

Rotor Position Detection of a **Switched Reluctance Drive**

This invention relates to sensorless rotor position detection in reluctance machines, particularly in switched reluctance machines.

The control and operation of switched reluctance machines generally are described in the paper "The Characteristics, Design and Applications of Switched Reluctance Motors and Drives" by J M Stephenson and R J Blake delivered at the PCIM'93 Conference and Exhibition held in Nurnberg, Germany, 21-24 June 1993, which is incorporated herein by reference. In that paper the "chopping" and "single-pulse" modes of energisation of switched reluctance machines are described for operation of the machine at low and high speeds, respectively.

A typical prior art drive is shown schematically in Figure 1. This includes a DC power supply 11 that can be either a battery or rectified and filtered AC mains. The DC voltage provided by the power supply 11 is switched across phase windings 16 of the motor 12 by a power converter 13 under the control of the electronic control unit 14. One of the many known converter topologies is shown in Figure 2, where the power supply 11 is provided on supply rails 26,27 which have a capacitor 25 connected across them to cater for any alternating components of current. The phase winding 16 is connected to the supply rails by an upper switch 21 and a lower switch 22. Energy return diodes 23,24 are connected in conventional fashion. A resistor 28 is connected in series with the lower switch 22 to provide a current feedback signal. A multiphase system typically uses several of the "phase

legs" of Figure 2 connected in parallel to energise the phases of the electrical machine.

The performance of a switched reluctance machine depends, in part, on the accurate timing of phase energisation with respect to rotor position. Detection of rotor position is conventionally achieved by using a transducer 15, shown schematically in Figure 1, such as a rotating toothed disk mounted on the machine rotor, which co-operates with an optical, magnetic or other sensor mounted on the stator. A signal, e.g. a pulse train, indicative of rotor position relative to the stator is generated by the sensor and supplied to control circuitry, allowing accurate phase energisation. This system is simple and works well in many applications. However, the rotor position transducer increases the overall cost of assembly. It also adds extra electrical connections to the machine and is, therefore, a potential source of unreliability.

Various methods for dispensing with the rotor position transducer have been proposed. Several of these are reviewed in "Sensorless Methods for Determining the Rotor Position of Switched Reluctance Motors" by W F Ray and I H Al-Bahadly, published in the Proceedings of The European Power Electronics Conference, Brighton, UK, 13-16 Sep 1993, Vol. 6, pp 7-13 which is incorporated herein by reference.

Many of these methods proposed for rotor position estimation use the measurement of phase flux-linkage (i.e. the integral of applied voltage with respect to time) and current in one or more phases. Position is calculated using knowledge of the variation in inductance of the machine as a function of angle and current. This characteristic can be stored as a flux-linkage/angle/current table and is depicted graphically in Figure 3. The storage of this data is a disadvantage as it involves the use of a large memory array and/or additional system overheads for interpolation of data between stored points.

Some methods make use of this data at low speeds where "chopping" current control is the dominant control strategy for varying the developed torque. Chopping control is illustrated graphically in Figure 4(a) in which the current and inductance waveforms are shown over a phase inductance period. (Note that the variation of inductance is depicted in idealised form.) These methods usually employ diagnostic pulses in non-torque-productive phases. A method suited to low-speed operation is that proposed by N M Mvungi and J M Stephenson in "Accurate Sensorless Rotor Position Detection in an S R Motor", published in Proceedings of the European Power Electronics Conference, Firenze, Italy, 1991, Vol.1, pp 390-393, incorporated herein by reference.

Other methods operate in the "single-pulse" mode of energisation at higher speeds. This mode is illustrated in Figure 4(b) in which the current and inductance waveforms are shown over a phase inductance period. These methods monitor the operating voltages and currents of an active phase without interfering with normal operation. A typical higher speed method is described in International Patent Application WO 91/02401, incorporated herein by reference.

Having to store a two-dimensional array of machine data in order to operate without a position sensor is an obvious disadvantage. Alternative methods have been proposed, which avoid the need for the majority of angularly referenced information and instead store data at one angle only. One such method is described in European Patent Application EP-A-0573198 (Ray), incorporated herein by reference. This method aims to sense the phase flux-linkage and current at a predefined angle by adjusting the diagnostic point in accordance with the calculated deviation away from the desired point. Flux-linkage is estimated by integrating (with respect to time) the measurement of the voltage applied to the phase. Two one-dimensional tables

16 MARCH 2005

are stored in the preferred embodiment, one of flux-linkage versus current at a referenced rotor angle and another of the differential of flux-linkage with respect to rotor angle versus current. By monitoring phase voltage and current, the deviation away from a predicted angle can be assessed, with the aid of the look-up tables, and system operation can be adjusted accordingly. This method has been shown to be reliable, provided that the flux-linkage can be determined with sufficient accuracy whenever required by the position-detecting algorithm. To avoid the flux-linkage integrator drifting (due to unwanted noise in the system and imperfections in the integrator) it is set to zero at the end of each conduction cycle, when the current has fallen to zero and the phase winding is no longer linking any flux. This method is a "predictor/corrector" method, in that it initially predicts when the rotor will be at a reference position, measures parameters of the machine when it believes the reference position has been reached, and uses the results of these measurements to detect error in the prediction and hence take corrective action by adopting a new prediction for the next reference position.

A special mode of operation of switched reluctance machines is the continuous current mode, as disclosed in US 5469039 (Ray) and incorporated herein by reference. In this mode, the winding is re-connected to the supply before the flux, and hence the current, have returned to zero at the end of the energy return period. The phase windings therefore operate with current continuously flowing through them and are always linked by flux. This is an important mode for systems which have to produce high levels of overload output at some points of their operating cycle. Although the efficiency of the drive falls in this mode, it allows specifications to be achieved which would otherwise require a larger machine. However, in this mode it has not hitherto been possible to use any of the prior art methods for sensorless rotor position detection, as there is no opportunity in the phase cycle to reset the integrators

16 MARCH 2005

at some known point of zero flux and current, since such a point does not exist.

Attempts to find a solution to this problem have included schemes which allow the drive to operate in the continuous current mode except when the control system judges it essential to re-estimate the position, at which time the continuous current mode is exited, the position estimated, and the drive put back into continuous current mode. Specifically, this can be done by running the machine in a mode which is predominantly continuous current but drops back into discontinuous current at predetermined intervals to allow positional information to be gained. The technique depends on the speed being virtually constant, which may be approximately true at higher speeds (at which continuous current is usually employed). Nevertheless, a loss of torque is associated with dropping out of continuous current. An alternative method is to operate each phase in continuous current for a given number of cycles, say 10, and then to excite the phase for a shorter time on the next cycle such that the current will definitely fall to zero, allowing the integrator to be reset and an accurate estimate of flux-linkage to be made. By interleaving this "short" cycle with the other phases operating in continuous current, the deleterious effect of the loss of torque is mitigated.

However, with all of these methods the loss of torque can render the machine performance unstable and several cycles are required before stability is reached again because the current must be built up over a period in the continuous current.

The present invention is defined in the accompanying independent claims. Some preferred features are recited in the dependent claims.

16 MARCH 2005

According to an embodiment of the present invention there is provided a method of detecting rotor position in a reluctance machine, comprising: deriving a value for the flux linkage associated with the or at least one phase of the machine at a first point, at a moment at which voltage is applied to that phase; deriving a value of the phase current and the phase flux linkage at a subsequent point of the rotor; combining the derived flux linkage values to give a value of total flux linkage at the subsequent point; and deriving the rotor position from the phase current and the value of the total flux linkage.

Preferably, there is provided a method in which the moment when voltage is applied to the phase is at the point when flux-linkage growth is initiated. The current at the said moment may be substantially zero or non-zero.

Preferably, the value of the flux linkage at the moment when voltage is applied to the phase is derived from the current at the said moment. For example, the flux linkage at the said moment is derived from the current and stored values of inductance for ordinates of current.

The embodiment of the invention is, therefore, particularly useful in the single-pulse mode of operation of a switched reluctance machine. The invention can use the value of current at the first point to derive the value of flux-linkage. When the current is discontinuous the zero current value gives rise to a zero value of flux-linkage. When the current is continuous the value of current can be used to derive the non-zero flux-linkage.

Preferably, the flux-linkage from the said first point is derived by integrating the phase voltage from the said moment to the subsequent point. The said flux-linkage at the subsequent point may be derived by integrating the phase voltage from the said moment to the subsequent point. The rotor position may

be derived from stored parameters having coordinates of phase current and flux-linkage.

The method of the invention according to one particular embodiment measures the current at turn-on of a phase winding when flux growth is initiated and uses this current value to index a table of inductance. The value of inductance provided by the table is then multiplied by the current to give an estimate of the standing flux-linkage in the phase. Also at turn-on, a flux-measuring integrator, which is set to zero, is put into integration mode. At a predetermined subsequent point, the value of flux-linkage provided by the integrator is added to the calculated value for standing flux-linkage, and the resulting total is used to determine rotor position.

Because the inductance is determined at switch turn-on, i.e. the initiation of flux growth in a phase inductance cycle, the method does not require large amounts of stored data. It is also robust in the presence of noise on the waveforms from which it deduces position.

Also according to the present invention there is provided a method in which rotor position is derived from values associated with each phase of a polyphase machine.

One embodiment of the present invention provides a robust and cost-effective method of monitoring rotor position and a rotor position detector, which can operate without a rotor position transducer in the single-pulse mode, with or without continuous current.

The invention can be put into practice in a number of ways, some of which will now be described by way of example and with reference to the accompanying drawings in which:

Figure 1 shows a typical prior art switched reluctance drive;

Figure 2 shows a known topology of one phase of the converter of Figure 1;

Figure 3 shows typical flux-linkage and phase current curves, with rotor position as a parameter;

Figure 4(a) shows a typical motoring current waveform in chopping control;

Figure 4(b) shows a typical motoring current waveform in single-pulse control;

Figure 5 shows in schematic form a switched reluctance drive in which the invention is embodied;

Figure 6 shows flux-linkage waveforms in the drive of Figure 5 in continuous current mode;

Figure 7 shows a continuous current waveform for the drive of Figure 5; and

Figure 8 shows flux-linkage waveforms in the drive of Figure 5 in discontinuous current mode.

The phase inductance cycle of a switched reluctance machine is the period of the variation of inductance for the, or each, phase, for example between maxima when the stator poles and the relevant respective rotor poles are fully aligned. The illustrative embodiment to be described uses a 2-phase switched reluctance drive in the motoring mode, but any phase number from one upwards could be used, with the drive in either motoring or generating mode.

Figure 5 shows a system for implementing the method in which the invention is embodied. Figure 7 illustrates graphically the continuous current waveform for the system of Figure 5. In this system, a power converter 13 is typically the same as that shown in Figure 1, and like reference numerals have been used where appropriate. The converter 13 controls the switched reluctance machine, as before. The converter 13 is itself controlled by a controller 42 which, in this embodiment, incorporates a digital signal processor 44, e.g. one from the Analog Devices 2181 family. Alternative embodiments could

incorporate a microprocessor or other form of programmable device, as are well-known in the art. The illustrated 2-phase machine has a stator 30 and a rotor 32. The stator has four poles 50, on which are wound phase windings 34/36. The rotor has rotor poles 52 and, to assist with starting the machine, has a pole face 54 that defines a stepped airgap with the face of a stator pole. One skilled in the art will realise that a machine with a different phase number or pole combinations could be used, since the invention is not specific to any particular machine topology. Similarly, the invention is not restricted to a particular type of control technique and any controller and converter can be used as long as it is suitably programmable.

Phase current is sensed by a current transducer 38 arranged in relation to each phase winding. The output signals indicative of current in each phase are fed to the controller 42. A look-up table 46 storing phase inductance for rotor angles is also connected with the controller 42. While a current transducer for each phase is shown, one or a selection of phases could be monitored for phase current according to the invention.

An integrator 40 depicted in the controller 42 is used to derive measurements of flux by integrating the phase voltage V across the winding provided by voltage transducer 43. For greater accuracy the voltage drop (IR) across the winding can be factored out of the integrated value. Only one voltage transducer 43 is shown in Figure 5 as the supply voltage will be common to each phase. It will be appreciated that each phase could have a respective voltage transducer. While the integrator is shown as a discrete device 40 it is preferably implemented in the software running in the processor 44.

The method according to this embodiment of the invention operates as follows. It is assumed that the machine is operating in continuous current mode and that the rotor position is known sufficiently well to allow the

winding to be energised. At the point of turn on, when positive voltage is applied across the phase, the value of current is measured by the transducer 38 and held by the controller 42. Knowing the turn-on angle, the look-up table 46 of phase inductance against angle is interrogated to return the phase inductance corresponding to the rotor angle. The value of inductance is multiplied by the stored current value to give the flux-linkage in the phase at the point of turn on. This value is stored. As the rotor turns, the integrator 40 operates to integrate the voltage across the phase winding. When the control system determines that the subsequent predetermined position has been estimated to have been reached, the current is measured using the transducer 38 for the active phase and the estimate of flux linkage from the integrator 40 is added to the stored value from the table 46 to give the total value of flux linkage in the phase at that position. This total value is then used, in conjunction with the current, to find the true position which, if necessary, can be used to correct the previous estimate.

The angular difference $\Delta\theta$ between the predicted rotor position θ_m and the reference rotor position θ_r can be calculated by the processor 42 as

$$\Delta\theta = \left\{ \frac{\partial\theta}{\partial\Psi_m} \right\} \cdot \Delta\Psi \quad (1)$$

In order to determine the angular difference between the predicted position (at which the measurement of flux and current are made) and the reference position, it is therefore also a feature of this embodiment to store in the processor for the reference position values of partial derivative $\partial\theta/\partial\Psi$ (or its inverse $\partial\Psi/\partial\theta$) for a set of values of phase current i .

Since the reference rotor position θ_r is known, the true rotor position at the predicted instant in time may be calculated from $\Delta\theta$ as

$$\theta_m = \theta_r + \Delta\theta \quad (2)$$

The expected time to the next rotor position can then be estimated using the known value of motor speed. Under accelerating or decelerating conditions a correction may need to be made to the motor speed.

If all phases are used for measurement the next rotor reference position will be that for phase 2 (or whatever is the next phase in the sequence). For an n -phase motor with p rotor poles, the angle of rotation to this position will be $(360/np)^\circ - \Delta\theta$ and, by dividing this angle by the speed, the time required to reach this next position can be estimated.

If only one phase is used for measurement, the next rotor reference position will be after a rotation of $(360/p)^\circ - \Delta\theta$ and, by dividing this angle by the speed, the time required to reach this position can be estimated.

The predicted time to the next reference position is then counted out using a high frequency clock (not shown) by known means and at the instant such time has elapsed a further measurement of flux Ψ_m and current I_m is made for the corresponding phase. Due to changes in speed, and tolerances in stored data and calculations, the predicted position θ_m will not be identical to the reference position θ_r . The angular difference $\theta_r - \theta_m$ can again be calculated using equations (1) and (2) and the procedure outlined above.

The process of predicting rotor positions on a phase by phase basis and measuring the true rotor position at each measurement instant is repeated to

provide an incremental indication of rotor position as a direct replacement for existing optical or electromagnetic rotor position sensors.

The procedure for the case of single-pulse operation under regenerating conditions is the same as described above except that the values of $\partial\theta/\partial\psi$ shown in Figure 6 will be negative (rather than positive) for the corresponding typical reference rotor position.

Various arrangements may be used for the measurement of flux. Any known form of flux transducer could be used. However, the measurement is preferably by means of analogue or digital electronic resettable integrators (which integrate the phase voltage with respect to time t), together with means for compensating for the resistive voltage drop in the phase winding.

The integrator executes the equation:

$$\psi = \int_{t_0}^{t_m} (v - iR) dt \quad (3)$$

where:

v	is the phase voltage
i	is the phase current
R	is the phase resistance
t_m	is the instant of measurement

The integrator start time t_0 is arranged to be the instant of application of voltage to the phase each time the phase is energised (for the higher speed mode). The digital processor is informed of the instant of application of the voltage to the phase by the electronic controller using a control interface (not shown). The integrator is reset by the digital processor after each flux reading has been made.

In applications for which the direct source voltage V is relatively large compared to the voltage drop across the semiconductor switches in the power converter, the direct source voltage may be measured and integrated in place of the individual phase voltage. This has the advantage that only one voltage need be measured.

The flux is then measured as:

$$\psi = \int_{t_0}^{t_1} (V - iR) dt \quad (4)$$

As an alternative to using separate electronic integrators, the digital processor may be used by multiplying the direct supply (or phase) voltage by time on a step by step basis. This has the disadvantage that the digital processor is substantially busy and may need to be a separate unit.

However, provided the supply voltage is substantially constant and large compared with the resistive voltage iR , various approximations may be made. For example:

$$\psi_m = (V - ki_m R) (t_m - t_0) \quad (5)$$

where k is a constant, typically $k = 0.5$, such that:

$$ki_m(t_m - t_0) \approx \int_{t_0}^{t_m} i dt$$

As a further embodiment, in the case where the supply voltage V is relatively large compared with the resistive voltage iR , the need to compensate for the

resistive voltage drop may be avoided by using a modified value for the flux in the stored data or ignoring iR altogether.

In this case the values of phase flux linkage ψ for a particular current I and particular rotor position θ stored in the digital processor are replaced by values of the volt-second integral ψ' required to create the phase current I for the rotor position θ are given by

$$\psi' = \int v dt$$

In testing the machine to establish the table of values of ψ' and $\partial\theta/\partial\psi'$, v may, for convenience, be held constant (provided v is relatively large) and is preferably equal to supply voltage. The rotor position measurement procedure is the same as already described in this application except that the measured flux ψ_m and expected flux ψ_e and partial derivative $(\partial\theta/\partial\psi)$ are replaced by ψ'_m , ψ'_e and $(\partial\theta/\partial\psi')$ respectively, where ψ'_e and $(\partial\theta/\partial\psi')$ are obtained as described from the stored data represented by Figures 4 and 6 and where the flux ψ'_m is measured as

$$\psi'_m = V (t_m - t_0) \quad (6)$$

Equations (3), (4), (5) and (6) represent different methods of evaluating the phase flux linkage for the purpose of identifying rotor position and these represent different implementations of the technique.

The various embodiments described above are all based on the measurement of flux ψ_m and current I_m at a predicted rotor position, the look-up of the expected flux ψ_e for the measured current i_m corresponding to the reference rotor position, and the calculation of the difference $\Delta\theta$ between the reference

rotor position and the predicted rotor position according to the equation:

$$\Delta\theta = \left\{ \frac{\partial\theta}{\partial\Psi} \right\}_m (\psi_m - \psi_e) \quad (7)$$

Figure 6 illustrates the method of the invention graphically. The saw-tooth waveform ψ_a represents the actual flux linkage associated with a phase while the machine is in the continuous current mode. The flux-linkage value ψ_s is the minimum, or "standing" value during the cycle. The saw-tooth waveform ψ_i represents the flux linkage indicated by the output of the integrator. The phase is switched on at the angle θ_{on} , prior to which the integrator has been held in reset for the period R by means of a signal from the processor 44. This period R is long enough to return the integrator output to zero. At θ_{on} , the current is measured (see Figure 7) and the look-up table 46 of inductance is interrogated to find the inductance of the phase for that rotor angle. The product of the current and the inductance is calculated by the processor 44. This gives an estimate of ψ_s , which is then stored by the controller 42. After θ_{on} , the actual flux linkage in the phase increases at a rate dictated by the applied voltage, and is tracked, with an offset of ψ_s , by the output of the integrator. At some point (not critical to this discussion) the phase is switched off and the flux linkage begins to ramp down. When the control system determines that the rotor is at the predetermined position θ_{ref} , the output from the integrator and the value of phase current are sampled and held. The stored estimate of ψ_s is added to the value of ψ_i to give an estimate of ψ_a . The current and ψ_a can then be used to find the actual rotor angle in the way described above and taught by Ray in EP-A-0573198.

This embodiment of the invention is particularly advantageous in that it works equally well when the phase current is discontinuous, i.e. in the conventional

16 MARCH 2005

single-pulse mode. This is illustrated graphically in Figure 8. Since the current is zero immediately before θ_{on} , the multiplication with the inductance value gives the correct result of zero standing flux-linkage. Thus, the same program code can be used in the controller 42 for both discontinuous and continuous current.

The method described above provides a simple, yet effective, way of combining continuous current operation with sensorless position detection, without any unwanted degradation in the performance of the machine.

The skilled person will appreciate that variations of the disclosed arrangements are possible without departing from the invention, particularly in the details of the implementation of the algorithm in the controller. Also, the diagnosis on which rotor position detection is based could be carried out in only one phase of a polyphase machine. Accordingly, the above description of several embodiments is made by way of example and not for the purposes of limitation. It will be clear to the skilled person that minor modifications can be made to the drive circuit without significant changes to the operation described above. The present invention is intended to be limited only by the scope of the following claims.

16 MARCH 2005

CLAIMS:

1. A method of detecting rotor position in a reluctance machine, comprising:

deriving a value for the flux linkage associated with the or at least one phase of the machine at a first point, at a moment at which application of voltage to that phase is initiated;

deriving a value of the phase current and flux linkage at a subsequent point in time;

combining the derived flux linkage values to give a value of total flux linkage at the subsequent point; and

deriving the rotor position from the phase current and the value of the total flux linkage.

2. A method as claimed in claim 1 in which the moment is at the point when flux-linkage growth is initiated.

3. A method as claimed in claim 1 or 2 in which the current at the said moment is non-zero.

4. A method as claimed in claim 1 or 2 in which the current at the said moment is zero.

5. A method as claimed in any of claims 1 to 4 in which the value of the flux linkage at the moment when positive voltage is applied to the phase is derived from the current at the said moment.

6. A method as claimed in claim 5 in which the flux linkage at the said moment is derived from the current and stored values of inductance.

16 MARCH 2005

7. A method as claimed in claim 1 in which the flux-linkage at the said subsequent point is derived by integrating phase voltage from the said moment to the subsequent point.
8. A method as claimed in claim 7 in which the said moment is the point of minimum flux linkage and the integration is started at the said moment.
9. A method as claimed in claim 1 in which the rotor position is derived from stored parameters of phase current and flux linkage.
10. A method as claimed in claim 1 in which rotor position is derived from values associated with each phase of a polyphase machine.
11. A method as claimed in claim 1 in which the rotor position is derived from values associated with one phase of a polyphase machine.
12. A rotor position detector for a reluctance machine comprising:
 - means for determining a value for flux linkage associated with the or at least one phase of the machine at a first point, at a moment when application of voltage to that phase is initiated;
 - means for deriving a value for the phase current and flux linkage at a subsequent point in time;
 - means for combining the derived flux linkage values to give a value of total flux linkage at the subsequent point; and
 - means for deriving the rotor position from the phase current and the value of total flux linkage.
13. A detector as claimed in claim 12 including a look-up table storing values of inductance for values of phase current.

16 MARCH 2005

14. A detector as claimed in claim 12 in which the means for deriving a value for the flux linkage at the subsequent point includes an integrator for integrating the phase voltage from the said moment to the subsequent point.

15. A detector as claimed in claim 14 including means for resetting the integrator for the said moment.

16. A detector as claimed in claim 12, including processor means operable to determine the value for the flux linkage when flux-linkage growth is initiated.

17. A detector as claimed in claim 16 in which the processor means is operable to derive the value for the flux linkage from the current at the said moment.

18. A detector as claimed in claim 12 in which the means for deriving the rotor position include means for storing values of rotor position for values of phase current and flux linkage.