in the stator windings, which is called a back electromotive force (back EMF or BEMF), as it opposes the rotation of the rotor.

By measuring the back EMF generated in each stator winding a motor control system can
5 determine the position of the rotor at a given time, as long as the rotor is moving. This allows the controller to drive the motor correctly.

If the rotor is stationary then no back EMF will be generated, as the stator windings will not be cutting a moving magnetic field. The back EMF will also be very low when the motor
10 speed is low, making it difficult to detect. It is therefore not possible to reliably determine the position of the rotor using back EMF measurements at zero or very low rotor speeds. It is crucial to know the position of the motor at zero or low speeds in order to correctly start the motor and to control the motor at low speeds. This is particularly important in personal transport systems, such as stairlifts.

15 It is possible to determine the position of the rotor at zero or low speeds in a sensorless brushless DC motor system based on the inductance of the phases of the motor. Inductive techniques require fewer electric cables or connections compared to a brushless motor with built-in sensors, therefore these methods (or systems) are less affected by dust or dirt.

20 The inductance (L) of an electric conductor is inversely proportional to the rate of change of current (dI/dt) for a given voltage (V) across the conductor. From Faraday's law of induction the inductance is given by:

$$V = L \frac{dI}{dt} \quad - (1)$$

25 As shown in equation 1 above, if the voltage across the winding is known, by measuring the current derivatives of at least two phases of the motor the inductance of the stator windings can be determined. Similarly, a change in the inductance of a conductor will result in an inversely proportional change in the derivative of the current (dI/dt) across the winding.

30 The inductance of a conductor, such as a stator winding, is an inherent property that is only affected by the amount and proximity of magnetic (e.g. ferrous, rare earth) material to the

-4-

conductor and the winding design itself. For example, placing an iron rod near to a stator winding will increase the inductance of the stator winding.

The position of the rotor relative to each stator winding will therefore affect the inductance of each winding. Accordingly, the inductance of the stator windings varies with the angle of the rotor. As the current derivative (dI/dt) is inversely proportional to the inductance, the current derivative therefore also varies with the angle of the rotor. It is therefore possible to measure the current derivative as a function of time for two or more stator windings and, from these measurements, the angle of the rotor can be determined (or estimated) using well-known vector mathematics. This approach is not dependent upon the motor speed, so it can be used even when the motor is stationary.

An example of such an inductive technique, and the calculations involved, is disclosed in WO2017/045810.

Specifically, the electrical angle (θ) of the rotor at a given time can be estimated from the current derivative measurements of two stator windings at that time using the ARCTAN2 or ATAN2 trigonometric function. This function determines the electrical angle θ in radians between the positive x-axis and the electrical position of the rotor.

For a motor, the electrical angle is the angle that the rotor has travelled through the electric cycle. In a complete electric cycle (North pole to North pole of the magnetic field) the electrical angle varies from 0° to 360° . The mechanical or physical angle is the angle at which the rotor has been rotated mechanically.

The relationship between the electrical and mechanical angle of the rotor is dependent on the number of magnetic poles (N) of the motor field as stated in equation 2 below:

$$\theta_{electric} = \frac{N}{2} \cdot \theta_{mechanical} \quad - (2)$$

For example, for a four pole motor ($N=4$) there are two North and two South poles. The rotor has to rotate 180 degree mechanically to reach from one North pole to another North pole. Thus, to pass through a complete electric cycle (360 electrical degrees) the rotor only has to

-5-

rotate by 180 degrees mechanically. As such, one mechanical degree of rotation is equal to two electrical degrees.

Given that the electrical angle can be found using the ARCTAN2 function the mechanical
5 angle of the rotor can then be determined using equation 2. It is then theoretically possible to work out the position of the rotor at a given time, as long as the starting position of the rotor is known at least to some extent (e.g. it is known which electric cycle the rotor is in when the motor starts). There are known ways of determining the starting position or starting cycle of the rotor, such as Ping techniques (or modulated PWM injection), described below.

10

As stated above, the windings (or phases) in a sensorless motor are driven using PWM signals. In order to measure the rate of change of current (dI/dt) across a phase of the motor it is known to 'inject' test signals, typically long square wave pulses, into the windings at regular intervals. The test signal or injection pulse interrupts the normal PWM duty cycle
15 used to drive the motor. The rate of change of the test signal or injection pulse is measured, which provides the dI/dt values for use with the ARCTAN2 function or other calculation techniques. Typically, the time taken for the current in the winding to reach a given threshold is measured.

20 The period and amplitude of the injection current pulse is much longer than the PWM signals used to drive the motor, which makes it much easier to accurately measure the rate of change of the injection pulse. However, the injection pulses cannot be applied too frequently as they disrupt the normal commutation of the motor, so the angle of the rotor is not known at all points in time. The injection pulses are generally applied at audible frequencies, which
25 causes the motor to buzz or generate an irritating noise.

It is also known to directly measure the current derivative of the injection pulse using specialist current sensors, such as Rogowski coils, as described in US2013/0293171. These specialist sensors are expensive and increase the size and weight of the motor control system.

30

It is also known for inductive motor control systems to only to apply a single injection pulse to the motor upon initialisation of the control system (i.e. as part of a start sequence). This

-6-

is sometimes known as 'pinging' the motor, or the Ping technique. This allows the controller to roughly estimate the starting rotor angle, so as to determine which 180° segment (or electric cycle) the rotor is initially located in.

- 5 There is therefore a need for a reliable motor control system which is cheaper, smaller and lightweight. There is also a need for a motor control system which determines the position of the rotor more frequently, thereby driving the motor more smoothly and efficiently.

Summary of the Invention

10

In a first aspect, the present invention provides a system for controlling an electric motor, wherein the motor comprises a rotor and stator windings, comprising:

- a sensor arrangement comprising: a first sensor configured to measure the current in a phase of the motor and a second sensor configured to measure the rate of change of
15 current (dI/dt) in the phase of the motor; and

a controller configured to drive the electric motor based on feedback received from the sensor arrangement.

- The sensor arrangement of the present invention measures both the current in a phase of the
20 motor and the rate of change of current in the phase of the motor, using a first sensor and a second sensor respectively. This provides an accurate and efficient motor control system, even at low motor speeds. Advantageously, the rate of change of current (dI/dt) does not have to be calculated from the current signal, thereby reducing processing time. The phase current is still measured for use in controlling or limiting the phase current and determining
25 the rotor angle.

- The current measured by the first sensor may be called the commutation current. The commutation current signal is defined as the current in the motor phase (or across the stator winding) which results from the controller driving the motor. The commutation current
30 signal does not include any test signals or injection pulses applied to the motor for the sole purpose of allowing the rate of change of the current (or current derivative) to be measured.

-7-

In other words, the commutation current signal is the current in the phase of the motor generated by the normal PWM cycles used to drive the motor.

Advantageously, the present invention has improved the sensing of the rate of change of current in the motor phases, so as to directly measure the commutation current signals used to drive the motor. There is no test current signal or injection pulse applied to the motor, just the normal signals used to drive the motor. As such there is no disruption to the normal commutation of the motor, so the motor runs more smoothly and with less noise.

10 In addition, as the commutation current signal is measured by the sensor arrangement, rather than a test signal, the position of the rotor can be calculated much more frequently. This is because the test signals (or injection pulses) can only be applied to the motor phases at intervals so as to not disrupt the driving of the motor too much, thereby limiting the quality of the feedback provided by the sensors. In comparison, the commutation current signal can
15 be almost constantly measured without any breaks or pauses.

The present invention discovered that is possible to measure the commutation current signal (or rate of change of the commutation current signal) directly (without using a test signal) as processors which are capable of processing the current signal data at the required speed are
20 now commercially available at relatively inexpensive prices.

The present invention may apply a single test signal (or injection pulse) upon initialisation of the motor control system (e.g. as part of a start up sequence), so as to determine which 180° segment (or electric cycle) the rotor is initially in. In other words, a Ping technique may
25 be used to roughly estimate the starting position of the rotor upon switching on the motor control system.

Each stator winding may correspond to one of the motor phases. It will be appreciated that each stator winding can comprise a plurality of coils connected in series.

-8-

Optionally, the first sensor is configured to measure the amplitude of the low frequency current in the phase of the motor. The first sensor may output a signal proportional to the level (or amplitude) of current in the motor phase.

- 5 Optionally, the first sensor is a Hall-effect sensor, preferably a linear Hall-effect sensor.

The second sensor may output a signal proportional to the rate of change of current in the motor phase. This may be called a differential signal.

- 10 Optionally, the second sensor is a current transformer sensor.

The current transformer sensor may comprise a primary coil, a secondary coil and a ferrite core or air core, wherein the primary coil is electrically coupled to the motor phase and the secondary coil is magnetically coupled to the primary coil via the ferrite core or air core.

15

The secondary coil may output a signal (or voltage) proportional to the rate of change of current in the primary coil.

- 20 The sensor arrangement may be provided on a single circuit board, preferably a PCB. Thus, the sensor arrangement of the present invention is more compact and cost effective compared to known motor control sensor units, such as those which comprise Rogowski coils, without reducing the quality of the signals output from the sensors.

- 25 The secondary coil comprises a greater number of turns than the primary coil. In some embodiments, the primary coil may only require 4 turns and the secondary coil may comprise around 60 turns. This may vary depending on the properties of the motor or the motor control requirements.

- 30 In some embodiments the system may comprise a plurality of sensor arrangements, wherein each sensor arrangement is connected to a respective phase of the motor. For example, the system may be configured to control a three-phase motor and so the system may comprise

-9-

two sensor units, or three sensor units. It will be appreciated that a sensor arrangement does not have to be connected to every phase of the motor, as explained below.

As the phases of a three-phase motor are connected together, it is not necessary to measure the current or rate of change of current of all three phases to estimate the angle of the rotor, as the current signals are dependent. Therefore, it is possible to control the motor by measuring the current in two of the phases. It may be preferred to measure only two of the motor phases, as this reduces the number of sensor arrangements required, therefore reducing the cost, size and complexity of the system.

10

Optionally, the plurality of sensor arrangements are provided on a single circuit board, preferably a printed circuit board. Thus, the present invention is smaller and lighter than many known motor control systems that comprise large bulky sensors (e.g. Rogowski coils).

15 Optionally, the controller is a microcontroller.

As mentioned above, the rate of change of current in the motor phase is inversely proportional to the inductance of the motor phase (see equation 1). The inductance of the motor phase changes with the angle of the rotor. Thus, the controller may be configured to use any known method of determining the estimated angle of the rotor from the measurements of the, or each, sensor unit, in order to drive the motor.

20

Optionally, the controller comprises a processor. The processor is configured to process the signals output from the sensor arrangement.

25

The processor may be configured to determine an estimated angle of the rotor. The estimated angle of the rotor is the estimated physical or mechanical angle of the rotor.

The controller may include a memory comprising stored data. The memory may be a flash memory.

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-10-

The processor may be configured to compare the outputs of the, or each sensor arrangement, or values derived from the outputs of the, or each, sensor arrangement, to the data stored in the memory to retrieve the estimated angle of the rotor.

- 5 Thus, the processor may not calculate the angle of the rotor from the outputs of the (or each) sensor arrangement. Instead, the processor may compare the outputs to the data stored in the memory and retrieve an estimated angle of the rotor. This may be quicker and more efficient, as it potentially reduces the amount of processing and calculation to be done by the processor.

10

The processor may comprise software configured to compare the outputs of the, or each, sensor arrangement, or one or more values derived from the outputs of the, or each, sensor arrangement, to the data stored in the memory to retrieve the closest match for the rotor angle.

15

Optionally, the data stored in the memory comprises recorded outputs of the, or each, sensor arrangement at known angles of the rotor, or values derived from the recorded outputs of the, or each, sensor arrangement at known angles of the rotor.

- 20 Optionally, the data stored in the memory comprises a plurality of look-up tables and/or a plurality of reference maps or reference graphs.

In some embodiments, the reference maps or reference graphs may be 2D or 3D contour plots, and/or polar graphs.

25

Optionally, the processor may be configured to determine the current vector in the motor from the signal output by the, or each, first sensor.

- 30 Optionally, the processor may be configured to process the signal output by the, or each, second sensor to determine a value indicative of the rate of change of current in the motor phase over a given time period.

-11-

The processor may use regression analysis on the signal output by the, or each, second sensor to determine a rate of change of current in the motor phase for a given time period. This may be called a processed rate of change of current.

- 5 The processor may be configured to modify the signal output from, the, or each, second sensor, or the processed rate of change of current, to eliminate the effect of the back EMF and/or I.R losses in the motor phase.

- 10 Optionally, the processor may process the signal output by the, or each, second sensor to determine a positive rate of change of current (A) and a negative rate of change of current (B) in the motor phase for a given time period. This may be done using regression analysis.

- The processor may then determine a modified rate of change of current (ΔI) in the motor phase by taking the difference between the positive and negative dI/dt values (i.e. $A - B$).
- 15 This modification works as the effect of the back EMF is to lift A (positive dI/dt) and lower B (negative dI/dt) by the same amount. Alternatively, equation 3 may be used (described below) which eliminates the scaling factor of 2 in the modified rate of change of current (ΔI).

- 20 Optionally, the data stored in the memory comprises a plurality of reference graphs or look-up tables, wherein each reference graph or look-up table is for a given current vector and displays the recorded outputs of the, or each, second sensor, against the angle of the rotor.

- 25 Optionally, the data stored in the memory comprises a plurality of reference graphs or look-up tables, wherein each reference graph or look-up table is for a given current vector and displays values derived from the recorded outputs of the, or each, second sensor, against the angle of the rotor.

- 30 Optionally, the data stored in the memory comprises a plurality of reference graphs or look-up tables, wherein each reference graph or look-up table is for a given current vector and displays the modified rate of change of current (ΔI) of the or each motor phase, against the angle of the rotor.

-12-

The data stored in the memory may be test data obtained during a one-off set-up procedure of the motor. The set-up procedure is preferably carried out with the motor not under load.

- 5 A flywheel may be connected to the motor during the set-up procedure to dampen movement during testing.

In the set-up procedure the input current vector and rotor angle may be set to a given starting value. The processor may then determine the modified rate of change of current (ΔI) for the,
10 or each, motor phase while the rotor angle is increased or decreased in increments to cover a total of 360° . The current vector is then increased, and the process is repeated.

The rotor angle may varied in increments of 5° between 0° and 360° .

- 15 The angle of the current vector may be varied in increments of 5° between 0° and 360° .

The amplitude of the current vector may be varied in increments (for each angle) between 0 amps and a maximum current limit (e.g. 80 amps).

- 20 The processor may then collate the recorded data (or data points) into a plurality of look-up tables or reference graphs.

Optionally, the processor is configured to calculate the back EMF in each phase of the motor based on the current measured by the, or each, first sensor.

25

- In some embodiments, when the motor speed exceeds a predetermined threshold, the controller is configured to determine an estimated angle of the rotor from the back EMF calculations. For example, if the motor speed exceeds a given threshold (e.g. 500 RPM) the processor is configured to determine the angle of the rotor from the back EMF calculations,
30 rather than retrieving the estimated angle from the memory.

-13-

Optionally, the processor may be configured to stop processing the outputs from the, or each, second sensor when the motor speed exceeds a predetermined threshold.

Optionally, the controller is configured drive the electric motor by applying a current
5 vector, or a voltage vector, having an angle of 90° from the estimated angle of the rotor.

It will be appreciated that there are circumstances (e.g. when wanting to build speed) in which it may be desirable to drive the using a current vector or voltage vector having an angle which is greater than 90° from the angle of the rotor. This is often known as 'Phase
10 Advance' or 'Field Weakening'.

Optionally, the controller comprises drive electronics configured to apply Pulse Width Modulation (PWM) signals to power each phase of the motor, thereby driving the motor.

15 Optionally, the drive electronics are configured to apply an AC (or sinusoidal) commutation sequence to each phase of the motor.

In some embodiments, the drive electronics are configured to emit PWM signals with a frequency of between 15 kHz and 25 kHz, preferably around 20 kHz.
20

In a second aspect, the present invention provides a method for controlling an electric motor comprising a rotor and stator windings, the method comprising:

using a sensor arrangement comprising a first sensor and a second sensor to:
measure the current in a phase of the motor using the first sensor; and
25 measure the rate of change of current in the phase of the motor using the second sensor;
determining an estimated angle of the rotor based on feedback from the sensor arrangement; and
driving the electric motor.

30

It will be appreciated that the method could be carried out using the motor control system of the first aspect of the invention.

The benefits of the method of the present invention are as recited in connection with the motor control system of the first aspect of the invention

- 5 Preferably, the method does not comprise applying or injecting a test signal to the motor.

Optionally, the method comprises using a plurality of sensor arrangements to measure the current and the rate of change of current in a plurality of phases of the motor. As mentioned above, the motor may be a multi-phase motor and the method may comprise measuring the
10 current and rate of change of current in two or more of the phases.

The step of determining the estimated angle of the rotor based on feedback from the, or each, sensor arrangement, may be carried out using any known technique or method.

- 15 The method may further comprise comparing the outputs of the, or each sensor arrangement, or values derived from the outputs of the, or each, sensor arrangement, to data stored in a memory and retrieving an estimated angle of the rotor. Thus, the method may comprise extracting the angle of the rotor for a memory rather than calculating the angle of the rotor in real-time from the measurements output by the, or each, sensor arrangement.

20

Optionally, the method includes extracting the estimated angle of the rotor from a look-up table, reference map or reference graph stored in the memory. In some embodiments, the reference map or reference graphs may be a 2D or 3D contour plot, or a polar map.

- 25 The method may comprise calculating the current vector in the motor from the outputs of the, or each, first sensor.

The method may comprise selecting the correct look-up table or reference map based on the calculated current vector in the motor.

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-15-

The method may comprise comparing the outputs of the, or each, second sensor to the recorded values in the selected look-up table or reference map and extracting the estimated angle of the rotor.

- 5 The method may comprise comparing values derived from the outputs of the, or each, second sensor to the recorded values in the selected look-up table or reference map and extracting the estimated angle of the rotor.

10 The method may comprise using interpolation to determine the estimated angle of the rotor if the outputs from the, or each sensor arrangement, fall between known values or points in the data stored in the memory.

The method may comprise calculating the back EMF in the, or each, phase of the motor based on the current measured by the, or each, first sensor.

15

Optionally, when the motor speed exceeds a predetermined threshold, the method comprises determining the estimated angle of the rotor from the back EMF calculations.

20 For example, if the motor speed exceeds a given threshold (e.g. 500 RPM) the method comprises determining the angle of the rotor from the back EMF calculations, rather than retrieving the estimated angle from the memory.

Optionally, driving the electric motor comprises applying a current vector, or a voltage vector, having an angle of 90° from the estimated angle of the rotor.

25

Optionally, driving the electric motor comprises applying Pulse Width Modulation (PWM) signals to each phase of the motor.

30 Optionally, an AC commutation sequence, or a sinusoidal commutation sequence is used to drive the motor.

-16-

Optionally, the PWM signals have a frequency of between 15 kHz and 25 kHz, preferably around 20 kHz. Advantageously, the PWM signals may have a frequency above human audible hearing range.

- 5 Optionally, a Locked Anti-phase PWM sequence is used to drive the electric motor.

Optionally, when the motor is stationary, the Locked Anti-phase PWM sequence applies pulses which generate no net current in the or each motor phase. This allows the angle of the rotor to be determined even if the motor is stationary or at very low speed, as signals will
10 still be output by the or each sensor arrangement.

The method may comprise carrying out a one-off set-up process for the motor, as described above in the first aspect of the invention.

- 15 In a third aspect, the invention provides a system for controlling an electric motor, wherein the motor comprises a rotor and stator windings, comprising:

 at least two measurement units, each measurement unit comprising a sensor configured to measure the commutation current signal across a respective stator winding; and

- 20 a controller configured to drive the electric motor based on feedback received from the measurement units.

It will be appreciated that this aspect of the invention may comprise any embodiment or feature of the first aspect of the invention, and vice-versa.

25

The commutation current signal is defined as the current across the stator winding which results from the controller driving the motor. The commutation current signal does not include any test signals or injection pulses applied to the windings for the sole purpose of allowing the current derivative to be measured.

30

In other words, the commutation current signal is the current along the stator winding generated by the normal PWM cycles used to drive the motor.

-17-

Advantageously, the present invention directly measures the commutation current signals used to drive the stator windings. There is no test current signal or injection pulse applied to the stator windings, just the normal signals used to drive the motor. As such there is no
5 disruption to the normal commutation of the motor, so the motor runs more smoothly and with less noise.

In addition, as the commutation current signal is measured by the sensor, rather than a test signal, the position of the rotor can be calculated much more frequently. This is because the
10 test signals (or injection pulses) can only be applied to the windings at intervals so as to not disrupt the driving of the motor too much, thereby limiting the quality of the feedback provided by the sensors. In comparison, the commutation current signal can be almost constantly measured without any breaks or pauses.

15 The present invention discovered that is possible to measure the commutation current signal directly (without using a test signal) as processors which are capable of processing the current signal data at the required speed are now commercially available at relatively inexpensive prices.

20 In use, a first measurement unit is preferably connected in series with a first stator winding, and a second measurement winding is preferably connected in series with a second stator winding.

The commutation current signals are preferably sinusoidal.
25

Optionally, each sensor is configured to continuously measure the commutation current signal.

Optionally, the controller comprises a processor configured to calculate the position or angle
30 of the rotor.

-18-

The processor may be configured to calculate the current derivative (dI/dt) of the commutation current signal measured by each sensor and to use these values to calculate the position or angle of the rotor.

- 5 The controller then drives the motor based on feedback from the processor.

Optionally, each sensor is configured to measure the amplitude of a high frequency current ripple in the commutation current signal.

- 10 The processor may be configured to calculate the current derivative (dI/dt) by measuring the positive and negative gradients of each period of the high frequency current ripple in the commutation current signals.

- The current flowing through each stator winding of a brushless motor generally comprises a
15 base commutation waveform, which has a low frequency, and a high frequency current ripple, as shown in Figure 2A. The high frequency current ripple is caused by the Pulse Width Modulation (PWM) signals used to energise the stator winding switching the power supply on and off. The amplitude of the high frequency current ripple is affected by the change in inductance of the stator winding, therefore it is the current derivative (or rate of
20 change) of this waveform that needs to be accurately measured in order to calculate the rotor position.

- Although it is possible to measure the commutation current signal as a function of time using a single sensor, it may be preferred to split (or separate) the commutation current signal into
25 a high frequency signal and a low frequency signal.

In some embodiments each measurement unit may therefore comprise:

- a filter configured to split the commutation current signal into a high frequency signal along a first path and a low frequency signal along a second path parallel to the first
30 path; and
- a first sensor to measure the amplitude of the high frequency current signal;

-19-

wherein the controller is configured to drive the electric motor based on feedback received from the first sensors.

5 The amplitude of the high frequency current waveform or signal is small relative to the low frequency current waveform or signal. For example, the low frequency current signal can have an amplitude which is roughly 10 times larger than the amplitude of the high frequency current signal. Thus, the detail of the high frequency current signal can be drowned out by the larger low frequency current signal.

10 Splitting (separating) the signals allows a more sensitive current sensor to be used to measure the high frequency current, wherein the sensor would be damaged or destroyed by the low frequency current signal. This allows a more accurate and precise measurement of the high frequency current signal as a function of time. In addition, the first sensor may be less expensive than a sensor which measures the high and low frequency signals together.

15 Throughout this application the term 'low frequency' refers to signals with a frequency of between 0 to 1 KHz (e.g. the base commutation waveform 2 in Figure 2A) and 'high frequency' refers to PWM current ripples with a frequency of between 5 KHz to 50 KHz (e.g. the high frequency waveform 3 in Figure 2A). As explained above, these two
20 components to the current signal are generated by the PWM signals used to drive the motor.

The filter may equivalently be referred to as a splitter. It will be appreciated that these two terms are interchangeable.

25 The first and second paths are defined by electrical connections, such as wires or electrical paths on a circuit board.

Optionally, the filter comprises an inductor positioned on the second path. The inductor may comprise a coil and a ferrite core. The ferrite core increases coil inductance and focuses the
30 magnetic field of the surrounding coil onto the second sensor.

-20-

The inductor at least partially separates the high frequency current from the low frequency current, as high frequency (AC) current is resistant to passing through an inductor. Therefore, almost all of the high frequency current travels along the first path rather than the second path.

5

It should be appreciated that the filter can comprise more than one component.

Optionally, each measurement unit further comprises a second sensor to measure the low frequency current signal, wherein the controller is configured to drive the electric motor
10 based on feedback received from the first sensors and the second sensors.

Whilst it is the high frequency current signal which is measured to determine the angle of the rotor, it is also beneficial to measure the low frequency current signal to correctly control the motor. For example, measuring the low frequency current is useful for measuring and
15 controlling the overall current applied to the motor and making fine adjustments to the motor phasing.

Optionally, the inductor has an inductance of between 1 μH and 10 μH . In particular, the inductor may have an inductance of 2 μH . It will be appreciated that the properties of the
20 inductor will depend in part on the properties and application of the motor system, such as the voltage supplied to the motor, the PWM frequency, the resistance of the first and second paths and the properties of the sensors.

The second sensor may comprise a Hall-effect sensor magnetically coupled to the inductor.
25 The Hall-effect sensor may be a linear Hall-effect sensor.

Optionally, the resistance of the first path is higher than the resistance of the second path.

The first sensor may comprise a high speed low current sensor. In particular, the first sensor
30 may be a coreless Hall-effect current sensor.

-21-

As the amplitude of the high frequency current signal is relatively small, the first sensor does not have to be a high speed high current sensor. This reduces costs and the size of the measurement unit, as high speed high current sensors are very expensive and large.

- 5 Optionally, the first sensor has a bandwidth of between 1 MHz and 5 MHz.

Optionally, the filter comprises a shunt resistor connected in series with the first sensor along the first path.

- 10 The shunt resistor may have a higher resistance than the inductor, thereby ensuring that the resistance of the first path is higher than the resistance of the second path.

Optionally, the shunt resistor has a resistance of around 20 m Ω .

- 15 Optionally, the filter comprises a capacitor positioned on the first path. The capacitor may be connected in series with the first sensor.

It is very difficult for low frequency (DC) current to pass through a capacitor, therefore the capacitor effectively blocks the low frequency current from the first path.

20

Optionally, the filter may comprise a capacitor and a resistor.

Optionally, the controller comprises a processor configured to calculate the position or angle of the rotor.

25

The processor may be configured to calculate the current derivatives (dI/dt) of the high frequency current signals measured by the first sensors.

- 30 The processor may be configured to calculate the current derivatives (dI/dt) of the high frequency current signals by measuring the positive and negative gradients of each period of the high frequency current signals.

-22-

Thus, the angle or position of the rotor can be determined at every period of the high frequency current signal, even at low motor speeds. This may be about every 200 μ s, or even every 50 μ s, which is much more frequent than known motor control systems which rely on measuring the current derivative of test signals. In comparison, the test signals can typically
 5 only be applied to the stator windings every 0.01 s.

The processor may calculate the positive and negative gradients of the high frequency current signals as a function of time by applying a best line fit to the measured current values.

10 As the current derivative is related to the inductance of the stator winding this allows the position or angle of the rotor to be determined from the measured current derivatives (as explained above in relation to equation 1).

If the motor is stationary then the voltage (V) in equation 1 would be equal to the voltage
 15 across the winding, or phase voltage (V_{phase}), which is known. The phase voltage may be directly measured (e.g. using the second sensors) or it may be taken to be equal to the supplied battery or drive voltage.

If the rotor is turning, even at low speeds, then a small amount of back EMF (BEMF) will
 20 be generated in the stator windings as they cut through the magnetic field of the rotor (as explained above). The voltage (V) in equation 1 is therefore equal to $V_{phase} + BEMF$. Thus, the back EMF distorts the measured current derivatives and should preferably be accounted for when determining the angle of the rotor.

25 Thus, the processor may modify the calculated current derivative to eliminate the effect of the back EMF. This may be done using equation 3 below:

$$\frac{\Delta I}{\Delta t} = \frac{(A + |B|)}{2} \quad - (3)$$

where A is the positive dI/dt gradient and B is the negative dI/dt gradient of the same period of the high frequency current signal (see Figure 2B).

-23-

This works as the effect of the BEMF over a single period of the high frequency current signal is to lift slope A (positive gradient) and lower slope B (negative gradient) by the same amount. Taking the average of the absolute values of the positive and negative gradients therefore eliminates the BEMF component.

5

In addition, the processor may also adjust the measured current derivatives to account for voltage loss across the winding due to resistance (I.R. losses). The adjusted current derivative may be calculated using equation 4 below:

$$\frac{\Delta I_{adj}}{\Delta t_{adj}} = \frac{(V_{phase} + I \cdot R)}{V_{phase}} \cdot \frac{\Delta I}{\Delta t} \quad - (4)$$

10

Where $\Delta I/\Delta t$ is calculated via equation 3, I is the current across the winding, which is preferably measured by the sensor or the second sensors in the current measurement units, and R is the resistance of the winding.

15

When plotted as a function of time, the modified current derivatives of each stator winding should produce a sinusoidal current derivate waveform.

The voltage across the winding (or phase) V_{phase} may be taken to be equal to the drive or battery voltage supplied to the motor.

20

The processor may conduct additional signal processing to eliminate noise.

The processor may be configured to determine the position or angle of the rotor from the calculated (or modified) current derivatives of each stator winding using the ARCTAN2 function. This allows the electrical angle of the rotor to be determined. The mechanical angle of the rotor can then be determined using equation 2.

25

Before using the ARCTAN2 function, the processor may be configured to amend the current derivative waveforms to have a relative phase difference of 90° . For example, the current derivative waveforms may have a phase difference of 120° . The ARCTAN2 function can

30

-24-

only be correctly used to calculate the angle between two points which are 90° apart (as this is a trigonometric function).

The processor may also remove any offset from the current derivative waveforms to centre
5 the current derivative waveforms (or signals) on 0 A/s. This is preferred to ensure that the ARCTAN2 function calculates the correct electrical angle.

The offset may be a known value for the particular motor or motor system being used.
Optionally, the technique by which the processor processes the current derivative signals
10 may eliminate the offset.

Optionally, the controller comprises drive electronics configured to apply Pulse Width
Modulation (PWM) signals to power each stator winding, thereby driving the motor. The
PWM signals may have a frequency of 20 KHz.

15 Optionally, the motor control system may be an AC motor control system. The drive electronics may be configured to apply an AC (or sinusoidal) commutation sequence to the stator windings. For example, in a three-phase motor system the commutation current signals generated to drive the motor may be three sinusoidal waveforms having a phase difference
20 of 120° . This control system can be used to drive an AC or DC motor.

Typically, a six-step DC commutation is used to drive sensorless brushless motors, particularly at low motor speeds. In the present invention it is possible to use an AC commutation system even at low speeds.

25 It is advantageous to use an AC commutation system (which produces sinusoidal commutation current signals) as this provides improved efficiency and reduces motor noise.

Advantageously, an AC commutation system may provide smoother motor operation from
30 standstill. This is particularly beneficial for motors which have to start under heavy load and personal transport systems, such as stairlifts or electric cars, where smooth starting of the motor and operation load at low speeds is important.

It will be appreciated that in some embodiments of the invention the drive electronics may apply a six-step DC commutation cycle.

- 5 In a further aspect, the invention provides a measurement unit for use in a motor control system, as described above in any embodiment of the third aspect of the invention.

In a further aspect, the invention provides an electric motor system comprising:

- a brushless motor having a rotor and stator windings; and
10 the system for controlling an electric motor according to any embodiment of the first or third aspects of the invention.

As the motor control system of the present application accurately tracks the movement of the rotor the electric motor system can be used as a servo motor system. Generally, a servo
15 motor system requires an encoder to be fitted to the motor to provide speed and rotor position feedback. However, the improved motor control system of the present invention removes the need for the encoder.

Optionally, the motor is a brushless sensorless DC motor.
20

Optionally, the motor is a brushless sensorless AC motor.

Although the present application is primarily directed towards sensorless motors, it should be appreciated that the motor control system of the present invention could be used with
25 other types of brushless motor, for example as a back-up control system.

Optionally, the motor may be a three-phase brushless sensorless DC motor, or a three-phase brushless sensorless AC motor.

30 The control system may comprise two measurement units, or two sensor arrangements, such that the current signals of two phases of the motor are measured. As mentioned previously, because the stator windings of a three phase motor are connected together, it is not necessary

-26-

to measure the current of all three phases to determine the position of the rotor, as the current signals are dependent. Therefore, it is possible to control the motor by measuring the current along two of the phases (i.e. two of the stator windings). It may be preferred to measure only two of the motor phases, as this reduces the amount of measurement units required, therefore
5 reducing the cost, size and complexity of the system.

In other embodiments it may be preferred to provide measurement units to directly measure the current in each phase of the motor.

10 Optionally, the motor system may further comprise a system for measuring or determining the back EMF generated in the stator windings. This may be advantageous for high speed commutation. The back EMF system may utilise the output from the second sensor (i.e. the low frequency current measurements).

15 It may be advantageous to use the current measurement units of the present invention to control the motor at zero and low speeds, and the back EMF measurement system to control the motor at medium and high speeds.

For example, the back EMF measurement system may be used when the motor is operating
20 at a speed above a predetermined threshold. The predetermined threshold may be 20% of the maximum operating speed.

The BEMF measurement system may be a software system. The software system may form part of the processor.

25

In a further aspect, the invention provides a method for controlling an electric motor comprising a rotor and stator windings, the method comprising:

measuring the commutation current signal across at least two of the stator windings;
calculating the position or angle of the rotor based on the measured commutation
30 current signals; and
driving the electric motor.

-27-

It will be appreciated that the method could be carried out using the motor control system of the third aspect of the invention.

The benefits of the method of the present invention are as recited in connection with the
5 motor control system of the third aspect of the invention

The method may further comprise calculating the current derivatives (dI/dt) of the commutation current signals and using these values to calculate the position or angle of the rotor.

10

Calculating the current derivatives may comprise measuring the positive and negative gradients of each period of a high frequency current ripple in the commutation current signals.

15 Optionally, the method further comprises splitting each commutation current signal into a high frequency signal along a first path and a low frequency signal along a second path parallel to the first path; and

measuring the amplitude of the high frequency current signal using a first sensor;

wherein the position or angle of the rotor is calculated based on feedback from the

20 first sensors.

The method may include calculating the current derivatives (dI/dt) of the high frequency current signals measured by the first sensors and using these values to calculate the position or angle of the rotor.

25

Calculating the current derivatives (dI/dt) may comprise measuring the positive and negative gradients of each period of the high frequency current signals. A line of best fit may be applied to the measured high frequency current signals to determine the gradients.

30 Optionally, the method may include modifying the measured current derivatives to account for any back EMF generated by movement of the rotor and/or to account for voltage losses across the windings.

-28-

Modifying the measured current derivatives may include taking an average of the absolute values of the positive and negative gradients of each period of the high frequency current signals measured by the first sensors.

5

The method may include plotting the measured or modified current derivatives as a function of time for each stator winding, thereby producing a current derivative waveform for the stator winding.

- 10 The method may further comprise determining the position or angle of the rotor from the current derivative waveforms using the trigonometric ARCTAN2 function.

Before using the ARCTAN2 function, the method may include amending the current derivative waveforms of each stator winding to have a relative phase difference of 90°.

15

Before using the ARCTAN2 function, the method may include removing any offset from the current derivative waveforms such that the waveforms are centred on 0 A/s.

- 20 Optionally, driving the electric motor comprises applying Pulse Width Modulation (PWM) signals to the stator windings. The PWM signals may have a frequency of 20 kHz.

Optionally, an AC commutation sequence, or a sinusoidal commutation sequence is applied to the stator windings to drive the motor.

- 25 Optionally, a Locked Anti-phase PWM sequence is applied to the stator windings. The Locked Anti-phase technique may be preferred in order to maximise the high frequency current ripple (or high frequency current signal) used to determine the position of the rotor.

- 30 When the motor is stationary, the Locked Anti-phase PWM sequence applies pulses which generate no net current in the stator windings.

-29-

Many variations in the way the invention may be performed will present themselves to those skilled in the art upon reading the following description.

The description which follows should not be regarded as limiting but rather, as an illustration
5 only of one manner of performing the invention. Where possible any element or component should be taken as including any or all equivalents thereof whether or not specifically mentioned.

Brief Description of the Drawings

10

Illustrative embodiments of the invention will now be described by way of example only and with reference to the accompanying drawings, in which:

Figures 1A and 1B – are schematic illustrations of three-phase brushless motors;

15

Figure 2A – is a schematic illustration of a commutation current signal from a stator winding and the PWM signal used to drive the stator winding;

Figure 2B – shows the high frequency commutation current signal separated from the low
20 frequency commutation current signal in Figure 2A, illustrating how the current derivative may be measured;

Figure 3 – shows the locked anti-phase PWM technique of the present invention at zero speed- **left**: shows time periods 1, 2 and 3 of the PWM signals and **right**: shows how the
25 stator windings U, V, W are powered at time periods 1 and 2;

Figure 4 – shows the locked anti-phase PWM technique of the present invention used to drive the motor at non-zero speed- **left**: shows the PWM signals and **right**: shows the commutation current signals of the stator windings U, V, W;

30

Figure 5 - shows a schematic circuit diagram of a current measurement unit according to an embodiment of the present invention; and

Figure 6 – is a schematic illustration of a motor and a motor control system according to an embodiment of the present invention;

- 5 Figure 7 – is a schematic illustration of a sensor arrangement according to an embodiment of the present invention;

Figure 8- is a schematic illustration of a motor and a motor control system including the sensor arrangement of Figure 7;

10

Figure 9- is a graph depicting an example of an output signal from the second sensor in Figure 7 and how it may be processed in the system of Figure 8; and

- Figure 10- is an example of a reference graph for a given current vector that may be stored
15 in the memory of the controller.

It should be appreciated that the accompanying drawings are schematic diagrams which are not shown to scale.

- 20 Figure 1A shows an example of a three-phase brushless motor. The motor comprises an internal rotor having a magnet mounted thereon. The poles of the magnet are marked N, S.

- Three stator windings of conductive wire U, V, W are connected together around the rotor in a star configuration. Each winding can comprise a plurality of wire coils connected in
25 series. The winding can be distributed around the stator.

- Figure 1B shows an alternative example of a three-phase brushless motor. The motor comprises an external (or outer) rotor having magnets mounted thereon. Three stator windings U, V, W are connected together and positioned internally to the rotor in a star
30 configuration.

-31-

In Figures 1A and 1B each winding U, V, W is one phase of the motor. When a voltage is applied to the windings an electromagnetic field is generated. In use, the windings U, V, W are connected to drive electronics which apply duty cycles of Pulse Width Modulation (PWM) voltage signals (shown in Figure 2A, 3 and 4) to energise each winding in a specific sequence to generate a rotating magnetic field which 'drags' the rotor around. In Figure 1B the rotor spins around the outside of the stator windings, whereas in Figure 1A the rotor spins in the cavity between the stator windings, as shown by the arrows.

Figure 2A is a very simplified diagram illustrating how a stator winding U, V, W is driven using PWM signals in an AC (or sinusoidal) commutations system. The drive electronics of the motor control system apply a PWM duty cycle to each winding which consists of a series of 'pulses' which turn the power supplied to the winding on and off in a sequence. To drive the motor the duration (width) of the pulses are selected such that a net commutation current is produced in the winding. In this example, the commutation current signal 1 produced is sinusoidal. In other examples, a six-step DC commutation system may be used, which does not generate a smooth sinusoidal commutation current signal.

The commutation current signal 1 comprises a low frequency sine wave 2 with a higher frequency ripple 3 overlaid (i.e. the triangular spikes). The high frequency current signal is caused by the PWM pulses turning the power to the winding on and off, as shown in Figure 2A.

Current starts to flow in the winding when the pulse is applied in the forward current direction and when the pulse is reversed the current flows back in the reverse direction. This is also known as attack / reverse attack PWM. If the width of the 'forward' and 'reverse' pulses are the same then there is no net current change, so the low frequency commutation signal 2 would be a straight line.

According to the present invention, the amplitude of the commutation current signal 1 is measured by a sensor. Unlike in the prior art, there is no injection pulse or test signal applied to the windings. The rate of change of this measured commutation current signal 1 can then

-32-

be calculated. Consequently, the position of the rotor can be determined at a given time, as explained in detail below.

Generally, the high frequency ripple in the commutation current signal 1 is seen as noise.

5 However, it is the amplitude of the high frequency current ripple which is affected by the change in inductance of the stator winding. Therefore, in the present invention it is the amplitude of this high frequency component of the waveform 1 which needs to be accurately measured in order to determine the position of the rotor at a given time.

10 Figure 2B shows an example of a high frequency current signal 3 which results from separating the low frequency waveform 2 from the commutation current signal 1. A best line fit has been applied to the measured current values resulting in the waveform 3 which is formed of slopes A and B.

15 The amplitude of the high frequency ripple 3 can be measured as a function of time without separating the high frequency signal 3 from the low frequency signal 2. However, the peak-to-peak amplitude of the high frequency ripple 3 is around 7 amps, whereas the peak-to-peak amplitude of the low frequency current signal is generally around 80 amps. Therefore, the change in amplitude of the high frequency signal 3 over time is small compared to the
20 commutation signal 1 as a whole. Separating the high and low frequency signals, as shown in Figure 2B, makes it easier to accurately measure the amplitude of the high frequency ripple 3.

To calculate the position of the rotor, the current derivative $\Delta I / \Delta t$ is calculated by measuring
25 the gradient of the positive slopes A and the negative slopes B of the best fit high frequency current waveform 3, as shown in Figure 2B.

To account for the back EMF generated in the windings, as explained above, equation 3 is used to calculate the BEMF free current derivative $\Delta I / \Delta t$ by averaging the absolute values
30 of the slope A and slope B gradients.

-33-

To account for voltage losses the BEMF free current derivative $\Delta I/\Delta t$ is adjusted using equation 4. The winding voltage may be measured by a sensor, or alternatively, in a three phase system, the winding voltage (V_{phase}) may be taken to be the drive or battery voltage supplied to the motor.

5

If the modified current derivative values for a given stator winding (or motor phase U, V, W) are plotted as a function of time this produces a sine wave. The current derivative waveforms of the motor phases may have a relative phase difference of 120° .

10 The position or angle of the rotor is then determined from the modified current derivative waveforms at a given time using the ARCTAN2 function. This allows the electrical angle of the rotor to be determined. The mechanical angle of the rotor can then be determined using equation 2.

15 Before using the ARCTAN2 function, the current derivative waveforms are amended to have a relative phase difference of 90° . The ARCTAN2 can only be correctly used to calculate the angle between two points which are 90° apart (as this is a trigonometric function).

The processor may also remove any offset from the current derivative signals to centre the
20 current derivative signals on 0 A/s. This ensures that the ARCTAN2 function calculates the correct electrical angle.

In the present invention, it is preferred to use a Locked Anti-phase PWM technique to drive the motor. Figure 3 shows the PWM signals applied to the three motor phases U, V, W using
25 the Locked Anti-phase technique when the motor is stationary (i.e. at zero speed). The PWM signals are divided into time periods 1 and 2.

At time periods 1 a 'forward' pulse is applied to motor phase U and a 'reverse' pulse is applied to motor phases V and W. The 'forward' and 'reverse' pulses of the PWM signals
30 are of the same width or duration, in this example 25 μ s. The 'forward' pulse generates positive slope A in the high frequency signal (see Figure 2B) and the 'reverse' pulse generates negative slope B. Phases V and W are 180° out of phase with phase U.

-34-

The left side of Figure 3 shows how the motor phases U, V and W are powered at time periods 1 and 2 of the PWM signals. In time period 1 the drive voltage (in this example 24 V) is applied to phase U, and phases V and W are at 0 V. In time period 2, the current
5 reverses as phase U switches to 0 V, and phases V and W are at 24 V. It will be appreciated that the drive voltage is not limited to 24 V and that other voltages may be supplied to the motor controller.

At time period 1 the commutation current signal across winding U will have a positive
10 gradient (slope A in Figure 2B) and the commutation current signal across windings V and W will have a negative gradient (slope B in Figure 2B).

There is no net commutation current generated in the windings U, V, W when the ‘forward’ and ‘reverse’ pulses are of the same duration, therefore the rotor remains stationary. The
15 position of the rotor can still be calculated however, as the position of the rotor will still affect the inductance of the windings and therefore the relative amplitude of the high frequency current signals of the measured motor phases.

If a non-zero motor speed is required then the Locked Anti-phase PWM technique drives the
20 motor as shown in Figure 4. Motor phase U is the reference phase, so there is no change between the pulses applied in Figure 3 and 4. The duration of the ‘forward’ and ‘reverse’ pulses for phase U are the same. For phases V and W the duration of the ‘forward’ pulses are different to the duration of the ‘reverse’ pulses and the pulses are offset from phase U. As all three phases (or windings) U, V and W are connected together there is a net flow of
25 current through each winding. Preferably, the duration and offset of the pulses is selected so that the net commutation current signal generated for each motor phase is sinusoidal and there is phase difference of 120° between each signal. A schematic representation of the commutation current signals for motor phases U, V and W is at the right hand side of Figure 4 (the high frequency current ripple is not shown).

30

Optionally, the Locked Anti-phase technique may only be used at low motor speeds.

-35-

An example of a current measurement unit 10 in accordance with the present invention is shown in Figure 5. The measurement unit 10 is connected in series with one of the stator windings (U, V, W) and measures the amplitude of the commutation current signal 1 across that winding.

5

The measurement unit 10 comprises a first (electrical) path 11 and a second (electrical) path 12. The first path 11 is connected in parallel to the second path 12.

10 A filter (or splitter) 13 splits the commutation current signal into a high frequency current signal (e.g. waveform 3 in Figure 2B) along the first path 11, and a low frequency current signal (e.g. waveform 2 in Figure 2A) along the second path 12.

In the embodiment shown in Figure 5, the filter 13 comprises a resistor 14 and an inductor 16. The resistor 14 is a shunt resistor positioned on the first path 11. In this example, the
15 resistor 14 has a resistance of 20 m Ω . The inductor 16 has a ferrite core and an inductance of 2 μ H. It will be appreciated that in other examples the values of the resistor 14 and inductor 16 may vary.

In other embodiments the filter 13 may comprise a capacitor instead of, or in addition to, the
20 resistor 14 along the first path 11.

The resistance of the first path 11 is higher than the resistance of the second path 12, which causes almost all of the low frequency current to travel along the second path (i.e. the path of least resistance).

25

The high frequency current is resistant to passing through the inductor 16 which acts like a choke. Accordingly, almost all of the high frequency current travels along the first path 11.

A first sensor 15 is connected in series with the resistor 14. In this preferred embodiment,
30 the first sensor 15 is a high speed low current sensor, or a coreless Hall-effect current sensor, configured to measure the high frequency component (e.g. waveform 3 in Figure 2B) of the

-36-

input commutation current signal. In this example the high speed low current sensor 15 has a bandwidth of 2 MHz.

As the first sensor 15 measures the amplitude of the high frequency current signal over time, the current derivative $\Delta I / \Delta t$ can be calculated, as pictured in Figure 2B and described above. This equipment is a relatively inexpensive compared to specialist sensors such as Rogowski coils.

A second sensor 17 is magnetically coupled to the inductor 16. In this preferred embodiment, the second sensor is a linear Hall-effect sensor 17 configured to measure the low frequency component (e.g. waveform 2 in Figure 2A) of the input current signal. This is also a standard and relatively inexpensive sensor.

The outputs of the current sensors 15, 17 are indicated by the dotted arrows in Figure 5.

It will be appreciated that in other embodiments of the invention the properties of the first and second current sensors 15, 17 may be different.

In some embodiments the high frequency current signal may not be separated from the low frequency current signal. As such, the measurement unit may not comprise the filter 13 and only a single sensor may be provided, wherein the sensor is capable of accurately measuring the amplitude of the commutation current signal.

Figure 6 is a schematic illustration of a motor and motor control system according to an embodiment of the present invention.

The motor 30 is a brushless electric motor which is connected to a motor control system to control and drive the motor 30. In this example, the motor 30 is a three-phase sensorless motor as depicted in Figures 1A and 1B.

The motor control system comprises two measurement units 10, wherein the measurement units 10 are shown in detail in Figure 5, and a controller 20. Each measurement unit 10 is

-37-

connected in series with one of the phases (or stator windings) U, V, W of the motor 30. In other embodiments, it may be preferred to directly measure the current of all three phases of the motor.

- 5 The outputs from the first sensor 15 and the second sensor 17 of the measurement units 10 are connected to (or in communication with) the controller 20 configured to drive the motor 30 based on the feedback received from the measurement units 10.

10 The controller 20 comprises a processor 21 configured to calculate the current derivatives $\Delta I/\Delta t$ of each measured current signal. The measured current derivatives are modified to account for any back EMF generated in the winding and for voltage losses across the winding (as described above using equations 2 and 3). The processor 21 calculates the position of the rotor from the measured current derivatives of the two motor phases using vector mathematics (i.e. the ARCTAN2 function). The calculations needed are well known in the art and described above.

15 The processor 21 then determines the correct PWM duty cycle which should be applied to all three stator windings in order to correctly drive the motor 30 at the chosen speed. The processor 21 then forwards the required instructions to the drive electronics 22 which outputs the selected PWM signals to the motor 30. As shown above, it is preferred for the motor control system to be an AC commutation system such that the drive electronics 22 applies three phase sinusoidal waveforms to drive the windings (see Figure 4).

20 In addition, the motor control system shown in Figure 6 comprises a system 23 for measuring the back EMF (BEMF) generated in the stator windings. This system 23 is a software system which is connected to the processor 21. Optionally, system 23 forms part of the processor 21.

25 The back EMF measurement system 23 is configured to use the measured low frequency current signals output from the second sensors 17 to determine the position of the rotor when the motor 30 is operating above a predetermined speed threshold. For example, the threshold may be 20% of the maximum operating speed of the motor, such as 500 RPM. The Locked

-38-

Anti-phase PWM may not be used when the back EMF system 23 is being used to control the motor.

Figure 7 shows an embodiment of a sensor arrangement 110 according to an alternative embodiment of the invention. The sensor unit 110 is an alternative to the measurement unit 10 in Figure 5.

The sensor arrangement 110 comprises a single path 111 for current to flow in the motor phase. Figure 7 shows that the sensor arrangement 110 is connected to phase W of the motor (see Fig. 1), but it will be appreciated that the sensor arrangement 110 may be connected to any of the motor phases.

In contrast to the measurement unit 10, the high frequency current is not separated from the low frequency current along separate paths. However, two sensors are still provided.

A first sensor 117 (equivalent to sensor 17 in Figure 5) is configured to measure the low frequency (or DC) current in the motor phase, I_w (i.e. the amplitude of signal 2 in Figure 2A). Preferably, the first sensor 117 is a linear Hall-effect sensor. The first sensor 17 is not electrically connected to the motor phase (or path 111).

A second sensor 115 is provided to measure the rate of change of current in the motor phase, ΔI_w . The second sensor 115 effectively measures the rate of change of the high frequency current ripple 3 in Figure 2A.

In the embodiment shown in Figure 7, the second sensor 115 is a current transformer sensor comprising a primary coil 118 and a secondary coil 119 both surrounding a ferrite core 116. In other examples, an air core may be provided, rather than ferrite core 116. It will be appreciated that the number of turns in the primary 118 and secondary coils 119 depicted in Figure 7 is for illustrative purposes only and is not limiting.

The primary coil 118 is electrically connected in series with the motor phase, such that the phase current flows through the primary coil 118. The secondary coil 119 is magnetically

-39-

coupled to the primary coil 118 via the ferrite core 116. The magnetic field or flux emitted by the primary coil 118 changes in proportion to any change in current flowing through the primary coil 118 (i.e. in response to the high-frequency current ripple 3). This alternating magnetic field generates a voltage in the secondary coil 119 that is proportional to the rate of change of current in the primary coil 118. As such, the signal output from the secondary coil 119 allows the rate of change of current in the motor phase to be measured.

In Figure 7, an amplifier 104 is connected to the output from the first sensor 117 and a second amplifier 106 is connected to the output from the second sensor 115.

10

Figure 8 is a schematic illustration of a motor and motor control system according to an embodiment of the present invention.

The motor 30 is a brushless electric motor which is connected to a motor control system to control and drive the motor 30. In this example, the motor 30 is a three-phase sensorless motor as depicted in Figures 1A and 1B.

15

The motor control system comprises two sensor arrangements 110, wherein the sensor arrangements 110 are shown in detail in Figure 7, and a controller 120.

20

Preferably, the sensor arrangements 110 are provided on a single PCB. The controller 120 may be a microcontroller. The controller 120 may be provided on the same PCB as the sensor arrangements 110, thus the system may be very compact and light.

Each sensor arrangement 110 is connected in series with one of the phases U, V, W of the motor 30. In other embodiments, it may be preferred to include three sensor arrangements 110, one connected to each motor phase.

25

The outputs from the sensor arrangements 110 are connected to (or in communication with) the controller 120 configured to drive the motor 30 based on the feedback received from the sensor arrangements 110.

30

-40-

The controller 120 may drive the motor using a Locked Anti-Phase PWM sequence, as described above in relation to Fig 3 and 4. The controller 120 may be configured to drive the motor 30 by applying PWM signals to generate a current vector in the motor having an angle of 90° from the angle of the rotor.

5

The controller 120 comprises a processor 121 and a memory 124. The memory 124 stores data regarding the performance characteristics of the motor 30. The data stored in the memory may be obtained by a one-off set-up process carried out for the motor. Preferably the set-up process can be completed by a layman without requiring specialist knowledge or
10 equipment.

Specifically, the memory 124 may comprise a plurality of look-up tables and/or graphs, as per the examples shown in Figure 10 and Table 1 (described below).

15 The processor 121 is configured to process the outputs from the sensor arrangements 110, compare the output signals or values derived from the output signals, to the data stored in the memory 124 and to thereby determine the estimated angle of the rotor. This allows the controller 120 to emit the correct PWM signals to drive the motor smoothly and at the desired speed.

20

The processor 121 may determine the current vector in the motor 30 from the outputs of the first sensors 117 (i.e. I_v and I_w). At any one instant there is only one current vector in the motor 30, having an angle and an amplitude. The amplitude of the current along phases V and W is measured (I_v and I_w) and the phase angle of U, V and W is known. In this example
25 a sinusoidal commutation sequence is used, so U, V and W have a phase angle of 0 , 120° and 240° respectively. This allows the processor 121 to determine the current vector, using the ARCTAN2 function and Pythagoras Theorem. This calculation is well known in the field of motor control.

30 An example of an output signal from one of the second sensors 115 is shown in Figure 9. The output signal provides a measurement of the rate of change of current (dI/dt) in the primary coil 118 over time. In theory, the output signal should be a square wave, as the

-41-

differential of the triangular high-frequency current ripple 3 is a square wave. However, in reality various factors skew or influence the output signal, particularly when the motor is operating under high load.

- 5 The peaks (labelled as x) do not appear to be dependent upon the rotor angle. The peaks (x) may be caused by the ferrite core 116, for example due to magnetic domain alignment in the ferrous material. Thus, the processor 121 may disregard or eliminate these peaks.

In this example, the processor 121 is configured to process the output signal by using
10 regression analysis to estimate the value of dI/dt at the 'flat' portions of the output signal. This is shown by the dotted lines in Figure 9. The processor 121 uses regression analysis to determine a positive dI/dt value (A) and a negative dI/dt value (B) for each period of the PWM cycle.

- 15 To account for the effect of back EMF and I.R. losses the processor may determine a modified rate of change of current (ΔI) by taking the difference between A and B.

Once the modified rate of change of current (ΔI) has been determined, together with the current vector at the same time period, the processor may compare these values to the data
20 stored in the memory 124 to estimate the angle of the rotor.

The graph shown in Figure 10 is an example of a reference graph that may be stored in the memory 124. For a given current vector (not shown) this plots the modified rate of change of current (ΔI) for the W and V phases recorded by the processor as described above (called
25 $V\Delta$ regressed sensor feedback and $W\Delta$ regressed sensor feedback respectively) at each rotor angle (varied from 0° to 360° in 5° intervals).

Therefore, during real-time control of the motor, when the processor 121 has finished processing the outputs from the sensor arrangement(s), the processor locates the graph
30 corresponding to the measured current vector (e.g. Figure 10), compares the measured modified rate of change of current (ΔI) for the or each motor phase to the recorded values to find the best match, and reads off the corresponding rotor angle from the graph.

If the measured data points do not exactly match the recorded data points then the processor may be configured to use interpolation to retrieve a more accurate estimated rotor angle from the graph.

5

Alternatively, a look-up table may be provided rather than a graph. An extract from an example of a look-up table is shown in Table 1 below. It will be appreciated that the data contained therein is just for example purposes.

Rotor angle (°)	235	240	245	255	260	265
VΔ (mA/μs)	247.9	249.4	250.9	252.1	253.4	254.9
WΔ (mA/μs)	227.9	226.5	225.3	224.0	222.6	221.2

10

Table 1: Partial Look-up Table for Current Vector = X amplitude at angle of Y degrees

During real-time control of the motor, when the processor 121 has finished processing the outputs from the sensor arrangement(s), the processor may locate the look-up table corresponding to the measured current vector (e.g. Table 1), compares the measured modified rate of change of current (VΔ, WΔ) for the or each motor phase to the recorded values to find the best match, and reads off the corresponding rotor angle from the table.

If the measured modified rate of change of current (VΔ, WΔ) falls between two sets of values in the table (e.g. see dotted line in Table 1), then the processor may use interpolation, such as inverse distance interpolation, to determine the estimated angle of the rotor between 240° and 245°.

It should be noted that, in the appended claims, any reference signs placed in parentheses shall not be construed as limiting the claims. The word "comprising" and "comprises", and the like, does not exclude the presence of elements or steps other than those listed in any claim or the specification as a whole. In the present specification, "comprises" means "includes or consists of" and "comprising" means "including or consisting of". The singular reference of an element does not exclude the plural reference of such elements and vice-versa. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

30

CLAIMS

1. A system for controlling an electric motor, wherein the motor comprises a rotor and stator windings, comprising:
- 5 a sensor arrangement comprising:
- a first sensor configured to measure the current in a phase of the motor;
- and
- a second sensor configured to measure the rate of change of current (dI/dt) in the phase of the motor; and
- 10 a controller configured to drive the electric motor based on feedback received from the sensor arrangement.
2. The system of claim 1, wherein the controller is configured to drive the electric motor without applying or injecting a test signal to the motor.
- 15 3. The system of claim 1 or claim 2, wherein the first sensor is configured to measure the amplitude of the low frequency current in the phase of the motor.
4. The system of any preceding claim, wherein the first sensor is a Hall-effect sensor,
- 20 preferably a linear Hall-effect sensor.
5. The system of any preceding claim, wherein the second sensor is a current transformer sensor.
- 25 6. The system of claim 5, wherein the current transformer sensor comprises a primary coil, a secondary coil and a ferrite core or air core, wherein the primary coil is electrically coupled to the motor phase and the secondary coil is magnetically coupled to the primary coil via the ferrite core or air core.
- 30 7. The system of any preceding claim, further comprising a plurality of sensor arrangements, wherein each sensor arrangement is connected to a respective phase of the motor.

-44-

8. The system of claim 7, wherein the plurality of sensor arrangements are provided on a single circuit board, preferably a printed circuit board.

9. The system of any preceding claim, wherein the controller comprises a processor
5 configured to determine an estimated angle of the rotor.

10. The system of claim 9, wherein the controller includes a memory comprising stored data, and wherein the processor is configured to compare the outputs of the, or each sensor arrangement, or values derived from the outputs of the, or each, sensor arrangement, to the
10 data stored in the memory to retrieve the estimated angle of the rotor.

11. The system of claim 10, wherein the data stored in the memory comprises recorded outputs of the, or each, sensor arrangement at known angles of the rotor, or values derived from the recorded outputs of the, or each, sensor arrangement at known angles of the rotor.
15

12. The system of claim 10 or 11, wherein the data stored in the memory comprises a plurality of look-up tables and/or a plurality of reference maps or reference graphs.

13. The system of claim 12, wherein the data stored in the memory comprises a plurality of
20 reference maps, wherein each reference map is for a given current vector and each reference map displays the recorded outputs of the, or each, second sensor, or values derived from the recorded outputs of the, or each, second sensor, against the angle of the rotor.

14. The system of any of claims 9 to 13, wherein the processor is configured to calculate the
25 back EMF in each phase of the motor based on the current measured by the, or each, first sensor.

15. The system of claim 14, wherein, when the motor speed exceeds a predetermined threshold, the controller is configured to determine an estimated angle of the rotor from the
30 back EMF calculations.

-45-

16. The system of any of claims 9 to 15, wherein the controller is configured drive the electric motor by applying a current vector, or a voltage vector, having an angle of 90° from the estimated angle of the rotor.
- 5 17. The system of any preceding claim, wherein the controller comprises drive electronics configured to apply Pulse Width Modulation (PWM) signals to power each phase of the motor, thereby driving the motor.
18. The system of claim 17, wherein the drive electronics are configured to apply an AC (or
10 sinusoidal) commutation sequence to each phase of the motor.
19. The system of claim 17 or claim 18, wherein the drive electronics are configured to emit PWM signals with a frequency of between 15 kHz and 25 kHz, preferably around 20 kHz.
- 15 20. An electric motor system comprising:
a brushless motor having a rotor and stator windings; and
the system for controlling an electric motor according to any preceding claim.
21. The electric motor system of claim 20, wherein the motor is a brushless sensorless motor.
- 20 22. A method for controlling an electric motor comprising a rotor and stator windings, the method comprising:
using a sensor arrangement comprising a first sensor and a second sensor to:
measure the current in a phase of the motor using the first sensor; and
25 measure the rate of change of current in the phase of the motor using the second sensor;
determining an estimated angle of the rotor based on feedback from the sensor arrangement; and
driving the electric motor.
- 30 23. The method of claim 22, wherein the method does not comprise applying or injecting a test signal to the motor.

24. The method of claim 22 or claim 23, further comprising using a plurality of sensor arrangements to measure the current and the rate of change of current in a plurality of phases of the motor.
- 5
25. The method of any of claims 22 to 24, further comprising comparing the outputs of the, or each sensor arrangement, or values derived from the outputs of the, or each, sensor arrangement, to data stored in a memory, and retrieving an estimated angle of the rotor.
- 10
26. The method of claim 25, comprising extracting the estimated angle of the rotor from a look-up table, reference map or reference graph stored in the memory.
27. The method of claim 25 or claim 26, further comprising using interpolation to determine the estimated angle of the rotor if the outputs from the, or each sensor arrangement, fall
- 15
- between known values or points in the data stored in the memory.
28. The method of any of claims 22 to 27, further comprising calculating the back EMF in the, or each, phase of the motor based on the current measured by the, or each, first sensor.
- 20
29. The method of claim 28, wherein when the motor speed exceeds a predetermined threshold, the method comprises determining the estimated angle of the rotor from the back EMF calculations.
30. The method of any of claims 22 to 29, wherein driving the electric motor comprises
- 25
- applying a current vector, or a voltage vector, having an angle of 90° from the estimated angle of the rotor.
31. The method of any of claims 22 to 30, wherein driving the electric motor comprises applying Pulse Width Modulation (PWM) signals to each phase of the motor.
- 30
32. The method of claim 31, wherein an AC commutation sequence, or a sinusoidal commutation sequence is used to drive the motor.

-47-

33. The method of claim 31 or claim 32, wherein the PWM signals have a frequency of between 15 kHz and 25 kHz, preferably around 20 kHz.

- 5 34. The method of any of claims 31 to 33, wherein a Locked Anti-phase PWM sequence is used to drive the electric motor.

35. The method of claim 34, wherein, when the motor is stationary, the Locked Anti-phase PWM sequence applies pulses which generate no net current in the, or each motor phase.

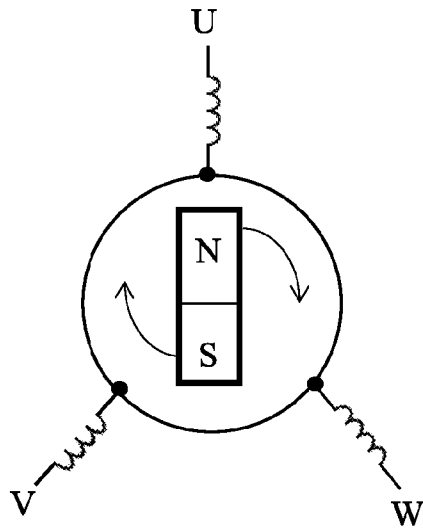


Figure 1A

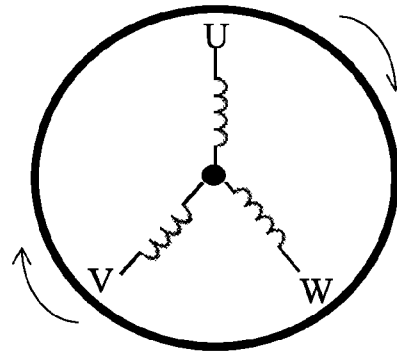


Figure 1B

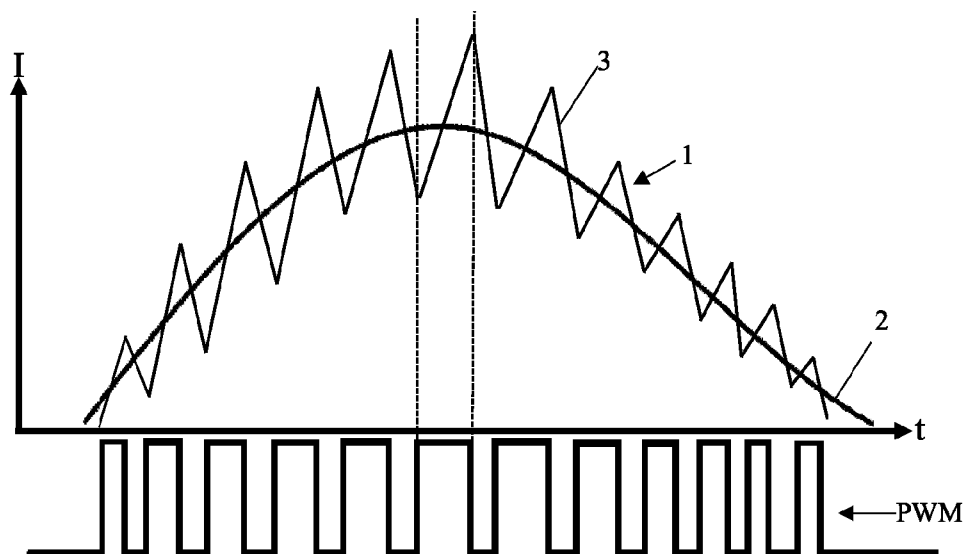


Figure 2A

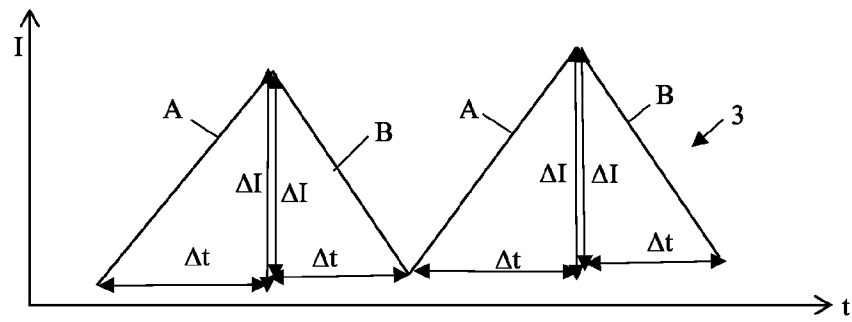


Figure 2B

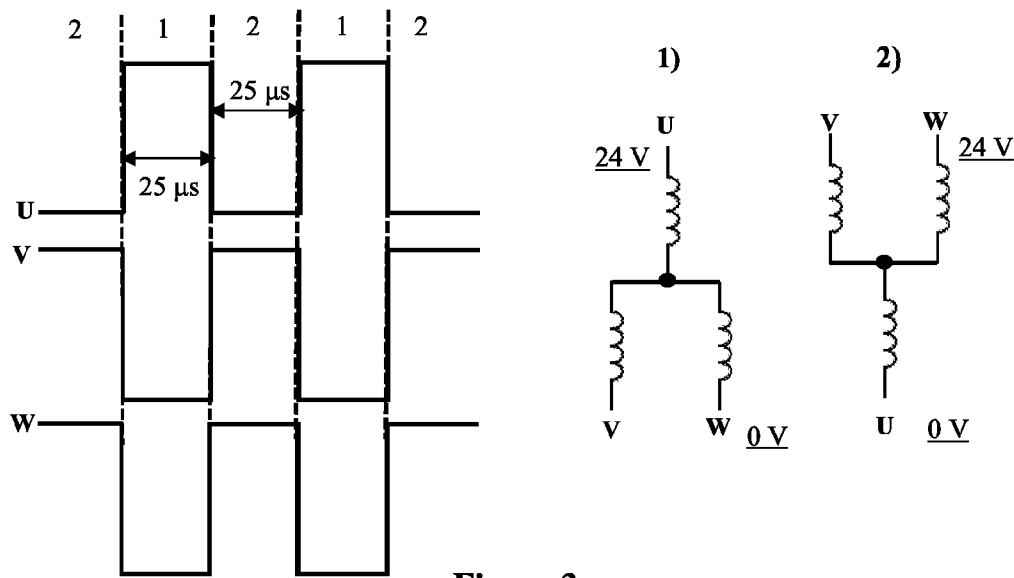


Figure 3

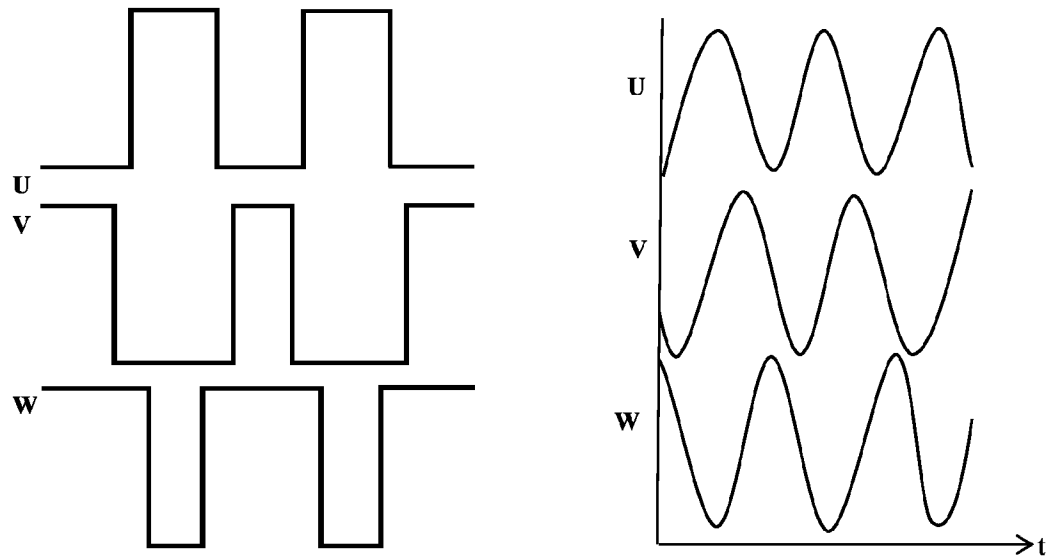


Figure 4

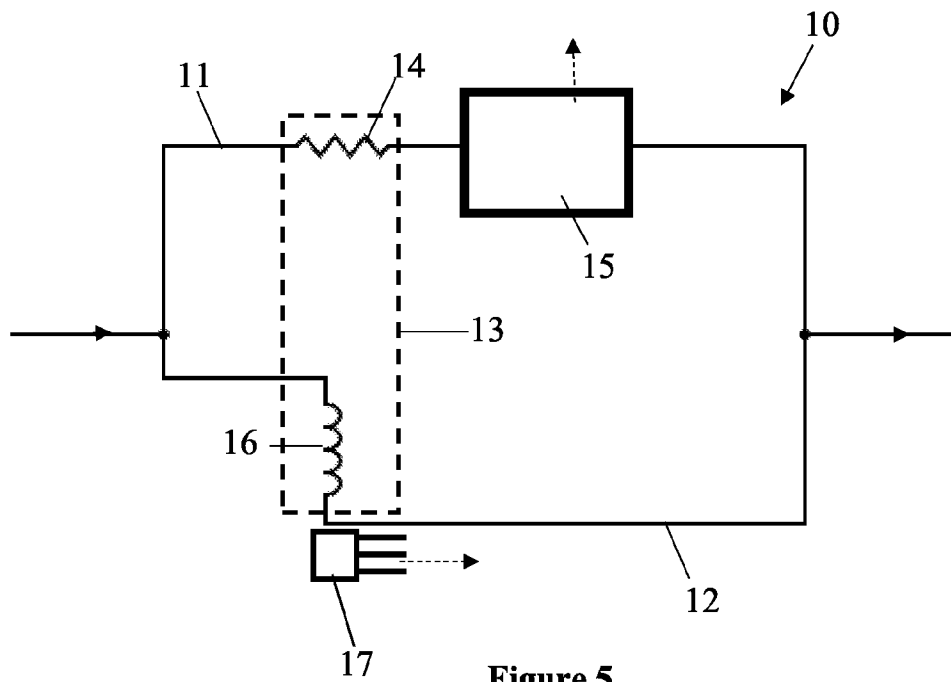


Figure 5

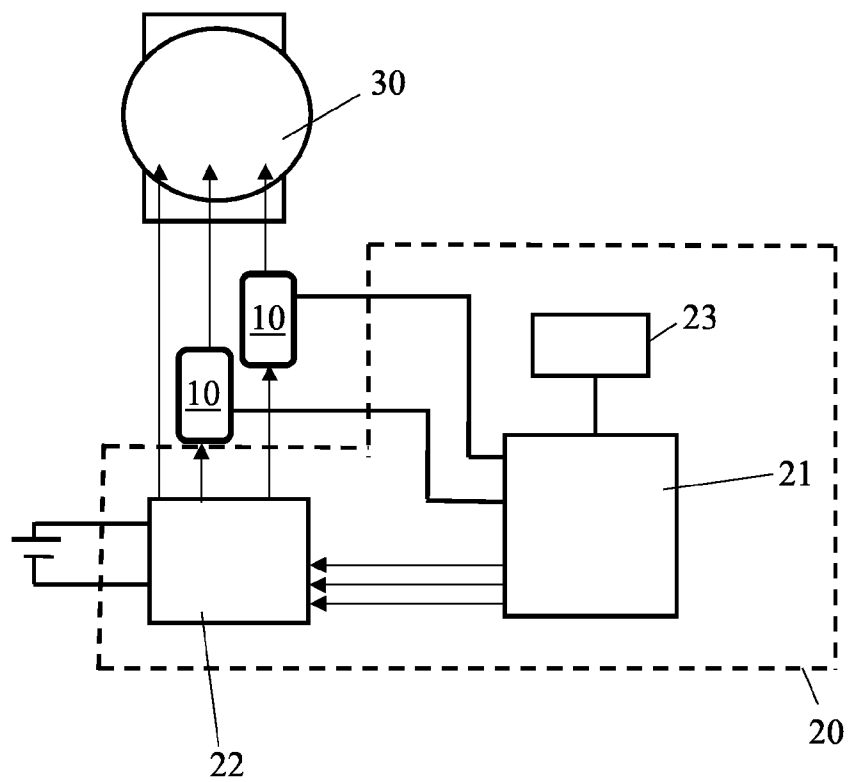


Figure 6

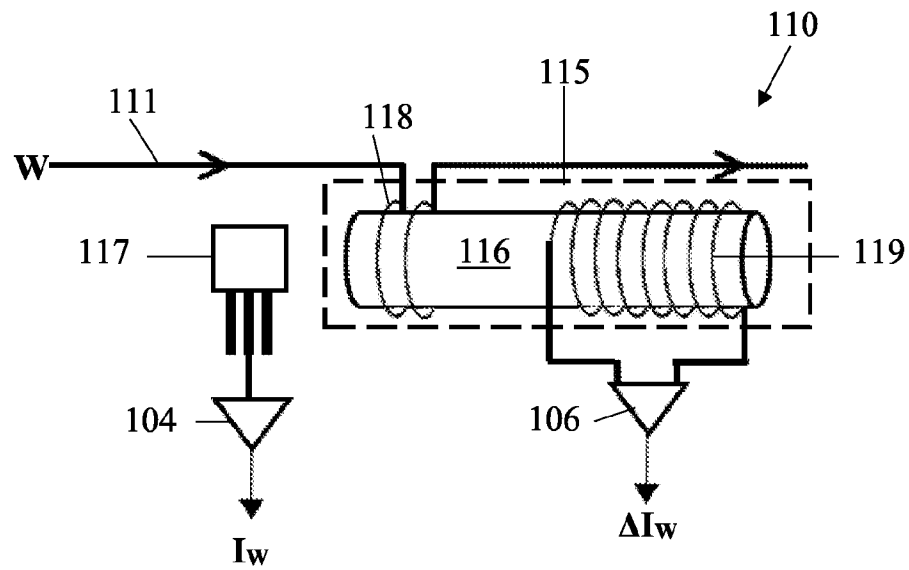


Figure 7

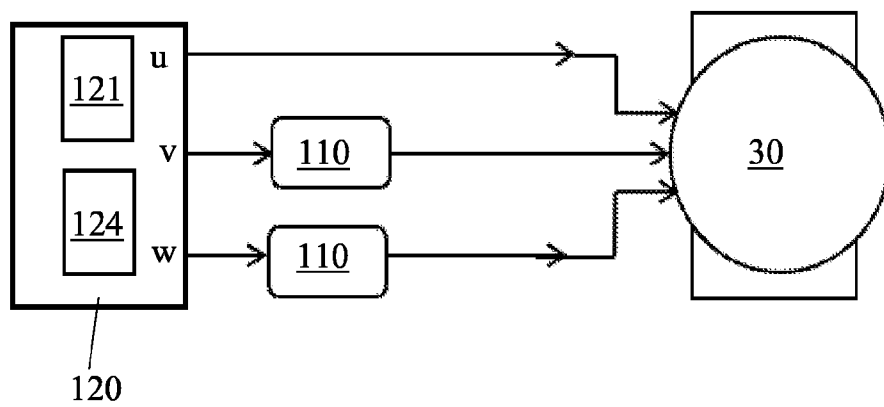


Figure 8

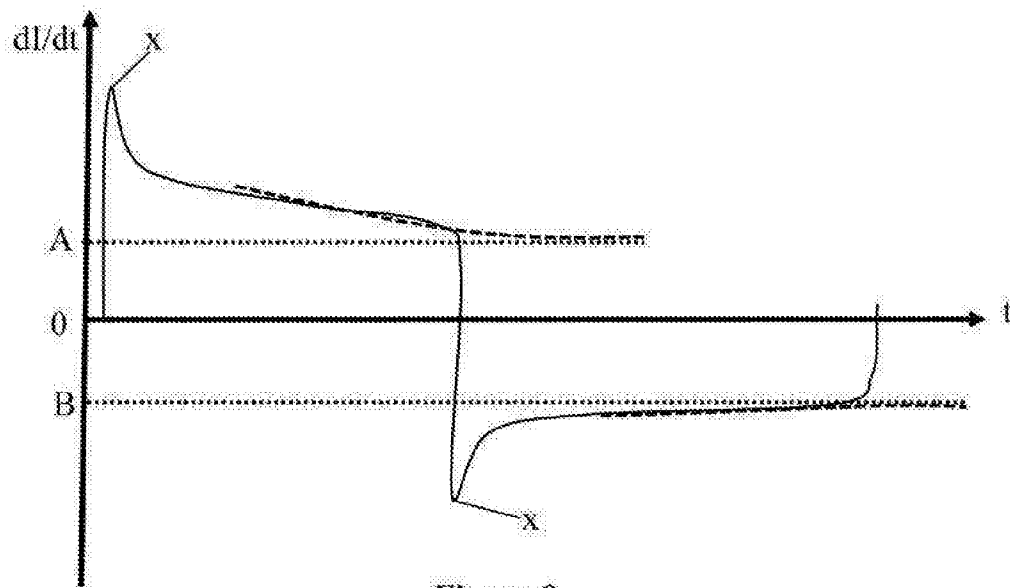


Figure 9

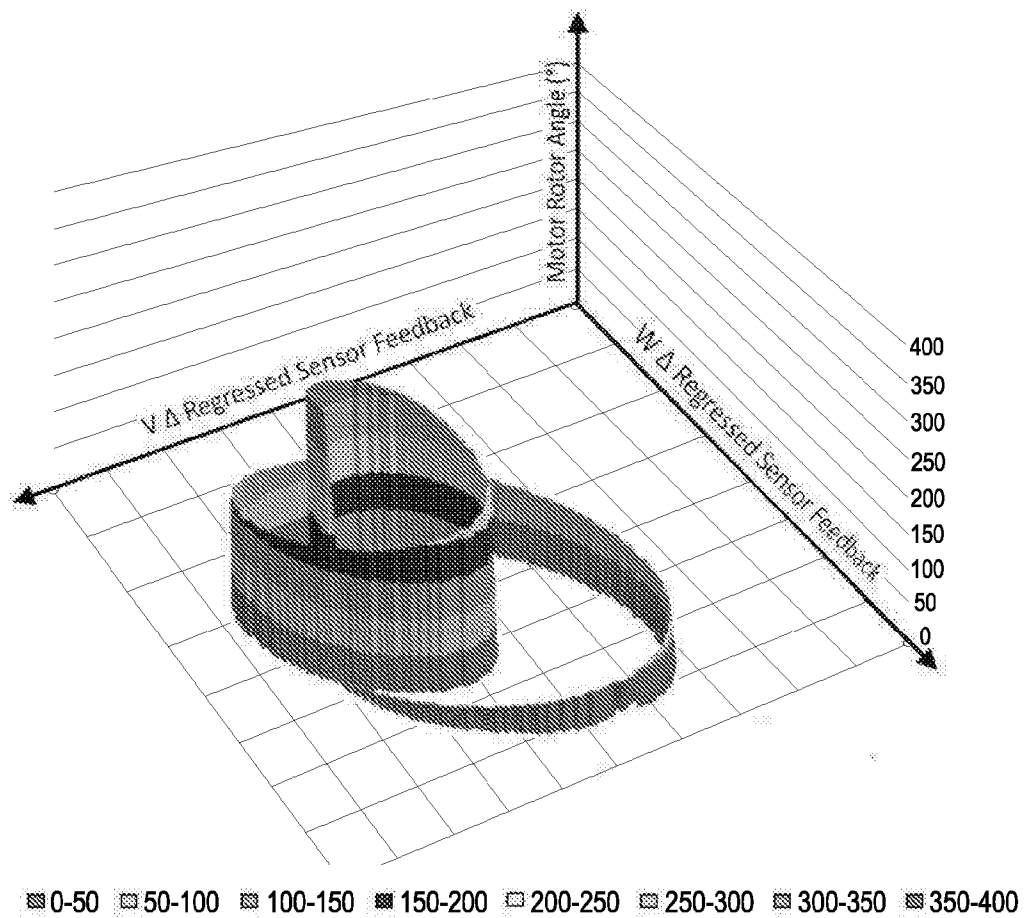


Figure 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2020/050271

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02P6/18 H02P6/185
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02P

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 2 276 167 A2 (UNIV CITY HONG KONG [CN]) 19 January 2011 (2011-01-19)	1-4,7-9, 16-24, 30-35
Y	paragraph [0065] - paragraph [0068]; figure 7 claim 8	5,6, 10-15, 23,25-29
Y	----- US 2015/061641 A1 (STROTHMANN ROLF [DE]) 5 March 2015 (2015-03-05) abstract paragraph [0022]; figure 2	5
Y	----- US 2010/270957 A1 (LI TIECAI [CN] ET AL) 28 October 2010 (2010-10-28) paragraph [0037]; figure 2 ----- -/-	6,23



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

20 April 2020

Date of mailing of the international search report

29/04/2020

Name and mailing address of the ISA/

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Schürle, Patrick

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2020/050271

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