TRANSIENT BEHAVIOUR OF SWITCHED RELUCTANCE DRIVE SYSTEMS FOR DIFFERENT OPERATING MODES

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ABSTRACT

The paper presents an investigation into the transient behaviour of a singly excited doubly salient reluctance machine energised from a unipolar non-bifilar drive circuit. The effect of the operating mode and the switching angles on the dynamic response were studied using a simple linear model. Experimental verification of the theoretical results using a commercially available switched reluctance drive system was made.

INTRODUCTION

An SRD is an abbreviation of Switched Reluctance Drive which is the recent development in the field of controlled speed motors supplied from a power electronic circuit. It consists of:
1) a doubly salient reluctance motor with a number of stator poles carrying windings and a rotor having a related number of poles without any windings, 2) a unipolar electronic circuit, 3) a position sensor and 4) a controller.

Many applications of SRD's require knowledge of the dynamic behaviour of the motor during the transient period as well as the steady-state performance. Over the past 15 year the various aspects of the steady-state characteristics of SRD's have been studied by many workers/1-3/. On the other hand work on the dynamics of SRDs is still very limited /4/. To predict accurately either the dynamic behaviour or the steady state performance of the SRD system, magnetic saturation must be taken into account. The effect of magnetic saturation is included by considering the dependence of phase inductances on both instantaneous currents and rotor position. This will result in representing the SRD system with a non-linear model in which the current against flux-linkage and angular position, as well as co-energy against current and angular position, are given in tabulated forms. Instantaneous phase torques are obtained by numerical derivation of the co-energy with respect to rotor position keeping the current constant through the derivation process. However, for a broad understanding of the combined effects which the different parameters have on the system characteristics, a much simpler model based on linear assumptions is more suitable than the non-linear model.

An investigation into the SRD dynamics is presented in this paper using a linear model. The effect of magnetic saturation is approximated by taking the effective value of phase inductance at the maximum inductance position. The effect of the operating mode and the switching angles on the transient behaviour of the system have been studied.

In order to understand the analysis made in the following sections some terms related to SRD systems have to be defined. These are:

1. *Minimum inductance*

The minimum inductance position is defined when the rotor interpolar axis coincides with the stator pole axis of the excited phase.

2. *Maximum inductance*

When the rotor polar axis is aligned with the stator pole axis of the excited phase the inductance of that phase is maximum. The angle measured from the minimum inductance position to the maximum inductance position is half the rotor pole pitch.

3. *Switching angles*

These are the main control parameters of SRD systems. Switch-on angle (θ_{on}) is the angle at which a phase winding is excited. Controlling the switch-on angle will affect the current waveform, torque, speed, efficiency and dynamic performance.

The conduction angle (θ_{con}) is the angle through which a phase winding is energised.

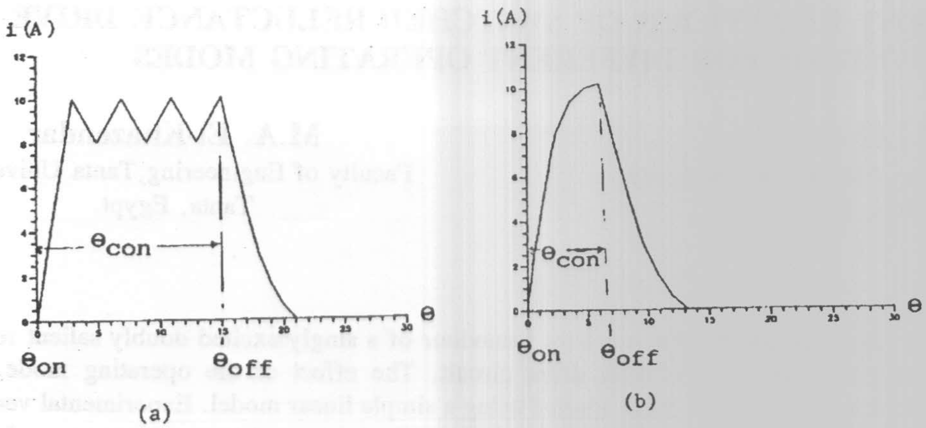

Figure 1. Phase current (a) chopping mode and (b) single pulse mode.

4. *Operating modes*

The two fundamental modes of operating for SRD are chopping and single pulse modes. In the chopping mode both the switch-on angle and the conduction angle are fixed. The current in the motor windings is controlled between two levels, as shown in Figure (1-a).

In the single pulse mode both the switch-on angle and the conduction angle are controlled such that the SRD gives the required characteristics without limiting the current as shown in Figure (1-b).

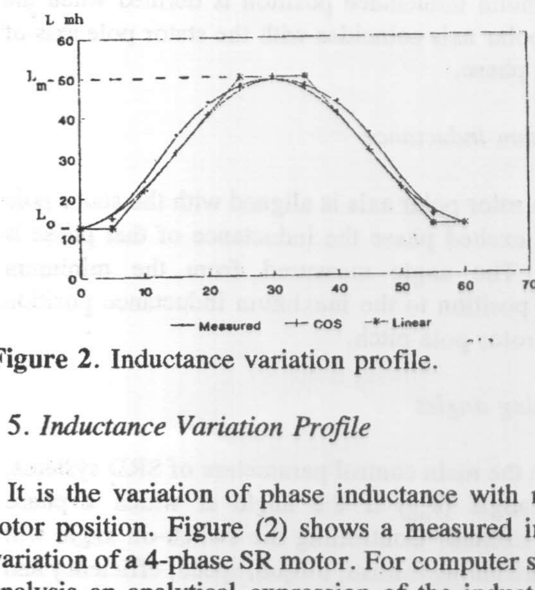

Figure 2. Inductance variation profile.

5. *Inductance Variation Profile*

It is the variation of phase inductance with respect to rotor position. Figure (2) shows a measured inductance variation of a 4-phase SR motor. For computer simulation analysis an analytical expression of the inductance as a function of rotor position should be defined. Two different approaches were used in this study. In the first the inductance variation is represented by a linear approximation, and in the second by a cosine curve as shown in Figure (2). The rotor position angle is said to be zero when the rotor pole starts overlapping the stator pole of the excited phase.

SYSTEM STATE EQUATIONS

The equivalent circuits for any phase "n" of an SRD system with a non-bifilar drive circuit are shown in Figure (3): (a) during the conduction period and (b) during the switch off period.

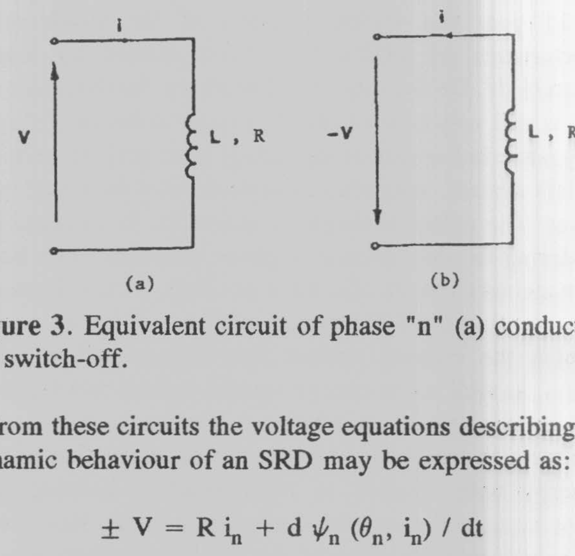

Figure 3. Equivalent circuit of phase "n" (a) conduction (b) switch-off.

From these circuits the voltage equations describing the dynamic behaviour of an SRD may be expressed as:

$$\pm V = R\, i_n + d\, \psi_n (\theta_n, i_n) / dt \qquad (1)$$

Where the +ve sign is applied during conduction period and the -ve sign is applied during the switch off period.

Neglecting the mutual coupling between different phases, the flux linkage of phase "n" is given by:

$$\psi_n(\theta_n, i_n) = L_n(\theta_n)\, i_n \qquad (2)$$

Substituting from equation (2) into equation (1) gives:

$$\pm V = R\, i_n + w\, i_n\, d\{L_n(\theta_n)\}/d\theta_n + L_n(\theta_n) di_n/dt \qquad (3)$$

Where; w is the rotor angular speed $d\theta/dt$.

Rearranging equation (3), the rate of change of the current of phase "n" can be written as:

$$di_n/dt = (\pm V - (R + w\, s\, \{L_n(\theta_n)\}/d\theta_n)\, i_n)/L_n(\theta_n) \qquad (4)$$

Where; $n=1,2,3,\ldots m$ (m is the total number of phases), $\theta_{n+1} = \theta_n + \tau_r/m$ (τ_r is the rotor pole pitch) and $\theta_1 = \theta$. The electromagnetic output torque T_e is the summation of torques produced by each phase:

$$T_e = \sum T_{en} = \sum \frac{1}{2} i_n^2 d\{L_n(\theta_n)\}/d\theta_n$$

The equation of motion is given by:

$$T_e = J\, dw/dt + F\, w + T_L$$

where:

J = Combined system inertia

F = Friction coefficient

T_L = Load torque.

From which the rate of change of angular velocity w is given by:

$$dw/dt = \sum \frac{1}{2} i^2 n d\{L_n(\theta_n)\}/d\theta_n - T_L - Fw)/J \qquad (5)$$

$$d\theta/dt = w \qquad (6)$$

Equations (4), (5) and (6) completely define the dynamic model of the non-bifilar SRD system, based on linear assumptions.

These equations can be rearranged in state space format as follows:

$$\dot{\underline{X}} = f(\underline{X}, V) \qquad (7)$$

Where the state vector $\underline{X} = i_1\, i_2 \ldots i_m\, w\, \theta\,]^T$

Equations (7) are non-linear differential equations, so that numerical integration techniques must be used to solve them.

COMPUTER SIMULATION PROGRAM

Figure (4) shows the simplified flow-chart for the digital computer program simulating the dynamic response of an SRD. The program was written in Fortran and used Euler integration algorithm with nominal fixed step. Additional iterations were used to determine accurately the switching instants. The program input data were machine parameters, supply voltage, switching angles, load torque and the integration step. The program output comprises the motor speed, electromagnetic torque, and winding current.

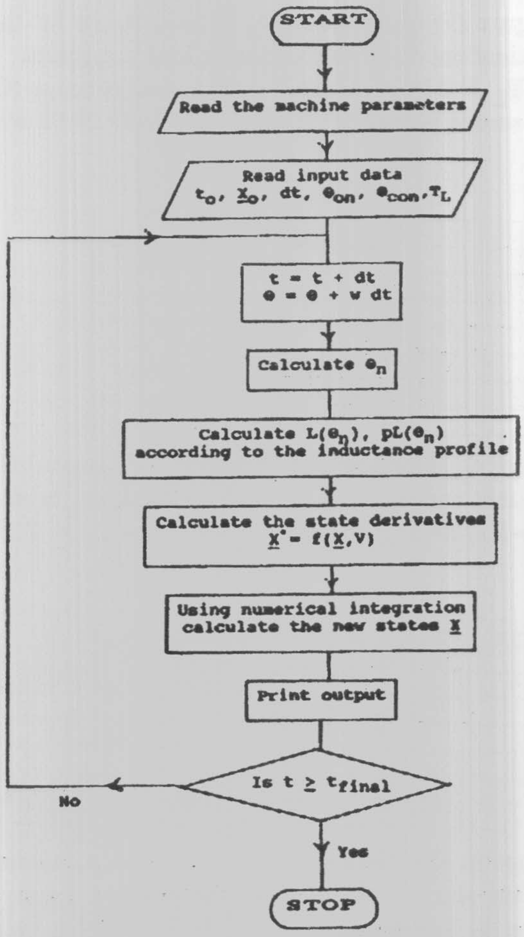

Figure 4. Simplified flow-chart.

RESULTS AND DISCUSSIONS

In order to verify the computer simulation program developed in the previous section a comparison between measured and simulation results were made. The SRD system used for purpose of comparison was 380/415 V,

4 kW, 4-phase, 112s Oulton drive.
The machine parameters are listed below:

d.c. link voltage	$V = 295V$
Effective maximum inductance	$L_m = 50$ mH
Minimum inductance	$L_o = 12.5$ mH
Phase winding resistance	$R = 0.833$ Ohm
Stator pole arc	$\beta_s = 20°$
Rotor pole arc	$\beta_r = 30°$
Combined system inertia	$J = 0.035$ kg.m^2
Total Friction coefficient	$F = 0.0064$ Nm.s

1. *Measured Results*

Figure (5) (a,b) shows the printout trace for the speed transient curves at two different load conditions: $T_L = 0$ and $T_L = 2$ N.m obtained from a storage scope (GOULD 104 screen plotter).

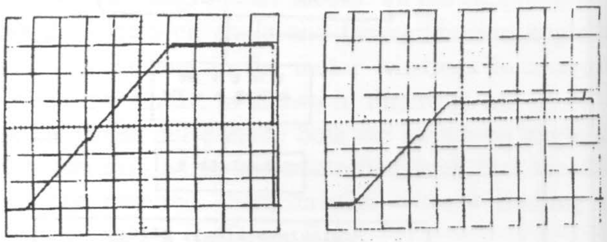

Figure 5. Oscilloscope printout of measured speed transient curves (vertical: 1 div=250 rpm, horizontal: 1 div=1 s) a- $T_L = 0$ and b- $T_L = 2$ N.m.

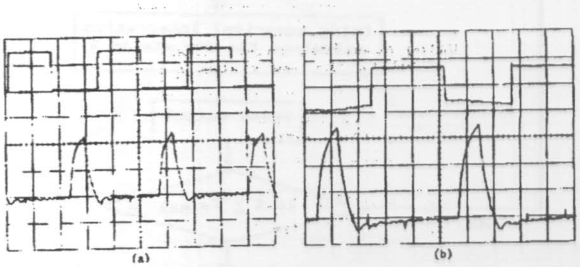

Figure 6. Oscilloscope printout of the measured phase current and the signal from the position sensor of that phase. a- T_L=0 and b- T_L=2.N.m (vertical: 1 div=2.5 A, horizontal:1 div=2 ms.

The printout steady-state phase current waveforms for the above loading conditions are shown in Figure (6). It is clear that the system operates in the single pulse mode. The signal from the position sensor for the same phase is shown at the top of the current trace. Both switch-on angle and conduction angle are measured from this Figure, $\theta_{on} = 3°$, $\theta_{con} = 9.6°$.

2. *Simulation Results*

Two different approaches were used for simulating the SRD system. The first is to represent the inductance variation profile by a linear approximation and the second by a cosine curve as shown in Figure (2).

For the same running condition, viz: $\theta_{on} = 3°$, $\theta_{con} = 9.6°$ and for both load conditions the simulated speed transient curves are shown in Figure (7) for both linear and cosine approaches.

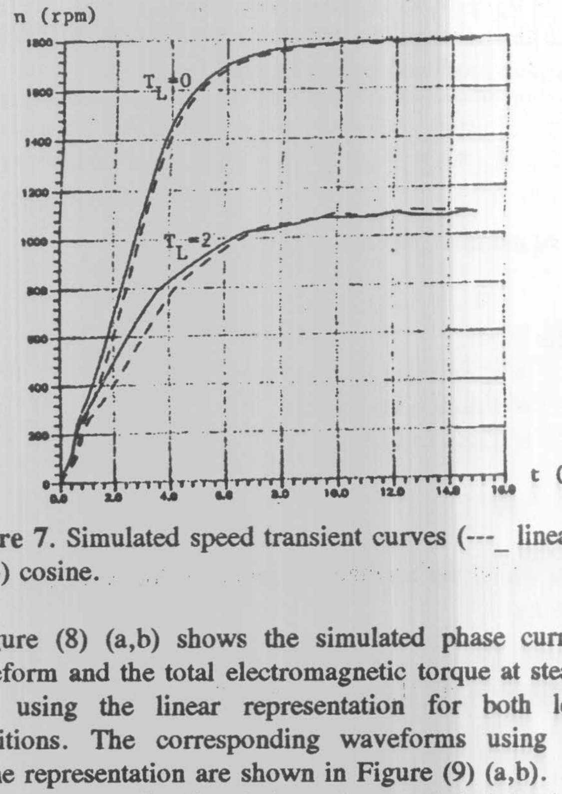

Figure 7. Simulated speed transient curves (---_ linear, (- - -) cosine.

Figure (8) (a,b) shows the simulated phase current waveform and the total electromagnetic torque at steady state using the linear representation for both load conditions. The corresponding waveforms using the cosine representation are shown in Figure (9) (a,b).

From Figures (7), (8), (9) it can be concluded that both linear and cosine representations give nearly the same simulated results. This conclusion was expected since the difference between the inductance variation profiles for both cases is small (Figure (2)). Comparing the measured and simulated results shows that:

1- The predicted steady-state speed is about 18% higher than the actual steady state speed.
2- The predicted peak phase current is about 15% higher than the measured value.
3- The predicted rise time is between ± 7 % of the measured one.

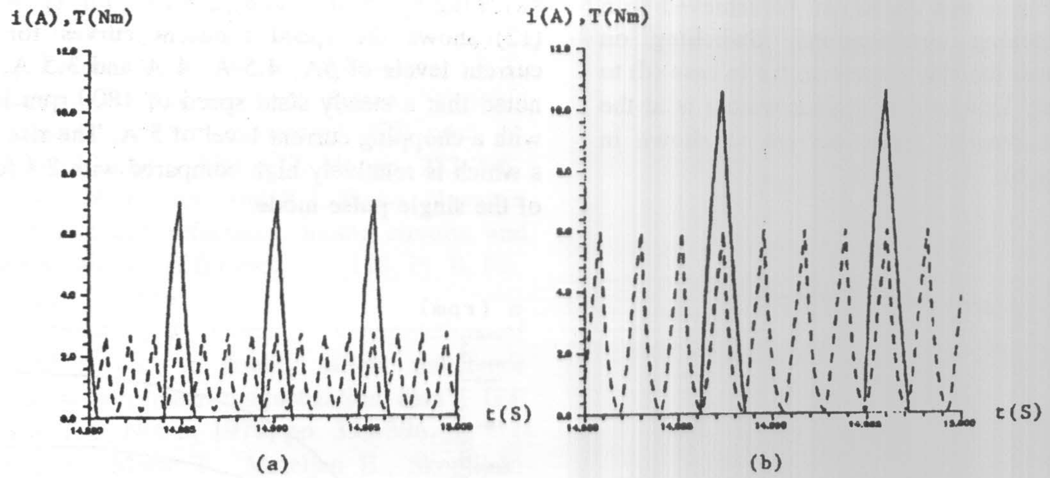

Figure 8. Simulated phase current (---) and torque (- - -) using linear approach a- $T_L = 0$ and b- $T_L = 2$ N.m.

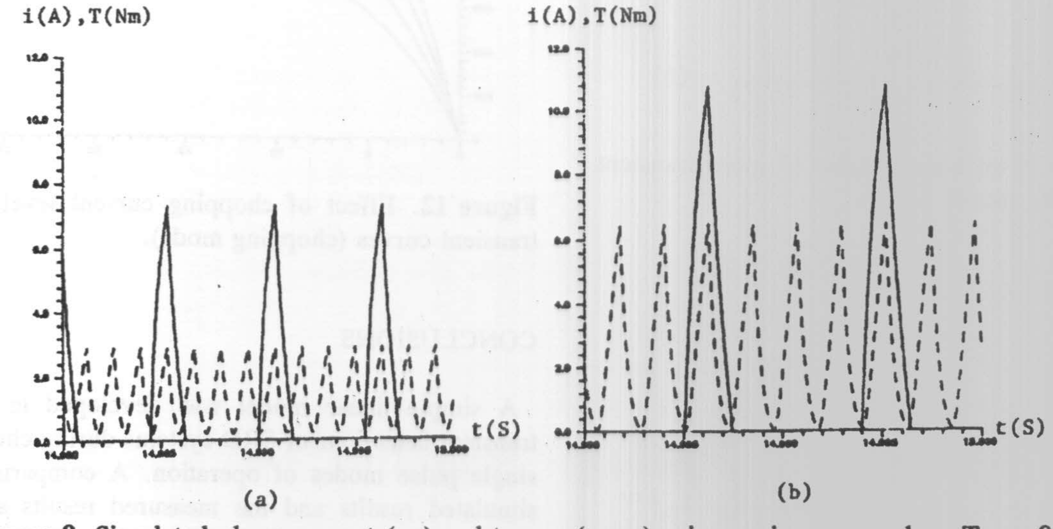

Figure 9. Simulated phase current (---) and torque (- - -) using cosine approach a- $T_L = 0$ and b- $T_L = 2$ N.m.

The above comparison shows that the linear model is not accurate in predicting the exact dynamic or steady state performance. Therefore a complicated non-linear model which takes into account the exact effect of magnetic saturation is required to give more accurate results. However, the linear model is suitable for a broad understanding of the combined effects which the different parameters have on the system characteristics as it gives acceptable relative results in much less computation time.

3. *Effect of Switching Angles*

To study the effect of switching angles on the transient speed characteristics of SRD in the single pulse mode, different combinations of (θ_{on} and θ_{con}) were fed to the simulation program such that steady state is kept constant with T_L=0. Figure (10) shows the results of four different combinations:

(a) (-1°, 7.35°), b (1°,8.5°), c (3°, 9.6°) and d

(5°, 11°). According to these results, the same steady state torque and speed can be achieved with different switching combinations. Switching on earlier decreases the rise time from 6 s in case (d) to 2 s in case (a). However this achievement is at the expense of increasing phase current as shown in Figure (11) (a,b).

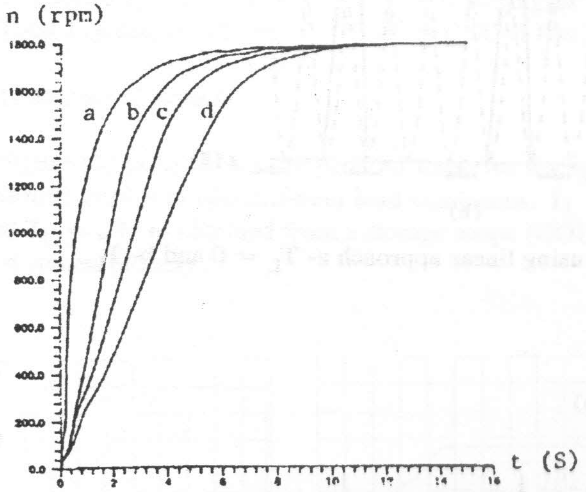

Figure 10. Effect of switching angles of speed transient curves (single pulse mode).

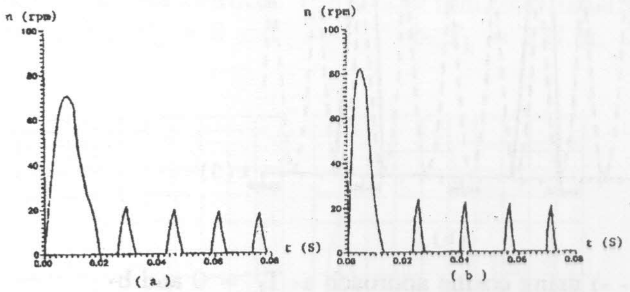

Figure 11. Transient phase current in the single pulse mode a- θ_{on} =-1, θ_{con}=7.35° b-θ_{on} = 5°, θ_{con} =11°.

4. *Effect of Chopping Current Level*

In the chopping mode, the switching angles are fixed and the chopping current level is controlled to give the required output torque at a certain speed (with a closed loop control on the speed).

On the other hand, without a speed feedback signal, the chopping current level determines the operating speed for a given load torque. In the simulation program the system is assumed to be an open loop system with fixed switching θ_{on} = 0° and θ_{con} =15°, for T_L = 0. Figure (12) shows the speed transient curves for chopping current levels of 5A, 4.5 A, 4 A and 3.5 A. It can be noted that a steady state speed of 1800 rpm is obtained with a chopping current level of 5 A. The rise time is 11 s which is relatively high compared with 2 s for case (a) of the single pulse mode.

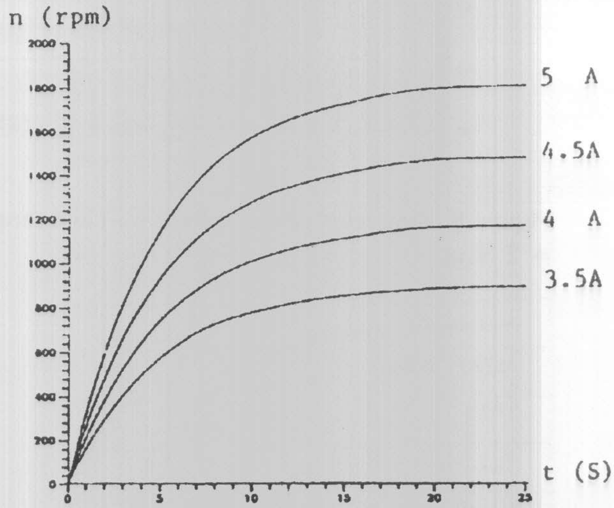

Figure 12. Effect of chopping current level on speed transient curves (chopping mode).

CONCLUSIONS

A simple linear model was developed to study the transient behaviour of SRD systems during chopping and single pulse modes of operation. A comparison of the simulated results and the measured results shows that accurate prediction of the dynamics of SRD systems requires a non-linear model which takes into account the exact of magnetic saturation. This conclusion agrees with the findings of other researches. On the other hand, the linear model successfully gives a clear picture of the relative effects of switching angles (in single pulse mode) and chopping current levels (in chopping mode) on the transient behaviour. The main conclusions drawn from this study are: In single pulse mode switching on earlier gives fast speed response and requires higher peak current and may thus require higher ratings for the electronic switches. On the other hand, providing a current limit in the chopping mode with fixed switching angles will result in a slow speed response.

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