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Online: WPI

# (54) Starting and direction control of two phase switched reluctance machine

(57) A method of starting a two phase switched reluctance machine 5 and direction control is achieved by sequencing the order by which the phase windings are energised. This includes the use of two-phase 'on' condition, which, when rotor poles are aligned with a set of stator poles, results in an asymmetric magnetic field. The start up sequence comprises energising one of the phase windings with a prescribed current magnitude and direction, after a prescribed time period, the remaining phase is energised with a prescribed current magnitude and direction, and after a prescribed time period with both phases energised, one phase current is de-energised such that torque is produced and the rotor rotates in the desired direction. Direction control from the position achieved with both phases 'on' is simply the case of turning one phase off. The method uses a sequence controller 4 and may use some form of shaft position control to control commutation. An optical or magnetic sensor 6 is described (Fig 8). Starting may be enhanced by using asymmetry in the machine design by wedges on the rotor poles (Fig 9) or by using a non-salient stator configuration by arranging the phase conductors (N1 and N2, Fig 10) in slots of the stator.

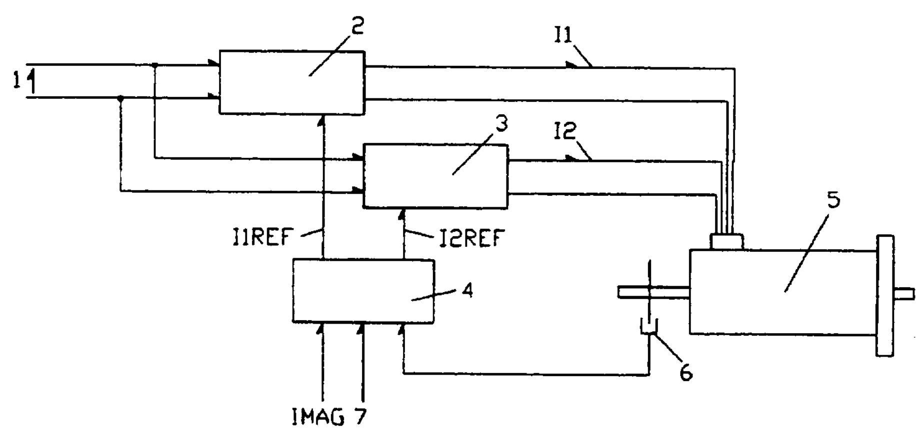


**Figure 1**

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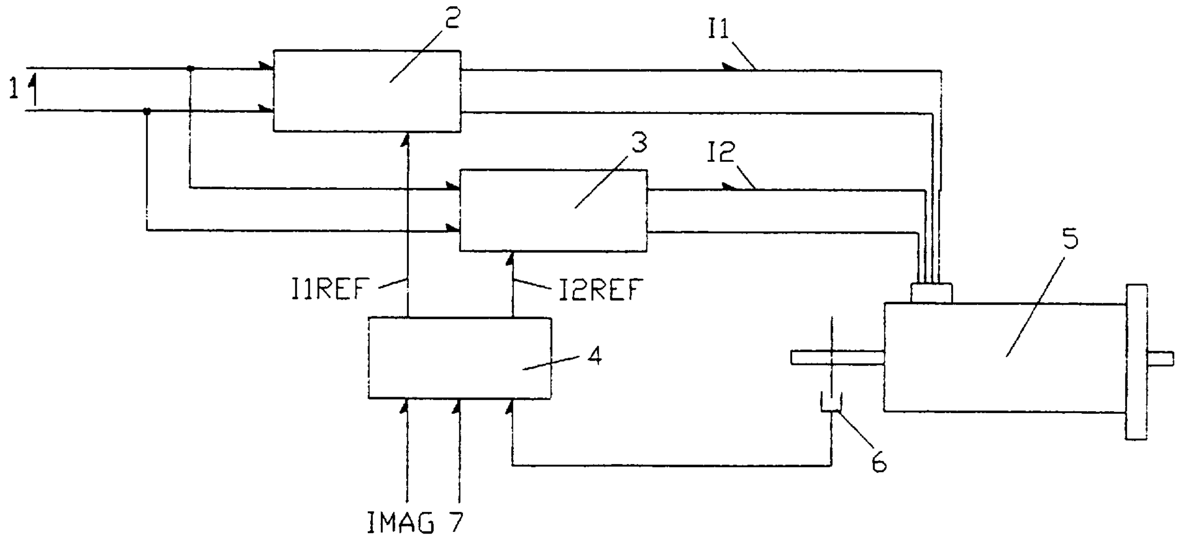


**Figure 1**

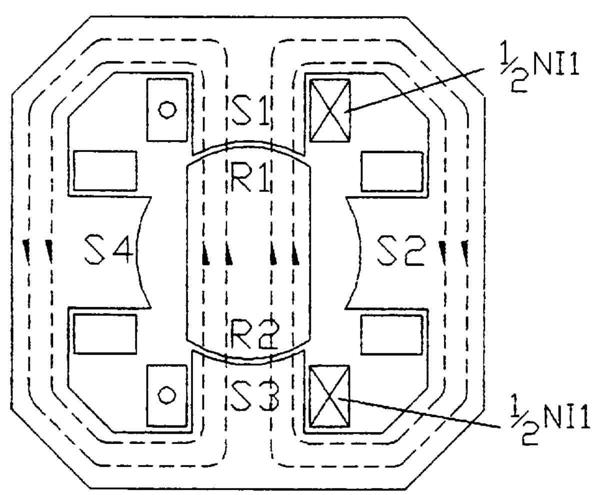


**Figure 2**

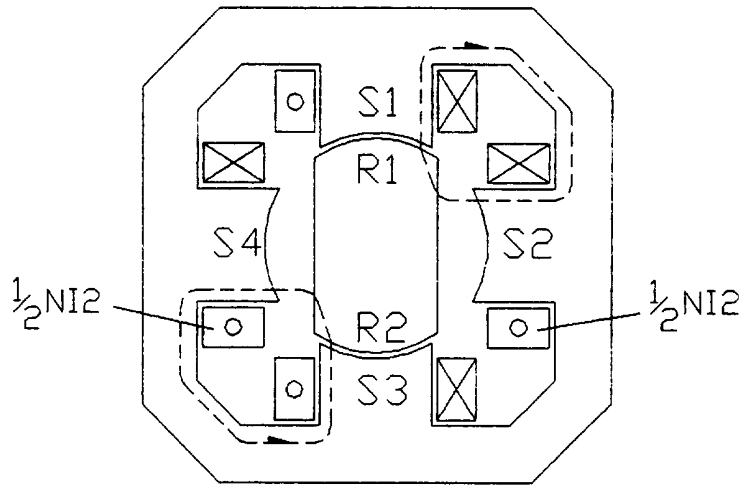


**Figure 3**

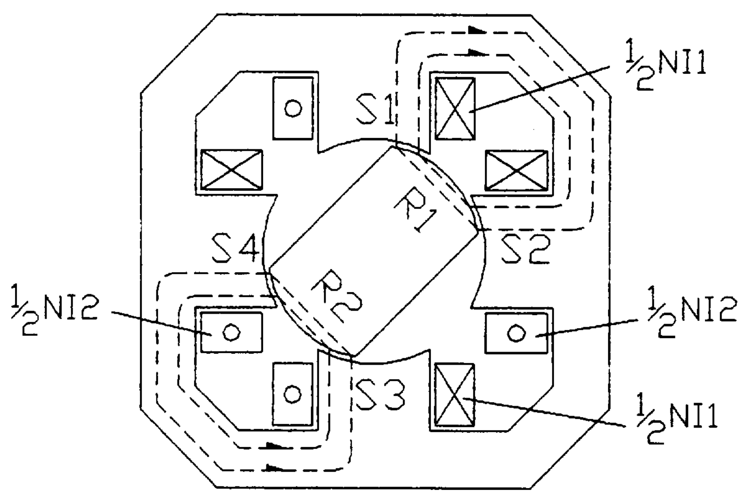


**Figure 4**

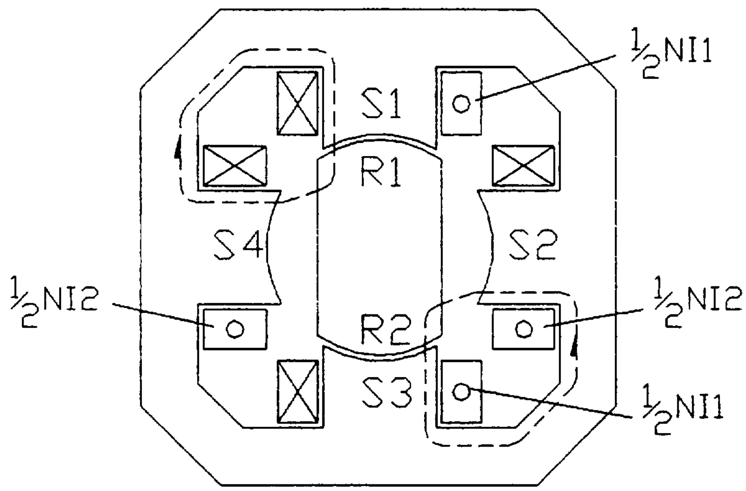


**Figure 5**

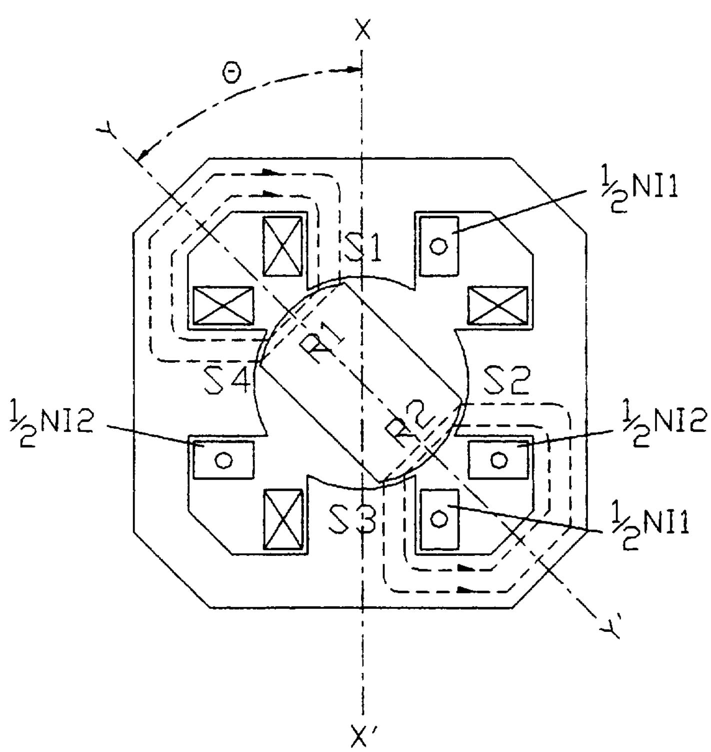


**Figure 6**

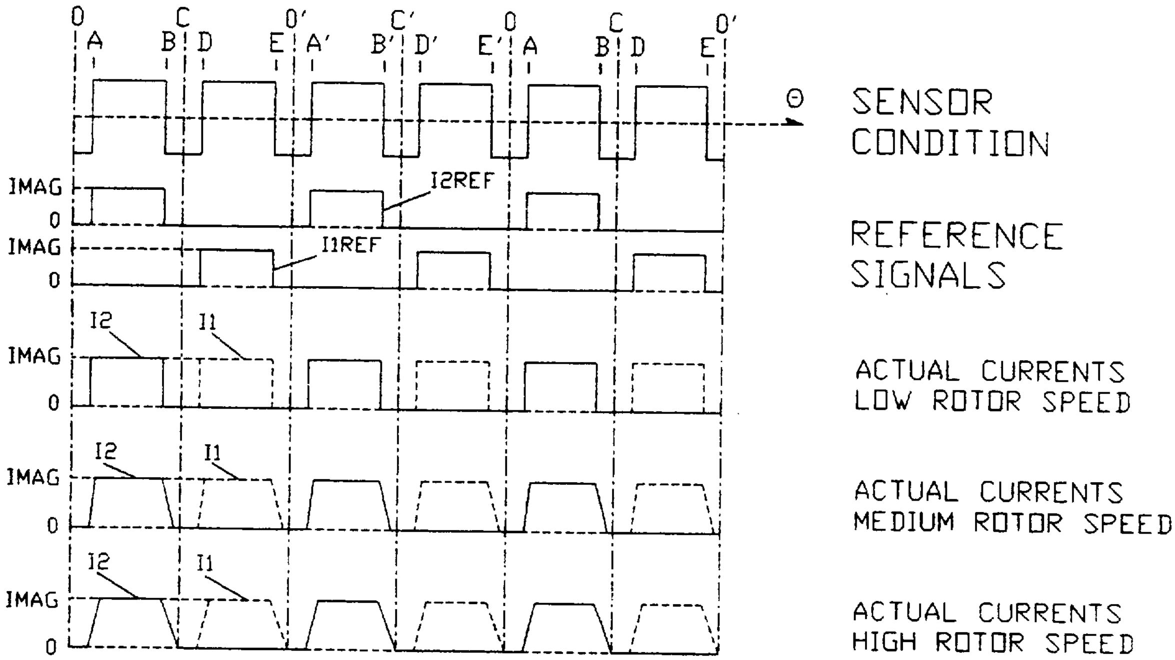


**Figure 7**

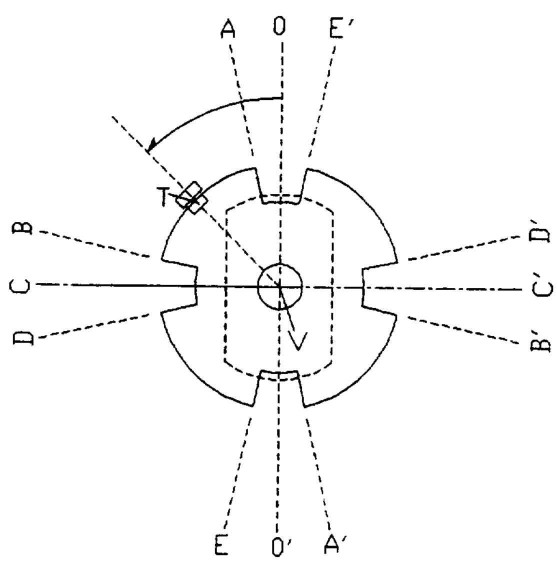


**Figure 8**

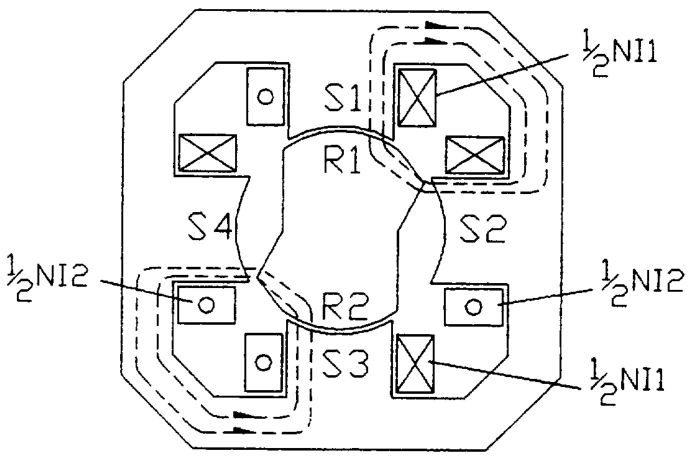


**Figure 9**

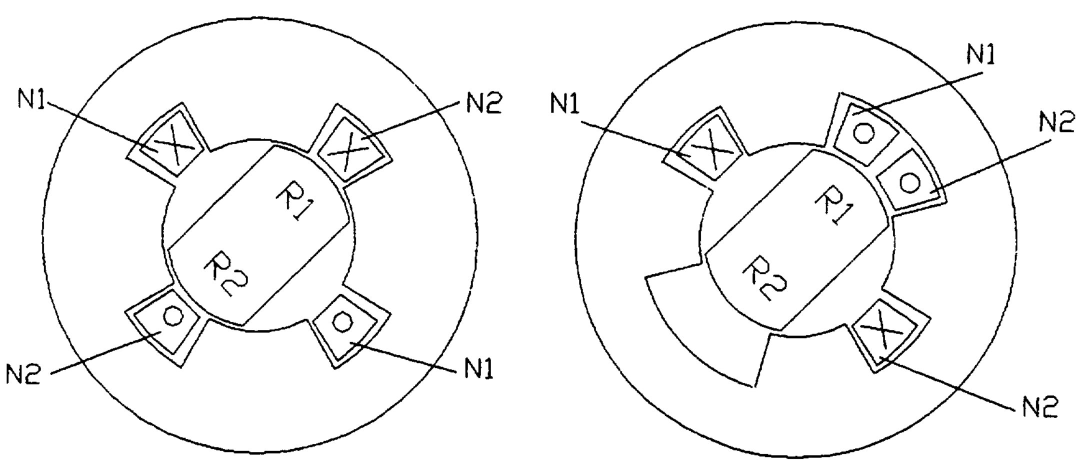


**Figure 10**

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# Self-starting and Direction Control of Two-phase Switched Reluctance Machines

## Technical Field

The invention provides a means of self-starting a two-phase switched reluctance machine giving control over rotor direction.

## Background Art

A two-phase switched reluctance machine is difficult to both start and control rotor direction. Methods which partly alleviate this problem include the use of auxiliary permanent magnet excitation, introducing asymmetry on rotor or stator poles or utilising shaded poles. A method of providing start-up and direction control of the two-phase switched reluctance machine is described which exploits the natural asymmetry of the magnetic field which occurs under certain conditions. A standard machine topology is used which has symmetrical rotor and stator pole configurations. The technique can be extended to asymmetrical pole configurations which gives improved starting torque. The method relies on rotor saliency and utilises a two-phase 'on' stage to position the rotor poles between specified stator poles from which direction control is simple. A robust shaft encoder is proposed specifically for this type of drive to provide information for phase winding current commutation after start-up. However, open loop or sensorless techniques may be adopted to eliminate direct position sensing

## Disclosure of Invention

According to the invention, there is a machine drive for a two-phase switched reluctance machine, the machine drive comprises a two-phase machine with an even number of rotor poles and stator poles, a phase current control means supplied by a dc supply means and a rotor position sensing means, the phase current control means configured such that under power-up or rotor standstill conditions a start-up sequence is initiated to control rotor direction, the start-up sequence comprises of energising one of the phase windings with a prescribed current magnitude and direction, after a prescribed time period, the remaining phase is energised with a prescribed current magnitude and direction, after a prescribed time period with both phases energised, one phase current is de-energised such that torque is produced and the rotor rotates in the desired direction, the phase current control means is also configured such that after the start-up sequence is complete, the phase currents are commutated in a manner to maintain net torque production in the desired direction with commutation instants controlled using information provided by the rotor position sensing means.

## Brief Description of Drawings

In order that the invention be more fully understood, reference will now be made to the accompanying drawings, in which:

*Figure 1* shows a block diagram of the drive system which is an embodiment of the invention.

*Figures 2-6* indicate, in accordance with the invention, the nature of flux paths in the machine under start-up conditions.

*Figure 7* shows explanatory waveforms indicating, in accordance with the invention, the manner of operation of the drive system shown in Figure 1 after start-up.

*Figure 8* shows a possible slotted disc arrangement suitable as a rotor position sensor in the drive system shown in Figure 1.

*Figure 9* indicates, in accordance with the invention, the nature of flux paths in an asymmetric machine under start-up conditions.

*Figure 10* shows two particular, but not exclusive, embodiments of switched reluctance machine topologies which utilise non-salient stator configurations for use with the invention.

## Best Modes for carrying out the Invention

A switched reluctance machine drive comprises a dc supply means, 1, which supplies two phase current controllers, 2 and 3. The phase current controllers regulate the currents, I1 and I2, in the two phases of the machine, 5. The reference currents, I1REF and I2REF, are supplied to the controllers by a current sequencing means, 4, which is operatively coupled to a position sensing means, 6, mounted on the machine, a means to set phase current magnitude, IMAG, and a means to set direction, 7. The phase current controllers may utilise a number of prior art techniques to control the machine currents, I1 and I2, so as to provide NI1 and NI2 ampere-turns in the two phase windings of the machine. Each phase winding produces N ampere-turns per phase per unit phase current. This is achieved using series or parallel connected pole windings of the required number of turns. Switched voltage techniques using fixed or variable switching frequencies may be used in conjunction with current feedback to provide high fidelity current control. Current feedback may be extracted using magnetic, electrical or electronic means. A variety of power electronic switching configurations allow both unipolar or bipolar current control.

Start-up and direction control is required from power-up, rotor standstill or near-standstill conditions. The current sequencing means includes a means to sense when the drive system is powered up. Information derived from the shaft position sensor is used to sense absolute or near-standstill rotor conditions. Providing power-up detection and rotor standstill detection enables the current sequencing means, 4, to implement the start-up sequence, which is in accordance with the invention, so as to provide start-up and direction control when required.

From power-up or rotor standstill (or near-standstill) conditions the current sequencing means controls the current in the phase windings of the machine in a specific order using the phase current controllers. One phase is energised with current I1 providing ampere-turns NI1 tending to align the poles of the rotor with the energised stator poles. The magnetic field induced in the machine by the excitation is indicated in Figure 2 with the rotor aligned. The magnetic field is symmetrical in the symmetrical machine. With the current sequencing means maintaining current, I1, in the energised phase, the remaining phase is energised with current I2, giving ampere-turns NI2. The magnetic field in the machine now becomes asymmetric with unequal flux in the stator limbs. Figure 3 indicates the induced magnetic field at the instant the second phase is energised. The asymmetry in the magnetic field causes a torque to be produced rotating the rotor towards a point between stator poles which minimises the reluctance of the magnetic flux path and results in maximum stored energy, Figure 4. Typically, the energising currents I1 and I2 will be equal and set to the maximum, or rated, phase current of the machine to ensure correct alignment. With both phases energised, the phase currents may be perturbed in anti-phase to improve start-up torque. It is noted that if the rotor lies in a zero torque producing region of the initially energised phase then the rotor will not align as shown in Figure 2.

However, the simultaneous energisation of I2 with I1 will result in the rotor orientation shown in Figure 4.

With the current directions shown in Figure 4, the rotor pole R1 will be situated between stator poles S1 and S2, and rotor pole R2 between stator poles S3 and S4. The position of the magnetic field asymmetry shown in Figure 3 can be changed by energising one of the phases with a current of opposite polarity. Figure 5 shows the situation with I1 reversed with respect to the current polarity shown in Figure 2. With the polarities shown in Figure 5, the rotor would rotate such that the rotor pole R1 lies between stator poles S1 and S4 and rotor pole R2 lies between stator poles S2 and S3, Figure 6.

The sequence of energisation of phase currents, along with their direction and magnitudes, guarantees that the rotor poles will always occupy a specific pair of quadrants within the machine - either the quadrants defined between S1 and S2 and between S3 and S4 or quadrants defined between S2 and S3 and between S4 and S1 - irrespective of whether the rotor lies in a zero torque producing region of the machine before the start-up sequence is initiated.

With both phases energised, torque may be generated in either direction by removing the current excitation from one of the phases. With the current excitations shown in Figure 4, clockwise torque is produced by turning off phase current I1, counter-clockwise torque produced by turning off phase current I2. Thus both rotor directions are achievable from the position obtained using the phase current energisation sequence. Similarly, with the current polarities shown in Figure 6, clockwise torque is produced by removing ampere-turns NI2 and counter-clockwise torque produced by removing ampere-turns NI1. Once one of the phase energisations is removed, the start-up sequence is finished and a current commutation means is required to maintain torque production.

At start-up, the torque produced when one phase is de-energised causes the rotor poles to rotate towards the excited stator poles. The current must be removed from the remaining energised phase before the rotor rotates past the aligned position with the excited stator poles. This avoids negative torque production with respect to the desired rotational direction. A short period may occur when no phase energisation is applied and during this idle period, the rotor inertia rotates the rotor such that the rotor poles lie in the positive torque producing region of the next phase. Positive torque is then produced by energising this phase. This current commutation requires some form of position sensor to sense instants when the current excitation is to be removed from the energised phase and when the excitation can be applied to the next phase. The current sequencing means can then control the commutation of the phase currents.

The position sensor may take a variety of forms. Figure 1 shows a direct method, with a suitable position transducer attached to the rotor shaft. Indirect position sensing means may be used with a suitable position estimator utilising information derived from one or more transducers measuring machine quantities such as current, voltage, inductance and temperature to estimate absolute rotor position. Indirect position sensing means eliminates the need for a rotor position transducer.

Figure 7 shows the required output, θ, from a suitable position sensor. The rotor angle, θ, is arbitrarily defined here as that between the centre line of the rotor poles, Y-Y′, and the centre line X-X′ of the diametrically opposed stator poles S1 and S3, Figure 6. The sensor requires one uni-polar output. Rotor angles A, B, D, E, A′, B′, D′ and E′ are values of θ where the state of the output changes, rotor angles 0, C, 0′ and C′ are values of θ where rotor poles and stator pole-pairs are aligned. The current sequencing means, 4, has, as one of its inputs, the output from the sensor. After the start-up sequence has been completed, the input from the sensor is utilised, in conjunction with the means to set the phase current magnitude, IMAG, to generate the reference phase currents I1REF and I2REF. This control function can be implemented in either digital or analogue electronics or a combination of both. Figure 7 shows the reference currents, I1REF and I2REF, generated by the current sequencing means. The actual rotor currents, I1 and I2, controlled by phase current controllers maintain net torque production in the desired direction thus maintaining rotation of the rotor as provided by the start-up sequence.

In the steady-state, the phase current controllers would ideally switch rectangular blocks of current into each phase winding as the rotor rotates. The current magnitude set by IMAG and the current commutation instants, when current is switched from one phase winding to the next so as to maintain positive torque production, are derived from information supplied from the position sensing means, 6. Finite convertor switching voltages limit rate of change of current and generally lead to trapezoidal instead of rectangular current waveshapes being supplied to the phases of the machine. As shown in Figure 7, high speed operation requires that the current commutation instants, B, B′, E and E′, are advanced at turn-off to allow the phase current to fall to zero before alignment of rotor and stator poles occurs hence avoiding negative torque production. However, in some situations a small amount of negative torque production is allowable. In these circumstances, the current commutation instants are defined such that the net loss of torque due to the periods of negative torque production is compensated by an extended positive torque production region which results in an overall improvement in torque output.

Figure 7 also indicates how the actual phase current trajectories change as the rotor speed increases. The choice of commutation instants affects the performance of the drive system. The idle angle, where no energisation is applied to either phase, is defined as between the commutation instants B to D or E to A′ or B′ to D′ or E′ to A. A short idle period improves low speed torque output. A larger idle period increases the time available for the phase current to decay to zero. This has important consequences at higher rotor speeds where negative torque production can only be avoided by ensuring the phase current has decayed to zero. The larger idle period extents the maximum operating speed. The electrical characteristics of the machine result in phase current decay times generally being slower than phase current rise times. The idle periods may be offset from the alignment positions between rotor and stator poles, angles 0, 0′, C and C′, to improve high speed output torque taking advantage of the different rise and fall times of the phase current. The performance gain is only apparent in one rotor direction. The alternative rotor direction suffers a loss of performance due to a reduction in time available for current decay thus the drive performance is biased in one direction.

A phase-locked loop means may be included between position sensor, 6, and current sequencing means, 4, to improve the angular resolution of the position encoder. The phase-locked loop locks on to the output frequency and phase from the position sensor.

The locking signal contains position and speed information in steady rotor speed conditions. Tracking in transient conditions is possible if the dynamic range and response of the phase-locked loop is sufficient.

A particular embodiment of rotor position sensor is now described which explicitly defines angles A, A′, B, B′, D, D′, E and E′ and requires minimal interfacing circuitry. It is optical in nature requiring a stationary optical beam source means and optical receiving means and a slotted disc means mounted on the machine shaft and positioned to interrupt or transmit the optical beam, T. A uni-polar signalling means interfaces the receiver to the current sequencing means. Figure 8 shows a typical disc with slots for a machine with four stator poles and two rotor poles and shows radial position of optical beam, T. There are four identical slots cut in quadrature positions around the periphery of the disc. As the rotor rotates, the disc interrupts or transmits the beam. The disc is orientated with respect to the stationary optical beam such that the angle formed by 0VT is equal to the rotor angle, $\theta$.

The edges of the disc slots define current commutation instants which either turn-off (or turn-on depending on the rotor direction) currents in the phase windings of the machine. The angular span of the slot sets the idle period and sets the commutation points A, A′, B, B′, D, D′, E and E′ in Figure 7. Turn-on and turn-off angles can be made different by offsetting the slots from the alignment positions 0, 0′, C and C′.

The number of commutations per rotor revolution is set by the number of slots cut in the disc. The rotor position sensor can easily be adapted for use with two-phase machines requiring a greater number of current commutations per rotor revolution. This situation occurs with machines having more than two rotor poles and four stator poles.

In place of the optical beam source means and optical receiving means with slotted disc means positioned to interrupt optical beam, the rotor position sensor may use an optical beam source means with a slotted disc means positioned to reflect optical beam to an optical receiving means. Alternatively, the rotor position sensor may utilise a magnetic source and sensing means with a ferromagnetic slotted disc positioned to vary magnetic field around the magnetic sensing means.

The starting torque available at start-up may be improved by incorporating asymmetry in the magnetic design of the machine. The asymmetry may be provided by wedges on rotor poles, Figure 9, or by asymmetric stator pole arc extensions or reductions. The improved starting torque comes from a greater asymmetry in the magnetic field during the start-up sequence when both phases are energised with rotor poles aligned with a set of stator poles, as in Figure 9. The start-up sequence needs to be altered to cover all initial rotor positions. The start-up sequence comprises of energising one of the phase windings with a prescribed current magnitude and direction, after a prescribed time period, the phase is de-energised, the other phase is then energised with a prescribed current magnitude and direction for a prescribed time after which, the initially energised phase is energised with a prescribed current magnitude and direction for a prescribed time, after which, with both phases now energised, one phase is then de-energised such that torque is produced and the rotor rotates in the desired direction. With asymmetry included in the machine design, the current directions must utilise the low reluctance flux path provided by the asymmetry as in Figure 9.

An enhancement to the starting torque may be obtained by using a non-salient stator configuration. Figure 10 shows two possible non-salient stator configurations with N1 and N2, the phase conductors associated with phase 1 and 2 of the machine respectively, situated in slots as shown. The phase windings may be split into two or more slots per phase and short-pitched if required. The starting torque available is improved and at higher operating speeds the operating mode may be switched to single phase operation where both phases are energised and de-energised simultaneously.

In addition to the specific start-up sequences described herein, there are a number of other possible start-up sequences that may be implemented to provide direction control from rotor standstill conditions. Central to each possible sequence would be the use of the two-phase 'on' mode where both phases are energised with a prescribed current magnitude and direction for a prescribed time period. This mode may be preceded by other phase energisation sequences as described here for symmetric and asymmetric machine designs. The two-phase 'on' mode gives a guarantee of which quadrant the rotor lies within and from which direction control is simple.

## Industrial Applicability

The invention provides a simple and effective method of controlling start-up direction of a two-phase switched reluctance machine. It does not require absolute position information to control rotor direction from start-up. This avoids the cost and possible reliability problems associated with absolute shaft mounted encoders. The invention can be used in conjunction with incremental encoder types or position estimators. The latter may require the use of a microprocessor based drive system although the invention is easily implemented in a combination of analogue and digital electronics if the proposed slotted disc encoder is utilised.

Claims

1. A machine drive for a two-phase switched reluctance machine, the machine drive comprises a two-phase machine with an even number of rotor poles and stator poles, a phase current control means supplied by a dc supply means and a rotor position sensing means, the phase current control means configured such that under power-up or rotor standstill conditions a start-up sequence is initiated to control rotor direction, the start-up sequence comprises of energising one of the phase windings with a prescribed current magnitude and direction, after a prescribed time period, the remaining phase is energised with a prescribed current magnitude and direction, after a prescribed time period with both phases energised, one phase current is de-energised such that torque is produced and the rotor rotates in the desired direction, the phase current control means is also configured such that after the start-up sequence is complete, the phase currents are commutated in a manner to maintain net torque production in the desired direction with commutation instants controlled using information provided by the rotor position sensing means.

2. A machine drive for a two-phase switched reluctance machine, according to claim 1, where the start-up sequence comprises of energising one of the phase windings with a prescribed current magnitude and direction, after a prescribed time period, the phase is de-energised, the other phase is then energised with a prescribed current magnitude and direction for a prescribed time after which, the initially energised phase is energised with a prescribed current magnitude and direction for a prescribed time, after which, with both phases now energised, one phase is then de-energised such that torque is produced and the rotor rotates in the desired direction.

3. A machine drive for a two-phase switched reluctance machine, according to claim 1, where the start-up sequence includes particularly but not exclusively a two-phase 'on' mode, where both phases are energised with a prescribed current magnitude and direction for a prescribed time period.

4. A machine drive for a two-phase switched reluctance machine, according to claim 2, where the switched reluctance machine incorporates asymmetry in the magnetic design of the machine using rotor or stator pole asymmetry or shaded poles.

5. A machine drive for a two-phase switched reluctance machine, according to claims 1-3, where during the start-up sequence with both phases energised, the phase currents are perturbed in anti-phase.

6. A machine drive for a two-phase switched reluctance machine, according to claims 1-5, where a non-salient stator configuration is used and the phase windings are split into two or more slots per phase.

7. A machine drive for a two-phase switched reluctance machine, according to claim 6, where at higher operating speeds the operating mode is switched to single phase operation with both phases energised simultaneously.

8. A machine drive for a two-phase switched reluctance machine, according to any preceding claims, where the rotor position sensing means comprises of a suitable position estimator providing position information derived from one or more transducers measuring machine currents, voltages, inductances or temperatures.

9. A machine drive for a two-phase switched reluctance machine, according to any preceding claims, where a phase-locked loop means is included between position sensing means and current sequencing means.

10. A machine drive for a two-phase switched reluctance machine, according to claims 1 through to 6, where the rotor position sensing means provides information to control current commutation instants so as to maintain net torque production in the desired direction.

11. A machine drive for a two-phase switched reluctance machine, according to claim 10, where the rotor position sensing means comprises of an optical beam source means, an optical beam receiving means and a slotted disc means mounted on the machine shaft with slots positioned to interrupt or transmit the optical beam, the optical receiving means interfaced to the phase current control means so as to commutate phase currents and maintain net torque production in the desired direction.

12. A machine drive for a two-phase switched reluctance machine, according to claim 10, where the rotor position sensing means comprises an optical beam source means with a slotted disc means positioned to reflect optical beam to an optical receiving means

13. A machine drive for a two-phase switched reluctance machine, according to claim 10, where the rotor position sensing means comprises a magnetic source and sensing means with a ferromagnetic slotted disc positioned to vary magnetic field around the magnetic sensing means.

14. A machine drive for a two-phase switched reluctance machine, according to claims 11 through to 13, where the slots cut in the slotted disc means are offset from the alignment positions between rotor and stator poles to improve high speed output torque.

15. A machine drive for a two-phase switched reluctance machine, according to claim 11 through to 13, where the slots cut in the slotted disc means define current commutation instants such that the net loss of torque due to periods of negative torque production are compensated by an extended positive torque producing region which results in an overall improvement in torque output.

16. A machine drive for a two-phase switched reluctance machine substantially described herein with reference to Figures 1-10 of the accompanying drawings.

The Patent Office

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**Application No:** GB 9624759.8
**Claims searched:** 1-16

**Examiner:** Brian Ede
**Date of search:** 30 January 1998

## Patents Act 1977
## Search Report under Section 17

**Databases searched:**

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.P): H2J(JCSD,JCSR, JCST, JCSX, JECP, JECX, JEST, JEX)

Int Cl (Ed.6): H02P 1/16 6/20 6/22 7/05 8/04 8/06

Other: Online: WPI

**Documents considered to be relevant:**

| Category | Identity of document and relevant passage | | Relevant to claims |
|---|---|---|---|
| A | GB2235098A | (TOKICO) see Fig 3 and page 5, line 26 - page 7, line 22 | |
| A | US 5051680 | (SUNDSTRAND) see Figs 1A and 4 and column 5, line 42 - column 6, line 14 | |

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|---|---|---|---|
| X | Document indicating lack of novelty or inventive step | A | Document indicating technological background and/or state of the art. |
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