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(54) **METHOD TO CONTROL A SWITCHED RELUCTANCE MACHINE**

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(57) **ABSTRACT**

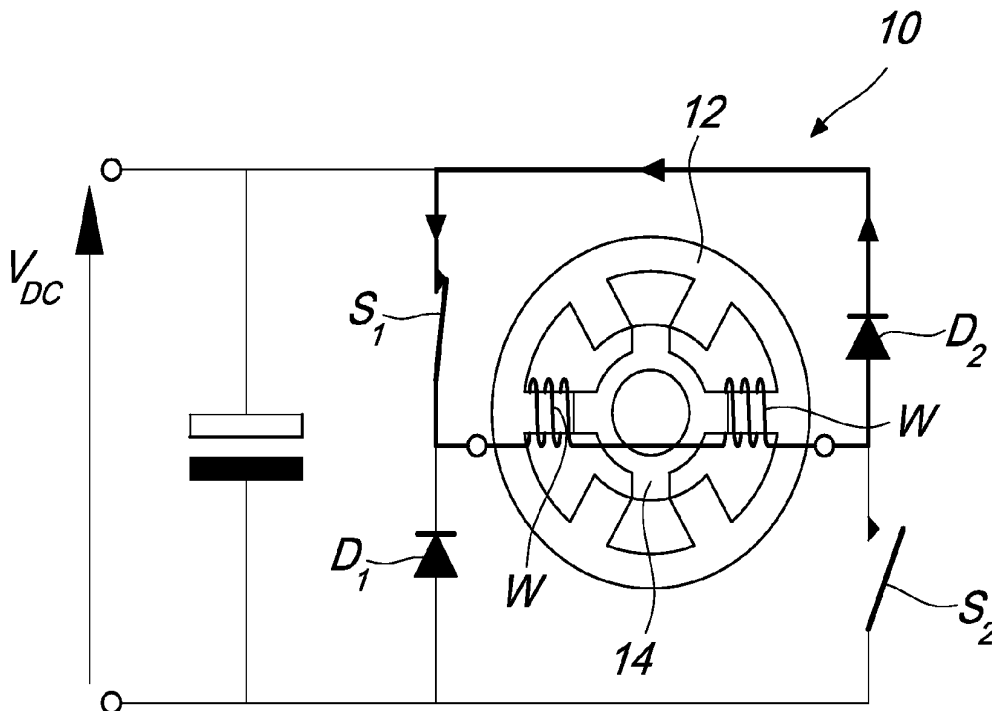
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A method to control the rotor position in a reluctance machine involves energizing the phase winding so to move the rotor relative to the stator, freewheeling current through the phase winding over a freewheeling period, sampling rate of change of phase current and amplitude of phase current, de-energizing the phase winding and computing the angular position of the rotor.

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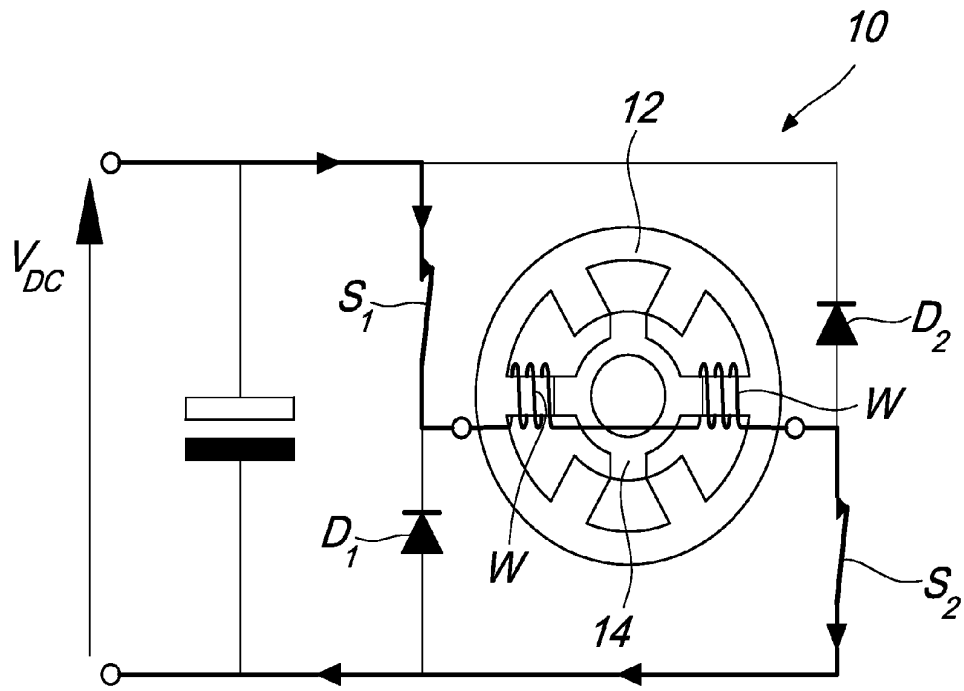


Fig. 1

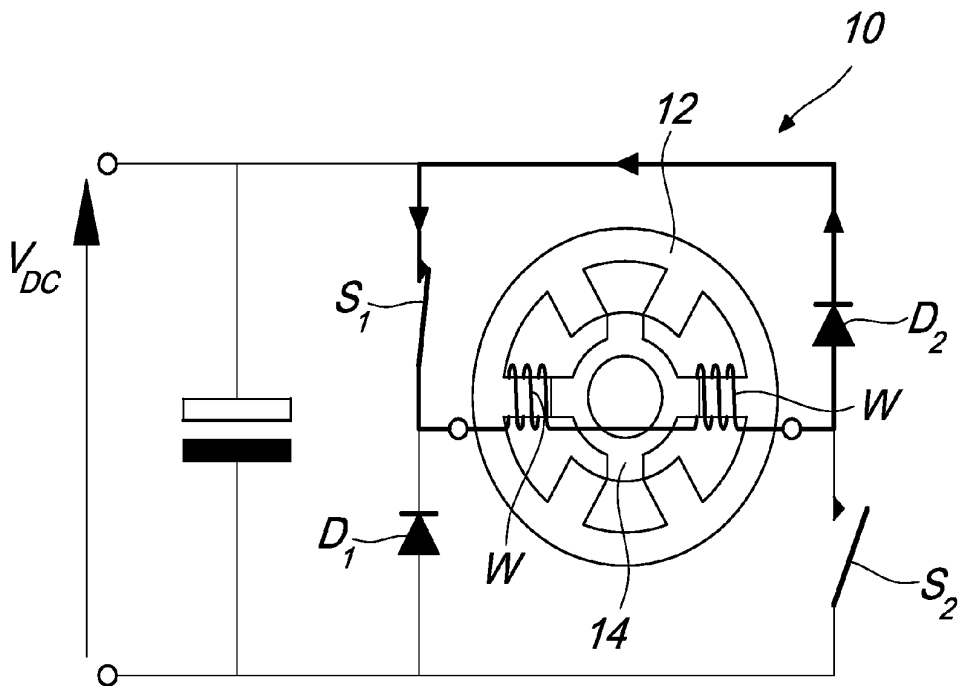
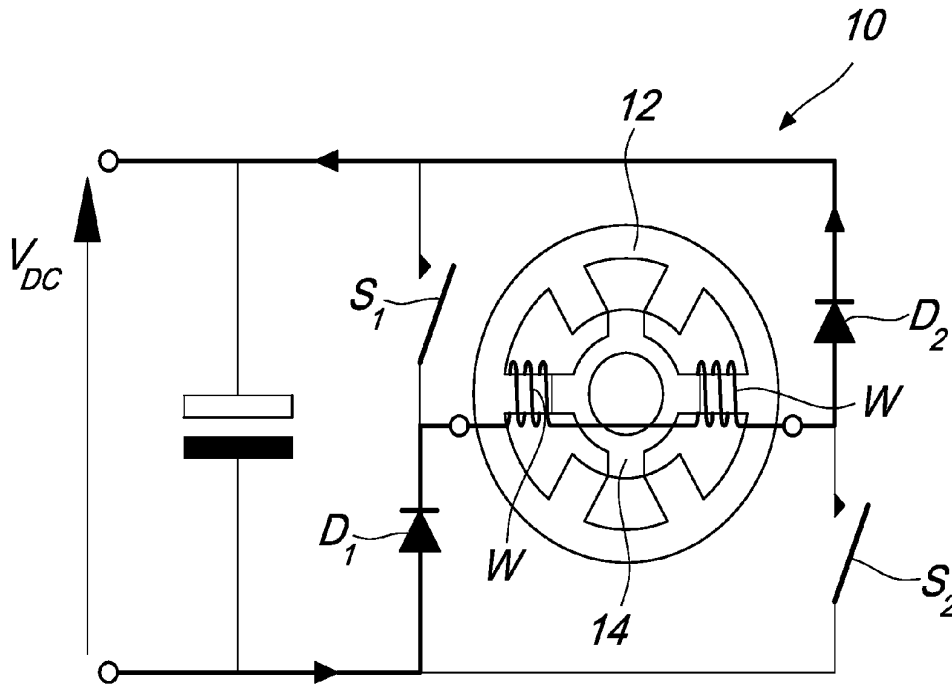
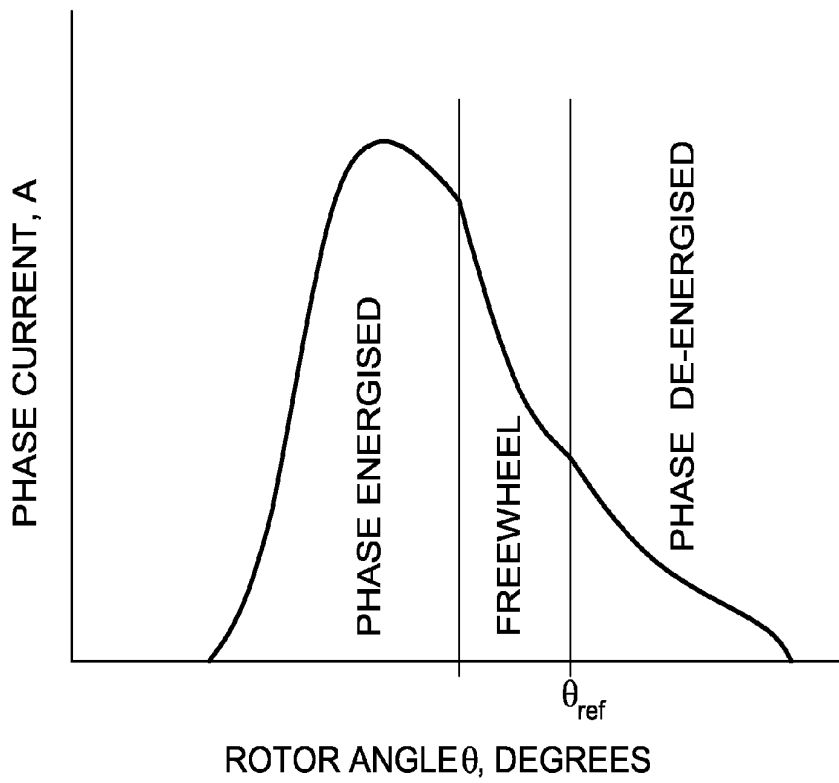


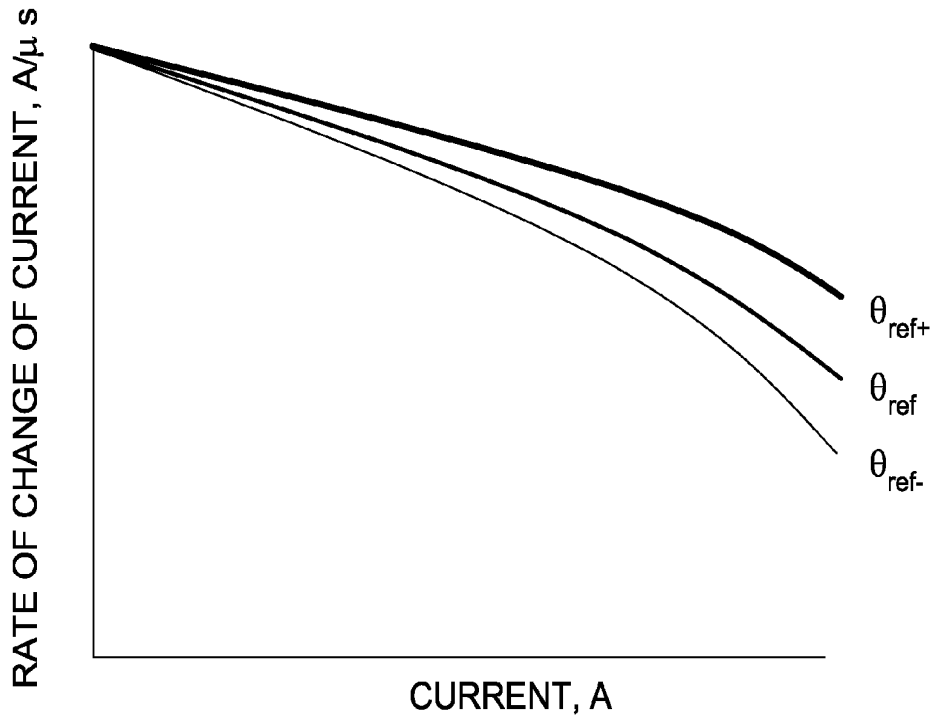
Fig. 2



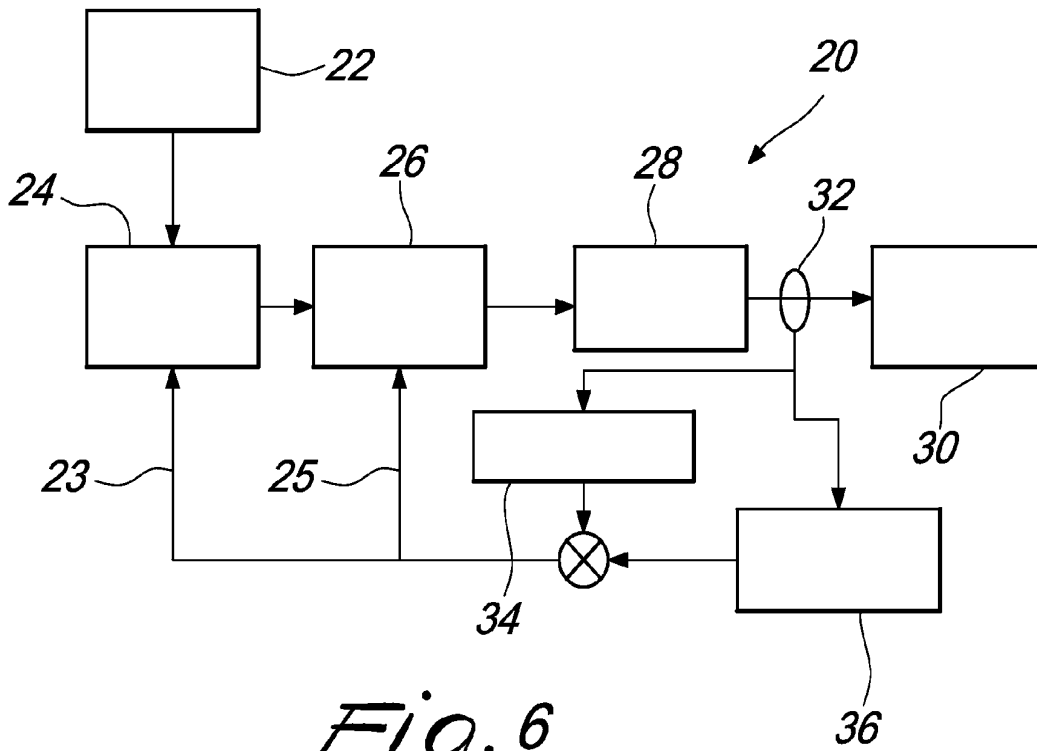
*Fig. 3*



*Fig. 4*



*Fig. 5*



*Fig. 6*

## METHOD TO CONTROL A SWITCHED RELUCTANCE MACHINE

### TECHNICAL FIELD

**[0001]** This disclosure relates to the field of sensorless monitoring and control of rotor position in a reluctance machine; in particular to switched reluctance machines and more particularly to high speed switched reluctance machines

### BACKGROUND

**[0002]** The accurate timing of the excitation of phases with respect to rotor position, in a switched reluctance machine, may be an important factor to obtain optimal performance. Rotor position sensors may be widely used in switched reluctance machines for monitoring rotor position. Such monitoring may be conventionally performed by an optical or magnetic sensor mounted on the stator. Control of the rotor position in the reluctance machine may be based on data relating to the rotor position.

**[0003]** To avoid dependency upon sensors, sensorless monitoring and control methods have been developed. Sensorless monitoring methods of switched reluctance machines may include signal injection methods and direct phase measurement methods.

**[0004]** Signal injection methods may rely on diagnostic energization pulses, for example non-torque producing pulses, that allow the controller to monitor the diagnostic current and accordingly the variation in inductance, from which the rotor position can be computed. In general, signal injection methods may be useful at starting and low operating speeds, but may adversely impact the motor performance at higher operating speeds.

**[0005]** Direct phase measurement methods may rely on monitoring phase current and voltage in order to determine the rotor position. A direct phase measurement method may use the concept of phase current freewheeling. Phase current freewheeling may be produced in a switched reluctance machine by setting voltage across a phase winding to zero for a period of time. During the freewheeling period current may circulate around the winding and the flux may be constant.

**[0006]** EP0780966B1 describes a method of sensorless rotor position monitoring in reluctance machines. The method comprises determining the rate of change of current at a particular point at which current in the winding may be arranged to freewheel. The point may coincide with alignment of a rotor and a stator pole such that the rate of change of current is predicted to be zero. The magnitude and polarity of any variation from the predicted rate of change may indicate a rotor position not in alignment with the actual rotor position and whether it is in advance of, or retreated from, the predicted position.

**[0007]** The present disclosure is directed, at least in part, to improving or overcoming one or more aspects of the prior art system.

### BRIEF SUMMARY OF THE INVENTION

**[0008]** In a first aspect, the present disclosure describes a method to control the rotor position in a reluctance machine comprising a stator, a rotor movable relative to the stator and at least one phase winding coupled to the stator, the method comprising the steps of: energising the phase winding to move the rotor relative to the stator; freewheeling current through the phase winding over a freewheeling period; sam-

pling rate of change of phase current and amplitude of phase current; de-energising the phase winding; and computing the angular position of the rotor.

**[0009]** In a second aspect, the present disclosure describes a system to control the rotor position in a reluctance machine comprising a stator, a rotor movable relative to the stator and at least one phase winding coupled to the stator, the system comprising: switches to energise the phase winding to move the rotor relative to the stator; to configure a freewheeling current through the phase winding over a freewheeling period and to de-energise the phase winding; a firing controller configured to command the sampling of rate of change of phase current and amplitude of phase current; and a microprocessor to compute the angular position of the rotor.

### BRIEF DESCRIPTION OF THE DRAWINGS

**[0010]** The foregoing and other features and advantages of the present disclosure will be more fully understood from the following description of various embodiments, when read together with the accompanying drawings, in which:

**[0011]** FIG. 1 is a schematic representation of an asymmetric half-bridge in phase energisation mode according to the present disclosure;

**[0012]** FIG. 2 is a schematic representation of an asymmetric half-bridge in freewheeling mode according to the present disclosure;

**[0013]** FIG. 3 is a schematic representation of an asymmetric half-bridge in de-energised mode according to the present disclosure;

**[0014]** FIG. 4 is a graph showing a phase current wave form according to the present invention;

**[0015]** FIG. 5 is a graph showing rate of change of current characteristics as a function of phase current according to the present invention; and

**[0016]** FIG. 6 is a schematic diagram illustrating a control circuit according to the present disclosure.

### DETAILED DESCRIPTION

**[0017]** This disclosure generally relates to a method of monitoring and controlling rotor position in a reluctance machine.

**[0018]** The method may be implemented in a reluctance machine which comprises a stator, a rotor that is movable relative to the stator and at least one phase winding coupled to the stator to control the rotor position. The method may comprise the steps of energising the phase winding to move the rotor relative to the stator; freewheeling current through the phase winding over a freewheeling period; sampling rate of change of phase current and amplitude of phase current; de-energising the phase winding; and computing the angular error in the rotor position.

**[0019]** The method may be used in ultra-high speed switched reluctance machines. An ultra-high speed switched reluctance machine may have a rotational speed of equal to or greater than 100,000 rpm.

**[0020]** FIGS. 1 to 3 illustrate an asymmetric half bridge power converter circuit **10** in three modes of operation for a switched reluctance machine having a stator **12** and a rotor **14**. A phase winding **W** may be connected between a switch **S1** associated with a diode **D1** and a switch **S2** associated with a diode **D2**.

**[0021]** With reference to FIG. 1, the phase winding may be energised from a DC source by closing switches **S1** and **S2** in

the circuit **10** so that current may flow through the phase winding **W** to move the rotor **14** relative to the stator **12**. The phase winding **W** may be in an energised state when switches **S1** and **S2** are closed.

**[0022]** Freewheeling current in a switched reluctance machine is generally known. Freewheeling current through a phase winding may be effected by setting the voltage across the phase winding of a switched reluctance machine to zero. The voltage may be set to almost zero by providing a short-circuit path across the ends of the phase winding so as to circulate current around the phase winding.

**[0023]** According to the method of the present disclosure, current is freewheeled through the phase winding **W** over a freewheeling period which corresponds to a portion of angular movement of the rotor **14**. With reference to FIG. 2, the phase winding **W** may be in a freewheeling state when either one of switches **S1** and **S2** is open.

**[0024]** The freewheeling of phase current may be performed during any part of the phase inductance cycle. A phase inductance cycle may be the period of inductance variance in a switched reluctance machine.

**[0025]** In an embodiment, the freewheeling period may start prior to the step of sampling rate of change of phase current and amplitude of phase current. In an embodiment, the freewheeling period may terminate after the step of sampling rate of change of phase current and amplitude of phase current.

The freewheeling period may be long. The freewheeling period may be a value selected on the basis of optimum efficiency performance at a given speed and torque operating point.

The freewheel period may be selected from greater than  $4^\circ$  of angular movement of the rotor **14**. The freewheel period may be selected from the range of  $5^\circ$  to  $20^\circ$  of angular movement of the rotor **14**. In an embodiment, the freewheel period may be selected from the range of  $8^\circ$  to  $15^\circ$  of angular movement of the rotor **14**. In an embodiment, the freewheel period may be selected from the range of  $10^\circ$  to  $12^\circ$  of angular movement of the rotor **14**.

**[0026]** In ultrahigh speed applications, a long freewheeling period may reduce machine inefficiency and obtain maximum power from the reluctance machine. A long freewheeling period may provide a low machine loss by minimising the iron losses.

**[0027]** With reference to FIG. 3, the phase winding **W** may be de-energised by opening both switches **S1** and **S2** in the circuit **10** so that no current may flow through the phase winding **W**. The phase winding **W** may be in a de-energised state when switches **S1** and **S2** are open. In the de-energised state mode, current will flow through phase winding **W** via **D1** & **D2** until the flux in the machine drops to zero.

**[0028]** FIG. 4 illustrates the phase current waveforms with respect to the angular position of the rotor **14**. In an embodiment, the  $0 \text{ ref}$  is the reference angle at the transition between the freewheeling stage of the phase winding **W** and the de-energised state of phase winding **W**.

**[0029]** According to the method, for a given speed the angle of the rotor **14** at which the both switches **S1** and **S2** are turned-off and the angle of the rotor **14** at which one switch **S1**, **S2** is turned-off may be characterised. The shaft power may be increased by advancing the angle at which both switches **S1** and **S2** are turned-on, and increasing the time over the flux in the motor builds-up. At a given speed, the energisation of the phase winding **W** may be adjusted until the

rate of change of phase current and amplitude of phase current may match the required turn-off angle (angle of the rotor **14** at which either both switches **S1** and **S2** are turned-off or at which one switch **S1**, **S2** is turned-off) point for that speed.

**[0030]** The characterisation may be performed for a switched reluctance machine to establish reference angular positions of the rotor **14** based on the turn-off points prior to commencement of operation. The reference rotor angular positions may be used to compare the angular positions of the sampled rate of change of phase current and amplitude of phase current. The reference rotor angular positions may enable optimal control of the switched reluctance machine.

**[0031]** The rate of change of phase current and amplitude of phase current may be sampled at an instantaneous interval. The sampling interval may be of the order of a microsecond. The sampling interval may be determined by an analogue to digital converter used in a control circuit. The analogue to digital converter may be a peripheral in a microcontroller such as a TI Piccolo 32-bit micro. Sampling rate of change of phase current and amplitude of phase current may be performed at the transition from the freewheeling state to the de-energisation state of the phase winding **W**. Sampling rate of change of phase current and amplitude of phase current may be performed at a sampling point when both switches **S1** and **S2** are opened.

**[0032]** In an embodiment, sampling rate of change of phase current and amplitude of phase current may be performed at or near the end of the freewheeling period. Sampling may be performed immediately prior to the start of de-energisation of the phase winding **W**. Sampling may be triggered by a gate signal transition. Noise in the samples may be reduced through a propagation delay in the gate drive circuitry. Sampling rate of change of phase current and amplitude of phase current may be performed at a sampling point before both switches **S1** and **S2** are opened.

**[0033]** In an embodiment, sampling rate of change of phase current and amplitude of phase current may be carried out at or near the start of the de-energisation of the phase winding **W**. Sampling may be performed immediately after the start of de-energisation of the phase winding **W**. Sampling rate of change of phase current and amplitude of phase current may be performed at a sampling point after both switches **S1** and **S2** are opened.

**[0034]** The rate of change of phase current and amplitude of phase current may be sampled in order to compute the angular position of the rotor **14**. The sampled rate of change of phase current and amplitude of phase current may be compared with reference rates of change of phase current and amplitudes of phase current in order to determine whether there is an angular error in the rotor position.

**[0035]** The sampling point may be selected based on a rotor position that corresponds to a transition between energy states, i.e. transition between energised and freewheeling state and transition between freewheeling and de-energised states.

**[0036]** The sampling point may be selected on the basis of optimal operation of the switched reluctance machine.

**[0037]** FIG. 5 shows the rate of change of current as a function of the phase current. Three curves  $\theta \text{ ref}$ ,  $\theta \text{ ref}^*$ ,  $\theta \text{ ref}^-$  may indicate angular position of the rotor **14** with respect to predetermined reference rates of change of phase current and amplitudes of phase current. The curves  $\theta \text{ ref}$ ,  $\theta \text{ ref}^*$ ,  $\theta \text{ ref}^-$  merely provide an indication of a graph that may have plotted therein all the possible angular positions of the rotor **14**. The

freewheel current slope may decrease as the angular position of the rotor **14** approaches the fully aligned position when the rotor **14** is fully aligned to the stator **12**.

[0038] Curve  $\theta_{ref}$  may indicate a specific angular position. Curve  $\theta_{ref}$  may indicate a reference angle at the transition between the freewheeling stage of the phase winding **W** and the de-energised state of phase winding **W**.

[0039] Curve  $\theta_{ref}^+$  may indicate an angular position greater than the angular position of curve  $\theta_{ref}$ . In an embodiment, curve  $\theta_{ref}^+$  may indicate an angular position  $2^\circ$  greater than the angular position of curve  $\theta_{ref}$ .

[0040] Curve  $\theta_{ref}^-$  may indicate an angular position lesser than the angular position of curve  $\theta_{ref}$ . In an embodiment, curve  $\theta_{ref}^-$  may indicate an angular position  $2^\circ$  lesser than the angular position of curve  $\theta_{ref}$ .

[0041] The angular position of rotor **14** may be obtained by determining the curve that coincides with the sampled rate of change of phase current and amplitude of phase current. An angular error may be present if the curve that coincides with the sampled rate of change of phase current and amplitude of phase current indicates an angular position different to that characterised for the sampling period. The angular error may be used to modify a timer to estimate the position of the rotor **14**.

[0042] FIG. 6 is a schematic diagram of a control circuit **20** for implementing a method of monitoring rotor position in a reluctance machine. The control circuit **20** may be incorporated in a reluctance machine which comprises a stator, a rotor that is movable relative to the stator and at least one phase winding coupled to the stator to control the rotor position. The control circuit **20** may control switches **S1**, **S2** that are actuable for energisation of the phase winding **W** to move the rotor **14** relative to the stator **14**, to freewheel current through the phase winding **W** over a freewheeling period and to de-energise the phase winding **W**.

[0043] The control circuit **20** may have speed controller **24**. The speed controller **24** may receive a speed demand signal **22**. The speed demand signal **22** may be compared to a feedback signal that is obtained from line **23**. The output of the speed controller **24** may be speed error signal that is sent as an input to the firing controller **26**. The firing controller **26** may not introduce a monitoring period. The firing controller **26** may command the sampling of rate of change of phase current and amplitude of phase current. The firing controller **26** may command the sampling of rate of change of phase current and amplitude of phase current at the transition from the freewheeling state to the de-energised state of the phase winding **W**.

[0044] In an embodiment, the firing controller **26** may command the sampling of rate of change of phase current and amplitude of phase current at or near the end of the freewheeling period.

[0045] In an embodiment, the firing controller **26** may command the sampling of rate of change of phase current and amplitude of phase current may be carried out at or near the start of the de-energisation of the phase winding **W**.

[0046] The output signal of the firing controller **26** may be used to control actuation of the power converter **28**.

[0047] Phase current sensing may be performed by current sensor **32**. The output signal of the current sensor **32** may indicate the amplitude of the phase current. The amplitude of the phase current may be used to compute the rate of change of phase current at the sampling point. The rate of change of phase current may be computed and sent out as an output

signal **36** and amplitude of phase current may be computed and sent out as an output signal **34**. The output signals **34**, **36** may form the basis for the indication of the position of the rotor **14** relative to the stator **12**. The output signals **34**, **36** may be compared to the respective reference rate of change of phase current and amplitude of phase current.

[0048] The firing controller **26** may command the current sensor **32** to perform sampling as the sampling period is dependent upon the timing of the switches **S1** and **S2**. The current sensor **32** conducts sampling at a time determined by the firing controller **26**.

[0049] Current sensor **32** may be a physical current sensor, such as a Hall effect device or resistor having a differential op-amp. An additional differentiator may be required for determining rate of change of phase current. The additional differentiator may be an op-amp circuit. The rate of change of phase current may be determined by initially double sampling in a micro and then computing rate of change of phase current.

[0050] Sampling of rate of change of phase current and amplitude of phase current may be performed at the phase winding **W**, or near the switches **S1** and **S2**. Sampling of rate of change of phase current and amplitude of phase current may be performed along the circuit comprising the phase winding **W** and the switches **S1** and **S2**.

[0051] If the error between the rate of change of phase current and the reference for the given current amplitude is zero, then the error in rotor position,  $\theta_{ref}$  may be zero. If there is an error in rotor position then the positional error may be applied to the speed controller **24** and firing controller **26** that is responsive to the magnitude and polarity of the position error.

[0052] In an embodiment, the error signal feedback sent to the speed controller **24** through line **23** may be processed as a positional error signal. The positional error signal may be used to re-calculate speed from the speed predicted by firing controller **26**. The error between the re-calculated speed based on positional error feedback and the speed demand may be sent to firing controller **26** by the speed controller **24**. The firing controller **26** may determine the control actions required to reduce the error between sampled and demanded speed.

[0053] In an embodiment, the error signal feedback sent to the speed controller **24** through line **23** and a positional error feedback may be sent to the firing controller **26** through line **25**.

[0054] The speed controller **24** may adjust the estimated speed based on the rotor position error. If the rotor position error indicates the rotor may be in advance of the expected position, the rotor **14** may be rotating faster than previously estimated. If the rotor position error indicates the rotor is retarded of the expected position, the rotor **14** may be rotating slower than previously estimated.

[0055] The firing controller **26** may include a free-running timer which is used to set the angular position of switching firing events. By deriving rotor position error from the current rate of change and the amplitude of phase current the timer may be reset for each phase. Then, for a given speed, the firing controller **26** may use the corrected assessment of the rotor position in one phase and a predetermined data of the firing control strategy in order to determine  $\theta_{ref}$ , the point of transition from freewheeling state to the de-energisation state of the next machine cycle.

[0056] For a given speed, the firing controller **26** may determine the time at which freewheeling should end ( $\theta_{ref}$ ) accord-

ing to the firing control strategy. At that time the firing controller **26** may actuate the measurement of current magnitude and rate of change.

**[0057]** When computing rate of change of phase current and determining amplitude of phase current the signals corresponding to rate of change of phase current signal **36** and determining amplitude of phase current signal **34** may be processed by a processor. The processor may be programmed with an equation or a look-up table to determine the rotor angular position. The equation or a look-up table may correspond to the graph of FIG. **5**. The processor may determine the angular position which is then compared to the characterised current amplitude and rate of change data.

**[0058]** Re-energisation may occur upon completion of a rotation by the rotor **14**, or in a machine with more than one phase, once the rotor is within sufficient proximity to the stator that the electromagnetic effect of the stator can influence the rotor.

**[0059]** A system to control the rotor position in a reluctance machine comprising a stator, a rotor movable relative to the stator and at least one phase winding coupled to the stator, the system comprising switches **S1**, **S2** to energise the phase winding to move the rotor relative to the stator; to configure a freewheeling current through the phase winding over a freewheeling period and to de-energise the phase winding; a firing controller **26** configured to command sampling of rate of change of phase current and amplitude of phase current; and a microprocessor to compute the angular position of the rotor.

**[0060]** The firing controller **26** may be configured to receive a speed error signal from a speed controller **24**. The system may comprise a timer to estimate the position the rotor **14**.

**[0061]** The skilled person would appreciate that foregoing embodiments may be modified or combined to obtain the method of the present disclosure.

#### INDUSTRIAL APPLICABILITY

**[0062]** This disclosure describes a method of monitoring a rotor position in a reluctance machine. The method of monitoring a rotor position may be employed in high speed switched reluctance machines for example reluctance motors having more than 100,000 rpm. The method involves a freewheel period that is long and obtaining an instantaneous sample of the amplitude and rate of change of phase current. The method involves computation of the rotor position that is based on the amplitude and the rate of change of phase current amplitude at the sampling point.

**[0063]** The method employs a high freewheeling duration to minimise iron losses at high operating speeds. The freewheeling phase current amplitude and rate of change of current are observed at an instantaneous interval of switching the phase from the freewheeling mode to the fully de-energized mode. Then the predetermined characteristics of the reluctance machine may be referenced to compute the angular position of the rotor.

**[0064]** The method overcomes the need for an electro-mechanical rotor position sensor, which may introduce additional moving components causing significant challenges in high-speed, compact or harsh environment applications. Sensorless control may be implemented via control software and a simple and robust electronic current sensor in the power electronic circuitry so as to exclude moving parts.

**[0065]** The method may improve accuracy of rotor position computation as phase current amplitude and rate of change current as used along with a pre-determined model of the non-linear electro-magnetic characteristics of the reluctance machine. Through the use of phase current freewheeling flux linkage may not be required. An advantage is that the continuous computation of flux linkage, which is equal to the integral of the DC link voltage over time, may not be required to compute the angular position of the rotor. The method has the advantage of reduced complexity of DC link voltage measurement and reduced computational demands. The measurement of rotor position by use of rate of change and amplitude of phase current may avoid the need for the use of DC link voltage measurement.

**[0066]** The method may be implemented in machines having switched reluctance motors. The method may be implemented in industrial machines or off-highway vehicles powered by an industrial, heavy-duty diesel engine, equipped with the Electric Turbo Assist system, or vacuum cleaners.

**[0067]** The freewheeling period may be selected on the basis of optimum efficiency performance at a given speed and torque operating point. The freewheeling period may be selected without specific reference to the position of the rotor **14**.

**[0068]** Accordingly, this disclosure includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the disclosure unless otherwise indicated herein.

**[0069]** Where technical features mentioned in any claim are followed by reference signs, the reference signs have been included for the sole purpose of increasing the intelligibility of the claims and accordingly, neither the reference signs nor their absence have any limiting effect on the technical features as described above or on the scope of any claim elements.

**[0070]** One skilled in the art will realise the disclosure may be embodied in other specific forms without departing from the disclosure or essential characteristics thereof. The foregoing embodiments are therefore to be considered in all respects illustrative rather than limiting of the disclosure described herein. Scope of the invention is thus indicated by the appended claims, rather than the foregoing description, and all changes that come within the meaning and range of equivalence of the claims are therefore intended to be embraced therein. The disclosures in European Patent Application No. 12185303.0 from which this application claims priority are incorporated herein by reference.

**1.** A method to control the rotor position in a reluctance machine comprising a stator, a rotor movable relative to the stator and at least one phase winding coupled to the stator, the method comprising the steps of:

- energizing the phase winding to move the rotor relative to the stator;
- freewheeling current through the phase winding over a freewheeling period;
- sampling rate of change of phase current and amplitude of phase current;
- de-energizing the phase winding; and
- computing the angular position of the rotor **14**.

**2.** The method of claim **1** wherein the period is selected from greater than  $4^\circ$  of angular movement of the rotor.



3. The method of claim 2 wherein the period is selected from the range of 5° to 20° of angular movement of the rotor.

4. The method of claim 3 wherein the period is selected from the range of 8° to 15° of angular movement of the rotor.

5. The method of claim 1 wherein the step of computing angular position of the rotor includes determining the angular error in the rotor position by comparing sampled rate of change of phase current and amplitude of phase current with reference rate of change of phase current and amplitude of phase current.

6. The method of claim 1 further comprising the step of modifying a timer to estimate the position the rotor.

7. The method of claim 1 wherein the freewheeling period starts prior to the step of sampling rate of change of phase current and amplitude of phase current.

8. The method of claim 1 the freewheeling period terminates after the step of sampling rate of change of phase current and amplitude of phase current

9. The method of claim 1 including sampling rate of change of phase current and amplitude of phase current at or near the end of the freewheeling period.

10. The method of claim 1 including sampling rate of change of phase current and amplitude of phase current at the transition from the freewheeling state of the phase winding to the de-energized state of the phase winding.

11. The method of claim 1 including sampling rate of change of phase current and amplitude of phase current at or near the start of the de-energization of the phase winding.

12. The method of claim 1 wherein sampling point is selected based on a rotor position corresponding to a transition between energization states.

13. A system to control the rotor position in a reluctance machine comprising a stator, a rotor movable relative to the stator and at least one phase winding coupled to the stator, the system comprising:

switches to energize the phase winding to move the rotor relative to the stator; to configure a freewheeling current through the phase winding over a freewheeling period and to de-energize the phase winding;

a firing controller configured to command the sampling of rate of change of phase current and amplitude of phase current; and

a microprocessor to compute the angular position of the rotor.

14. The system of claim 13 wherein the firing controller is configured to receive a speed error signal from a speed controller.

15. The system of claim 13 further comprising a timer to estimate the position of the rotor.

16. The system of claim 14 further comprising a timer to estimate the position of the rotor.

17. The method of claim 2 wherein the step of computing angular position of the rotor includes determining the angular error in the rotor position by comparing sampled rate of change of phase current and amplitude of phase current with reference rate of change of phase current and amplitude of phase current.

18. The method of claim 5 further comprising the step of modifying a timer to estimate the position the rotor.

19. The method of claim 18 wherein the freewheeling period starts prior to the step of sampling rate of change of phase current and amplitude of phase current.

20. The method of claim 19 the freewheeling period terminates after the step of sampling rate of change of phase current and amplitude of phase current.

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