A METHOD OF CONTROLLING A BRUSHLESS PERMANENT-MAGNET MOTOR

Field of the Invention

The present invention relates to a method of controlling a brushless permanent-magnet motor.

Background of the Invention

There is a general desire to improve electric machines, such as brushless motors, in a number of ways. For example, improvements may be desired in terms of size, weight, power density, manufacturing cost, efficiency, reliability, and noise.

Summary of the Invention

A first aspect of the present invention provides a method of controlling a brushless permanent-magnet motor, the method comprising: measuring a plurality of values indicative of back EMF induced in a phase winding of the motor; determining estimated phase angles associated with the measured values indicative of back EMF; integrating the measured values indicative of back EMF to determine an integrated back EMF; integrating the estimated phase angles to determine an integrated phase angle; determining a peak back EMF based on the integrated back EMF and the integrated phase angle; and controlling the motor based on the peak back EMF.

Back EMF induced in the phase winding of the motor may take a generally sinusoidal form with multiple peaks and troughs, and may be measured to determine various properties of the motor. For example, the back EMF may be used to determine a temperature of a permanent-magnet of the motor. To help increase a lifetime of the motor, and prevent de-magnetisation of the permanent-magnet caused by overheating, a temperature of the permanent-magnet may be controlled such that it stays below a desired

threshold value during use. The temperature of the permanent magnet may also be used to estimate temperatures of other components of the motor, such as an exhaust or a bearing. Peaks in the temperature of the permanent-magnet of the motor may be determined from peaks of the back EMF induced in the phase winding of the motor. However, it may be difficult to directly measure the peaks of the back EMF. For example, when the back EMF is larger than a dc-link voltage, this may cause clipping through conduction of anti-parallel diodes. Any direct measurement of back EMF using an analogue-to-digital converter may therefore be capped at the dc-link voltage. As such, when the back EMF is larger than the dc-link voltage, it may not be possible to directly measure the accurate back EMF.

The method of the first aspect of the present invention may help to provide an accurate determination of peaks of back EMF induced in the phase windings of the motor, for example even when the peak exceeds the dc-link voltage. The method provides an unobtrusive way to determine peaks of the back EMF, which does not require additional sensors.

Although methods for calculating peaks of back EMF using derivatives may be known, these methods are particularly liable to errors introduced by noise in the ADC measurement. The noise is exaggerated by the derivative function, which may result in inaccurate measurements. As such, filters (e.g. finite impulse response filters) may be used to mitigate the noise. However, such filters may add complexity to the system and may require additional memory in a controller. Moreover, filters are frequency dependent, such that different motor speeds/frequencies may affect the filter performance. By using the integration method of the first aspect of the present invention, the impact of noise may be minimised without the need for filters. This may result in more accurate and consistent results as compared to the derivative method.

The method may comprise determining a temperature of a permanent-magnet of the motor based on the peak back EMF and controlling operation of the motor based on the determined temperature of the permanent-magnet. The temperature at which the

permanent-magnet of the motor operates may have an impact on the working and/or lifetime of the motor. As such, it may be useful to determine and/or monitor the temperature that the permanent-magnet reaches during use. By determining the temperature of the permanent-magnet of the motor based on the back EMF, the temperature of the permanent-magnet may be determined without the need for additional sensors.

By controlling the operation of the motor based on the temperature of the permanent-magnet, the motor may be controlled to prevent the permanent-magnet from exceeding the desired threshold value. This may help to improve the lifetime and efficiency of the motor and reduce damage being caused to the permanent-magnet and/or motor.

Controlling operation of the motor may comprise controlling power (e.g. by controlling a voltage and/or current) applied to the phase winding of the motor such that the determined temperature of the permanent-magnet is below a desired threshold value. By controlling the power applied to the phase winding such that the determined temperature of the permanent-magnet is below the desired threshold value, this may help to improve the lifetime of the motor and reduce damage being caused to the permanent-magnet and/or motor. For example, if the determined temperature is higher than the desired threshold value, the voltage applied to the phase winding may be reduced to reduce the temperature of the permanent-magnet.

Measuring the plurality of values indicative of back EMF induced in the phase winding of the motor may comprise using an analogue-to-digital converter (ADC) to measure the plurality of values indicative of back EMF induced in the phase winding of the motor. The use of an analogue-to-digital converter (ADC) may provide a straightforward way in which to directly measure the values indicative of back EMF induced in the phase winding of the motor. The direct measurement of the values indicative of back EMF may then be used to provide an accurate determination of the peak back EMF.

The method may comprise: exciting the phase winding of the motor by applying a voltage to the phase winding using an inverter of the motor; and turning off the inverter for a time period, wherein measuring the plurality of values indicative of back EMF induced in the phase winding of the motor occurs during the time period. By measuring the plurality of values indicative of back EMF induced in the phase winding of the motor during a time period in which the inverter is turned off, this may lead to increased accuracy of the measurements. For example, when the inverter is turned off, there may be no applied voltage to the phase winding, and hence any voltage across the phase winding may be caused directly by the back EMF induced in the phase winding. Therefore, any measurement of voltage across the phase windings during the time period may provide an accurate measurement of the values indicative of back EMF.

Measuring the plurality of values indicative of back EMF induced in the phase winding of the motor may comprise measuring a voltage across the phase winding of the motor during the time period. As there may be no applied voltage to the phase winding when the inventor is turned off, any voltage across the phase winding may be caused directly by the back EMF induced in the phase winding. Therefore measuring the voltage across the phase windings during the time period may provide a direct measurement of the induced back EMF.

Determining the peak back EMF may comprise dividing the integrated back EMF by the integrated phase angle. This may provide an accurate measurement of the peak back EMF even when the peak back EMF exceeds the dc-link voltage. This may also provide an unobtrusive way to the measure the peak back EMF which does not require additional sensors.

Integrating the measured values indicative of back EMF may comprise integrating absolute values of the measured values indicative of back EMF induced in the motor. By integrating the absolute values of the measured values of the back EMF, the method may be equally applicable to positive and negative back EMF measurements. As such, the method may be used over a wide range of back EMF measurements.

Integrating the estimated phase angles may comprise integrating absolute values of sine functions of the estimated phase angles. By integrating the absolute values of sine functions of the estimated phase angles, the method may be equally applicable to positive and negative phase angles. As such, the method may be used over a wide range of phase angles.

The method may comprise modifying the estimated phase angles based on a difference between the estimated phase angles and actual phase angles, wherein integrating the estimated phase angles comprises integrating the modified estimated phase angles. By modifying the estimated phase angles, a more accurate estimate of the phase angles of the back EMF may be determined. For example, modifying the estimated phase angles may help to compensate for errors (such as those caused by noise) in the estimated phase angles. The modified estimated phase angles may take into account a phase angle delay which may affect the determination of peak back EMF. As such, using the modified estimated phase angles in the method of the first aspect of the present invention may result in a more accurate determination of the peak back EMF.

Modifying the estimated phase angles may comprise determining a phase angle delay between the estimated phase angles and the actual phase angles and adding the phase angle delay to the estimated phase angles. By determining the phase angle delay between the estimated phase angles and the actual phase angles, the effect of noise on the determination of peak back EMF may be minimised. The estimated phase angles may be modified using a proportional integral (PI) controller (also known as a PI loop). It may be assumed that the integrated phase angle should be equal to zero in ideal circumstances and that the integrated phase angle is therefore equal to an error. The integrated phase angle may be input into the PI controller with a set point at zero, to determine the phase angle delay. As the calculation of the modified estimated phase angles includes the phase angle delay, this may lead to a more accurate determination of the phase angle of the back EMF. As such, using the modified estimated phase angles in the method of the first aspect

of the present invention may result in a more accurate determination of the peak back EMF.

According to a second aspect of the present invention, there is provided a brushless permanent-magnet motor comprising a phase winding and a controller configured to perform a method according to the first aspect of the present invention.

According to a third aspect of the present invention, there is provided a data carrier comprising machine-readable instructions for the operation of one or more controllers of a brushless permanent-magnet motor to perform the method according to the first aspect of the present invention.

According to a fourth aspect of the present invention, there is provided a vacuum cleaner comprising a brushless permanent-magnet motor according to the second aspect of the present invention.

According to a fifth aspect of the present invention, there is provided a haircare appliance comprising a brushless permanent-magnet motor according to the second aspect of the present invention.

Brief Description of the Drawings

Figure 1 shows a schematic view of a motor system;

Figure 2 shows a further schematic view of the motor system of Figure 1;

Figure 3 shows a table indicating switching states of the motor system of Figures 1 and 2;

Figure 4 shows an example waveform of back EMF induced in a phase winding of a brushless permanent-magnet motor together with associated ADC back EMF measurements;

Figure 5 shows a flow diagram of a method of controlling a brushless permanent-magnet motor;

Figure 6 shows a further flow diagram of the method of Figure 5;

Figure 7 shows a schematic illustration of a vacuum cleaner comprising the motor system of Figures 1 and 2; and

Figure 8 shows a schematic illustration of a haircare appliance comprising the motor system of Figures 1 and 2.

Detailed Description of the Invention

A motor system, generally designated 10, is shown in Figures 1 and 2. The motor system is powered by a DC power supply 12, for example a battery, and comprises a brushless permanent-magnet motor 14 and a control circuit 16. It will be recognised by a person skilled in the art that the methods of the present invention may be equally applicable to a motor system powered by an AC power supply, with appropriate modification of the circuitry, for example to include a rectifier.

The motor 14 comprises a four-pole permanent-magnet rotor 18 that rotates relative to a four-pole stator 20. Although shown here as a four-pole permanent-magnet rotor, it will be appreciated that the present invention may be applicable to motors having differing numbers of poles, for example eight poles. Conductive wires wound about the stator 20 are coupled together to form a single-phase winding 22. Whilst described here as a single-phase motor, it will be recognised by a person skilled in the art that the teachings of the

present application may also be applicable to multiphase, for example three-phase, motors.

The control circuit 16 comprises a filter 24, an inverter 26, a gate driver module 28, a current sensor 30, a first voltage sensor 32, a second voltage sensor 33, and a controller 34.

The filter comprises a link capacitor C1 that smooths the relatively high-frequency ripple that arises from switching of the inverter 26.

The inverter 26 comprises a full bridge of four power switches Q1-Q4 that couple the phase winding 22 to the voltage rails. Each of the switches Q1-Q4 includes a freewheel diode. As illustrated in Figure 2, the switches Q1 and Q3 comprise a pair of high-side switches, and the switches Q2 and Q4 comprise a pair of low-side switches.

The gate driver module 28 drives the opening and closing of the switches Q1-Q4 in response to control signals received from the controller 34.

The current sensor 30 comprises a shunt resistor R1 located between the inverter and the zero-volt rail. The voltage across the current sensor 30 provides a measure of the current in the phase winding 22 when connected to the power supply 12. The voltage across the current sensor 30 is output to the controller 34 as signal I_SENSE. It will be recognised that in this example it is not possible to measure current in the phase winding 22 during freewheeling, but that alternative examples where this is possible, for example via the use of a plurality of shunt resistors, are also envisaged.

The first voltage sensor 32 comprises a voltage divider in the form of resistors R2 and R3, located between the DC voltage rail and the zero-volt rail. The voltage sensor outputs a signal, V_DC, to the controller 34 that represents a scaled-down measure of the supply voltage provided by the power supply 12.

The second voltage sensor 33 comprises a pair of voltage dividers constituted by resistors R4, R5, R6, and R7, that are connected either side of the phase winding 22. The second voltage sensor 33 provides a signal indicative of back EMF induced in the phase winding 22 to the controller, as bEMF.

The controller 34 comprises a microcontroller having a processor, a memory device, and a plurality of peripherals (e.g. ADC, comparators, timers etc.). In an alternative example, the controller 34 may comprise a state machine. The memory device stores instructions for execution by the processor during operation. The controller 34 is responsible for controlling the operation of the motor 14 and generates four control signals S1-S4 for controlling each of the four power switches Q1-Q4. The control signals are output to the gate driver module 28, which in response drives the opening and closing of the switches Q1-Q4.

During normal operation, the controller 34 estimates the position of the rotor 18 using a sensorless control scheme, i.e. without the use of a Hall sensor or the like, by using software to estimate the waveform indicative of back EMF induced in the phase winding 22 via signals V_DC and I_SENSE. In particular, zero-crossings of back EMF induced in the phase winding 22 can be estimated to estimate aligned positions of the rotor 18. The details of such a control scheme will not be described here for the sake of brevity, but can be found, for example, in published GB patent application GB2582612. Another sensorless control scheme that utilises hardware components to estimate back EMF induced in the phase winding 22 is disclosed in published PCT patent application WO2013/132247A1. With knowledge of the position of the rotor 18 in normal operation, the controller 34 generates the control signals S1-S4.

Figure 3 summarises the allowed states of the switches Q1-Q4 in response to the control signals S1-S4 output by the controller 34, and such allowed states may be referred to as switch configurations here. Hereafter, the terms “set” and “clear” will be used to indicate that a signal has been pulled logically high and low respectively. As can be seen from Figure 3, the controller 34 sets S1 and S4, and clears S2 and S3 to excite the phase winding

22 from left to right. Conversely, the controller 34 sets S2 and S3, and clears S1 and S4 to excite the phase winding 22 from right to left. The controller 34 clears S1 and S3, and sets S2 and S4 in order to freewheel phase winding 22. Freewheeling enables current in the phase winding 22 to re-circulate around the low-side loop of the inverter 26. In the present example, the power switches Q1-Q4 are capable of conducting in both directions. Accordingly, the controller 34 closes both the low-side switches Q2, Q4 during freewheeling such that current flows through the switches Q2, Q4 rather that the less efficient diode.

Conceivably, the inverter 26 may comprise power switches that conduct in a single direction only. In this instance, the controller 34 would clear S1, S2 and S3, and set S4 to freewheel the phase winding 22 from left to right. The controller 34 would then clear S1, S3 and S4, and set S2 to freewheel the phase winding 22 from right to left. Current in the low-side loop of the inverter 26 then flows down through the closed low-side switch (e.g. Q4) and up through the diode of the open low-side switch (e.g. Q2).

Appropriate control of the switches Q1-Q4 can be used to drive the rotor 18 at speeds up to or in excess of 100krpm during normal operation, for example in a steady-state mode. In particular, the phase winding 22 can be excited and freewheeled sequentially, with commutation of the phase winding 22 occurring between excitations of the phase winding 22.

When exciting and freewheeling the phase winding 22 using a sensorless control scheme, it may be desirable to monitor the temperature of the permanent-magnet of the motor 14. The motor 14 can then be controlled based on the determined temperature (e.g. by changing the voltage applied to the phase winding 22) to help prevent the permanent-magnet from overheating. The back EMF induced in the phase winding 22 is indicative of the temperature of the permanent-magnet. Therefore, in accordance with the present invention the temperature of the permanent-magnet is determined from a measurement of the back EMF induced in the phase winding 22. Determining the temperature in this way may help to avoid the need for physical temperature sensors within the motor system 10.

To measure the back EMF induced in the phase winding 22, the signal bEMF from the voltage sensor 33 is monitored during a time period when switches Q1-Q4 are turned off, i.e. when the inverter 26 is turned off. Measuring the back EMF induced in the phase winding 22 of the motor 14 during the time period in which the inverter 26 is turned off may lead to increased accuracy in the measurements. For example, when the inverter 26 is turned off, there may be no applied voltage to the phase winding 22, and hence any voltage across the phase winding 22 may be caused directly by the back EMF induced in the phase winding 22. Therefore, any measurement of voltage across the phase windings 22 during the time period may provide an accurate measurement of the back EMF induced in the phase winding 22.

Figure 4 shows an example waveform of the back EMF induced in the phase winding 22. As can be seen in Figure 4, the back EMF (shown by dashed line 104) has a substantially sinusoidal waveform which includes multiple peaks 101 and troughs 102. The values of the amplitudes of the peaks 101 and troughs 102 (in particular, the absolute values of the amplitudes of the peaks 101 and troughs 102) are indicative of the temperature of the permanent-magnet at a given time. Where used herein, the phrase “peak back EMF” may refer to any one of the peaks 101 or troughs 102.

As the peak back EMF induced in the phase winding 22 is indicative of the temperature of the permanent-magnet, it may be desirable to determine the peak back EMF. However, it may not be possible to directly measure the peak back EMF as, when the value of the back EMF exceeds a dc-link voltage 107, clipping through conduction of anti-parallel diodes may occur. Therefore, the measurement of the back EMF induced in the phase winding 22 is capped at the dc-link voltage. If a capped back EMF measurement is used to determine the temperature of the permanent-magnet, this may lead to an incorrect determination of the temperature which is lower than the actual temperature of the permanent-magnet. As such, the permanent-magnet may operate at a higher than desired temperature, which may cause damage to the permanent-magnet.

In Figure 4, solid line 105 illustrates the back EMF measured by the ADC and horizontal lines 106 illustrate a software limit of the motor system 10. The software limit is set such that values below the software limit are not affected by dc-link voltage capping. As such, any values below the software limit can be assumed to be accurate measurements of the back EMF. Any values of back EMF above the dc-link voltage have been capped at the dc-link voltage and are therefore not able to be accurately measured directly by the ADC (via the second voltage sensor 33). This means that the peaks of the back EMF (i.e. the peaks 101 and troughs 102) are not able to be directly measured and it is therefore not possible to accurately determine the temperature of the permanent-magnet at the peak back EMF.

Figure 5 shows a method 200 which may help to address these problems and allow for an accurate determination of peak back EMF even when the back EMF exceeds the dc-link voltage. The method 200 comprises measuring 202 a plurality of values indicative of back EMF induced in a phase winding 22 of the motor 14 and determining 204 estimated phase angles associated with the measured values indicative of back EMF. The method 300 comprises integrating 206 the measured values indicative of back EMF to determine an integrated back EMF and integrating 208 the estimated phase angles to determine an integrated phase angle. A peak back EMF is determined 210 based on the integrated back EMF and the integrated phase angle, and the motor 14 is controlled 212 based on the peak back EMF.

Figure 6 shows a further flow diagram 300 illustrating the method 200 of Figure 5. Due to the measurement of back EMF being capped at the dc-link voltage, direct measurements of back EMF are only accurate in shaded regions 103 of Figure 4. As such, measuring 202 the plurality of values indicative of back EMF induced in the phase winding 22 comprises measuring the values within a voltage region covered by the shaded regions 103. At box 302 of Figure 6, the plurality of values indicative of back EMF induced in the phase winding 22 are received from the ADC and a voltage region is detected. The voltage region corresponds to the shaded regions 103 of Figure 4 (i.e. where direct measurements of back EMF are not capped).

The integration of the measured values indicative of back EMF is carried out at box 304 by summing absolute values of the measured values indicative of back EMF over phase angles -α to α. This is illustrated by the equation:

$$Bemf_{pk} = \sum_{-\alpha}^{\alpha} abs(Bemf_{ADC})$$

where $Bemf_{pk}$ is the peak back EMF and $Bemf_{ADC}$ is the value of the back EMF measured by the ADC.

Similarly, the integration of the estimated phase angles is carried out by summing the estimated phase angles over the phase angles -α to α, as illustrated by the equation:

$$\sin\theta_{int} = \sum_{-\alpha}^{\alpha} abs(\sin\theta_{est})$$

where $\sin\theta_{int}$ is the integrated phase angle and $\sin\theta_{est}$ is the estimated phase angle. In some examples, the summation term may be simplified to a constant, or may be simplified in another way for convenience.

The peak back EMF, $Bemf_{pk}$, is then calculated by dividing the integrated back EMF by the integrated phase angle, as illustrated by the equation:

$$Bemf_{pk} = \frac{Bemf_{int}}{\sin\theta_{int}} = \frac{\sum_{-\alpha}^{\alpha} abs(Bemf_{ADC})}{\sum_{-\alpha}^{\alpha} abs(\sin\theta_{est})}$$

Determining the peak back EMF in this way may help to provide an accurate value for the peak back EMF even when the peak back EMF exceeds the dc-link voltage. Moreover, as the method 200 uses integrals to determine the peak back EMF, it is less

susceptible to noise in the measurement of the back EMF at the ADC, which may help to increase the accuracy of the determined peak back EMF. This also reduces the need to include filters to remove noise, helping to simplify the motor system 10.

The estimated phase angle, θ_{est}, is determined using one of the sensorless control schemes previously discussed. In some examples, the estimated phase angle may be determined through interpolation of zero crossing points. The sensorless control schemes estimate the waveform indicative of back EMF induced in the phase winding 22 via signals V_DC and I_SENSE. However, the estimated phase angle is not equal to the actual electrical phase angle, θ_{ele}, as there is a phase angle delay, θ_{delay}, between the estimated phase angle and the actual electrical phase angle. As such, the estimated phase angle can be illustrated by the equation:

$$\theta_{est} = \theta_{ele} - \theta_{delay}$$

To increase the accuracy of the peak back EMF determination, the estimated phase angle is modified to account for the phase angle delay and produce a modified estimated phase angle, $\hat{\theta}_{est}$. In an ideal situation, the phase angles around a zero-crossing of the back EMF are symmetric. As such, the integral of the phase angle between -α and α should be equal to zero in such a situation. The integral of the phase angles is therefore considered to be an error when non-zero, and the estimated phase angle is modified to account for this error and determine the modified estimated phase angle.

To modify the estimated phase angle, as shown by box 308 of Figure 6, the integral of the estimated phase angles is used as an input in a proportional integral (PI) controller (also known as a PI loop) with a set point of zero. The output of the PI controller 310 is the phase angle delay which is added to the estimated phase angle to determine the modified estimated phase angle. This is shown by the equation:

$$\hat{\theta}_{est} = \theta_{est} + \theta_{delay}$$

The modified estimated phase angle is then used in the determination of the integrated phase angle, such that the calculation of the integrated phase angle (in box 312 of Figure 6) becomes:

$$\sin\theta_{int} = \sum_{-\alpha}^{\alpha} abs(\sin\hat{\theta}_{est})$$

and the calculation of the peak back EMF (carried out at box 306) becomes:

$$Bemf_{pk} = \frac{Bemf_{int}}{\sin\theta_{int}} = \frac{\sum_{-\alpha}^{\alpha} abs(Bemf_{ADC})}{\sum_{-\alpha}^{\alpha} abs(\sin\hat{\theta}_{est})}$$

This may help to provide a more accurate determination of the peak back EMF over methods which do not compensate for phase angle delay. This may also help to ensure that the method 200 is resistant to disturbances in the system, such as those caused by large phase angle delays.

Once the peak back EMF has been determined, the temperature of the permanent-magnet is calculated using the equation:

$$T_{mag} = \frac{1}{a_{mag}}\left(1 - \frac{Bemf_{pk}}{Bemf_{amb}}\right) + T_{amb}$$

where T_{mag} is the calculated permanent-magnet temperature, a_{mag} is the thermal coefficient of remanence (Br) of the permanent-magnet, and $Bemf_{amb}$ is the back EMF measured at ambient temperature T_{amb}. When it is known that the permanent-magnet is at ambient temperature, the temperature is measured, and the motor is accelerated to a high speed by turning on the inverter 26. The inverter 26 is then turned off and the back EMF is measured to determine $Bemf_{amb}$. Both $Bemf_{pk}$ and $Bemf_{amb}$ may be compensated for a speed of the motor 14.

The operation of the motor 14 is controlled based on the determined temperature of the permanent-magnet. This is done by controlling the voltage applied to the phase winding 22 to ensure that the determined temperature of the permanent-magnet remains below a threshold value (also known as derating). The threshold value is the value above which the lifetime of the motor 14 may be limited or the performance of the motor 14 may decrease. Controlling operation of the motor 14 based on the threshold value may also be used to control other properties of the motor 14, such limiting an exhaust temperature or controlling another parameter that scales with the temperature of the permanent-magnet. In some examples, a further threshold value is indicative of a temperature above which damage to the motor 14 may occur. When the determined temperature of the permanent-magnet exceeds the further threshold value, the inverter 26 is switched off to help protect the motor 14 from damage.

Although the above method 200 has been discussed in relation to determining the peak back EMF, it may be equally used to determine any value of back EMF induced in the phase winding 22 of the motor 14, especially a value of back EMF induced in the phase winding which is larger than the dc-link voltage.

A vacuum cleaner 300 comprising the brushless permanent-magnet motor 14 is illustrated schematically in Figure 7. A haircare appliance 400 comprising the brushless permanent-magnet motor 14 is illustrated schematically in Figure 8.

Claims

1. A method of controlling a brushless permanent-magnet motor, the method comprising:

measuring a plurality of values indicative of back EMF induced in a phase winding of the motor;

determining estimated phase angles associated with the measured values indicative of back EMF;

integrating the measured values indicative of back EMF to determine an integrated back EMF;

integrating the estimated phase angles to determine an integrated phase angle;

determining a peak back EMF based on the integrated back EMF and the integrated phase angle; and

controlling the motor based on the peak back EMF.

2. The method according to claim 1, comprising determining a temperature of a permanent-magnet of the motor based on the peak back EMF and controlling operation of the motor based on the determined temperature of the permanent-magnet.

3. The method according to claim 2, wherein controlling operation of the motor comprises controlling a voltage applied to the phase winding of the motor such that the determined temperature of the permanent-magnet is below a desired threshold value.

4. The method according to any one of claims 1 to 3, comprising:

exciting the phase winding of the motor by applying a voltage to the phase winding using an inverter of the motor; and

turning off the inverter for a time period,

wherein measuring the plurality of values indicative of back EMF induced in the phase winding of the motor occurs during the time period.

5. The method according to any one of claims 1 to 4, wherein determining the peak back EMF comprises dividing the integrated back EMF by the integrated phase angle.

6. The method according to any one of claims 1 to 5, wherein integrating the measured values indicative of back EMF comprises integrating absolute values of the measured values indicative of back EMF induced in the motor.

7. The method according to any one of claims 1 to 6, wherein integrating the estimated phase angles comprises integrating absolute values of sine functions of the estimated phase angles.

8. The method according to any one of claims 1 to 7, comprising modifying the estimated phase angles based on a difference between the estimated phase angles and actual phase angles, wherein integrating the estimated phase angles comprises integrating the modified estimated phase angles.

9. The method according to claim 8, wherein modifying the estimated phase angles comprises determining a phase angle delay between the estimated phase angles and the actual phase angles and adding the phase angle delay to the estimated phase angles.

10. A brushless permanent-magnet motor comprising a phase winding and a controller configured to perform a method according to any one of claims 1 to 9.

11. A data carrier comprising machine-readable instructions for the operation of one or more controllers of a brushless permanent-magnet motor to perform the method according to any one of claims 1 to 9.

12. A vacuum cleaner comprising a brushless permanent-magnet motor according to claim 10.

13. A haircare appliance comprising a brushless permanent-magnet motor according to claim 10.