OPTIMUM EXCITATION OF SWITCHED RELUCTANCE MOTORS

HC Lovatt[1] and JM Stephenson[2]

[1]CSIRO, Australia, and [2]The University of Leeds, UK

ABSTRACT

The paper demonstrates, using an example switched reluctance motor (SRM), excitation waveforms that are optimised in terms of least RMS current for a given mean torque. Two classes of waveform are described: least-current and smooth-torque. The least current waveforms neglect torque ripple, whilst the smooth-torque waveforms eliminate torque ripple. The new classes of waveform are contrasted with the conventional single-pulse and chopping waveforms. Of particular importance is the medium speed, smooth-torque, waveform that has a lower RMS current and a similar peak current to its chopping counter part. Thus it is possible to increase the mean torque produced by the SRM and simultaneously smooth its torque production, without increasing the electronics VA rating.

INTRODUCTION

Since Lawrenson *et al's* paper [1], the switched reluctance motor (SRM) has gained in popularity. They [1] described two modes of excitation, chopping and single-pulse, suitable for low speed and high speed respectively. These modes are still the most commonly used for the SRM.

This paper for the first time brings together two different objectives in improving the performance of the SRM: increasing the output ([2] and [3]) and eliminating the torque ripple ([4] and [5]). The paper describes a computer search technique that can find excitation waveforms optimised for least RMS current for a given torque for two different torque ripple regimes (i) neglecting torque ripple and (ii) eliminating torque ripple. The waveforms are referred to as the least-current and smooth-torque waveforms respectively.

Attempts have been made to analytically find the optimum excitation for the SRM, this approach has to rely on approximate models of the motor. This problem of analytically modelling the SRM is well documented, with the design of SRMs almost exclusively done using numerical modelling. A further problem with analytical approaches is that it has proved difficult to include the limitations of the power converter in the optimisation.

Early attempts at optimum excitation using computer search techniques [2] led to impractical waveforms. Recently, added constraints on maximum voltage and current have led to the finding of practical waveforms [3] - [5].

A common feature of both the analytical and numerical techniques is the use of RMS current as the penalty function to be minimised, i.e. the optimum waveform is defined as the waveform with the least RMS current for a given torque. This is a good choice for the penalty function since it is easy to calculate and represents the copper loss in the machine. However, it does neglect the iron loss which will be a function of the excitation.

NUMERICAL ROUTINES, PENALTY FUNCTION, AND ACCURACY

Numerical routines are used to search for the best solution within constraints, to interpolate between data points, and to differentiate. The numerical routines used are all from the NAG library. The choice of which routine to use is discussed in [3].

The search routine requires a penalty or objective function to be minimised. The sum of the square of the current at each angle interval is chosen. This is easier to calculate than RMS current, but otherwise similar. Using RMS current neglects the change in iron loss with change in current waveform.

The iron loss, suitably scaled, could be added to the penalty function. However iron loss is difficult to calculate and for this reason this is not attempted. The errors introduced by neglecting iron loss will depend upon the balance of losses in the machine. In small low speed motors the iron loss tends to be small portion of the loss. The waveforms given are for a D80 frame, 1500 rpm, motor and the use of RMS current for the penalty function is therefore considered reasonable.

The accuracy of the searching, modelling of the motor, and prediction of EMF are tested in [3] and [5] against: (i) analytical methods (where possible) and (ii) against other numerical methods. Three figure accuracy was achieved in all cases.

In the case of the low speed, smooth torque, waveform that is given below the torque ripple index was measured as 8.19×10^{-6} [6]. The high speed, smooth torque, waveforms given below are not tested, because of the difficulty of measurement [6].

EXAMPLE MOTOR

The motor used as an example is described in [7], it is a 3 phase, 12 stator pole, 8 rotor pole, motor. Therefore one electrical cycle is 22.5° mechanical degrees. By convention, zero degrees is taken as the aligned position for phase 1. Therefore the first unaligned position is at 22.5° and the next aligned position at 45° for phase 1. The phase shift between phases is 15°. The motor is wound such that, at its maximum operating voltage of ±300 V and using conventional excitation, chopping is used up to approximately 750 rpm and then single pulse used to the top speed of approximately 1500 rpm. The motor is designed to have a considerable overload capability [7] and therefore the number of turns is conservatively low.

To get the best from the motor it is important to accurately characterise it. The characteristics could be predicted using standard design techniques like finite element. But, for best results, measurement is preferred. The motor was characterised using the method given in [8]. Figure 1 shows the measured flux linkage and Figure 2 shows the torque from a co-energy analysis.

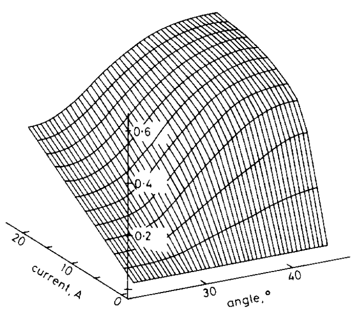

Figure 1. Flux linkage (Wb) vs. current and angle

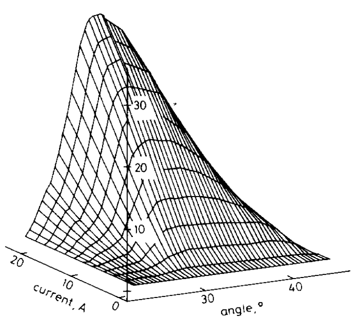

Figure 2. Torque (Nm) vs. current and angle

DESCRIPTION OF METHOD

The technique of finding the best waveform is conceptually simple. There are four aspects, a search algorithm that decides upon a trial solution, calculation of the RMS current (to be minimised), calculation of the motor torque, and calculation of the terminal voltage.

For the purpose of finding an optimum current waveform, it is useful to represent the current waveform as a function of rotor angle. Another alternative is to use current as a function of time. Some of the mathematics are simplified if angle is used, hence this choice.

Search algorithms adjust the values of a set of variables, calculate constraints and test these against limits, and calculate a penalty or objective function. The set of variable values that does not violate constraints and has the smallest penalty function is the best solution found. The search algorithm can, however, find a local minimum and not the global minimum. It is important to test that the algorithm used is finding the global minimum. The finding of the global minimum is demonstrated using algebraic solutions to simpler problems than a real motor in [3] and [5].

The current waveform is represented by a set of variables. The variables are the value of the current at a set of equally spaced angles. This is analogous to sampling the current waveform at equal intervals.

To speed up the search for an optimum waveform, it is important to minimise the number of variables and to start the search with a good initial guess.

The number of variables is minimised by exploiting symmetry in the motor. In particular, it is only necessary in a three phase motor to find the waveform for one third of an electrical cycle for each phase[1].

The initial guess used is the set of values found from a previous run, at the nearest torque value available. For the initial run a value of zero is assumed for all the current variables.

The set of current variables is i_{jk}, where j is the angle number and k is the phase number. Using the surfaces in Figure 1 and Figure 2 and exploiting symmetry between the phases, the torque T_{jk} and flux linkage ψ_{jk} can be found.

The penalty function, P, to be minimised is:

$$P = \sum_j \sum_k i_{jk}^2 \ . \tag{1}$$

The constraints are that the solution should be within the VA ratings of the converter, i.e. below the peak converter current $\hat{i}$ and between plus and minus the peak converter voltage $\hat{V}$:

$$0 \le i_{jk} \le \hat{i} \ , \tag{2}$$

$$-\hat{V} \le \frac{d\psi_{jk}}{dt} + i_{jk} R \le \hat{V} \ , \tag{3}$$

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[1] Another alternative is to find the whole of an electrical cycle of just one phase. However, it is conceptually simpler to consider a third of all three phases because this is one symmetry cycle of the real motor.

where t is time and can be found knowing the motor speed and R is the phase resistance. For the least-current waveform, just the mean torque is constrained:

$$\overline{T} = \sum_j \sum_k \frac{T_{jk}}{\hat{j}} , \qquad (4)$$

where $\hat{j}$ is the total number of angles. For the smooth-torque waveform, at each angle the torque is constrained to the mean torque. That is to say, (4) is replaced by the set of constraints:

$$\overline{T} = \sum_k T_{jk} \ . \qquad (5)$$

For details of the implementation, in particular further techniques for speeding up the search, see [3] and [5].

RESULTS

The results show waveforms at different speeds and in particular demonstrate the voltage constraint (3). The less interesting constraint on peak current (2) is not shown. In all cases the waveforms are given for a mean torque of 10 Nm, this is the thermally rated torque using the 750 rpm smooth-torque waveform. 10 Nm represents a realistic thermal rating for the example SRM, it can also be achieved at 1500 rpm using the least-current waveform.

When the voltage constraint is not active, e.g. at zero speed. The, 0 rpm, least-current, Figure 5 is similar in shape to the torque profile (Figure 2). However the, 0 rpm, smooth-torque waveform (Figure 5) is quite different in shape, with peaks close to the aligned and unaligned rotor positions. That is to say, a larger current at angles were the motor produces less torque per ampere (Figure 2).

Table 1 compares the performance of optimum waveforms with the conventional waveforms. At 0 rpm the conventional chopping waveform has the lowest peak current, but the two 0 rpm optimum waveforms have a lower RMS current. For the least-current waveform this is, of cause, as expected[2]. The fact that the smooth-torque waveform also has less RMS current is interesting. It means that the mean torque production of an SRM and the smoothness of its torque production can both be simultaneously improved. A better smooth-torque waveform, in terms of peak current, than the 0 rpm, smooth-torque, waveform is given below.

It is worth looking more closely at the torque production of the waveforms. The torque/angle characteristic using the 0 rpm, least-current, waveform is shown in Figure 3. Similarly, for a chopping waveform the torque/angle characteristic is in Figure 4. It is obvious that the torque production of the least-current waveform is not as smooth as the conventional excitation. The torque production of the smooth-torque waveform is a constant 10 Nm, by definition.

[2] The waveform is optimised for lowest RMS current.

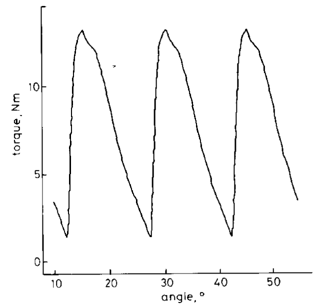

Figure 3. Torque/angle for least-current, 0 rpm, waveform

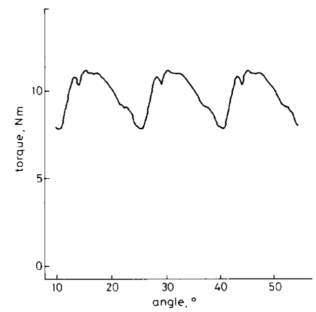

Figure 4. Torque/angle for conventional chopping waveform

As the speed rises the waveforms become wider because the voltage limit comes into effect (Figure 5). As well as the current waveform, at 750 and 1500 rpm the voltage waveform is given. The limit on the applied voltage can clearly be seen as a flat top or flat bottom. When the voltage limit is reached the rate of rise of current is limited and it is necessary to widen the waveform to compensate for this. That is to say, less ideal parts of the torque profile are used to compensate for reduced current in the more ideal parts at the expense of increased overall RMS current.

Table 1 shows the increase in RMS current with increasing speed and also contrasts the high speed waveforms with conventional waveforms. The table shows that the 750 rpm waveform uses less RMS current than the chopping waveform and little more peak current, yet still produces smooth torque. This waveform is therefore of great interest, since it can be used at all speeds up to 750 rpm and does not incur a significant peak current penalty (unlike the 0 rpm, smooth-torque, waveform).

The 1500 rpm, least-current, voltage waveform is either at full positive volts or at full negative volts, i.e. it is a single-pulse waveform. This shows that single-pulse mode is optimum in terms of RMS current at high speeds.

Reference [5] discusses the differences between the different smooth-torque waveforms further.

CONCLUSIONS

This is the first time that both least-current and smooth-torque waveforms are presented in the one paper and contrasted with each other. Bringing together the two classes of waveform allows them to be easily contrasted and shows clearly where one waveform may be used in preference to the other. The waveforms and their characteristics are given for an example motor at rated torque of 10 Nm in Figure 5 and Table 1.

The implementation of the waveforms can be achieved by storing current ([3] and [5]), voltage, or flux [4] profiles as functions of torque, speed, and angle. An inner control loop then tracks the stored profile. The optimisation described assumes that this loop is infinitely fast. In practice, therefore, it will not be possible to use the waveforms up to their maximum speed due to delays in the inner loop.

In conventional SRMs a transition is made between chopping and single pulse modes. Using either the least-current or smooth-torque waveforms allows a smooth blending between different speeds, i.e. no mode change.

However, the designer may still choose to mode change between smooth-torque at low speeds and least current at high speeds, since smooth torque production is not so important at high speeds.

At high speeds, the conventional, single-pulse, waveform is shown to be the same as the optimum, least-current, waveform.

At low speeds, the mean torque and the smoothness of torque can be simultaneously improved using the optimum, smooth-torque, waveforms when compared to conventional chopping waveforms.

The most important waveform demonstrated is the 750 rpm, smooth-torque, waveform. This waveform may be used at all speeds up to 750 rpm. It has little more peak current than the chopping waveform, has less RMS current, and produces smooth torque (Table 1).

ACKNOWLEDGMENTS

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	Least-current		Smooth-torque		Chopping		Single-pulse	
rpm	i_{pk} (A)	i_{rms} (A)	i_{pk} (A)	i_{rms} (A)	i_{pk} (A)	i_{rms} (A)	i_{pk} (A)	i_{rms} (A)
0	11.6	5.20	15.6	6.01	9.50	6.71	-	-
750	11.8	5.25	12.5	6.14	-	-	-	-
1500	10.9	5.84	14.6	8.12	-	-	10.9	5.84

Table 1. Comparison of performance of optimised and conventional waveforms

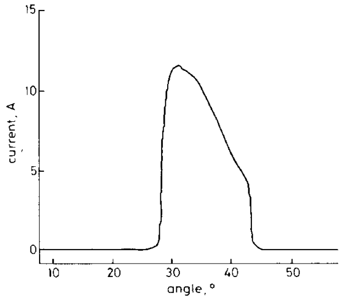
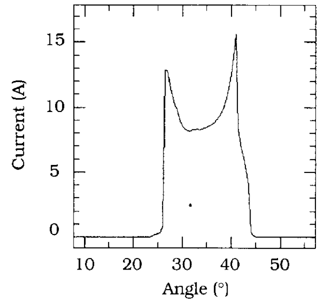
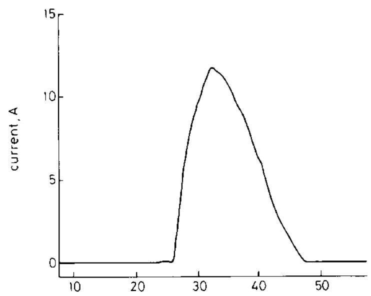
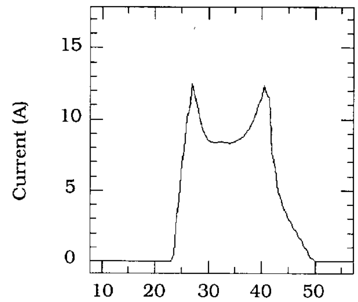
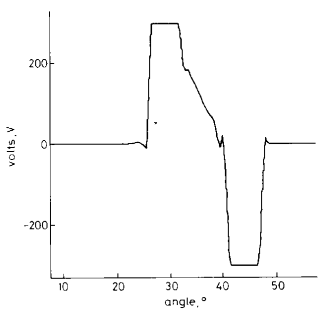
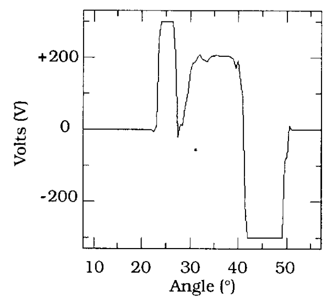
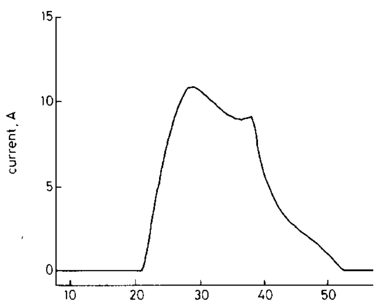
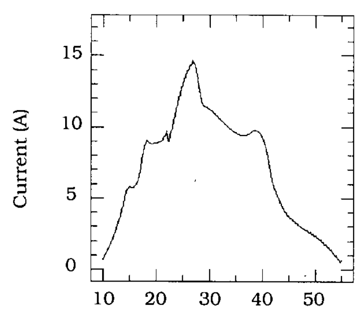
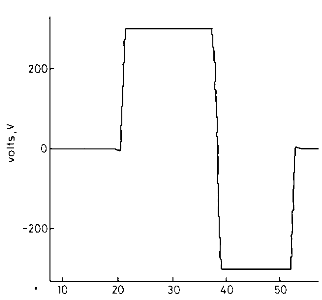
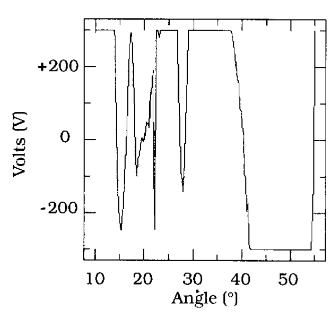
rpm		Least-current	Smooth-torque
0	Current		
750	Current		
	Voltage		
1500	Current		
	Voltage		

Figure 5. Optimised current waveforms and associated voltage waveform