CED: A New Method for High Speed Stepping Motor Driving

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Abstract.- Stepper motors are indexing devices widely used today in microcomputer controlled machines because of their low cost, simplicity, accuracy and repeatability. Even though their speed is presently adequate for many purposes, there is still some room for improving this parameter. In this article we propose a new electrical driving method especially designed for small stepper motors, fed with unidirectional currents. The method is called "Controlled Energy Discharge" (CED) and is based on changing the time response constant of the current due to winding inductance by the addition of a charged capacitor. The theory of the method, its implementation and performance comparisons with traditional control schemes are presented. From these comparisons, our proposal appears as an excellent alternative for driving stepping motors.

I. Introduction

Evolution has given our brain the ability to control every muscle of our body in as little and precise increments as necessary. Thus, if robots are to partly replace men, our natural indexing capabilities should be emulated with suitable actuators.

Today, this purpose is well served with servo motors and stepping motors. The former are compact and fast machines, but for indexed usage they require closed loop automatic control with at least position feedback. Moreover, they can behave unstable if suddenly loaded while in standstill condition. On the other hand, stepping motors are indexed devices that show some advantages regarding cost, precision, repeatability and holding torque stability; they can be open or closed loop controlled [1] and they are especially appropriate to operate under constant loads. Their main disadvantage is that they can only be driven at comparatively low speeds unless special electrical control schemes are applied. In this paper, after a brief discussion about the more traditional procedures to control stepping motors, we describe the theory and implementation of a new driving method, called CED for "controlled energy discharge". This open-loop method, while simple and inexpensive, allows for a substantial increase in the operating speed of these actuators.

II. Traditional Control Schemes

Stepping motors are devices that, when energized, stop in a very precise position with a holding torque (instead, other motors rotate when energized). The spinning action of stepping motors is achieved by energizing their windings (commonly two to four) in appropriate sequence. Since these motors do not have commuters, they must be switched externally by a logic controller [2]. Recently, there have been a great integration improvement on them.

In stepping motors the rotor and stator are connected through a magnetic field whose strength is proportional to the current. But, since the establishment of the steady state current is delayed by coil inductance, steady state torque cannot be reached instantly. Thus, if a given winding is switched on well before the steady state has been attained in preceding winding, average torque will decrease, eventually reaching a point where it will not be able to sustain the load. At that time, synchronization between the rotor and stator fields is lost. Besides, the back emf produced at high speeds, reduces the amplitude of the steady-state current. Various control schemes have been devised to overcome the rotating speed limit imposed as a consequence of this behavior [3-6]. Their description can be followed with the help of the basic electric model of a motor winding as depicted in Fig. 1, where R is the circuit resistance, L is the coil inductance and V is an external power source.

The electrical behavior of this circuit is described by the following equation:

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$$V = RI + \frac{\mathrm{d}(LI)}{\mathrm{d}t} \quad (1)$$

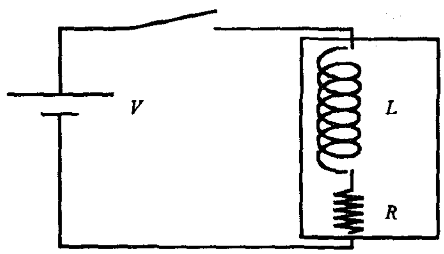

Fig. 1. Basic circuit.

$$V = RI + L\frac{dI}{dt} + \omega_M \frac{dL}{d\theta} I \quad (2)$$

where θ is the angular position of the rotor, and $\omega_M = d\theta/dt$. The term $\omega_M \cdot dL/d\theta \cdot I$ in (2) is the back emf. During the time the coil is being excited by V, usually $dL/d\theta \approx K$ (constant), and hence:

$$V = L\frac{dI}{dt} + (R + K\omega_M)I \quad (3)$$

When the coil is initially excited, $I(0)=0$, and for a particular speed ω_M, the solution of (3) becomes:

$$I = \frac{V}{R + K\omega_M}\left(1 - e^{-\frac{R+K\omega_M}{L}t}\right) \quad (4)$$

A. R/L Method.

This was the first control scheme implemented by stepping motor manufacturers [7]. From (4) it is clear that I increases faster as $(R+K\omega_M)/L$ is increased. This can be done easily by adding a series resistance to the circuit. However, doing so lowers the steady state current $I_{SS} = V/(R+K\omega_M)$. If this is compensated by a proportional increase in electric potential V, most of the energy would be wasted as heat. For this reason – despite its simplicity– the R/L method is seldom used nowadays.

B. VSI Method.

The name of this method comes from "volt second insertion", whereby the controller switches to successively higher electric potentials above given threshold speeds. However, if for some reason the controller stops generating steps while operating at high power, the ensuing current surge may destroy the motor. Moreover, this method provides discrete increments in energy to satisfy continuos changes in demanded power. As a consequence, when operating near one of the switching speeds, a sudden small increment in load may cause some steps to be lost.

C. Chopper Method.

This technique is the most popular today. Its name comes from chopping the current produced by a source V much greater than the nominal e.m.f $Vnom$ [7]. The maximum stepping frequency f is on the order of the inverse of the time to reach the nominal steady state current $Vnom/(R+K\omega_M)$. Thus:

$$f \approx \frac{R + K\omega_M}{L \ln\left(\frac{V}{V - V_{nom}}\right)} \quad (5)$$

The controller used with this method requires fast calibrated circuits to set the average current applying PWM by on-time control of the power circuitry. Also, a current sensor is needed for each winding. Therefore, implementing this method may become quite expensive. Moreover, the high chopping frequency produces electromagnetic interference and low amplitude oscillations in the bearings of the motor, thereby shortening their life [8].

III. CED: A New Control Method

From the above discussion it may be seen that the clue to successful motor control lies in providing a high driving e.m.f. to quickly reach a high value of the current but without overheating the windings. The proposed method achieves this goal by providing energy through a combination of an external source V and a charged capacitor C in such a way that the discharge time of the latter is not much longer than the time the current takes to reach its maximum value and that this maximum is not much bigger than the winding steady state current I_{SS}. The basic circuit is depicted in Fig. 2, where path a-b is needed to maintain the positive flow of current after the capacitor becomes discharged. One of the functions of diode D is to force the capacitor discharge through the inductance. The other function will be explained below.

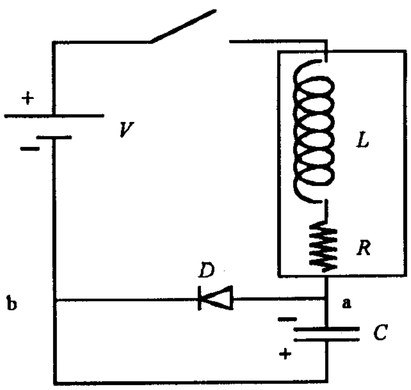

Fig. 2. Basic circuit for CED.

When path a-b is inactive, the circuit is described by the following classical equation in terms of electric potential:

$$V = L\frac{\mathrm{d}I}{\mathrm{d}t} + (R + K\omega_M)I + V_C \qquad (6)$$

where V_C is the time dependent electric potential stored in the capacitor (note its initial polarity with respect to source V). Since $I = C\,\mathrm{d}V_C/\mathrm{d}t$, (6) becomes:

$$V = LC\frac{\mathrm{d}^2 V_C}{\mathrm{d}t^2} + (R + K\omega_M)C\frac{\mathrm{d}V_C}{\mathrm{d}t} + V_C \qquad (7)$$

The solution of this equation depends on the ratio $r=\alpha/\omega_0$, where $\alpha=R+K\omega_M/2L$ and $\omega_0 = \sqrt{1/LC}$. We distinguish among three cases: overdamped ($r>1$), critically damped ($r=1$) and underdamped ($r<1$). It may be shown that the maximum current is reached sooner in the third case, *i.e.*, when $C < 4L/(R+K\omega_M)^2$. We then have:

$$Vc = (Vco - V)\sqrt{1 + \frac{\alpha^2}{\omega_1^{\,2}}}\,\mathrm{e}^{-\alpha t}\cos(\omega_1 t - \varphi) + V \qquad (8)$$

where: $\omega_1 = \sqrt{\omega_0^2 - \alpha^2} = \sqrt{\frac{1}{LC} - \frac{(R + K\omega_M)^2}{4L^2}}$,

$\varphi = \arctan(\alpha/\omega_1)$ and V_{C0} is the (negative) electric potential initially stored in the capacitor. In terms of current:

$$I = C(V - Vco)\frac{\alpha^2 + \omega_1^2}{\omega_1^2}e^{-\alpha t}\sin(\omega_1 t) \qquad (9)$$

The derivative of this equation evaluated at $t = 0$ shows that the current increases faster as ω_1 is made bigger, thus allowing for an increase in motor speed. The only reasonable way of increasing ω_1 is to select a small capacitance C, because to decrease either R or L the motor should be rewound (increasing L is obviously not convenient).

Let us now analyze the situation from an energy point of view. The energy delivered by the source up to time t after the switch is closed is given by the integral of product VI. Thus, from (7):

$$VC(Vc - Vco) = \frac{1}{2}LI^2 + R_\omega\int_0^t I^2\,\mathrm{d}t + \frac{1}{2}C(Vc^2 - Vco^2) \qquad (10)$$

Where $R_\omega=R+K\omega_M$. This equation is valid only up to time t_d when the capacitor is completely discharged. At that time:

$$C\,Vco\left(\frac{1}{2}Vco - V\right) = \frac{1}{2}LI_d^2 + R_\omega\int_0^{t_d} I^2\,\mathrm{d}t \qquad (11)$$

where I_d is the current at the time the capacitor becomes discharged. The integral term, which represents energy dissipated as heat, is made small if t_d is short and if the maximum current, I_{max}, is not much greater than the winding steady state current I_{SS}. As we have seen, the first requirement is fulfilled by selecting a small value of C. To analyze the second requirement, we note from (9) that I_{max} occurs at $t_{max} = \frac{\arctan(\alpha)}{\omega_1}$. Substituting this time in (9) we get:

$$n \equiv \frac{I_{max}}{I_{ss}} = CR_\omega\frac{(V - Vco)}{V}\frac{\alpha^2 + \omega_1^2}{\omega_1}\exp\left[-\alpha\frac{\arctan(\alpha)}{\omega_1}\right]\sin[\arctan(\alpha)] \qquad (12)$$

Thus, according to this "maximum" criterion, capacitance C should be selected such that, given a value of V_{C0}, the value of n falls in the range between 1 and a "reasonable" upper bound, say 2. Also, to assure that the maximum is really reached, it is important to check that $tmax$ be on the order of the capacitor discharge time t_d, or less.

A second criterion to select C comes from the fact that the capacitor should be initially charged with an amount of energy at least enough for the current to reach the winding steady state current without the help of source V. Therefore, according to this "energy" criterion, the ratio:

$$m \equiv \frac{\frac{1}{2}CV_{CO}^{\ 2}}{\frac{1}{2}LI_{SS}^{\ 2}+R_{\omega}\int_0^{t_{ss}} I^2 dt} \qquad (13)$$

should fall between 1 and, say, 5.

The minimum value of V_{CO} is found by first noting that the energy initially stored in the capacitor should be greater than that stored by the inductance up to the time when the current first reaches the winding steady state current, *i.e.*, $\frac{1}{2}CV_{CO}^{\ 2} > \frac{1}{2}LI_{SS}^{\ 2}$. Also, recall that for the underdamped case we need $C<L/R_{\omega}^{\ 2}$. From both inequalities we get $|V_{CO}| > V/2$.

Note that (6) is valid up to time td. Thereafter the presence of the diode effectively eliminates the capacitor from the circuit (thereby reducing it to the one shown in Fig. 1) so the damped energy oscillation between capacitor and inductance indicated by (9) will not exist. The current *vs* time curve as obtained with the CED control method will then appear as depicted in Fig. 3, where for comparison purposes we have drawn the "normal" curve corresponding to the basic circuit without special control (Eq. (4)).

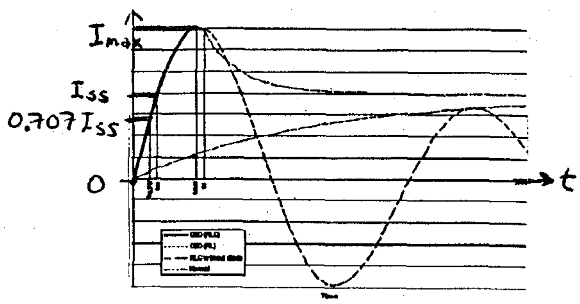

Fig. 3. Theoretical CED current *vs* time.

Finally, having selected an appropriate value of C for a given V_{CO} (satisfying both the "energy" and "maximum" criteria) it is desirable to find the theoretical maximum operating frequency. As shown in [8, 9], load torque τ should not be greater than $0.707\tau max$. Equivalently, current I should be greater than $0.707I_{SS}$. Therefore, maximum frequency is $fmax = 1/t_{0.707}$, where $t_{0.707}$ is defined in Fig 3.

IV. Implementation and Performance of CED

A. The circuit.

The implementation of the CED controller is depicted in Fig. 4. Components for this circuit are listed in Table 1 (total cost under US$ 150). Note that $V = 5$ V and $V_{CO} = -40$ V.

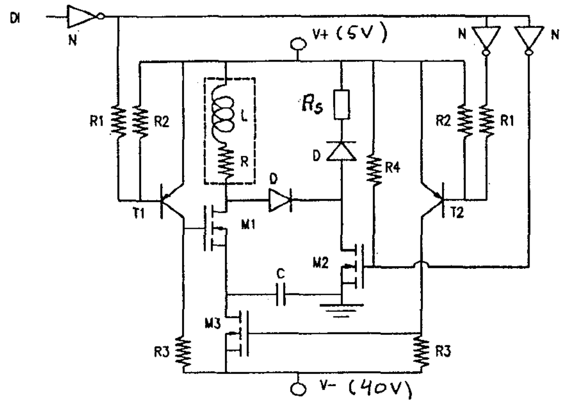

Figure 4. CED circuit.

TABLE 1

List of Components

Cts	Current transient suppresser (110 W resistor).
C	33 μF as calculated (see below).
D	Fast high voltage (400 V) rectifier diode (50 ns) UFR603.
DI	Digital input connected to a TTL O.C. inverter
L	Winding inductance, see Table 2
M1, M2 and M3	Mosfet Power Transistor N-channel enhanced mode, high current (14 A), 100 V, IRF530.
N	TTL O.C. inverter, 74LS05.
R	Winding internal resistance, see Table 2
R1	510 W, 0.25 W.
R2	330 W, 0.25 W.
R3	5,1 kW, 0.25 W.
R4	2,2 kW, 0.25 W.
T1 and T2	High voltage transistor (300V) PNP, MPSA92.
V+	5 V regulated power source (obtained from a PC)
V-	-40 V capacitor charging source, a diode rectified 220-40 V transformer.

Note that when DI is logically 1 (5 V) M1 and M2 are conducting and M3 is open, so the circuit is in the "on state", exactly as in Fig. 2 (with the switch closed). When DI is logically null the circuit is in the "off state": M1 and M2 are open, Rs is dissipating the current that remains in the inductance and M3 is charging the capacitor with the required polarity. The implicit (small) charging resistance of the transistor, cables and connections assures a fast capacitor charge (see Fig. 5).

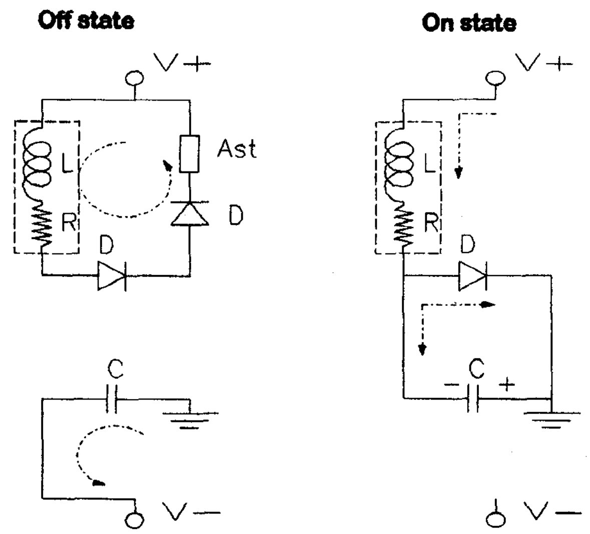

Figure 5. Circuit states.

Two Step-Syn model, Nema #23 and #34 size, single stack unipolar Sanyo motors were used for testing purposes. Their measured and nominal characteristics are listed Table 2.

TABLE 2
MOTOR CHARACTERISTICS

Description	Symbol	Motor A, #23 size	Motor B, #34 size
Internal winding resistance	*R*	3.9 W	3.3 W
Winding inductance	*L*	9.3 mH	6.4 mH
Nominal potential difference	*V*	5 V	5 V
Steps per revolution		200	180

B. Capacitor selection

The theoretical performance of the CED circuit was investigated for each motor using six commercial capacitors. The following parameters were calculated: maximum frequency ($fmax = 1/t_{0.707}$), t_{SS} (time for the current to first reach the winding steady state current, see Fig. 3), t_d (time to discharge the capacitor), *tmax* (time to reach the maximum current) and ratios *n* and *m* (Eqs. (12) and 13)). Also, as a measure of efficiency in energy usage we calculated the ratio between energy stored in the inductance up to time t_{SS} and total energy required for the current to reach the value I_{SS}, *i.e.*, the ratio:

$$\eta = \frac{\frac{1}{2} L I_{SS}^{2}}{\frac{1}{2} L I_{SS}^{2} + R\int_{0}^{t_{SS}} I^{2}\,\mathrm{d}t} \times 100 \qquad (14)$$

The results are shown in Tables 3 and 4.

TABLE 3.

CHARACTERISTIC PARAMETERS FOR MOTOR A

C / mF	*fmax* (kHz)	*tSS* (ms)	*td* (ms)	*tmax* (ms)	*n*	*m*	η
4.7	3.858	-	313	328	0.737	-	-
10	4.702	371	462	479	1.045	0.921	88.0
22	4.949	305	699	712	1.480	2.105	91.4
33	5.010	296	867	873	1.752	3.172	91.8
47	5.045	291	1050	1045	2.024	4.529	92.0
100	5.088	285	1597	1542	2.690	9.663	92.3

TABLE 4.

CHARACTERISTIC PARAMETERS FOR MOTOR B

C (mF)	*fmax* (kHz)	*tSS* (ms)	*td* (ms)	*tmax* (ms)	*n*	*m*	η
4.7	4.873	-	260	272	0.751	-	-
10	5.806	294	384	397	1.063	0.965	88.6
22	6.094	247	580	591	1.502	2.192	91.5
33	6.166	240	720	725	1.782	3.302	91.8
47	6.207	236	872	868	2.055	4.714	92.1
100	6.258	232	1328	1281	2.727	10.055	92.3

The most acceptable values for both *n* and *m* are obtained with the 22 mF and 33 mF capacitors. For both motors we chose the latter since its larger current overshoot is favorable for mechanical acceleration. From the maximum frequency for this capacitor and the steps per revolution for each motor maximum speeds of 1503 r/min for motor A and 2055 r/min for motor B were calculated.

Note that still higher speeds would be possible if the capacitor charging electric potential *VC0* is increased. A plot of maximum and steady state frequencies (1/*t0.707* and 1/*tSS* respectively) as a function of *VC0* shows that speed is nearly proportional to initial capacitor charge, see Fig. 6. Obviously, increasing *VC0* requires an appropriate smaller capacitance selection. (It is interesting to compare this plot with the *f vs V* curve resulting from (5) for the chopper method. It may be shown that the slope of this curve is almost constant starting from a small value of V and that it tends quickly to the value $1/LI_{ss}$).

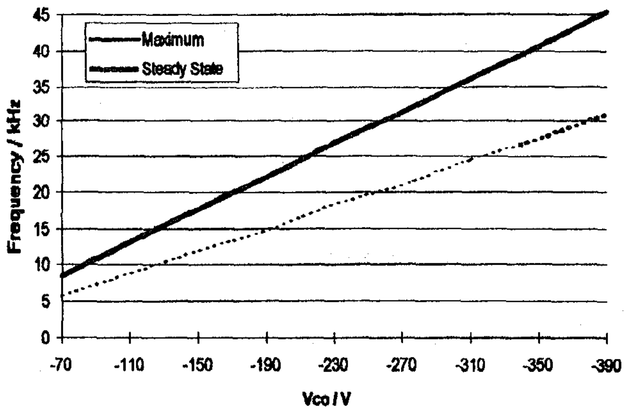

Figure 6. Maximum and steady state frequency vs initial capacitor charge.

C. Theoretical performance

For comparison purposes we also calculated the performance of the normal, CED and chopper operating schemes. Current for the CED method was calculated from (9) (which is valid only up to time t_d). Currents for the normal and chopper circuits were calculated from Eq. 2 with $V = 5$ V and $V = 45$ V, respectively (this last value is equal to $V - V_{C0}$). Results obtained using the *RLC* values applicable to motor A are plotted in Fig. 7, where the ordinate is current divided by the nominal steady state current. Observe that for capacitances 22 mF and over, the time to reach I_{SS} is about the same for the chopper and CED methods. Note also that the curve for the chopper drive is strictly valid up to $I = I_{SS}$. Therefore, a further advantage of CED is that it renders an over current that helps to mechanically accelerate the motor.

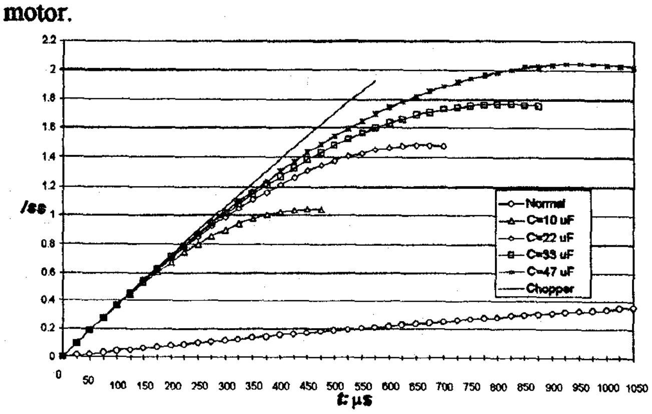

Figure 7. Curves of current vs time for the CED and Chopper methods.

V. Experimental Results

The current through one of the windings of motor A was measured, with and without the CED method for a step of 1/60 s. Results are shown in Fig. 8, where the upper and lower curves are for the CED and "normal" (no special control) circuits, respectively. Note that the upper curve is very similar to our prediction (Fig. 3). Note also that, from this curve, the value of n is about 2.15 whereas the predicted value is 1.752, while *tmax* is about 0.7 ms as measured and 0.873 ms as calculated. (Table 3).

We also measured resulting torque and output mechanical power as a function of speed for motor B operating both under the CED controller with the 33 µF capacitor and under the normal driver. Results are shown in Figures 9 and 10. Observe that speed increases to about 18 times for the same torque.

Weaknesses.

The CED method is not suitable for microstepping (at least without some modifications). Also, the controller capacitor should be changed if the system is used with a motor whose resistance and inductance are very different from the values for which the capacitor was calculated. Even though this should not be a problem because in most cases the controller is made specifically for a given motor, a solution would be to have a capacitor bank and switch them as appropriate.

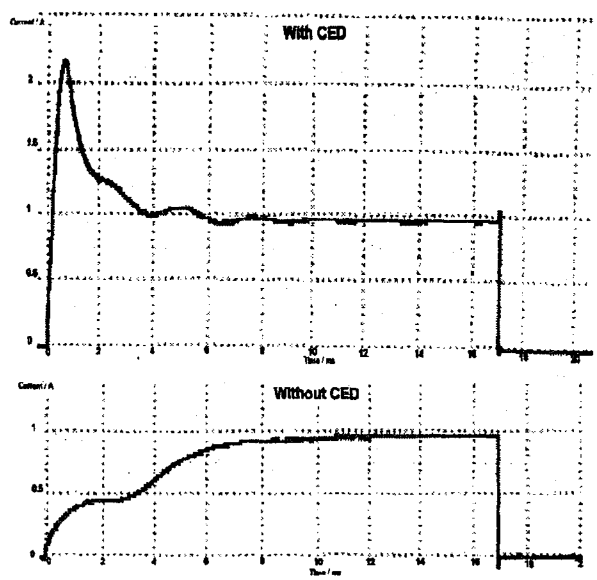

Fig. 8. Current vs time with and without CED.

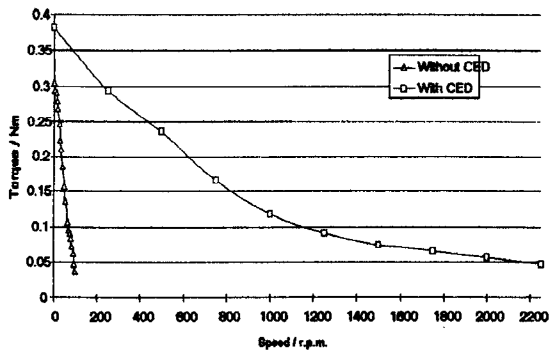

Fig. 9. Torque *vs* speed, with and without CED.

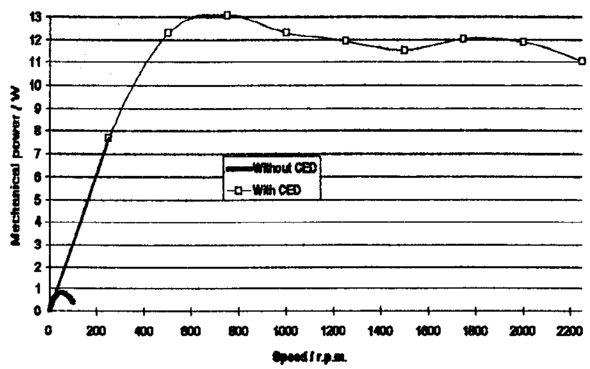

Fig. 10. Output mechanical power *vs* speed, with and without CED.

V. Conclusions

In this paper we have described a new approach for stepping motor electrical control. In our implementation the method has proven to be advantageous in terms of speed, torque and cost, but speed could be increased even more at almost no extra cost by increasing the initial capacitor charging electric potential *VC0* (and selecting an appropriate lower capacitance). Thus, due to cost and simplicity, the proposed method appears to be an excellent alternative to traditional control schemes such as the chopper method.

Acknowledgment

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References

[1] Grimbleby, J.B., "Simple algorithm for closed-loop control of stepping motors", IEEE Proceedings Electric Power and Applications, vol. 142, N°1, Jan 1995. Pg: 5-13.

[2] T. J.E. Miller, "Brushless Permanent-Magnet and Reluctance Motor Drives", Chapter 7: Switched reluctance drives, Oxford Science Publications, 1989.

[3] R. Krishnan and P. N. Materu, "Design of a single-switch-per-phase converter for switched reluctance motor drives", IEEE Trans. on Industrial Electronics, Vol. 37 N° 6, Dec. 1990.

[4] R. M. Davis, W. F. Ray, and R. J. Blake, "Inverter drive for switched reluctance motor: circuits and component ratings", IEE Proc., 128, Pt.B, N°2, Mar. 1981, pp. 126-136.

[5] C. Cini, "Smarter power chips move up a notch", Electronic Engineering Times, Vol. 824, Nov. 1994, page 53.

[6] B. Carlisle, "Stepping motors: edging into servomotor territory", Machine Design, Nov. 6, 1986, pp. 88-93.

[7] P. P.Acarnley, "Stepping motors: a guide to modern theory and practice", IEE Contro Engineering Series 19, 3rd ed. 1992, Chapter 5.

[8] "Slo.Syn AC Synchronous, Gearmotors and DC Stepper Motors", Catalog ACDC90, 1989. The Superior Electric Company Bristol, Connecticut, USA, pp. 37-42.

[9] "SKF General Catalog", SKF 1989, Italy, pp. 50-51

[10] D. Jones, "Control of stepping motors, a tutorial", at internet address: http://www.cs.uiowa.edu/~jones/step, Chapter 1-3.