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Título : STEPPER MOTOR DRIVES

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Este trabalho aborda alguns aspectos de fundamental importância sobre motores de passo . São apresentados os tipos de motores, os modos de acionamento em malha aberta, e sua operação em micropassos. É apresentada também a sua aplicação em sistemas de malha fechada, com controle através da técnica da fase da corrente. Finalmente são analizadas algumas técnicas modernas de acionamento de motores de passo.

STEPPER MOTOR DRIVES

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Abstract

The motor where it is possible to have only discrete stationary angular positions is called a stepper motor. The stepper motor is directly compatible to digital control techniques, for this reason it can be easily interfaced with computers, and also operated in a open-loop manner with a good positioning accuracy. Motor construction is simple and rugged. The motor generally has a long maintenance-free life.

There are the following varieties of stepper motors: Variable reluctance (VR) type, Permanent magnet (PM) type, "Hybrid" type, whose is operated under the combined principles of the permanet magnet and variable-reluctance motors, and the "Linear" motor, designed to perform linear motion.

The basic problem of drive circuitry for high speed operation of stepper motor is to provide a high voltage to move current into and out of the winding at pulse transition times, and a low voltage to sustain only the correct current during the steady-state portion of the current pulse. Another important aspect to consider is the problem of mechanical resonance; the motor comes to rest at the equilibrium position in a oscillatory way. An drive approach that produces smother low speed operation is the ministepping mode. In this mode, currents in two or more windings have to be simultaneously controlled at discrete levels.

Open loop control is widely used , it has the advantages of greater simplicity and lower cost of implementation. However we have to obey some capabilities, and accelerate the motor in an adequate velocity profile.

In close loop control each change in phase excitation must occur earlier relative to the rotor position. The need for a speed-dependent switching angle is a major obstacle to implementation of closed-loop control system, for this reason is required a way to detect the position of the rotor. This task can be made through the measure of phase chop current rise time.

In last decade this kind of motors was spreaded, the semiconductor industries designed some integrated circuits that made easier driving small stepper motors and intensive researches on stepper motors and applications of control theories has been performed around the world. Up to now these actuators have been used in small robots, in computer peripherals, in equipments related to the areas of process control, machines tools and medicine.

Chapter 1

INTRODUCTION

It is possible to have a motor in which the rotor is able to assume only discrete stationary angular positions; rotary motion occurs in a stepwise manner from one of these equilibrium positions to the next, such a device is called a stepper motor.

The stepper motor is directly compatible with digital control techniques, consequently, it can readily be interfaced with computers.

Up to now these actuators have been used in small robots, in computer peripherals (e.g., printers, tape drives, capstan drives), in equipments related to the areas of process control, machines tools and medicine [15]. There are several general characteristics of a stepper motor that have made it the actuator of choice in such a large number of applications:

- The device can ben operated in a open-loop manner with a positioning accuracy of ±1 step (assuming that the rotor angular velocity is low enough so that no steps are lost during a move). Thus if a certain angular distance is specified, the motor can be commanded to rotate an appropriate number of steps, and the mechanical elements couple to the shaft will move the required distance. It exhibits excellent positioning accuracy and errors are noncumulative.
- The motor exhibits high torque at small angular velocities. This is useful in accelerating load up to speed, without mechanical transmission like belts and pulleys, gears, lead screw and harmonic drives.
- The motor exhibits a large holding torque with a DC excitation. Thus it has the property of being "self-locking" device when the rotor is stationary. In fact, the rotor can move only when the terminal voltage changes with time. This feature is interested in "fail-safe systems", since a commom failure mode for the power amplifier is for an output transistor to short from collector to emitter; the result of this is to apply the full voltage to the motor. If a DC servomotor is being used, the rotor will "run away" until an obstacle or mechanical limit stop is encoutered, in either case, an extremely danger situation could result; however, if a stepper motor is being used, the application

of full supply voltage will cause the motor to move one step and hold; thus the device is seen to be safer under this type of failure being used for drive Moderater Sticks that control nuclear reactions.

- Motor construction is simple and rugged. There are usually only two bearings, and the motor generally has a long maintenance-free life, for this reason it is a cost-effective actuator.

Although safety and cost are two factors that make the stepper motor an attractive alternative, the open-loop-control feature, which contributes to its cost advantage, may actually turn out to be a disadvantage. For example, if a robotic manipulator encouters an unforeseen obstacle in its workspace during a move, the controller will nevertheless continue to output the calculated number of pulses required to cause a specific arm motion, thus large position errors can result. If a position sensor is added to the system, enabling the closed-loop, the stepper motor's cost advantange would disapear.

Position errors can also be caused when one attempts to move the rotor too rapidily, in this instance the motor cannot respond fast enough to the pulses coming from the controller, so that each pulse does not produce an actual step in the shaft position. This phenomenon of dropped steps will cause the mechanical system to reach a erroneous final position. In order to fix this, it is possible to reduce the maximum rotor velocity and/or the inertia reflected back to the motor shaft. Clearly, such a compromise causes a degradation in perfomance.

Another potential difficulty is that the stepwize motion can excite significant oscillations. Since no velocity feedback is normally used, the way to improve the response is to employ a much more elaborate controller that is capable of ministepping. This increases the cost of the drive electronics, further increasing the cost differential among another motor drives choices.

1.1 Classification of Stepper Motors

There are two basic varieties of stepper motors that can be constructed:

1. Variable reluctance (VR) type
2. Permanent magnet (PM) type.

There are other types derived from VR and PM, like the "Hybrid" type, whose is operated under the combined principles of the permanet magnet and variable-reluctance motors, and the "Linear" motor, designed to perform linear motion.

The principles of VR stepper motor are explained in chapter 2, here is worth to mention that there is a stator with opposing teeth, and coils (named by phases) wounded to produce

Characteristic	PM motor	VR Motor
1. Motor	Magnetized	Not magnetized
2. Rotor position	Depends on stator excitation polarity	Independent of stator excitation
3. Rotor inertia	High due to magnet	Low (no magnet)
4. Mechanical response	Not as good (due to high inertia)	Good (low inertia device)
5. Inductance	Low due to rotor offset	Generally high for same torque rating
6. Electrical response	Faster current rise (due to low inductance)	Slower current rise (due to higher inductance)

Table 1.1: Differences Between PM and VR Stepper Motors

a magnetic field. The rotor has some teeth, both stator and rotor are normally made of laminated silicon steel, and have high permeabillity, being capable of allow high magnetic flux through them.

When a phase is turned ON, will appear a torque to align the stator teeth, in order to minimize the lenght of air gap. This is called as the principle of "minimum reluctance".

A device using a permanent-magnet in the rotor is called a PM stepper motor, there is a feature in this motor: it comes to rest a fixed position even if excitation ceases. There are two disadvantages in the use of a permanent magnet: (1) the magnet is costly; (2) the maximum flux density level is limited by the level of magnetic remanence of the magnet, though ferrite magnet is cheap, it does not produce a high torque because of its inherently low remanence. Once there is a magnet, the flux produced by the phases have to be bidirectional, so the drive circuit must be capable of produces bipolar excitation. The principles of PM stepper motor are also explained in chapter 2. In table 1.1 are some comparisons between PM and VR stepper motors.

Chapter 2

MODELING VR AND PM STEPPER MOTORS

There are two general types of variable-reluctance stepper motors: single and multistack. At a first approximation the behaviour of both types may be described from similar equations, the principle of operation of variable-reluctance (VR) stepper motors is similar to the reluctance machines but there are some details to consider.

In its basic form the multistack variable-reluctance stepper motor consist of three or more single-phase reluctance motors on a common shaft, with their stator magnetic axes displaced from each other. In figure 2.1 is shown the rotor of an elementary two-pole three-stack variable-reluctance stepper motor. It has three cascaded two-pole rotors with a minimum -reluctance path of each aligned at the angular displacement θ_{rm}, each of the two-pole rotors is said to have two teeth. suppose that each of these rotors has its own single-phase stator with the magnetic axes of the stator displaced from each other. In figure 2.1 the rotors are labeled by a, b, c and the corresponding stators are show in figure 2.2; the stator with the as winding is associated with the a rotor, the bs winding with the b rotor, etc...

It is interesting to note that each of the single-phase stator has two poles, like in configuration of a DC machine, with the stator winding wound around both poles. In particular, positive current flows into as_1 and out as_1'; as_1' is connected to as_2' so that positive current flows into as_2 and out as_2'. Another important consideration is that the angle θ_{rm} (or θ_r) is from the as axis to the minimum-reluctance path of a salient-pole rotor, this consideration is not done in reluctance and synchronous machine but it is standard in stepper-motors.

Each stack is called a phase, so a three stack machine is a three phase machine, although more than three stacks (phases) might be used, perhaps as many as seven, three-stack variable-reluctance stepper motor are quite common.

Let us take a look at the operation of the device. At first the bs and cs windings are open-circuited, we will apply a dc voltage to the as winding, assuming only to simplify, that i_{as} is immediately established.

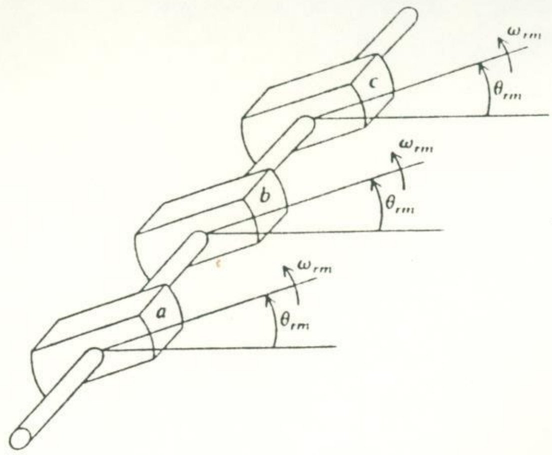

Figure 2.1: Rotor of an elementary 2-pole 3-stack VR stepper motor.

Since the magnetic system of the three single-phase stators are separate, flux set up by one winding does not link with the others windings; hence, with only the *as* winding energized, flux exists only in the *as* axis. Considering that the load torque is zero, the minimum-reluctance path of the *a* part of the rotor will align with the *as* axis at $\theta_{rm} = 0$. The rotor will be remained in this position as long as i_{as} is flowing. Suppose that instantaneously we deenergize the *as* winding and immediately establish a direct current in the *bs* winding. Desconsidering the transitories, the minimum reluctance-path of the rotor will align with the *bs* axis. To do this, the rotor would rotate clockwise from $\theta_{rm} = 0$ to $\theta_{rm} = -60°$. Note here that advancing the mmf from the positive *as* axis to the positive *bs* axis (120°) counterclockwise, caused a 60° clockwise rotation of the rotor.

If instead of energizing the *bs* winding, we energize the *cs* winding in figure 2.2 the rotor would have stepped counterclockwise from $\theta_{rm} = 0$ to $\theta_{rm} = 60°$. Thus applying a dc voltage separately in the sequences as, bs, cs, as... produces 60° steps in the clockwise direction, whereas the inverse sequence as, cs, bs, as, ... produces 60° steps in the counterclockwise direction. It is necessary at least three stacks to achieve rotation in both directions.

Suppose now that *as* winding is energized, and the *bs* winding is energized without turn-off the *as* winding, what happens? The rotor rotates from $\theta_{rm} = 0$ to $\theta_{rm} = -30°$. so we have reduced our step length by one half, this is referred to as half-step operation.

Let us denote RT the number of rotor teeth per stack and ST the number of stator teeth per stack. The number of stacks (phases) is N. The tooth pitch, which we will denote as TP, is the angular displacement between rotor teeth, so we can write the relation 2.1. Another term to define is the step length, denoted as SL. It is the angular rotation of the rotor as we change the excitation from one phase to the other. Producing a sequence *as*, *bs* , *cs* and going back to *as* causes the rotor to rotate one tooth pitch. In other words, the number of stacks (phases) times the step length is a tooth pitch, that is TP = N(SL), substituing in 2.1 we obtain the equation 2.2.

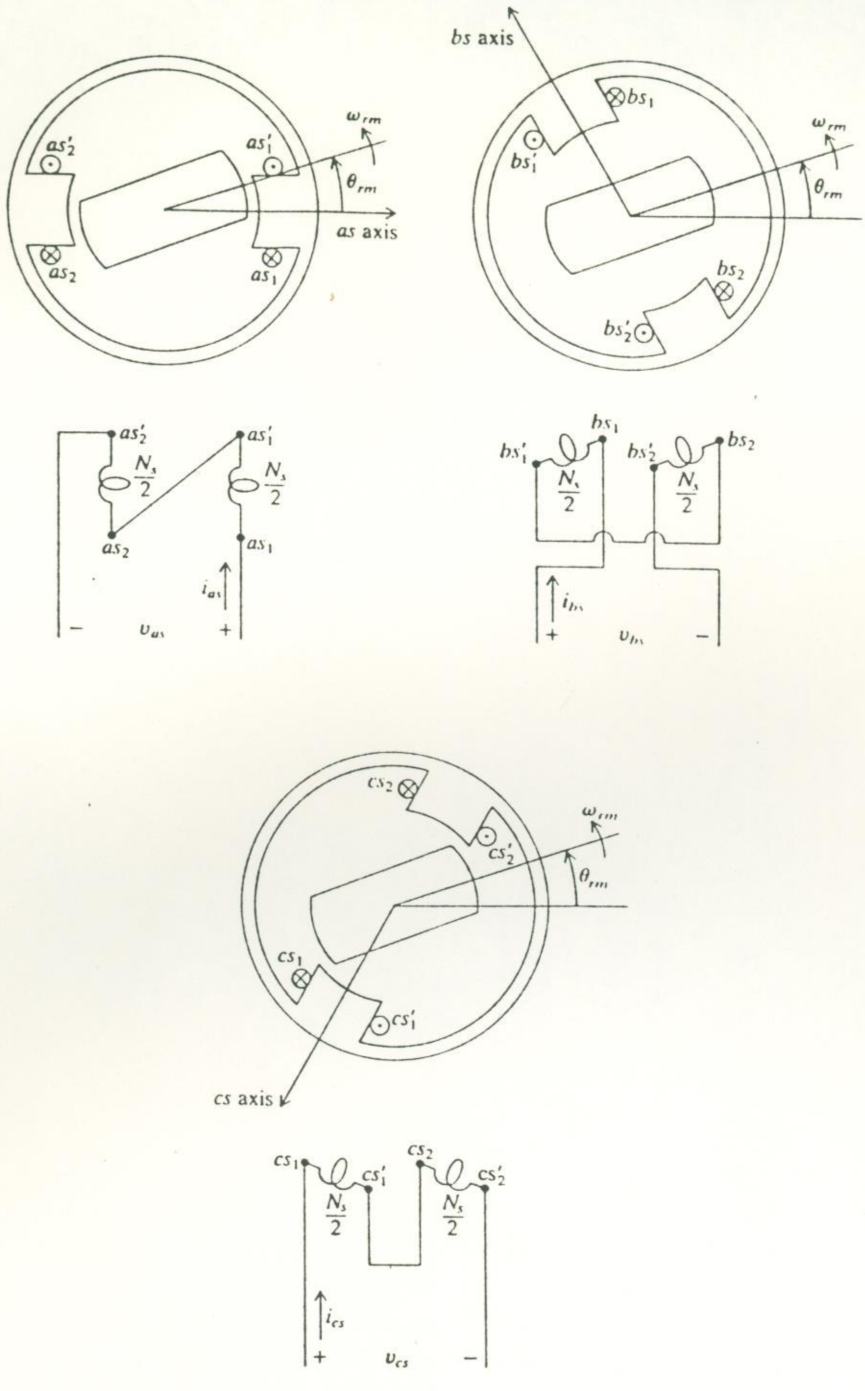

Figure 2.2: Stator of an elementary 2-pole 3-stack VR stepper motor.

$$TP = \frac{2\pi}{RT} \tag{2.1}$$

$$SL = \frac{TP}{N} = \frac{2\pi}{RTN} \tag{2.2}$$

2.1 Equations for Multistack VR Stepper Motor

The voltage equations for a three-stack variable-reluctance stepper motor may be written as 2.3 to 2.5.

$$v_{as} = r_s i_{as} + \frac{d\psi_{as}}{dt} \tag{2.3}$$

$$v_{ts} = r_s i_{ts} + \frac{d\psi_{ts}}{dt} \tag{2.4}$$

$$v_{cs} = r_s i_{cs} + \frac{d\psi_{cs}}{dt} \tag{2.5}$$

Since magnetic coupling does not exist between phases, we can write the flux linkages as matricial equation 2.6:

$$\begin{pmatrix} \psi_{as} \\ \psi_{ts} \\ \psi_{cs} \end{pmatrix} = \begin{pmatrix} L_{asas} & 0 & 0 \\ 0 & L_{tsts} & 0 \\ 0 & 0 & L_{cscs} \end{pmatrix} \cdot \begin{pmatrix} i_{as} \\ i_{ts} \\ i_{cs} \end{pmatrix} \tag{2.6}$$

For the purpose of expressing the self-inductances L_{asas}, L_{tsts} and L_{cscs} let us first consider the elementary two-pole device illustrated in figure 2.2. They will be like the equations from 2.7 to 2.9, where L_{ls} is the leakage inductance, L_A and L_B are constants with $L_A > L_B$. The rotor displacement is expressed as 2.10 [12].

$$L_{asas} = L_{ls} + L_A + L_B cos2(\theta_{rm}) \tag{2.7}$$

$$L_{tsts} = L_{ls} + L_A + L_B cos2(\theta_{rm} - \frac{2}{3}\pi) \tag{2.8}$$

$$L_{cscs} = L_{ls} + L_A + L_B cos2(\theta_{rm} - \frac{4}{3}\pi) \tag{2.9}$$

$$\theta_{rm} = \int_0^t \omega_{rm}(\xi)d\xi + \theta_{rm}(0) \tag{2.10}$$

The inductances may be expressed in terms of step length SL like 2.11 to 2.13. An expression for the electromagnetic torque may be obtained from 2.14, we are assuming a linear magnetic system, and the mutual inductances are zero, so we can get the expression of energy 2.15 [12].

$$L_{asas} = L_{ls} + L_A + L_B cos(RT\,\theta_{rm}) \tag{2.11}$$

$$L_{tsts} = L_{ls} + L_A + L_B cos(RT(\theta_{rm} - SL)) \tag{2.12}$$

$$L_{cscs} = L_{ls} + L_A + L_B cos(RT(\theta_{rm} + SL)) \tag{2.13}$$

$$T_e = \frac{\delta W_c(i, \theta_{rm})}{\delta \theta_{rm}} \tag{2.14}$$

$$W_c = \frac{1}{2} L_{asas} i_{as}^2 + \frac{1}{2} L_{tsts} i_{ts}^2 + \frac{1}{2} L_{cscs} i_{cs}^2 \tag{2.15}$$

Substituting the self-inductances into 2.15 and taking the partial derivative with respect to θ_{rm} yields in the expression for the torque 2.16, where the $+\frac{TP}{3}$ in the second argument and the $-\frac{TP}{3}$ in the third apply when the rotation of the stator mmf and the stepping are in opposite directions, the opposite signs of TP apply for the same direction of rotation, it is possible to observe that the magnitude of torque is proportional to the number of rotor teeth RT.

$$T_e = -\frac{RT}{2} L_B \{ i_{as}^2 sin(\frac{2\pi}{TP}\theta_{rm}) + i_{ts}^2 [sin(\frac{2\pi}{TP}(\theta_{rm} \pm \frac{TP}{3})] + i_{cs}^2 [sin(\frac{2\pi}{TP}(\theta_{rm} \mp \frac{TP}{3})]\} \tag{2.16}$$

The torque and rotor position have the relation 2.17, where J is the total inertia in $Kg.m^2$, B_m is the viscous friction proportional to mechanical rotation in N.m.s. The electromagnetic torque T_e is positive in the counterclockwise direction (positive direction of θ_{rm}) whereas the load torque T_L is positive in the clockwise direction.

$$T_e = J\frac{d^2\theta_{rm}}{dt^2} + B_m\frac{d\theta_{rm}}{dt} + T_L \tag{2.17}$$

2.1.1 Operating characteristics

In order to gain insight in the operation of multistack VR-stepper motor let us consider the expression for torque given by 2.16. This equation is plotted in figure 2.3, considering constant currents in each phase and assuming that there is no load torque ($T_L = 0$).

At first $i_{as} = I$ while i_{bs} and i_{cs} are zero. So only the first term of 2.16 is present, that is: only the steady-state torque due to i_{as} exists, so the stable steady-state rotor position would be at $\theta_{rm} = 0$, denoted as point 1 on figure 2.3.

Now assuming that i_{as} is instantaneously decreased from I to zero while i_{bs} is increased from zero to I, desconsidering here the electrical and mechanical transients involved, the torque due i_{as} would instantaneously disappear from figure 2.3, and the torque due to i_{bs} would immediately appear, imposing the torque at point 2. This torque is negative, so the rotor would rotate in the clockwise direction proceeding along the i_{bs} torque plot until we have reached the point 3. This way one step length (SL) was moved. If, instead of energizing the bs winding , we energized the cs winding, then the torque at point 4 would appear. This is a positive T_e so the rotor would rotate in the counterclockwise direction along the i_{cs} torque plot towards the point 5. Considering the mechanical transients there would be a damped oscillation about each new operating point.

Half-step operation is depicted in figure 2.4. Suppose again start at point 1, where $T_L = 0$ and only the as winding is energized ($i_{as} = I$). Instantaneously the bs winding is energized and $i_{bs} = I$ together with $i_{as} = I$, this way the $as + bs$ torque would appear, it is shown in figure 2.4, immediately the torque at point 2 appears and the rotor starts to rotate in the clockwise direction coming to rest at point 3, so the rotor has moved $\frac{SL}{2}$ clockwise. If we consider the action of a load torque T_L the figure 2.5 shows what happens; assume that initial operation is at point 1, with $i_{as} = I$ and $i_{bs} = 0$, recall that T_e is positive in the counterclockwise direction while T_L is positive in the clockwise direction, and stable point occurs when $T_e = T_L$ (point 1).

The as winding is instantaneously deenergized while i_{bs} is increased from zero to I, i_{as} would instantaneously disappear, and the torque due to i_{bs} would immediately appear, imposing the torque at point 2. This torque is negative, so the rotor would rotate along the i_{bs} torque plot reaching the point 3, where $T_e = T_L$. If the cs winding is energized rather than the bs winding,the torque at point 4 would appear and the rotor would rotate to point 5. Note that the step length is still the same in both directions, however the rotor will move fast in the clockwise direction because the load torque helps the movement, accelerating it in

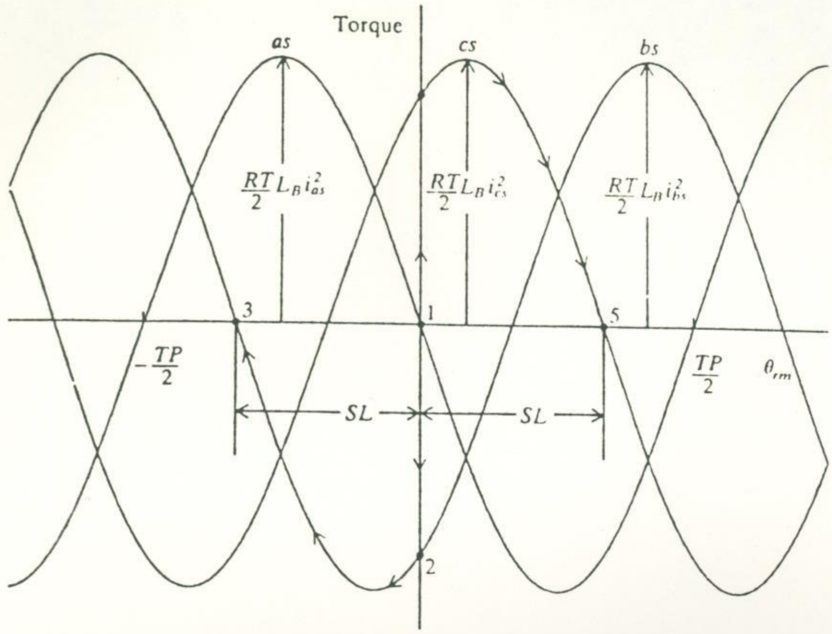

Figure 2.3: Steady-state torque-angle plots of a three-stack VR stepper motor without load torque; Full-step operation.

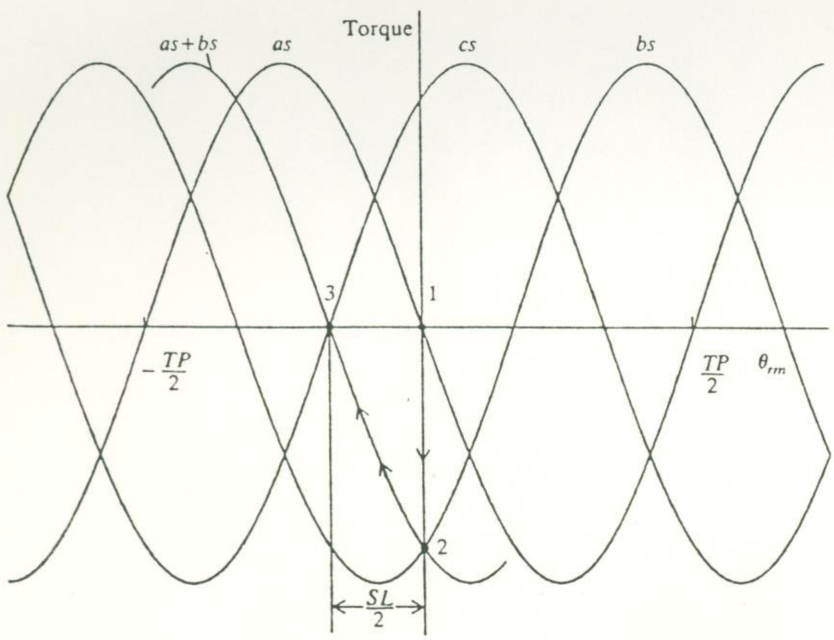

Figure 2.4: Steady-state torque-angle plots of a three-stack VR stepper motor without load torque; Half-step operation.

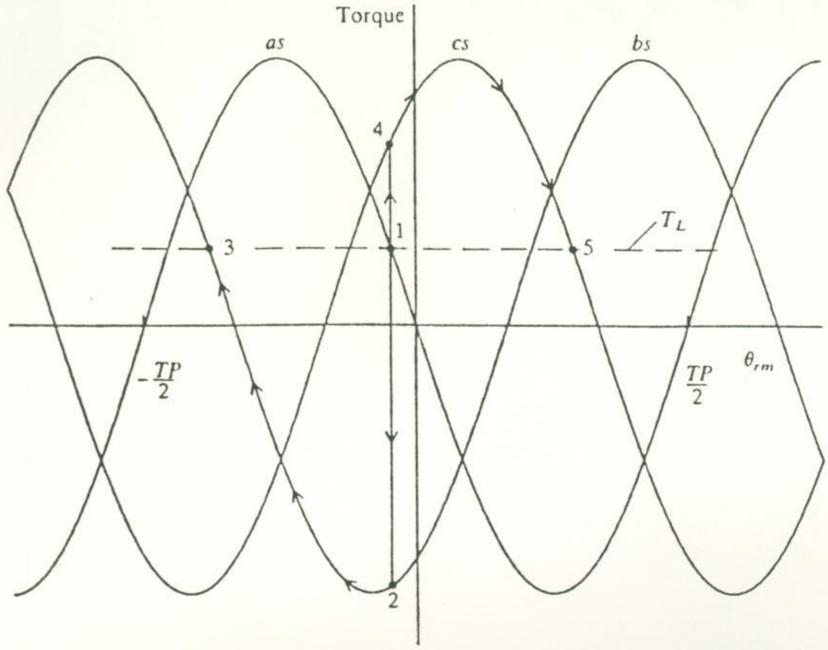

Figure 2.5: Stepping operation of a three-stack VR stepper motor with load torque.

that direction and retarding in counterclockwise direction.

Considering the transitory, when the motor comes to rest at the appropriate equilibrium position after each excitation change the response of the system is generally very oscillatory, a typical response is shown in figure 2.6. The response can be matched with a second-order system with damping.

There are some ways to damp out the rotor oscillation, by adding a viscous inertia (often called a Lancheste damper) or by using either a friction disk or eddy-current damper. Although these techniques achieve the desired goal, they also add inertia and may affect the transient response of the rotary system.

An electronic technique called *bang-bang damping* [2] avoids the problem. The idea is to accelerate the motor in the normal way. However, before the rotor reaches its desired position, the phase excitation sequence is reversed, causing the rotor do decelerate more rapidily. If the phase reversal is timed correctly, the rotor can be made to come to rest at the equilibrium point with almost no overshoot. However the timing of the reversal is critical and the switching instants are a function of system parameters (friction and load inertia), so this scheme can be used only in systems without load variations and upon constant speed.

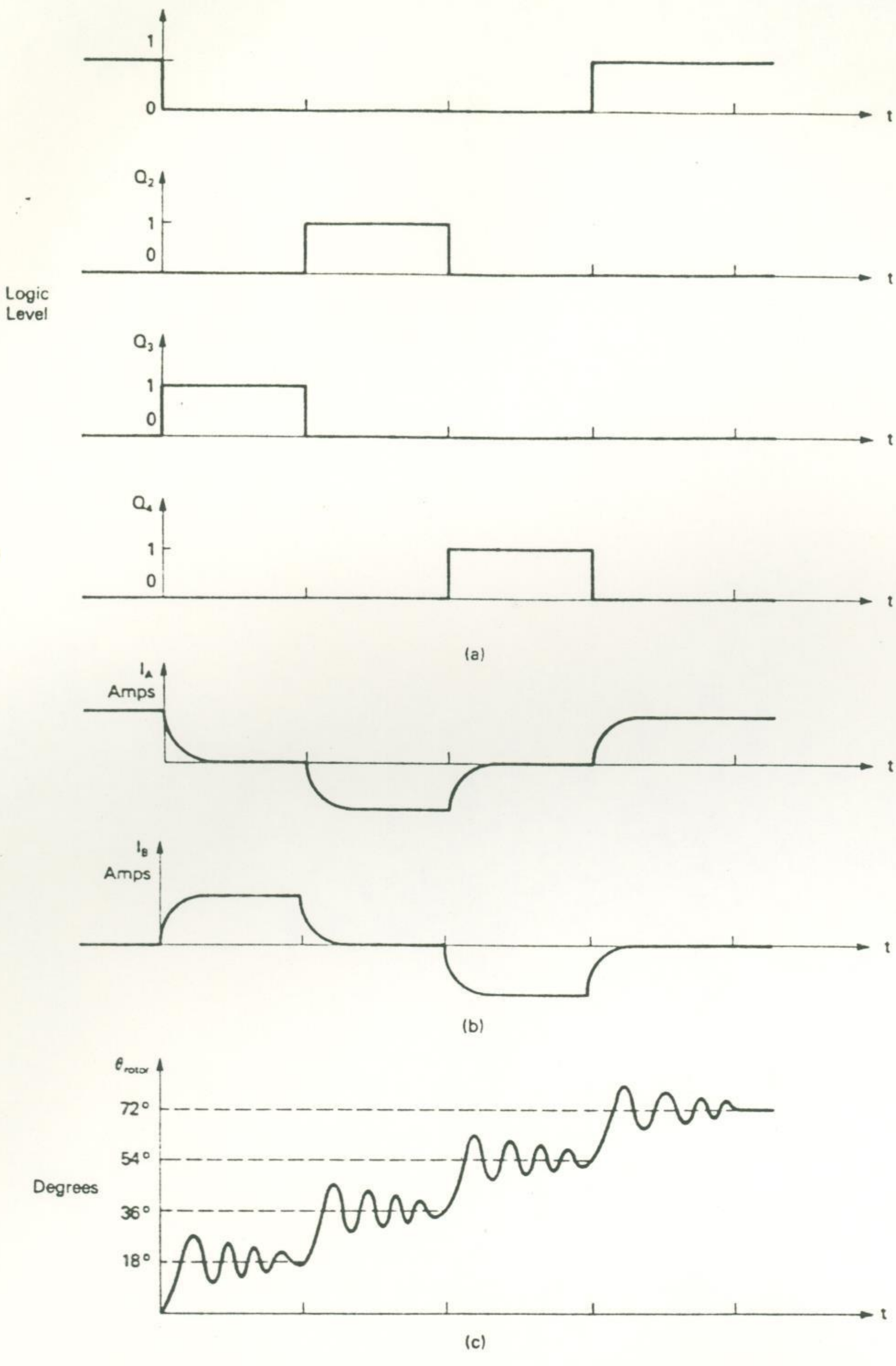

Figure 2.6: Stepping operation depicting mechanical oscillations.

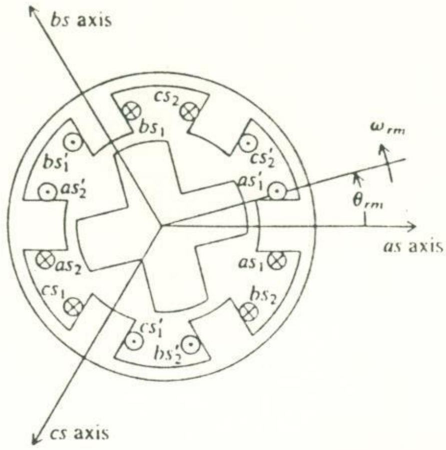

Figure 2.7: Typical 2-pole 3-phase single-stack VR stepper motor with 6 stator teeth and 4 rotor teeth.

2.1.2 Single stack VR stepper motors

A three-phase single-stack VR stepper motor is shown in figure 2.7; it appears that we have taken the three two-pole single-phase stator shown in figure 2.2 and squeezed them into one stack. The magnetic axes of the stator windings are displaced 120° as in the case of the three-phase machines, however the stepper motor generally has stator teeth or protrude poles rather than a circular inner stator surface.

Recall that in the case of the multistack variable-reluctance motor the number of rotor and stator teeth per stack is the same, but in the case of single-stack stepper motor, the number of rotor teeth per stack RT, is never equal to the number of stator teeth per stack, ST. If it was equal would occur diagonally opposite rotor teeth aligned with two diagonally opposite stator teeth and stepping action could not occur. The equations 2.1 and 2.2 also apply for the single-stack VR stepper motor.

The expressions given for the self-inductances of the three-stack (phase) 2.11 through 2.13 also apply to three-phase single-stack VR stepper motor. It would appear that the operation of the single-stack and multistack VR stepper motor may be described by the same set of equations. Although this perception is essentially valid from an idealized point of view, it is not valid in the practical world. The stator windings share the same magnetic system, hence, there is a possibility of mutual coupling between stator phase. The figure 2.8 shows the rotor at position $\theta_{rm} = 0$. The dashed lines are the flux linking the bs winding due to positive current flowing in the as winding. If we assume that the reluctance of the iron is small the mutual linkage can be neglected, however stepper motor are generally designed to operate at current levels which saturate the iron of the machine. Hence, owing to the increased reluctance of the saturated iron, less flux will be circulating around the longer paths through between stator phases, and there would be a net flux in the direction of the positive bs axis as a result of the saturation of the iron. Although small in amplitude, a mutual inductance

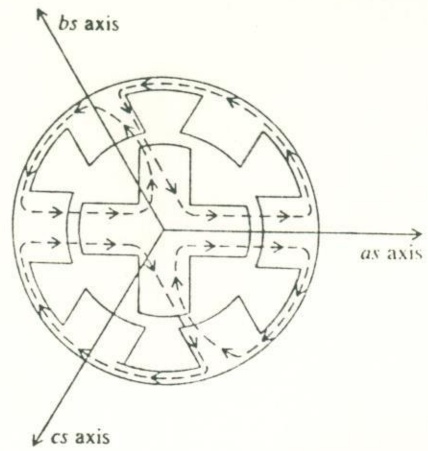

Figure 2.8: Path of the linkage flux at $\theta_{rm} = 0$.

does exist in the practical application of single-stack VR stepper motors, complicating the analysis of these devices at these conditions.

2.2 Basics of PM Stepper Motors

The permanent magnet stepper motor is quite common, actually, it is a permanent-magnet synchronous machine and it may be operated either as a stepping motor or as a continuous-speed device. Here we will concern only its application as a stepping motor since continuous-speed operation is similar to the operation of a synchronous machine with a constant field excitation [12].

A two-pole two-phase PM stepper motor with five rotor teeth is shown in figure 2.9, which is sufficient to understand the principle of operation of this kind of motor.

The axial cross-sectional view shown in figure 2.9 illustrates the permanent magnet mounted on the rotor which magnetizes the iron end caps also mounted on the rotor and slotted to form the rotor teeth. The view looking from left to right at X is shown in figure 2.9.(a) and the view from left to right at Y is shown in figure 2.9.(c). The left end cap is magnetized as a north pole and the right end cap as a south pole. It is important to note that the rotor teeth of the left end cap is displaced one-half a tooth pitch from the teeth on the right end cap.

The path linking the bs winding for the rotor position shown in figure 2.9 might be visualized in three dimensions: flux leaves the left end cap through the rotor tooth at the top of the rotor that is starting to align with the stator tooth which has the bs_2 part of bs winding, the flux travels up through the stator tooth in the stator iron, splitting around the circumference of the stator and returning to the south pole of the rotor through the stator tooth, positioned at the bottom in figure 2.9.(c) on which the bs_1 part of bs winding is wound.

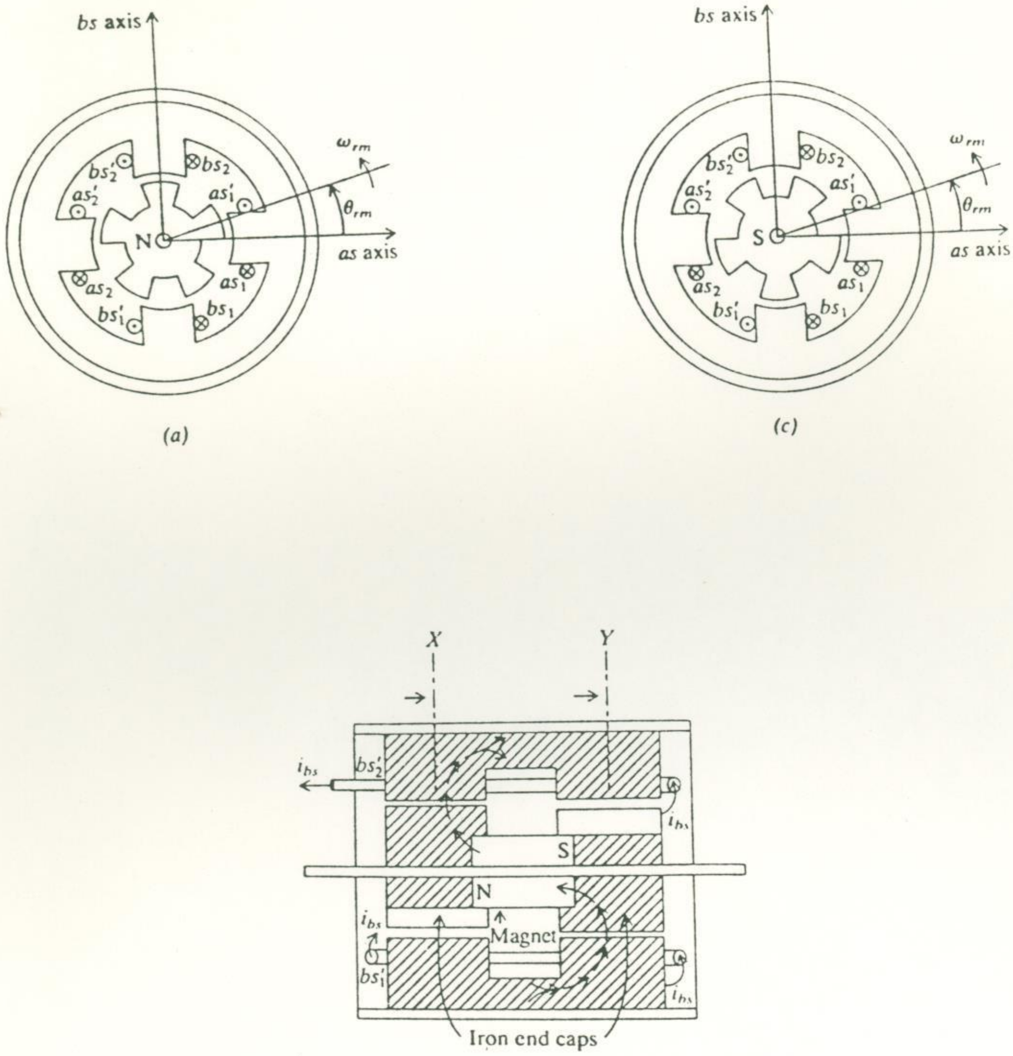

Figure 2.9: 2-pole 2-phase PM stepper motor. (a) Axial view at X; (b) side cross-sectional view; (c) axial view at Y.

Stepping action can be explained by first assuming that the *bs* winding is open-circuited and a constant positive current is flowing in the *as* winding. As a result of this current, a south pole is established at the stator tooth on which the as_1 winding is wound, and a stator north pole is established at the stator tooth on which the as_2 winding is wound. The rotor would be positioned at $\theta_{rm} = 0$. Suppose that simultaneously deenergize the *as* winding while energizing the *bs* winding with a positive current, the rotor will move one step length in the counterclockwise direction, in order to continue stepping in the counterclockwise direction, the *bs* winding is deenergized and the *as* winding is energized with a negative current. Hence the counterclockwise stepping occurs with a current sequence of i_{as}, i_{bs}, $-i_{as}$, $-i_{bs}$, i_{as}... Clockwise rotation is achieved by i_{as}, $-i_{bs}$, $-i_{as}$, i_{bs}, i_{as}... It is important to note that in VR stepper motor is not necessary to reverse the direction of the current in stator windings, however to achieve rotation in PM stepper motor the drive circuit must have the capability of applying positive and negative voltage to each phase winding.

As an alternative, PM stepper motors can be equipped with bifilar windings, eg rather than only one winding on each stator tooth, there are two identical windings with on wound opposite to the other, each one has separate independent external terminal. With this type of winding configuration the direction of magnetic field established by the stator windings is reversed, not by changing the direction of the currents but by turning on the other winding, so the drive circuit can be unipolar, but are necessary two circuits per phase.

The derivation of the equations for the PM stepper motor is made in a similar way that was made for VR stepper motor, but there are some differences that are worth to mention: from the idealized standpoint, the self-inductance of the stator phase of the device is constant, and the reluctance seen by the permanent magnet is also constant, independent of the rotor position, when doing so, we are neglecting the reluctance torques caused by variation in self-inductance and the permanent-magnet, both of which attempt to place the rotor in its minimum-reluctance position. This torque is referred as the *detent or retention torque*, since it exits whether or not the stator windings are excited, and if the load torque is not too large, this torque will preserve the rotor position during a power failure.

The voltage equations for the PM stepper motor become those of the permanent-magnet synchronous machine, with the difference of using θ_{rm} correlated to the minimum reluctance rather than maximum reluctance path; also is possible to apply Park's transformation to transform the stator circuits to its fictitious circuits with constant inductances fixed in the rotor in PM stepper motor, but this transformation is not possible to apply in VR stepper motor because the mutual inductance must exist between stator phases in order to exist a transformation K_s^r that satisfies the equation:

$$K_s^r L_s (K_s^r)^{-1}$$

There are some theories based in periodic systems that possibility this transformations in VR stepper motors, one of that is based on Floquet transformation [4] [7].

2.3 Modeling with Floquet's Transformation

The voltage relations for the VR stepper motors are shown in 2.3 to 2.5 and the matrix form is in 2.18, where p is the operator d/dt, $\boldsymbol{R}$ is the resistance matrix of the stator (diagonal), $\boldsymbol{\psi}$ denotes the flux in any of the three phases.

$$\boldsymbol{V}_{atcs} = \boldsymbol{R}\boldsymbol{I}_{atcs} + p\boldsymbol{\psi}_{atcs} \tag{2.18}$$

A crucial difference between the VR stepper motor and nonsalient machines lies that in fact the dependence of flux linkage on the current does not vary sinusoidally with the rotor position θ_r, in fact it can be any periodic function of θ_{rm}. Under the commonly made assumption of magnetic linearity (saturation neglected) the flux can be approximated as equation 2.20. From this equation, combining with the equation 2.18 we obtain the equation 2.19.

$$\frac{d\boldsymbol{\psi}}{dt} = -\boldsymbol{R}\boldsymbol{L}^{-1}(\theta)\boldsymbol{\psi} + \boldsymbol{V} \tag{2.19}$$

$$\boldsymbol{\psi}(\theta, i) = \boldsymbol{L}(\theta)\mathrm{i} \tag{2.20}$$

Supposing angular speed is constant, eg, $\omega = \omega_r = constant$, the normalized equation with respect to rotor position (rather than time) becomes as equation 2.21, whose gives the change of flux linkages with rotor position change, and $\boldsymbol{A}(\theta)$ is the matrix

$$\boldsymbol{A}(\theta) = -\boldsymbol{R}\boldsymbol{L}^{-1}(\theta)$$

$$\frac{d\boldsymbol{\psi}}{dt} = \boldsymbol{A}(\theta)\boldsymbol{\psi} + \boldsymbol{V} \tag{2.21}$$

Let us now define a state vector $\boldsymbol{X}$ to be the vector of flux linkage and the input $\boldsymbol{U}$ to be the vector of voltage sources applied to stator terminals $\boldsymbol{V}$. Then equation 2.21 takes on a form 2.24 where matrix $\boldsymbol{A}(\theta)$ is diagonal. It is good to emphasize here that for these derivations is important to assume that the mutual inductances between the phases can be neglected, this is true in multi-stack VR stepper motor and in single-stack VR stepper motor some experiments show that the mutual inductance is less than 7% of the self-inductance, so the matrix $\boldsymbol{A}(\theta)$ takes the form indicated in 2.22, and the matrix $\boldsymbol{B}$ is like 2.23.

$$\boldsymbol{A}(\theta) = diag[-R_1/L_1(\theta), -R_2/L_2(\theta), \ldots, -R_p/L_p(\theta)] \tag{2.22}$$

$$\boldsymbol{B} = [\frac{1}{\omega_r}, \cdots, \frac{1}{\omega_r}]^T \tag{2.23}$$

As we are considering ω_r = constant the matrix $A(\theta)$ becomes a function of time only, since

$$\theta_{rm} = \theta_{rm}(0) + \omega_{rm} t$$

and equation 2.24 yields in 2.25.

$$\frac{dX}{dt} = A(\theta)X(t) + B\mathrm{u}(t) \qquad (2.24)$$

$$\frac{dX}{dt} = A(t)X(t) + B\mathrm{u}(t) \qquad (2.25)$$

The next step is to introduce change of variables via a transformation T so that a new state vector X_N is related to the original state vector X as $X_N = TX$ where T is a function of θ and ω.

If X_N possesses the follow properties, it is said to be admissible, and defining an reference frame for new state variables X_N :

- For every fixed $\frac{d\theta}{dt} = \omega_r > 0$, T is nonsigular and of period $\frac{2\pi}{n}$, where n is the number of pole pairs (phases).
- $T(\theta, \omega)$ has continuous partial derivatives with respect to θ and ω (so it is unique)

According to Floquet theory and its application to rotating machinery, the transformation T exists even for doubly salient machines, and this transformation is given by the matricial equation 2.26 [11] where $C(\omega)$ is not a function of rotor position θ; if ω_r is constant (steady-state) the righthand side of the transformation becomes time invariant.

$$TAT^{-1} - \omega\frac{\partial T}{\partial \theta}T^{-1} = \omega C(\omega) \qquad (2.26)$$

Finally we get equation 2.28 that express the equations of the VR stepper motor in a rotating reference frame, the transformation T can be easily obtained if the matrix A is diagonal, by deriving each term for separate decoupled phase flux linkage. This way the condition 2.26 is only a scalar per phase $\overline{a}$ [11].

In the case when the saturation is not neglected, the inductance matrix $L(\theta)$ and the transformation TX depend on current, making $\overline{a}$ a function of current, whose can be considerate via a piecewise linearization technique [11].

In rotating reference frame we have $\overline{a}$ defined by 2.27 and TX is the transformation per phase 2.29.

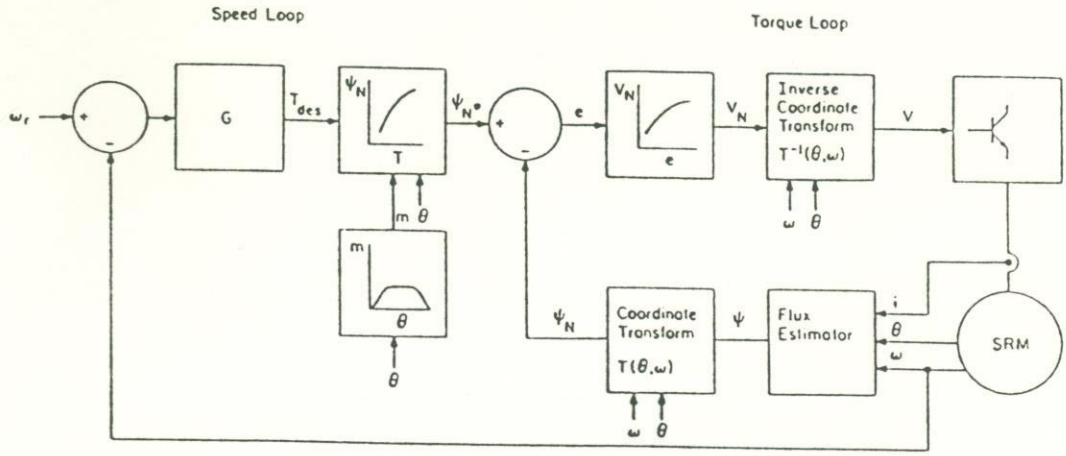

Figure 2.10: Controller Block Diagram.

$$\overline{a} = \frac{1}{2\pi}\int_0^{2\pi} \frac{R}{L(\theta)} d\theta \tag{2.27}$$

$$\frac{dX_{Ni}}{dt} = -\overline{a}X_{Ni} + TV_i \tag{2.28}$$

$$T = e^{\frac{h(\theta)}{\omega}} \tag{2.29}$$

The equation 2.28 could be solved in order to find a control input V_i which causes the resulting closed loop system to follow a desired torque trajectory. A closed loop control scheme with this approach is proposed in figure 2.10, where the error is defined as the difference between the flux linkages seen in the new reference frame X_N, in respect to the set-point coming from a speed comand ω_r.

Chapter 3

DRIVING STEPPER MOTORS

The step motor winding may be considered as an inductance in series with a resistance. The time constant of the winding $\frac{L}{R}$ determines the time that full current is reached after a voltage source is impressed. The basic problem of drive circuitry for high speed operation of stepping motor is to provide a high voltage to move current into and out of the winding at pulse transition times, and a low voltage to sustain only the correct current during the steady-state portion of the current pulse. Another important aspect to consider is the problem of mechanical resonance; at very low stepping rates the motor comes to rest at the equilibrium position in a oscillatory way, so we have to provide any damping scheme to extract store mechanical energy. Hence the drive circuit must incorporate this feature. An approach that produces smother low speed operation is the ministepping mode.

3.1 Unipolar Resistance Current Limiting

The most commom method of driving stepping motor is simply do add one or more resistor in series with the motor winding, and raise the supply voltage to yield normal current under steady state conditions, like figure 3.1. The idea is to force a current generator into the windings.

Unipolar resistance current limiting are simple and reliable, and are frequently used where speed and torque requirements are low. However, there are several inherent problems:

- If voltage overdrive is raised to improved high speed performance, the system efficiency becomes very low. For instance, a small (10W) motor may use a driver dissipating 200W!
- The windings in the motor are not completely utilized, since the current duty cycle in the windings can be only 50%, in order to have enough time to discharge the energy from inductance of the winding.

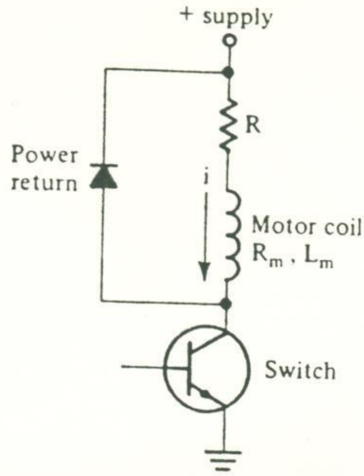

Figure 3.1: Resistance Current Limiting.

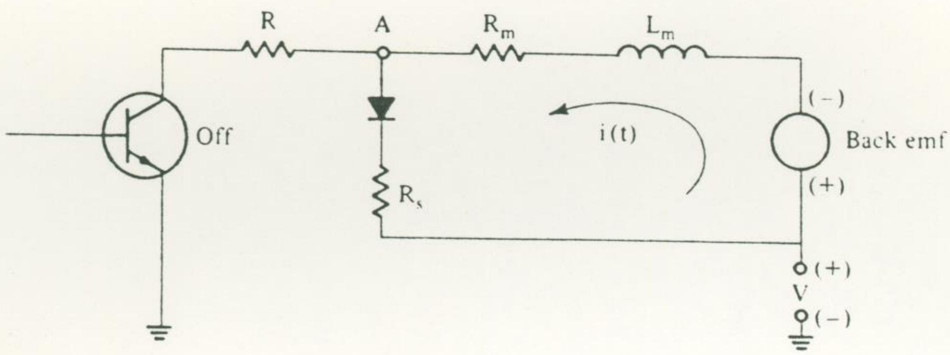

Figure 3.2: Equivalent circuit of the discharge of a motor phase.

- The voltage applied to the motor windings is a decaying exponential, and the current is a rising exponential. For a given supply voltage, the current rate of rise (and the high speed performance) is considerably less than in a system where the full supply voltage is impressed until the desired current is reached.

3.1.1 Suppression circuits

When a motor phase is ready to be turned off, a low-level voltage signal is applied to the base of the switching transistor. The current in the motor phase decays through the diode and the discharge resistance R_s indicated in figure 3.2. The inductance varies with the position which has a direct effect on the motor back-emf.

At high speeds it is necessary larger values of R_s in order to decay the current more rapidly, maintaining a high average torque. Large values of R_s however causes high reverse voltage across the output transistor. Another interesting supression circuit is using a zener

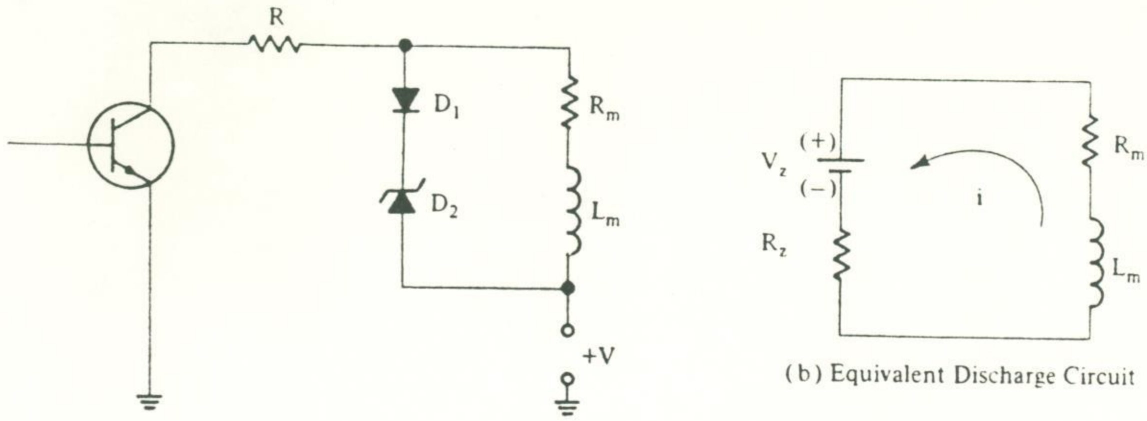

Figure 3.3: Zener diode suppression circuit.

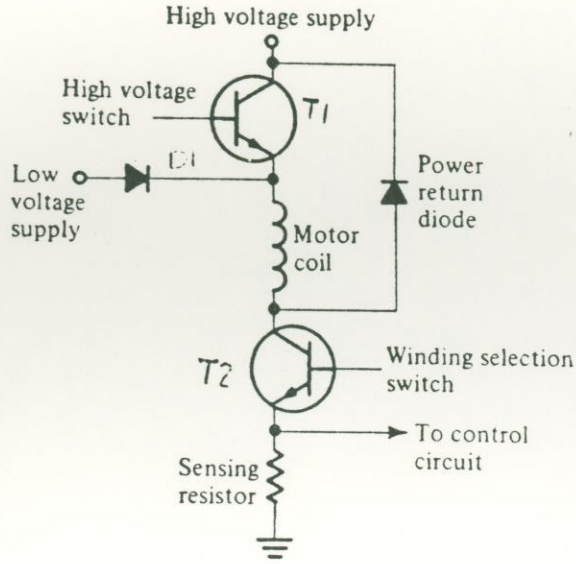

Figure 3.4: Bilevel current limiting.

diode instead of R_s indicated in figure 3.3.

For small motors the current may be suppressed by allowing the output transistor to go into second breakdown, however this usually raises the cost of the output transistor and results in extra heating across it.

3.2 Bilevel drive

Bilevel drive is shown in figure 3.4, it involves two supplies: a high voltage source used during pulse initiation and termination, and a low voltage source during the flat top of the pulse.

The high voltage supply is turned ON until the motor current reaches the operating

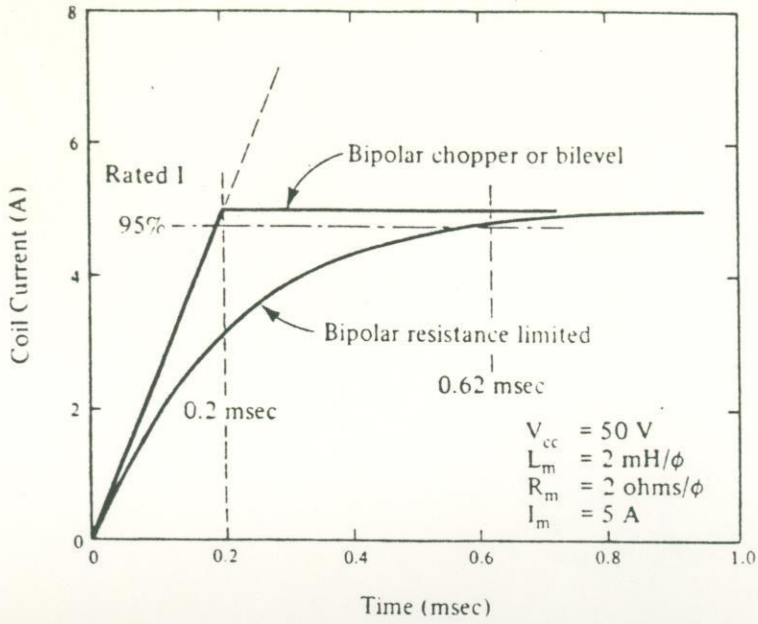

Figure 3.5: Comparison of current rise times.

level, when the high voltage is turned OFF, the diode D1 allows the low voltage supply maintain the current in the winding. At the end of the pulse, the transistor T1 is turned ON, and the current in the winding is returned to the high voltage supply. Further, the current rate of rise is much higher than in the resistance-limited case, where the voltage is a falling exponential. This is ilustrated in figure 3.5, where the two cases are compared for equal supply voltage.

3.3 Chopper Phase Driver

A "chopped" waveform is generated through a circuit like figure 3.6. A high voltage is applied to the windings at the beginning of the step to allow the current to build up, then the high voltage is time modulated into pulses during the remainder of the step to hold motor current at its correct value.

An important consideration in designing high efficiency driving system is the method used to remove current from the winding at the end of the driving pulse. In low efficiency resistance limited drivers, the current usually is returned through the charging resistance, so that the time constant is the same on discharge as it is on charge.

In high efficiency systems, it is desirable to provide a return path to the highest available voltage without merely dissipating the energy stored in the winding, since losses can be substatial at high speeds, is vital to remove the current from the winding as rapily as possible. A switching circuit to accomplish discharge of the winding is shown in path indicated by the dashed line in figure 3.6. The motor winding is charged with both switches closed, when the switches are opened, current is returned to the supply, through the diodes. A bipolar chopper

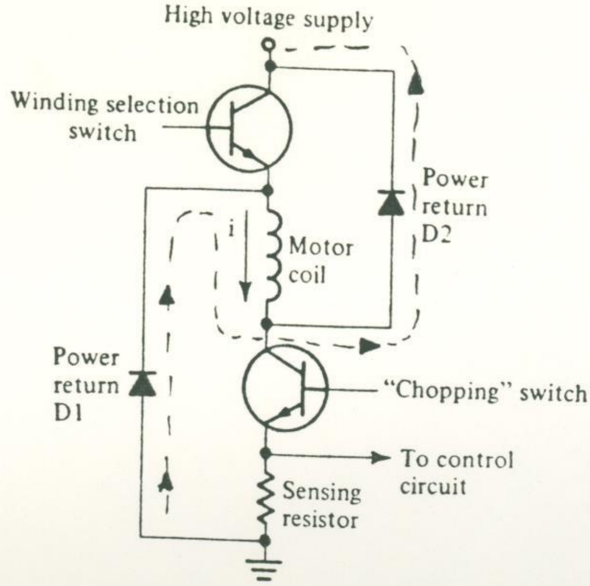

Figure 3.6: Unipolar chopper phase driver.

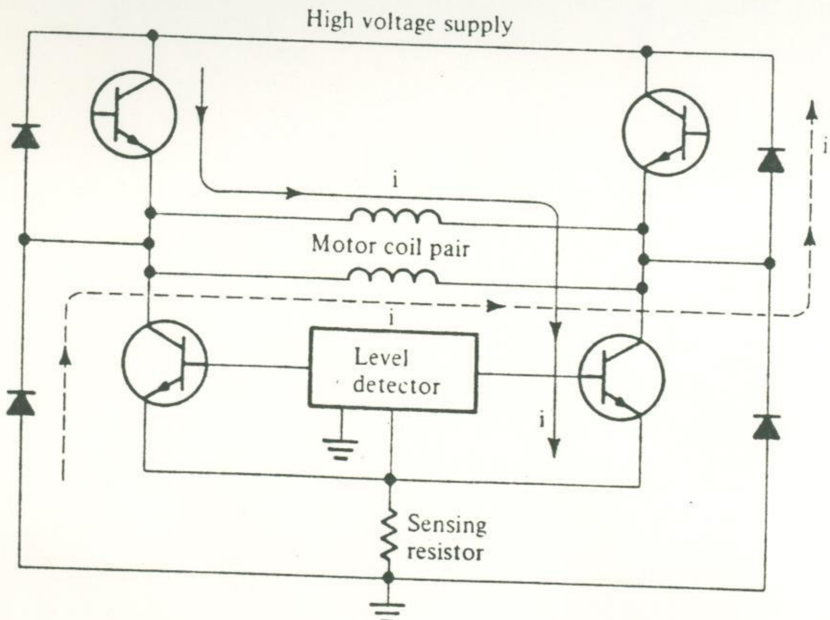

Figure 3.7: Bipolar chopper phase driver.

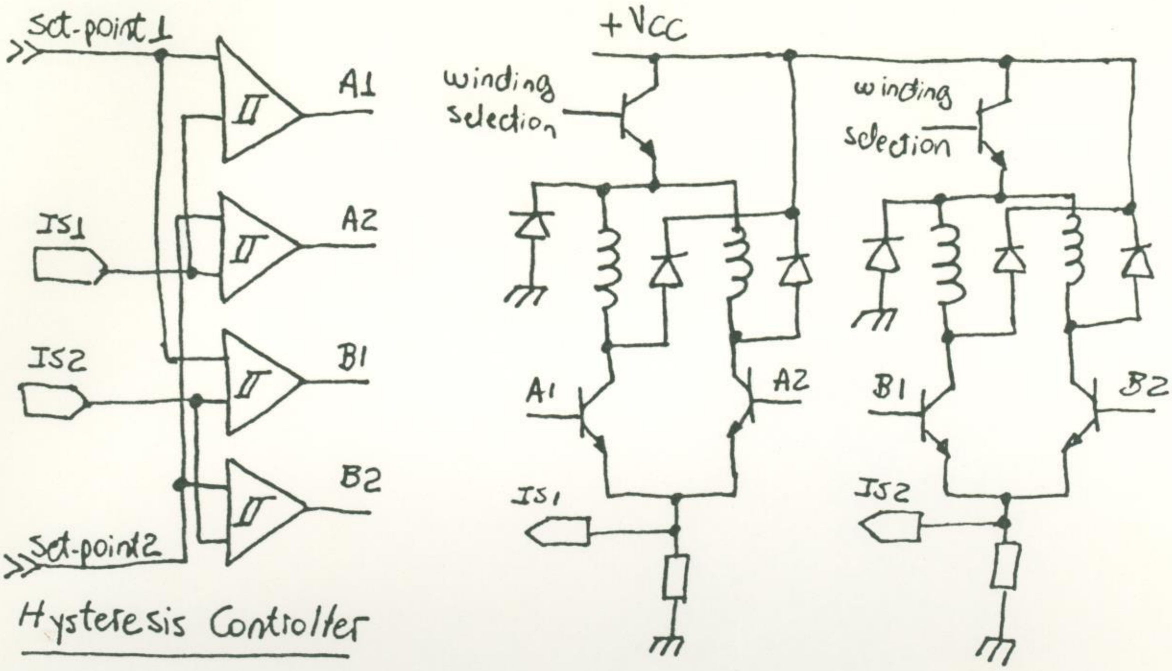

Figure 3.8: Programmable current driver.

phase driver is shown in figure 3.7.

Regardless of the basic drive system , high efficiency is attainable if the voltage source can be programmed to deliver the required current at all stepping rates. In this case is frequently used a hysteresis controller (figure 3.8), the voltage is applied to the motor winding until the correct current level is reached. The voltage is then switched OFF, and the current is allowed to circulate in the motor winding. When the current decays to a pre-determined level, voltage is again applied to drive the current back to the correct level. This cycle is continued throughout the driving pulse time. At the termination of the driving pulse, the motor winding current is recirculated rapidly to the high voltage supply.

With this kind of drive is possible to programme the current in each adjacent phase. Instead of have only half-step operation with a sequence of currents i_A, i_A and i_B, i_B, it is possible to vary continuously the currents: increase i_A, when i_A is at the maximum value start to increase i_B at the same time i_A is decreasing, and so on. This scheme produces a mode of operation generally referrred to as ministepping. Ministepping is important to lack the effects of the ressonances between two steps, decreasing the ripple of the torque [2]. Most often, the ministep size is determined by dividing the angular distance of a full step by an integral power of 2, to make easier the implementation on the stepper motor controller. This description give us an idea of have a rectified sinusoid and a rectfied cosinusoid as set-points to the controler in figure 3.8. In fact, is very commom to have this current references, however it is necessary to take account the motor nonlinearities, to have a better performance.

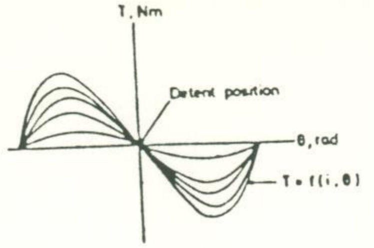

Figure 3.9: Motor torque-displacement ($T-\theta$) characteristics.

3.4 Ministep Current References - MCR

In order to ministep a motor so that detent positions may exist in between these detents, currents in two or more windings have to be simultaneously controlled at discrete level. Thus the main task of designing a ministepping controller involves design of current controllers for individual motor windings. The references (set-points) for these controller may be obtained from the memory of the system, these current references can be obtained in a number of ways. Some of these are:

1. Calculation of MCR from motor data;
2. Calculation from motor static torque-displacement ($T-\theta$) characteristic data; and
3. Determination of MCR directlly from test.

Option 1 involves motor simulation from its inductance or flux measurements. An accurate simulation is often difficult due to heavy magnetic saturation of iron and asymmetry of motor parametes at different shaft positions. Option 2 involves representation of measured motor $T-\theta$ curves by some approximation. Option 3 involves a test procedure in which various current combinations can be determined from a test which uses rotor position feedback; so options 2 and 3 are easier to considerate.

3.4.1 MCR from motor $T-\theta$ curve basis

The restoring torque T, of a stepping motor around a detent position, is related to motor current i, and displacement θ as shown in figure 3.9. Thus

$$T = f(i, \theta)$$

Expressing T in terms of one variable while keeping the other fixed, the torque can be expressed as

$$T = f_\theta(i), \quad \textit{where } \theta \textit{ is kept constant}$$
$$T = f_i(\theta), \quad \textit{where } i \textit{ is kept constant}$$

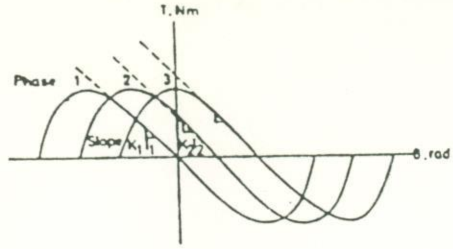

Figure 3.10: Approximation to $T-\theta$ curves.

If detent positins are desired at angle $n(\theta_s/m)$ where m is the factor by which normal step size θ_s is to be subdivided, and n is any integer 1,2,..., the current references $[i]_k$ –here k indicates the number of motor phases– have to be calculated for each n from the assumptions above, so that torque is zero at the detent position.

In order to obtain unambiguous results we have to consider the conditions:[10]

- Torque characterististics of the original motor will be retained for all combinations of currents, eg the slope of the motor $T-\theta$ curve at the new detent must be equal do those of original $T-\theta$ curve.
- Torque characteristic for each phase are identical.
- All ministeps are to be equal in size.
- Total motor dissipation will not exceed a certain rated value.

Considering an approximation to $T-\theta$ curves, is possible to get the relationship for the currents. We can consider any approximation to $T-\theta$ curves, like triangles, sinusoids or trapezoids. One common consideration is that $T-\theta$ curves are linear approximation, but sine approximations indicated in figure 3.10 are better, like

$$\begin{aligned} T_1 &= -T_0 I_1 sin(\theta) \\ T_2 &= T_0 I_2 sin(\theta + \theta_s) \end{aligned}$$

Through the adequate conditions it can be shown that equation 3.1 gives the current at phase 1 and equation 3.2 gives the relantishiop between the currents in each phase (1 and 2) [10].

$$I_1 = \frac{sin(\frac{\theta_s}{m})}{\frac{tan\theta}{tan\theta cos\theta_s + sin\theta_s} sin(\theta' + \theta_s) - sin\theta'} \tag{3.1}$$

$$\frac{I_2}{I_1} = \frac{tan\theta}{tan\theta cos\theta_s + sin\theta_s} \tag{3.2}$$

From equations 3.1 and 3.2 we can found I_1 and I_2 for various ministep detent positions and stored them in a lock-up table.

This was a sine approximation but we know that step motors are usually driven hard into saturation and their $T-\theta$ curves do not lend themselves to simple approximations. These curves also differ for different positions. In order to incorporate these nonlinearities we can have a experimental set-up to takes the set of $T-\theta$ data for a range of motor currents and use an interpolation routine to obtain the MCR's. An interesting approach is to have a *learning* start-up procedure: the microprocessor system increments or decrements motor currents while noting the encoder counts for equal ministeps –in the same away in which the interpolation does– So current references are obtained through an A/D conversion and the stored in a table from which the motor might be subsequently driven. In this case is taking account all motor nonlinearities and shaft asymmetries.

The operation under ministepping inproves resonance stability of the stepper motors, enabling to have smooth response and get rid off dampers.

Chapter 4

STEPPER MOTOR CONTROLLERS

Open loop control is widely used , its non-feedback control have the advantages of greater simplicity and lower cost of implementation. However we have to obey the start-stop capability and accelerate the motor in an adequate velocity profile. In closed-loop the instantaneous rotor position is detected and feedback to the control unit, each step command is issued only when the motor has responded satisfactorily to the previous command and so theres is no losing steps. The effective implementation of close-loop control is sometimes inhibited by some problems that will be discussed.

4.1 Open-Loop Control

A block diagram for a typical open-loop control system is shown in figure 4.1. Digital phase control signals are generated by the microprocessor and amplified by the drive circuit before being applied to the motor. Although the system illustrated receives its phase controls signals from a microprocessor, is possible to generate the signals with digital and analogic circuits, however nowadays the implementation in a microprocessor-based control is a better choice.

In order to design the timing of the control signal, we have to know the maximum stepping rate with a given load torque, but more restrictions arise when transient performance

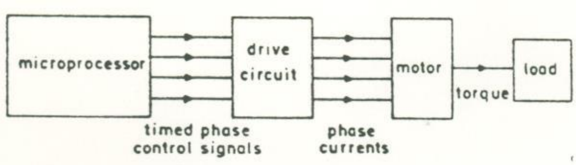

Figure 4.1: A microprocessor-based open-loop control.

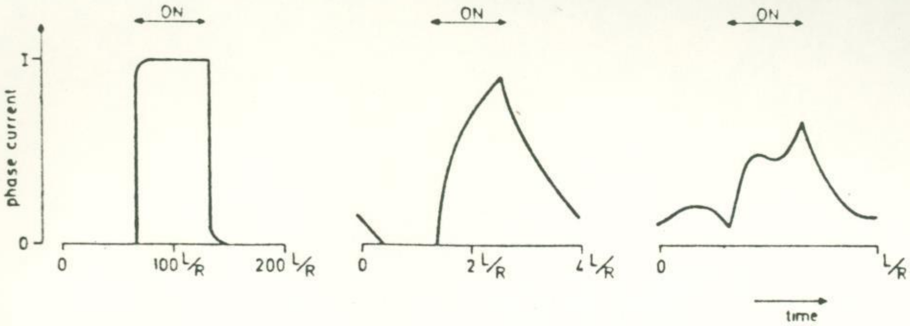

Figure 4.2: Typical current waveforms: a)Low-speed, b)Medium, c)High-speed.

is considered. If the system has a high inertia, the maximum stepping rate cannot be attained instantaneously; it must be gradually increased towards the maximum value so that the motor has sufficient time to accelerate the load inertia.

At high stepping rates each phase current is excited only a short time interval and the build-up time of the phase curent is a significant proportion of the excitation interval. When a motor is operating at the highest speeds the current in each phase may not even reach its rated value before the excitation interval finishes and the phase is turned off. In addition the time taken for the phase current continues flowing (through the freewheeling diode) beyond the excitation interval dictaed by the drive transistor swith. Consequently the pull-out torque falls with increasing stepping rate for two reasons:

- the phase currents are lower, so the motor torque produced at any rotor position is reduced,
- phase currents may flow at rotor positions which produce a negative phase torque.

In figure 4.2 we can observe in (a) the current waveform for the lowest operating speeds, the build-up of current to the rated level occupies a minor portion of the excitation time; for stepping rates where the phase is only excited for a time similar to the winding time constant the waveform of figure 4.2.b exists, and the exponential rise and decay is shown; at very high operating speeds the voltage induced in the phase windings by the rotor motion must also be considered, this effect can be seen in the high speed waveform of figure 4.2.c, we can conclude that there is no longer a simple relationship between the static torque/rotor position characteristic and the pull-out torque.

If we operate in open-loop control scheme, we must be carefull, since there is no feedback of load position to the controller and therefore it is imperative that the motor responds correctly to each excitation changes, if it does not happen there will be a permanent error in the actual load position compared to the position expected by the controller.

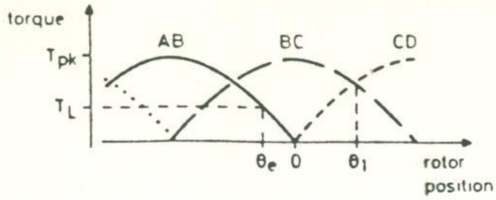

Figure 4.3: Static torque/rotor position characteristics.

4.1.1 Starting-stopping rate

The simplest form of open-loop control is a constant stepping rate which is applied to the motor until the load reaches the target position. The software on the microprocessor system produces the phase control signals at constant clock frequency, the instantaneous position of the motor relative to target is recorded in a up-down counter. If the constant frequency is set too high the motor is unable to accelerate the load inertia to the corresponding stepping rate and the system either loses steps or fails to operate at all.

The maximum demanded stepping rate to which the motor can respond without loss of steps when initially at rest is known as the "starting rate" or the "pull-in rate". Similarly the "stopping rate", is the maximum stepping rate which can be suddenly switched off without the motor overshooting the target position. Frequently is chosen the lower of the two rates, and is used the same value for start/stop operation. Considering a sinusoidal approximation for the T–θ curves of the stepper motor,when a load torque T_L is applied the rotor is displaced from the demanded position by the angle θ_e, as shown in figure 4.3 the static position error is given by equation 4.1 and the starting rate can be derived from the average torque necessary to move from θ_e position to θ_1 position [14], for a four-phase motor this is approximately given by equation 4.2.

$$\theta_e = \frac{sin^{-1}(-T_L/T_{pk})}{p} \tag{4.1}$$

$$starting\ rate\ = 1/t_p = \left[\frac{T_M - T_L}{J(\theta_1 - \theta_e)}\right]^{1/2} \tag{4.2}$$

4.1.2 Acceleration and deceleration capability

The starting rate of a stepping motor system is generally much lower than its pull-out rate, so positioning time can be reduced substantially by continuing to accelerate the motor over several steps until the pull-out rate is attained. As the target position is approached the stepping must be gradually reduced to starting/stopping rate, so that the motor can be halted when the final position is reached. A graph of the stepping rate against time as the motor moves between the initial and target position is referred to as the velocity profile.

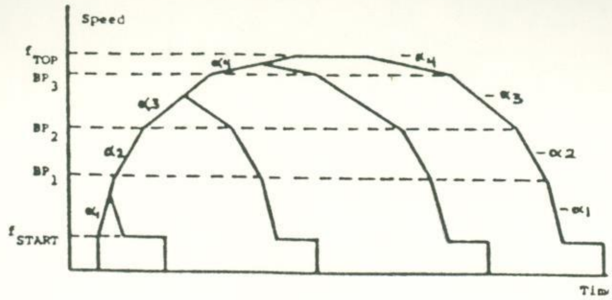

Figure 4.4: Velocity profile.

For high performance systems where operating speeds above the maximum starting frequency range are required, we have to be careful in define the velocity profile to achieve high speeds with fast acceleration, it is not uncommon to find stepper drive systems capable of achieving stepping rates as high as 40 times the maximum starting rate.

An useful approach to implement the profile [9] is defining multilinear segments like figure 4.4. Each segment is tailored to be optimum for a given motor-drive and load combination. In order to define the profile is necessary some parameters; accelerations values α_n, break frequencies BP_n at which accelerations are changed, start and stop frequencies $fstart$ and $fstop$.

At a steeping rate f the pull-out torque is denoted by $T(f)$ and the load torque by $T_L(f)$. If the motor is to accelerate as quickly as possible the maximum (pull-out) torque must be developed at all speeds. This torque overcomes the load torque and also accelerates the system inertia or, expressed algebraically:

$$T(f) = T_L(f) + J(d^2\theta/dt^2)$$

For a motor with n phases and p rotor teeth the step length is $2\pi/np$ and so the stepping rate is related to the rotor velocity by:

$$\frac{d\theta}{dt} = \frac{2\pi f}{np}$$

With these two last equations we can arrive to 4.3, where it can be integrated to give the time t, taken to reach the stepping rate f, as the motor accelerates from rest.

$$\frac{np}{2\pi J}\int_0^t dt = \frac{npt}{2\pi J} = \int_0^f \frac{df}{T(f) - T_L(f)} \tag{4.3}$$

In general this integral must be performed graphically, as both $T(f)$ and $T_L(f)$ are non-analytic functions. One good solution is use SIMNON to simulate it, achieving the velocity profile.

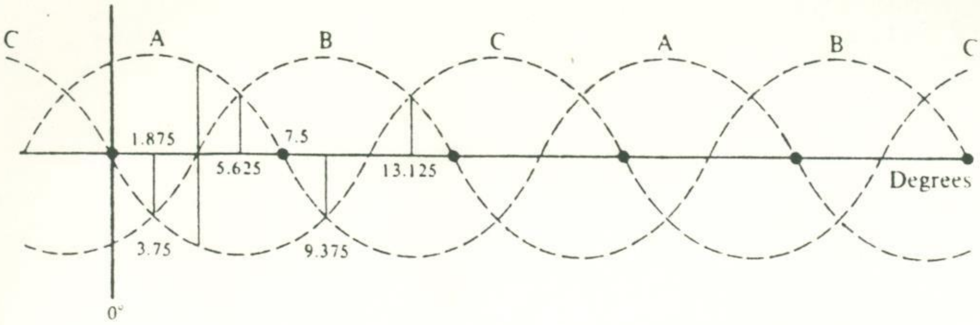

Figure 4.5: Static torque curves of a three-phase 7.5° Stepper Motor.

4.2 Closed-Loop Control

In a close-loop system a position detector generates a pulse which signals to the control unit that a step has been completed; so the question then arises of exactly position should be detected?

At low operating speeds the optimum detected position can be deduced [3] from the static torque/rotor position characteristic ($T-\theta$). Figure 4.5 shows the idealized (sinusoidal approximation) static curves of a three-phase 7.5°/step motor. In order to maintain maximum positive torque, supposing that at the instant of switching, the current in the deenergized phase decays instantaneously, we have to change the phases at the point where the curves overlap.. For example, let the motor be stationary at 0°, with a steady-state current in phase C, the first forward pulse would be applied at 0°, the next at 5.625°, and the next at 13.125°, and all subsequents at 7.5° intervals. This is an idealization, since the currents do not build up or decay instantaneously, so the switching process is dependent upon the rise and decay times of the current as well as the position of the rotor. The time constants for these two processes are also dependents on the resistances in power electronics circuit and resistance of the windings of the motor. We have to consider the self and mutual inductances of the windings, as well as the back-emf of the motor; the inductances of the windings are function of the rotor position and the motor current, since the magnetic material of the motor is subject to saturation.

If the positional feedback is employed, as is done in most practical applications, the angle at which the motor is switched from one torque curve to another must be chosen so that the motor should maintain a high average torque, and be capable of starting from a stationary position. In these circumstances each change in phase excitation must occur earlier relative to the rotor position, so that the phase current has sufficient time to become established before the rotor reaches the position of maximum phase torque. This process is commonly referred to as "ignition advance"; the change in detected rotor position relative to the low speed detected position is called as "switching angle". The pull- out torque is maximized at a supply angular frequency ω when the switching angle is set to its maximum value, given by equation 4.4 [14], where L is the average winding inductance, R is the total phase resistance,

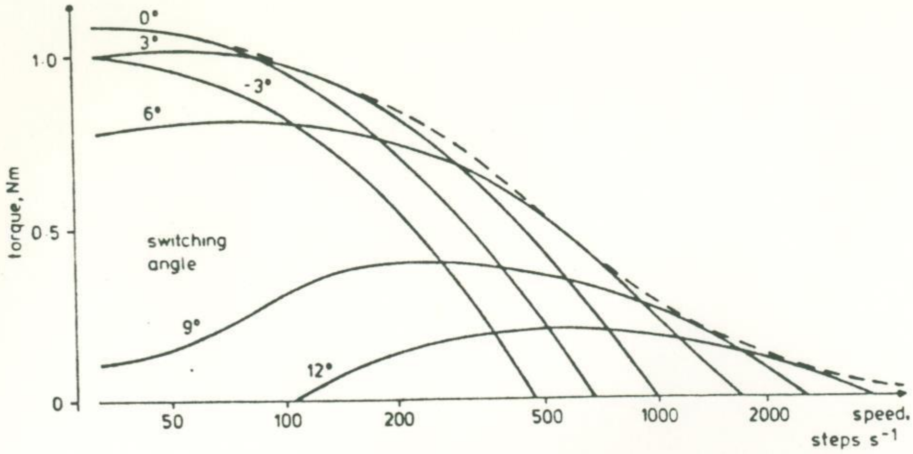

Figure 4.6: Typical torque/speed/switching angle characteristics.

p is the number of rotor teeth.

$$Optimum\ switching\ angle\ =\ (tan^{-1}\omega L/R)/p \tag{4.4}$$

If the switching angle is not optimized at any operating speed then the motor torque is less than the pull-out torque. The variation of torque with switching angle and speed for a three-phase, 15° step motor (p=8) is shown in figure 4.6. These characteristics include a negative value of switching angle, for which the phase excitation is changed after the static torque/position "crossover" points. The figure shows that an injudicious choice of choice of switching angle may prevent the motor from producing any torque at certain speeds, for example in figure switching angle = 12° at speeds below 100 steps per second. Although large switching angles must be used to attain high pull-out rates, these angles are inappropriate for low-speed operation.

The need for a speed-dependent switching angle is a major obstacle to the successful implementation of closed-loop control system. Most optical position detectors produce a pulse at a fixed position. Encoders generating up to 5000 pulses per revolution produce several pulses for each step, so the pulse used to trigger the control unit can be varied according to the time between successive pulses, given control of switching angle with operating speed, however the cost of such encoder are prohibited when compared to the cost of the stepper motor itself, most of the controllers available to date use direct rotor position sensors such as optical encoders or Hall-efrect devices. The use of direct rotor-position sensors increases the overall cost of the system as well as the number of connections between the motor and controller, it is desirable to eliminate the use of them, one approach is detect position through current waveforms.

4.3 Position with Waveform Detection

In VR motors, the flux linked with a phase winding is a function of phase current and rotor position. A typical flux-link curve of a VR step motor is shown in figure 4.8. Flux linkage is maximized when the stator and rotor poles are aligned and is minimized when they are misaligned. The incremental phase inductance is defined as the ratio of change in flux linkage to the corresponding change in phase current. At rated current the incremental phase inductance is lower at the aligned position as compared with that at the misaligned position, this is because at rated current when the rotor and stator poles are aligned the motor is under highly saturate conditions due to the small air gap. On the other hand, at the stator and rotor misaligned position, the magnetic path is dominated by a large air gap, which causes the flux linkage to vary linearly with rotor position. Hence the incremental phase inductance at the stator-rotor misaligned position is higher. The phase chop current rise time in a chopper drive is given by equation 4.5 [13].

$$T_r = \frac{\frac{\partial\psi}{\partial i} \times \Delta I}{V - I \times R - \frac{\partial\psi}{\partial\theta} \times \frac{d\theta}{dt}} \tag{4.5}$$

In a chopper drive, ΔI is kept constant, and if supply voltage V is made much higher than the back-emf, then the drop current rise time T_r is directly proportional to the incremental phase inductance $\frac{\partial\psi}{\partial i}$. If the motor is characterized in terms of chop current rise time as a function of rotor position, then by comparing the chop phase current rise time with a preselected detect time T_d it is possible to get rotor position information in a continuous manner.

It is necessary to characterize experimentally the test motor in terms of chop current rise time as a function of rotor position; the chop current rise time as a function of rotor position for a typical motor is shown in figure 4.7. As a rotor pole moves into alignment with the energized stator pole, the chop current rise time decreases from a maximum of 55 μs to a minimum of $30\mu s$. Thus, in the controller, the chop current rise time T_r is compared with a detect time T_d, and when it falls bellow T_d, the phase advance signal is generated. In practice however it is necessary to set T_d to a higher value to overcome the back-emf effects at higher operating speeds. In WD technique, a full conduction angle pulse is applied, and the detect time is varied to match the torque produced by the motor to that demanded by the load. Phase currents can be sensed by measuring the voltage drop across a series resistance in each phase winding, as shown in figure 4.10.

A digital controller based on WD technique is shown in figure 4.9 [13]. The outputs of the current comparators are applied to the chopping transistors as base drive signals (in order to form a kind of hysteresis band) as well as to the digital counter clock block as a RESET signal for the counters which are set when the phase current is rising between I_{min} and I_{max} and resets when the current is falling. The outputs of the counters are applied to a digital comparator as an input signal, this is compared to a set of 12 bits, which change the detect time. The comparator sends a signal to a logic sequencer which advances the phase

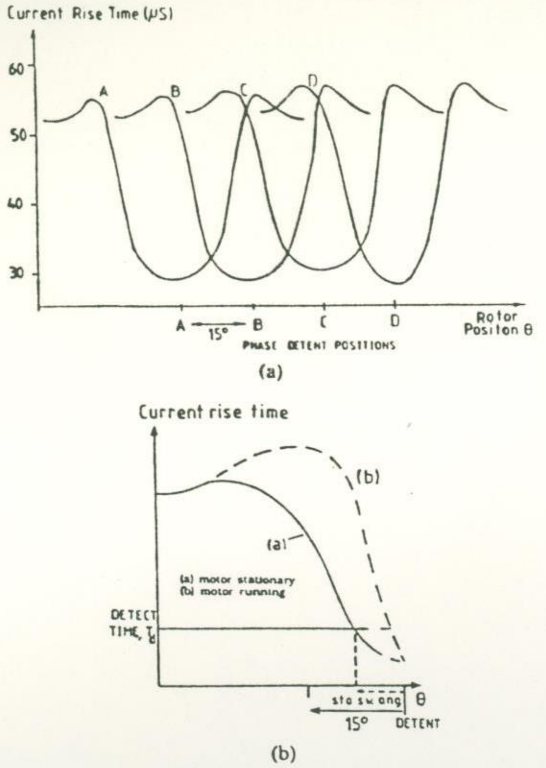

Figure 4.7: (a) Measured chop current rise time versus rotor position (b) Influence of back-emf on chop current rise time.

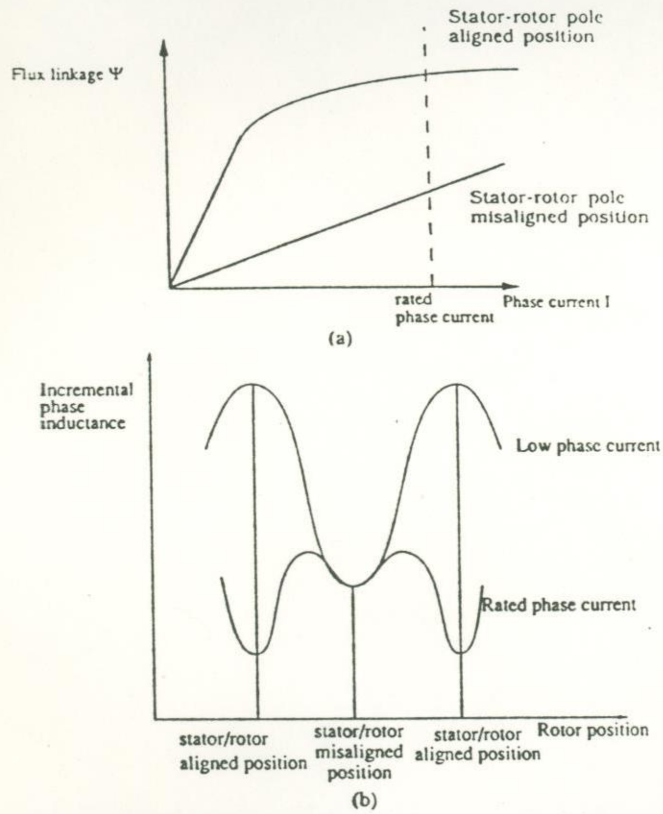

Figure 4.8: (a)Typical flux-linkage versus current characteristics at stator/rotos aligned and misaligned (b)Typical incremental phase inductance curve.

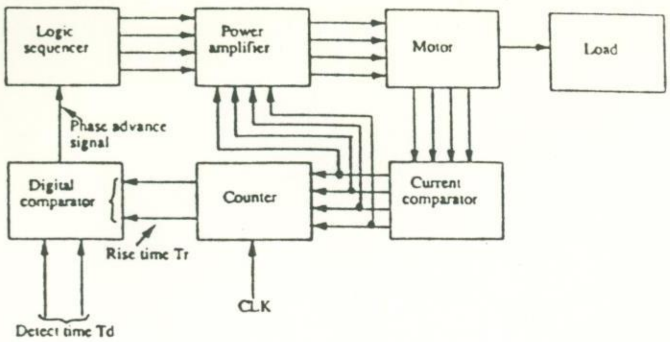

Figure 4.9: Waveforms detection closed-loop drive system for step motor.

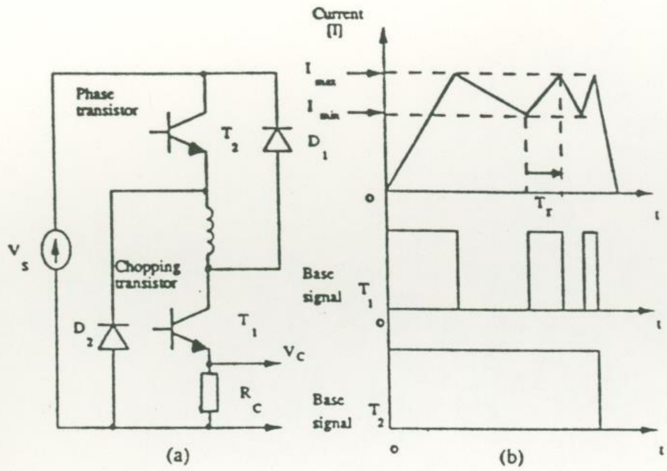

Figure 4.10: (a) One phase of a chopper drive circuit; (b)Chopped current waveforms and base drive signal for transistor T_1 and T_2.

when $T_r < T_d$.

Chapter 5

CONCLUSION

Since the first publication known about steppers motor in an issue of JIEE published in 1927 with the article "The Application of Electricity in Warships" [18], whose described a three-phase variable-reluctance stepper motor which was used to remote-control the direction indicator of torped tubes and guns in British warships, the stepper motor developed a lot, mainly due the advent of digital systems which could easily be interfaced with them.

In last decade this kind of motors had been spreading, the semiconductor industries designed some integrated circuits that made easier the utilization in driving small stepper motors [6]. Intensive researches on stepper motors and applications of control theories has been performed in the universities and laboratories around the world, improving the methodologies of analysis and design of stepper motor systems.

Nowadays stepper motors are very well established in some applications like computer peripherals, CNC machines and medicine instruments, of course there is a competition among another types of drives but this is a very good aspect in order to go down the costs and reaches better applications.

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