

ELECTRIC MACHINE CONTROLLER

This invention relates to electric motor controllers. The invention is particularly applicable to a controller
5 for a switched reluctance machine.

Known controllers for switched reluctance (SR) motors and generators can offer reasonably flexible control, i.e. wide torque and speed ranges with high efficiency, but
10 this is at the expense of complexity and, therefore, manufacturing cost.

A form of single-phase SR machine is shown in Figure 1 of the drawings. This is more fully described in EP-A-0343845. It comprises a stator 10 defining four stator
15 poles 12 and a rotor 14 defining four rotor poles 16. Windings 18 are arranged, in this form of SR machine, to create adjacent poles of similar polarity. More conventional single-phase SR machines are arranged to
20 create poles of alternate polarity.

The term 'motor' is used below, but it will be appreciated by the skilled person that, where appropriate, the term covers the same machine in a
25 generating mode unless a distinction particular to one or the other is being made.

The theory of operation of SR motors is well known. For example, the paper 'The Characteristics, Design and Applications of Switched Reluctance Motors and Drives' by
30 Stephenson et al. presented at PCIM '93 Conference and Exhibition at Nurnberg, Germany, June 21st-24th 1993, discusses the general principles. Figures 2(a) to (d) of the drawings illustrate well-known examples of switching

circuits used for controlling the applied voltage and the current in the phase winding of a switched reluctance motor.

5 Figure 3(a) of the drawings illustrates the 'chopping' mode of motor torque control at low speed. The torque is controlled by inhibiting the winding current from rising above a maximum level by repeatedly chopping it during the phase conduction period. At higher speeds the rise and fall times for the current will be such that the current is switched on and off only once for each phase conduction period and is not chopped in normal operation. The torque is controlled through the switching angles, ie. the angular positions at which voltage is applied to and reversed at the phase winding(s). This is the so-called 'single-pulse mode' of operation (See Figure 3(b)). The skilled person will be aware that the included angle between switch-on and switch-off is known as the conduction angle. The switch-on and switch-off angles in the single-pulse mode are derived with reference to some form of rotor position transducer, or other means of sensorless rotor position detection as is known in the art, collectively called a 'transducer' herein.

25 It is an object of the present invention to provide a simplified controller for an electric machine, such as a switched reluctance machine and some forms of permanent magnet machine.

30 According to the present invention there is provided a controller for an electric machine, comprising a stator defining stator poles and having at least one phase winding, a rotor defining rotor poles and switch means

for controlling current in the or each winding, the controller comprising:

a transducer for deriving rotor position information;

5 a timer operable to produce switch-on and switch-off signals to which the switch means are responsive, the timer being arranged to receive a first output from the transducer indicative of a position of one of the rotor poles relative to one of the stator poles coincident with
10 a switch-off point in the phase inductance cycle for operating the machine in one of a motoring and a generating mode, and to produce the switch-off signal in response thereto; and

15 first delay means responsive to the output from the transducer within the phase inductance cycle to generate a switch-on signal, subsequent to the switch-off signal, after a delay.

20 The first and second outputs from the transducer may be coincident. Alternatively, the second output may be a point in the phase inductance cycle toward minimum or maximum phase inductance for motoring and generating modes, respectively.

25 The invention represents a very simple control technique for, e.g., an SR motor in which the switch-off angle coincides with a point on the phase inductance cycle which is chosen according to the motor being controlled. Usually, this will correspond to the optimum switch-off
30 angle at a desired operating torque and speed for the motoring mode.

Preferably, the controller also includes a comparator

operable to generate a trigger signal in response to a first input indicative of a winding current which is in excess of a current reference value, a pulse generator responsive to the trigger signal to generate a switch-off signal to which the switch means are also responsive, and a logic gate by which the switch-on signal applied to the switch means is at least dependent upon switch-on signals from both the pulse generator and the first delay means.

The controller may also include second delay means arranged further to delay the output from the first delay means to the logic gate, the said output from the first delay means being arranged to actuate one part of the switch means and the output of the logic gate being arranged to actuate another part of the switch means. In this case, it is preferable that the output of the comparator is also connected directly to the logic gate as overcurrent protection for the machine.

Preferably, the switch-off signal from the pulse generator is of a predetermined minimum duration.

The current reference value provides a chopping control reference threshold. Preferably the threshold current is above the peak value arranged to occur in the single-pulse mode which is effected by the timer and delay means.

It will be appreciated by those skilled in the art that as the speed of rotation of the rotor rises, the times required for the initial growth and final decay of current correspond to an increasing angle of rotor rotation. Thus, as the speed rises still further, the rise and fall times for the current in the windings will

be such that the current is switched on and off only once in each conduction period and never reaches the threshold level at which chopping takes place. In the controller according to the present invention the speed of the motor reaches a stage at which the pulse generator is never triggered because the winding current fails to reach the threshold level in the phase inductance period. The logic gate is then constantly supplied with an enabling signal from the pulse generator and control of the motor in the high speed region is effected by the timer and delay means according to the rotor position information from the transducer. By adjusting the value of the delay time while the machine is operating at a given speed, the torque of the machine is controlled. Thus, preferably, the first delay means are adjustable to vary the delay to control the motor torque.

Preferably, the said second output from the transducer means to which the first delay means are responsive is indicative of a moment on the phase inductance cycle towards minimum inductance for motoring and towards maximum inductance for generating.

Alternatively, the first delay may be initiated by the first output from the transducer.

The new controller is simple and cheap to produce and can provide very effective control for applications such as fans, food processors, vacuum cleaners and other cost-sensitive devices.

The invention also extends to a method of single-pulse control of a switched reluctance machine comprising a stator, having at least one phase winding, a rotor and

switch means associated with the phase winding, the method comprising:

5 timing actuation of the switch means to a point coincident with a switch-off point in the phase inductance cycle for operating the machine in one of a motoring and a generating mode to switch off current to the phase winding, and thereafter timing actuation of the switch means to switch on current to the phase winding after a delay.

10 Preferably, the method includes: comparing a maximum reference current value with a phase winding current; generating a switch-off signal when the phase winding current exceeds the reference current value; and gating
15 the switch-off of the current to the phase winding in accordance with the phase inductance period.

20 Preferably, the method includes: timing switching on of a first part of the switch means to a first timed delay; and then further delaying switching off a second part of switch means, allowing the phase current to freewheel when the first part of the switch means are open and the second part of the switch means are closed.

25 Preferably, a pulse is initiated at the switch-off point which is of a predetermined duration. To cater for over-current situations, it is further preferable that the switch-off pulse is adjustable only down to a minimum duration.

30 The invention also extends to a switched reluctance drive including a switched reluctance machine, comprising a stator, having at least one phase winding, a rotor, a transducer for generating rotor position information,
35 switch means for switching current to the

winding and a controller, the controller comprising:

a comparator operable to generate a trigger signal in response to a first input indicative of a winding current exceeding a current reference value;

5 a logic gate arranged to transmit switch-off and switch-on signals to the switch means;

a pulse generator responsive to the trigger signal to generate the switch-off signal of predetermined duration to which the switch means are responsive;

10 a timer circuit operable to generate further switch-on and switch-off signals to which the switch means are also responsive, the timer circuit being arranged to receive a first output from the transducer indicative of a position of one of the rotor poles relative to one of the stator poles coincident with a switch-off point in the phase inductance cycle for operating the machine in one of a motoring and a generating mode, and to generate the switch-off signal in response thereto; and

15 delay means responsive to a second output from the transducer within the phase inductance cycle to generate the switch-on signal, subsequent to the switch-off signal, the switch means actuation signal from the logic gate being dependent upon switch-on signals being received together from the pulse generator and the delay means.

20 The present invention can be put into practice in various ways, some embodiments of which will now be described by way of example with reference to the accompanying drawings in which :

30 Figure 1 is an cross-section of a prior art switched reluctance motor construction;

Figures 2(a)-(d) illustrate schematically known

switched reluctance motor switching circuits;

Figures 3(a) and (b) are graphs respectively of chopping mode and single-pulse mode switched reluctance motor winding current over a phase inductance period;

5 Figure 4(a) is a schematic block diagram of a controller according to the invention;

Figures 4(b) and (c) are graphs of switching strategies of two embodiments of the invention;

10 Figure 5 is torque/speed characteristic of a switched reluctance motor controlled according to one embodiment of the invention; and

Figure 6 is a schematic block diagram of a further embodiment of the invention.

15 The controller according to the invention may be used with machines having any number of phases. For clarity it will be described with reference to a single-phase motor.

20 Referring to Figure 4(a), a controller for a switched reluctance motor comprises a comparator 20 which is arranged to receive a first input 22 that is a signal proportional to the phase winding current in the motor. A typical comparator for this application would be an
25 LM339 manufactured by National Semiconductor with or without additional hysteresis components. In a multiphase machine the individual winding currents are monitored. The sum of the winding currents is not necessarily a sufficiently accurate indicator of the
30 individual winding currents at any one time due to current overlap between the phases. If no overlap were present, or if the overlap could be compensated for, then a signal proportional to one phase winding current could be used as an indicator for all phases. Also, in

principle one controller could multiplex between phases. However, care must be taken to avoid errors due to fault currents and noise from corrupting the information.

5 A second input 24 corresponds to a predetermined or adjustable maximum current reference signal. In the case of a fixed value of current reference a simpler comparator can be used, such as an appropriately biased transistor. In this embodiment, having the simplified
10 comparator, the reference signal is chosen for a particular motor to correspond to a level of current which is above the peak value of current which will be allowed to occur in the single-pulse mode. This allows an automatic transition between chopping and single pulse
15 modes of operation, as will be described below.

An output 26 from the comparator 20 triggers a simple pulse generator in the form of a monostable multivibrator 28 which has a pulse output of fixed duration at logic
20 level '0' corresponding to a switch-off signal which is connected with one input of a two-input AND gate 30. The other input to the AND gate 30 is the output 32 from a timer and delay circuit 34. A first input 36 to the timer and delay circuit 34 is the output from a rotor position transducer 35 (RPT). The RPT 35 is conventional
25 in the art. It is used to derive timing signals corresponding to the movement of the rotor poles past the stator poles in an SR or other electric motor. Conveniently, the output from the RPT is more or less a square or other wave shape providing transitions at fixed
30 rotor positions with respect to the stator. A further input 38 to the timer and delay circuit 34 is a time delay control signal which adjusts the delay applied before a switch-on signal is applied to the AND gate 30.
35 While an AND gate is

illustrated it will be apparent that other mutual gating arrangements could be used to equal effect.

5 The running speed of the motor may be adjusted by manual adjustment of the delay introduced by the timer and delay output 32 which is itself controlled by the signal 38, or in response to a signal from an overall control system also adjusting the delay time. Alternatively, the output 32 may be fixed. The delay strategy is discussed below.

10 In a low-speed chopping mode the comparator 20 generates its output when the winding current (or the winding current for each respective phase in turn in a multiphase machine) exceeds the predetermined maximum current
15 reference signal 24, which reference signal 24 is set for a particular motor to which the controller is connected. As mentioned above, this may be equivalent to a winding current which is in excess of the single-pulse mode current at which the motor in question is designed to
20 operate. Typically, the maximum current reference level is chosen with regard to the ratings of the semiconductor switches in the converter switching circuits and the thermal rating of the motor. The maximum current reference signal may be user adjustable,
25 within the current rating of the switches, so that a particular controller can be adjusted and set for a particular motor or as a means of speed-torque adjustment while the motor is running.

30 At low speeds there is sufficient time in a phase conduction period for the winding current to rise above the maximum current reference level. The output from the comparator generated when the maximum current reference is exceeded triggers the multivibrator 28 which produces

a pulse of a fixed duration at logic level '0' which is a winding current switch inhibit (switch-off) signal. This logic '0' output will produce a logic '0' (switch-off) output from the AND gate 30 so that the switching circuit associated with the phase winding is opened for at least the duration of the low pulse, i.e. to allow the winding current to fall below the maximum current reference level. After the pulse is removed, the switch or switches reclose subject to the state of the signal from the timer and delay circuit 34. Thus, chopping current control is established about the maximum current reference level when the motor speed is low.

As the motor speed increases there will come a point at which the maximum current reference level is not reached in a phase inductance cycle such that the output from the monostable is a constant logic '1'. This permanently enables the AND gate 30 subject to the timed output of the timer and delay circuit 34, which is then used to control the switching of current to the windings, ie. for operating in the single pulse mode. The motor speed/torque is then controllable by adjustment of the delay before a switch-on signal is generated by the timer and delay circuit.

Two methods of triggering the time delay are illustrated graphically in Figures 4(b) and (c).

The RPT output has a leading edge which is used conventionally to switch current to the phase winding, usually at a position in the phase inductance cycle corresponding to an optimum switch-on position eg. the position of minimum inductance for motoring and maximum inductance for generating. The use of an RPT from which

to derive timing signals for winding switches in single and multiphase SR motors is well known to those skilled in the art and will not be described further here.

5 In Figure 4(b) the delay is initiated by the trailing (in
this case falling) edge of the RPT signal. To the same
end, the delay could be arranged to be initiated by the
leading edge of the RPT signal. The time delay from
switch-off may be set to give, for example, the optimum
10 conduction angle at the desired full-power operating
condition according to the motor being controlled, or it
may be varied, using the delay circuit to control the
torque and running speed of the motor. It will be noted
that the mark/space ratio of the RPT signal is
15 unimportant in this embodiment as only one transition of
the signal, ie. the leading edge, is used for controlling
switching. Previously, the mark/space ratio of the RPT
output has been critical to successful operation of the
drive. According to the invention the need for only one
20 transition can be used to realise a saving in the cost of
the control electronics.

In this arrangement, as the speed is reduced with a given
constant time delay, the delay angle is reduced as well
25 and, therefore, the conduction angle increases.
Eventually, at low motor speeds, the 'OFF' angle of the
winding switches becomes negligible relative to the
increasing conduction angle. This is an undesirable
condition because excessive winding current and/or torque
30 of the undesired polarity can result. The effect can be
countered by increasing the time delay as the speed
falls.

In the Figure 4 (c) embodiment the time delay output of the timer and delay circuit (34) is initiated by the leading (in this case rising) edge of the RPT signal. The timer and delay circuit, the mark/space ratio of the RPT signal and its position in the inductance cycle may be set to give the optimum conduction angle for the single-pulse mode operation of the motor at the desired full power operating conditions, whilst additionally maintaining acceptable conditions at low speeds.

As the speed of the motor rises, the time delay remains fixed and, therefore, the delay angle of switch-on increases. This delay angle is the angle corresponding to the time delay and is the angle by which the switch-on lags behind the fixed angle corresponding to the RPT leading edge. This increasing delay angle reduces the conduction angle. There is, therefore, a fall in the peak flux with rising speed caused by two effects: (a) the reducing conduction angle itself; and (b) the rising speed giving a reducing conduction time for a given conduction angle. The torque, therefore, falls more rapidly with rising speed than in a conventional system in which the conduction angles are fixed. Figure 5 illustrates the torque/speed curve of a motor control system according to this embodiment of the invention when a fixed chopping level and a fixed time delay are used. The relatively steep fall-off in torque is advantageous in applications in which the load torque varies significantly in normal operation. It can be beneficial that the rise in speed consequent upon a reduction in load torque is more limited than in conventional control systems for universal motors.

In some circumstances the second embodiment of the invention may be preferred. At low speed, for a given delay, the delay angle becomes small and the conduction angle becomes substantially equal to the on-state signal of the rotor position transducer. This is an acceptable condition for low speed running.

The first embodiment of the invention does give rise to an even steeper torque/speed curve in the single-pulse operating region. The timer and delay circuit delay is set for a desired normal operating condition. This delay is much longer in the first method than in the second method. A given percentage rise in speed from this initial operating condition will cause an equal percentage rise in the delay angle, provided the delay time is constant. This causes a corresponding reduction in the conduction angle. Because the delay time for the given initial operating condition is greater in the first than in the second method, the reduction in conduction angle, for the given percentage rise in motor speed, is greater in the first method. This results in a greater reduction in the peak flux and in torque for the same percentage rise in speed in the first method than in the second. The torque/speed curve, therefore, falls more rapidly with the first method and the speed of the motor will vary less with given rates of load torque. Thus, the first method may be preferred in some applications.

The single-phase SR motor illustrated in Figure 1 is not inherently self-starting. It is necessary to ensure that the initial rotor position is not one of zero torque when the motor winding is excited. To address this a magnet arranged on a stator pole may be used in accordance with the teachings in EP-A-0601818. The magnet serves to bias

the rotor to a non-zero torque position by urging a near rotor pole past the zero torque orientation. The force exerted by the magnet may be limited and its use attached to one of the stator poles is restricted to drives requiring only modest starting torque.

The invention is not restricted to single-phase motors. It is equally applicable to multiphase machines. In the case of multiphase machines the motor phase switching signals are further controlled, according to well-known motor control techniques, to control the actuation of the windings of the various phases in turn.

Referring to Figure 6 of the drawings, the invention can also be used with a freewheeling switch configuration in which a two switch per phase arrangement (as shown in Figure 2(a)) can be actuated to allow current to recirculate around the phase winding. Freewheeling is a technique well-known in the art of controller design for SR machines. It is often used to reduce peak currents, switching frequencies and/or acoustic noise. In Figure 6 a further freewheel delay circuit 40 is added between the output of the timer and delay circuit 34 and an AND gate 30'. The AND Gate 30' is now confined to controlling switching of only one of the two winding switches (eg. the 'top switch').

The freewheel timer delay signal is gated according to the monostable output. Additionally, a direct connection 42 from the comparator itself is connected to the AND gate 30'. This direct connection 42 provides overcurrent protection in the event that the winding current has not fallen sufficiently during the monostable pulse output duration.

The timer and delay circuit 34 sends a timing switch-off signal which is applied directly to the other of the two winding switches (eg. the 'bottom switch'). After a freewheel delay in which the bottom switch is open and the top switch is closed the switch-off signal is applied as a low signal to the AND gate 30'. The switch-off signal applied to the top switch is then gated according to the output of the monostable 28 as before (subject to no overcurrent low signal from the comparator 20 on the line 42. The freewheel time delay is determined for a particular machine and its operating regime. Typically, it will be a fraction of the delay from the timer and delay circuit. Thus, a freewheel configuration is available in which the bottom switch is open, according to the timer and delay circuit output, and the top switch closed, according to the further delayed timing signal from the freewheel delay, as gated by the monostable 28, for each inductance period.

While the invention has been described in connection with the illustrative embodiments discussed above, those skilled in the art will recognise that many variations may be made without departing from the present invention. For example, it will be appreciated by the skilled person that the signals from the RPT 35 can be derived in other ways to equal effect. The RPT 35 is an arrangement of a member mounted on the rotor shaft and arranged to influence the output of a sensor to produce appropriately timed pulses. However, as well as other physical/electrical/magnetic ways of deriving rotor position information for movement of the rotor, the same information can be derived from monitoring the phase current. The invention is able to use such rotor position information however it is derived.

Accordingly, the above description of several embodiments is made by way of example and not for the purposes of limitation. The present invention is intended to be limited only by the scope of the following claims.

**CLAIMS:**

1. A controller for an electric machine, comprising a stator defining stator poles and having at least one phase winding, a rotor defining rotor poles, and switch means for controlling current in the winding, the controller comprising:

a transducer for deriving rotor position information;

a timer operable to produce switch-on and switch-off signals to which the switch means are responsive, the timer being arranged to receive a first output from the transducer indicative of a position of one of the rotor poles relative to one of the stator poles coincident with a switch-off point in the phase inductance cycle for operating the machine in one of a motoring and a generating mode, and to produce the switch-off signal in response thereto; and

first delay means responsive to a second output from the transducer within the phase inductance cycle to generate a switch-on signal, subsequent to the switch-off signal, after a delay.

2. A controller as claimed in claim 1 in which the first and second outputs from the transducer are the same output.

3. A controller as claimed in claim 1 in which the second output is a point in the phase inductance cycle towards minimum phase inductance when the machine is motoring and maximum phase inductance when the machine is generating.



4. A controller as claimed in claim 1, 2 or 3, including a comparator having a first input for a signal indicative of a winding current and a second input for a signal indicative of a current reference value, the comparator being operable to generate a trigger signal in response to the winding current being in excess of the current reference value, a pulse generator responsive to the trigger signal to generate a further switch-off signal of predetermined duration and a further switch-on signal to which the switch means are also responsive, and gate means by which the switch-on signal for the switch means is at least dependent upon the switch-on signals from both the pulse generator and the first delay means.
5. A controller as claimed in any of claim 3, including a comparator having a first input for a signal indicative of a winding current and a second input for a signal indicative of a current reference value, the comparator being operable to generate a trigger signal in response to the winding current being in excess of the current reference value, a pulse generator responsive to the trigger signal to generate a further switch-off signal of predetermined duration and a further switch-on signal to which the switch means are also responsive, and gate means by which the switch-on signal for the switch means is at least dependent upon on the switch-on signals from both the pulse generator and the first delay means, the controller further including second delay means arranged further to delay the second output from the transducer to the gate means.
6. A controller as claimed in claim 5 in which the trigger signal output of the comparator is connected directly with the gate means, such that the switch-on



signal is inhibited when the first input is indicative of the winding current exceeding the current reference value.

5 7. A controller as claimed in claim 4 in which the pulse generator is arranged to generate the switch-off signal as an adjustable pulse of predetermined minimum duration.

10 8. A controller as claimed in any of claims 1 to 7 in which the transducer is arranged to produce a pulse output, having a leading edge and a trailing edge.

15 9. A controller as claimed in claim 8, when dependent on claim 2, in which the output from the transducer is one of the leading and trailing edges of the said pulse output, the switch-on signal being independent of the other of the leading and trailing edges of the pulse.

20 10. A method of single pulse control of a switched reluctance machine comprising a stator, having at least one phase winding, a rotor and switch means associated with the phase winding, the method comprising :

25 timing actuation of the switch means to switch off current to the phase winding to a point coincident with a switch-off point in the phase inductance cycle for operating the machine in one of a motoring and a generating mode, and thereafter timing actuation of the switch means to switch on current to the phase winding
30 after a delay.

11. A method as claimed in claim 10, including initiating the start of the delay at a later point in the phase inductance cycle.



12. A method as claimed in claim 10 or 11, including timing switching on of a first part of the switch means to a first timed delay; and then further delaying switching off of a second part of the switch means
5 allowing the phase current to freewheel when the first part of the switch means are open and the second part of the switch means are closed.

13. A method as claimed in claim 10, 11 or 12, further
10 including chop controlling the machine by comparing a maximum reference current value with a phase winding current; generating a switch-off signal when the phase winding current exceeds the reference current value; and
15 gating the switch-off of the current to the phase winding in accordance with the phase inductance period.

14. A method as claimed in claim 10, 11, 12 or 13 in which the output of the machine is varied by adjusting the duration of the delay above a predetermined minimum
20 period.

15. A method as claimed in any of claims 10 to 14 including deriving timing pulses from rotation of the
25 rotor.

16. A method as claimed in claim 15 in which the timing of the actuation of the switch means to switch-off current to the phase winding is dependent on the occurrence of one of the leading and trailing edges of
30 the said timing pulse, and timing actuation of the switch means to switch-on current to the phase winding is independent of the other of the leading and trailing edges of the pulse.



17. A switched reluctance drive including a switched reluctance machine comprising a stator, having at least one phase winding, a rotor, a transducer for generating rotor position information, switch means for switching
5 current to the winding and a controller, the controller comprising:

a comparator operable to generate a trigger signal in response to a first input indicative of a winding current exceeding a current reference value;

10 a logic gate arranged to transmit switch-off and switch-on signals to switch means;

and a pulse generator responsive to the trigger signal to generate the switch-off signal of predetermined duration to which the switch means are responsive;

15 a timer circuit operable to generate further switch-on and switch-off signals to which the switch means are also responsive, the timer circuit being arranged to receive a first output from the transducer indicative of a position of one of the stator poles relative to one of
20 the stator poles coincident with a switch-off point in the phase inductance cycle for operating the machine in one of a motoring and a generating mode, and to generate the switch-off signal in response thereto; and

delay means responsive to a second output from the
25 transducer within the phase inductance cycle to generate the switch-on signal, subsequent to the switch-off signal, the switch means actuation signal from the logic gate being dependent upon switch-on signals being received together from the pulse generator and the delay
30 means.