

SENSORLESS ROTOR POSITION MEASUREMENT IN
ELECTRIC MACHINES

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This invention relates to the measurement of rotor position for an electric machine. The invention is particularly applicable to switched reluctance machines.

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The principle of operation of a switched reluctance (SR) motor and its construction, energisation and control are well known with many publications such as that by P.J. Lawrenson et al "Variable-speed switched reluctance motors" IEE Proc B, Electr Power Appl., Vol 127, No 3, pp 253-265, 1980.

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It is also well known that to obtain the best performance from an SR motor or generator the excitation of its phases should be carefully timed in relation to rotor position (see GB 1591346). This has previously necessitated the use of an incremental rotor position transducer which has generally been a disc with teeth or lines together with an optical or electromagnetic sensor which is able to detect the instants the teeth or lines cross prescribed positions.

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The incorporation of a rotor position transducer on an SR motor creates additional electrical connections, additional cost and a potential source of unreliability. Various methods have therefore been proposed to eliminate the rotor position transducer. As an alternative it is possible to deduce rotor position by measurement and examination of the current and flux-linkage in one or more phases of the motor. This is commonly known as sensorless rotor position measurement. Since phase current generally needs to be measured in any case for control purposes and flux-linkage can be inexpensively

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obtained from measurement of phase voltage, sensorless rotor position measurement is commercially beneficial.

Sensorless methods generally depend on stored information of the flux-current-rotor position characteristics of the motor. A typical example of these characteristics is shown in Figure 1. The storage of this data entails a two-dimensional array of significant size to achieve acceptable accuracy. Some methods are only appropriate for relatively low speed operation for which the well known 'chopping' mode of current control applies and other methods are only appropriate for relatively high speed operation for which the well known 'single-pulse' mode of current control applies.

A method which is more suited to lower speed operation that is known (for example, N M Mvungi and J M Stephenson "Accurate sensorless rotor position detection in an SR motor" EPE Conf Proc 1991 Vol I pps 390-393) involves the application of exploratory current pulses to each phase winding at periods during which the phase is not energised for torque production. To avoid a counter-productive torque these pulses need to be small in magnitude and, as a result, the measured flux is influenced by currents in other phases. This can cause error and corrections need to be made which require the additional two-dimensional storage of mutual magnetisation data.

A method by Hedlund (see WO91/02401) which is more suited to higher speed operation utilises the normal phase currents for position measurement purposes. However this method necessitates the continual sampling of flux and current and comparison of flux with stored values for a reference position. This may necessitate a dedicated digital processor to perform the sensorless position measurement.

An object of the present invention is to provide sensorless position measurement by sampling the current and flux in a phase only once per energisation cycle. This may enable the same digital processor which is used for the SR motor control to be used also for determining rotor position.

According to the invention a rotor position sensing system for an electric machine with one or more phases, comprises at least one current transducer arranged for measurement of the current in a monitored phase winding, means for deriving a measurement of the magnetic flux linking the monitored phase winding, and control means operable to measure, for the monitored phase winding, the current and flux simultaneously at a predicted position for a reference rotor angular position, the angular error between the predicted position and an actual reference angular position being determined by a comparison of the measured current and flux with the expected current and flux at the actual reference position.

Other aspects and features of the invention are defined in the accompanying claims.

The invention can be put into practice in various ways one of which will now be described with reference to the accompanying drawings, in which:

Figure 2 shows two typical reference rotor positions for different modes of operation as related to the inductance for a phase;

Figure 3 is a schematic diagram illustrating one embodiment of the sensorless rotor position measurement system of the invention;

Figure 4 is a graph of variations of a phase flux-linkage with current for reference rotor positions;

Figure 5 is a graph of the variation with current of the partial derivative of angle with respect to flux for

a given reference rotor position; and

Figure 6 is a schematic diagram illustrating another embodiment of the sensorless rotor position measurement system of the invention.

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In the following:

θ represents rotor position

Ψ represents phase flux linkage

i represents phase current

Ψ' represents phase volt-seconds

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v_s represents direct source voltage

The reference rotor position θ_r for a phase will be different depending on whether the machine is motoring or generating and on whether the speed is above or below some threshold value.

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If the speed is above the threshold (the "higher speed mode") and the machine is motoring, the reference position for a phase is preferably such that for this position the phase inductance is increasing (shown typically as position A in Figure 2). The reference position for this case should also preferably be chosen such that current will normally be present in the phase at this position.

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If the speed is above the threshold and the machine is generating, the reference position for a phase is preferably such that, for this position, the phase inductance is decreasing (shown typically as position B in Figure 2). The reference position for this case should also be chosen such that current will normally be present in the phase at this position.

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If the speed is below the threshold (the "lower speed mode") and the machine is motoring, the reference position for a phase will be preferably the same as position B but may be another position in the falling inductance region.

If the speed is below the threshold and the machine is generating, the reference position for a phase will be preferably the same as position A but may be another position in the rising inductance region.

5 The threshold speed will depend on the motor design and application but in general will be set as low as is commensurate with satisfactory sensorless rotor position measurement using the higher speed reference position. For some applications only the higher speed reference
10 position need be used, in which case the threshold speed will be zero.

Speed may be measured by timing the interval between measured rotor positions or by using known frequency to voltage conversion techniques as for previous SR motor
15 control systems.

Figure 3 is a schematic diagram showing a particular embodiment whereby rotor position can be measured. A switched reluctance motor 1 has a number of phase windings 2 which are energised by means of a power
20 switching circuit 3 containing semiconductor switches and drawing power from (or returning power to) a direct voltage source 4. The direct voltage source may be obtained by rectifying an ac mains supply. The semiconductor switches are turned on and off, depending
25 on the rotor position, according to previously known strategies, by an electronic controller 5. To execute these strategies the electronic controller requires information on the phase currents and the rotor position and speed.

30 The invention does not concern the form of direct voltage source, the power switching circuit or the control strategies, which have all been described in various publications, and these aspects will not be further detailed.

The means necessary for determining the rotor position comprise a digital processor 6, one or more current transducers 7 for providing the digital processor with a measurement of phase current(s), and one or more voltage transducers 8 and resettable electronic integrators 9 for providing the digital processor with a measurement of phase flux linkage. The current measurement signals are also provided to the electronic controller and to the resettable integrators. Although for the convenience of illustration Figure 1 shows the current and voltage transducers in the box representing the motor 1, in practice these transducers will be contained in the power switching circuit 3 so as to minimise the number of connections to the motor.

A control signal interface 10 connects the electronic controller with the digital processor and control signals for initiating and resetting the integrators 9 pass from the digital processor along lines 11. The digital processor may also include analogue to digital converters to convert the measured values into digital form if necessary.

Consider operation in the higher speed mode under motoring conditions and suppose that, at a predicted instant in time, the rotor position θ_m is close to the reference position θ_r for a particular phase which for convenience will be called phase 1. At the predicted instant, measurements are made of the flux ψ_m and current i_m for phase 1.

Figure 4 shows the variation of flux ψ with current i for the reference rotor position θ_r and from this characteristic the expected flux ψ_e for the measured current i_m can be calculated. Flux ψ_e is the flux which would be measured if the predicted rotor position θ_m was identical to the reference position θ_r .

In order to compare ψ_m with ψ_e for any measured current i_m it is therefore a feature of this embodiment to store in the digital processor, for the reference position, values of flux ψ for a set of values of phase current i . This has the advantage, compared to other methods of sensorless position detection, that only a single dimensional array of values is required. The difference between the measured flux ψ_m and the expected flux ψ_e is calculated by the digital processor as

$$\Delta\psi = \psi_m - \psi_e \quad (1)$$

Figure 4 also shows the variation of flux ψ with current i for position $\theta_r - \Delta\theta$, slightly before the reference position, and for $\theta_r + \Delta\theta$, slightly after the reference position. It will be seen that for a given current, ψ increases with θ for the region of the reference position for the case of the higher speed mode under motoring conditions.

Figure 5 shows the variation of the change of flux with rotor angle ($\partial\theta/\partial\psi$) with current i for the reference rotor position θ_r and from this characteristic the value ($\partial\theta/\partial\psi$)_r can be determined for the measured current i_m .

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

$$\Delta\theta = \left[\frac{\partial\theta}{\partial\psi} \right]_r \cdot \Delta\psi \quad (2)$$

In order to determine the angular difference between the predicted position (at which the measurements of flux and current are made) and the reference position, it is therefore also a feature of this embodiment to store in the digital 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 position θ_r is known, the true

rotor position at the predicted instant in time may be calculated from $\Delta\theta$ as

$$\theta_m = \theta_r + \Delta\theta$$

5 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.

10 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.

15 If only phase 1 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.

20 The predicted time to the next reference position is then counted out using a high frequency clock by known means and at the instant such time has elapsed a further measurement of flux Φ_m and current i_m is made for the corresponding phase. Due to changes in speed, and
25 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.

30 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 higher speed operation under regenerating conditions is the same as described above except that the values of $\partial\theta/\partial\psi$ shown in Figure 5 will be negative (rather than positive) for the corresponding typical reference rotor position shown as position B in Figure 2. If position B is symmetrically opposite position A (with respect to the maximum inductance position) then only one set of values for each of Figures 4 and 5 need to be stored in the digital processor and the sign change for regenerating conditions appropriately taken into account in the calculations. However, if positions A and B are essentially different then a set of values for both Figure 4 and Figure 5 for both motoring and regenerating conditions will need to be stored.

For the lower speed mode when the well known current chopping control is operative it is not appropriate to utilise the main excitation current for the phase for rotor position measurement purposes. In this case exploratory current pulses are injected at such times as the phase is not normally energised.

Consider the case of lower speed motoring. The rotor reference position for a phase is now taken to be position B (i.e. the same or approximately the same position as for higher speed generating). As for the higher speed cases the next rotor reference position is predicted on a phase by phase basis. On arriving at the predicted position a short duration voltage pulse is applied to the phase by the power switching circuit and the flux and current are measured at the termination of the voltage pulse. The instruction for executing the voltage pulse is supplied to the electronic controller 5 by the digital processor 6 using the control interface 10

shown in Figure 3. The difference between the predicted rotor position θ_m and the rotor reference position θ_r is calculated on the same basis as described above. The true rotor position is thereby established at each instant in time the measurements are made.

The case of lower speed regenerating is the same as for lower speed motoring except that the reference rotor position is typically position A rather than position B.

The invention is therefore applicable to all speeds of operation whether the machine is motoring or regenerating.

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 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) or each time an exploratory pulse is applied (for the lower speed mode). At time t_0 the current i is zero. The digital processor is informed of the instant of application of the voltage to the phase by the electronic controller using the control interface (10) shown in

Figure 3.

The integrator is reset by the digital processor after each flux reading has been made.

The digital processor is only required to start and terminate the integration process and to execute the calculations following the current and flux measurement which enable the next rotor reference position to be predicted. This may represent only a short part of the time interval between successive predicted positions and for the remaining time the digital processor will be idle. It is therefore possible to utilise the existing electronic controller 5 in Figure 3 also to fulfil the role of the digital processor 6 in Figure 3 and thereby avoid the need for a separate digital processor for the purpose of rotor position measurement. The use of a single processor/controller is an advantage of the invention, and the corresponding system is shown schematically in Figure 6.

In applications for which the direct source voltage v_s (see Figure 3) is relatively large compared to the voltage drop across the semiconductor switches in the power switching circuit, 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. However, in this case for the higher speed mode of operation it is necessary for the reference position to be in advance of the commutation position for the phase. This can be arranged by suitable choice of the reference position.

The flux is then measured as:

$$\psi_m = \int_{t_0}^{t_m} (v_s - iR) dt \quad (4)$$

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 would 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:

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

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_s 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 represented by Figures 4 and 5.

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 as represented by Figures 4 and 5 are replaced by values of the volt-second integral ψ' required to create the phase current i for the rotor position θ as 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 v_s .

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 5 and where the flux ψ'_m is measured as

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

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

In the case of equations (5) and (6) the resettable electronic integrators are not required. The measured supply voltage v_s is provided directly to the digital processor. The phase flux ψ_m (or ψ'_m) is then computed using equations (5) or (6) by the digital processor.

The various embodiments of the invention 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:

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

Equation (7) is the combination of the previous equations (1) and (2).

As a further set of embodiments, still based on the measurement of flux ψ_m and current i_m as is the subject of this invention, the expected current i_e for the measured flux ψ_m corresponding to the reference rotor position can be looked up from the characteristic shown in Figure 4 and used to calculate the true rotor position, instead of

using the expected flux ψ_e for the measured current i_m .
In this case:

$$\Delta\theta = \left\{ \begin{array}{c} \frac{\partial\theta}{\partial i} \end{array} \right\}_m \cdot (i_m - i_e) \quad (8)$$

5 Equation (8) is the corollary of equation (7).

For these embodiments it is therefore necessary to store in the digital processor for the reference position values of the partial derivative $\partial\theta/\partial i$ (or its inverse $\partial i/\partial\theta$) for a set of values of flux ψ (rather than storing values of $\partial\theta/\partial\psi$ for a set of values of current i as shown in Figure 5).

10 The alternative calculation defined by equation (8) is particularly relevant for the lower speed mode of operation for which exploratory pulses of voltage are applied to the phase windings as described above. Since these pulses may be of fixed time duration and the phase voltage may be substantially the same as the supply voltage, the "measured" flux ψ_m will be substantially the same for each voltage pulse. It is therefore possible, 15 if the supply voltage remains substantially the same, to store only one value for $\partial\theta/\partial i$ (or $\partial i/\partial\theta$) corresponding to this particular value of ψ for the reference rotor position. 20

CLAIMS:

- 5 1. A rotor position sensing system for an electric machine with one or more phases, comprising at least one current transducer arranged for measurement of the current in a monitored phase winding, means for deriving a measurement of the magnetic flux linking the monitored phase winding, and control means operable to measure, for the monitored phase winding, the current and flux
- 10 simultaneously at a predicted position for a reference rotor angular position, the angular error between the predicted position and an actual reference angular position being determined by a comparison of the measured current and flux with the expected current and flux at
- 15 the actual reference position.
2. A system as claimed in claim 1, including means operable to calculate the time before the rotor reaches the next rotor reference angular position and to enable
- 20 the control means to repeat the said measurements at the next predicted reference angular position.
3. A system as claimed in claim 1 or 2 in which the control means include a digital processor.
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4. A system as claimed in claim 1, 2 or 3 in which the reference rotor angular position of the monitored phase winding coincides with an angular position at which the monitored phase inductance is increasing or decreasing.
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5. A system as claimed in any of claims 1 to 4, in which the means for deriving a measurement of flux comprise integrator means for receiving input signals related to the current through and the voltage across the



monitored phase winding.

5 6. A system as claimed in any of claims 1 to 5, in which the control means store a machine current and flux prediction algorithm, the algorithm being arranged to provide a measured rotor angular position based on the product of the difference in measured and predicted flux and the rate of change of rotor angle with respect to flux.

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7. A system as claimed in claim 6 in which the control means are arranged to store a look-up table of values of the partial derivative of the rotor angle with respect to flux for each of a set of values of monitored phase 15 current, or of rotor angle with respect to current for each of a set of values of monitored phase flux linkage.

20 8. A system as claimed in any of claims 1 to 7 in which the control means are operable to predict the moment at which a following reference angular position will be passed based on timing the rotor at a measured speed from the determined actual reference angular position.

25 9. A system as claimed in any of claims 1 to 8, including voltage generating means controlled by the control means for inducing a voltage pulse across the monitored phase at the predicted rotor angle position, the control means being arranged to measure the current in the monitored phase winding and the flux linking the 30 monitored phase winding upon termination of the voltage pulse.

10. A electric reluctance machine controller including a position sensing system as claimed in any of claims 1



to 9.

11. A method of sensing the position of a rotor relative to a stator on an electric machine, the method comprising:

measuring the current through a monitored phase winding of the machine;

measuring the flux linking the monitored phase winding simultaneously with the measurement of the current at a predicted position for a reference angular position; and

determining the error between the predicted position and an actual reference angular position by a comparison of the measured current and flux with the expected current and flux at the actual reference position.