Computer Simulation of Bang-Bang Control of Rotor Impedance

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التمثيل على الحاسبة الالكترونية للتحكم في ممانعة دوار محرك حثي

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الخلاصة

باستخدام مجموعة مكونة من ثلاث ثايرسترات مربوطة بشكل دلتا يمكن التحكم في سريان التيار في المحركات الحثية الملفوفة الدوار . وبقدح الثايرسترات في ظروف معينة يمكن التحكم في سرعة المحرك نفسه

يحوي البحث على دراسة لتمثيل تصرف وخواص المنظومة من الثايرسترات المربوطة في دوار المحرك الحثي على الحاسبة الالكترونية ومقارنة تلك الخواص مع تجارب عملية لغرض التحكم في سرعة المحرك

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Summary :

The use of a delta connected thyristors in the rotor circuit of induction motor has been examined The bang-bang performance of such connection for the control of the motor has been simulated using a continuous system simulation language DARE — P

The complete performance of such connection is studied and merits of the control becomes clear

1. Introduction

The use of thyristors has entered the area of speed control of induction motors in a variety of ways. Per the most straight forward application is the use of thyristors in the supply lines of induction machines to a the effective voltage applied to the stator terminals. When a relatively high rotor resistance is incorporat the design of the induction machine, speed ranges of 5 to 1 can be readily obtained.

The most common way of control of speed of induction motors using thyristors is by the use of a circuit containing a pair of thyristors connected back-to-back in each time of a Y-connected mot shown in figure (1). Such a circuit provides a high average torque per stator amp but it does result in gr copper losses owing to waveform distortion, especially at low speed.

A second method of speed control for wound rotor induction motors is by the control of the rotor resista Such contorl may be achieved by connecting a diode bridge rectifier in the rotor circuit to convert the a.c. d.c. after rectifying and smoothing it, it is then dissipated in a resistance. A simple thyristor in parallel wit resistance is switched on and off by a chopper to control the motor speed by altering its torque s characteristic. This type of rotor circuit may be used separetely or in combination with stator voltage co circuits. When the load torque is small, speed control is obtained by variation of stator voltage and r resistance control is used in the high torque range[3]

A simpler circuit (figure 2) which employs rotor resistance control of wound rotor machines is the one interest here and will be studied in detail.

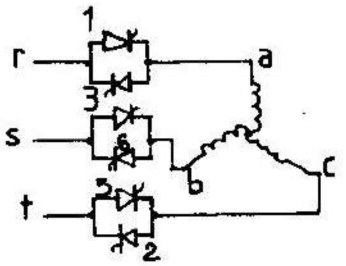

Figure 1
Back_to_Back connected thyristors for speed control of induction motor

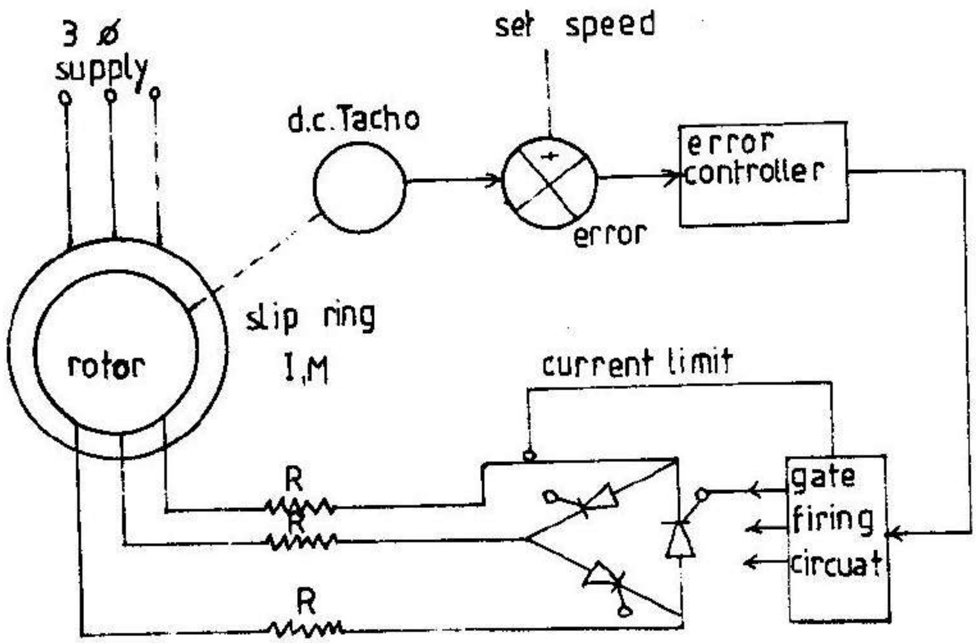

Figure (2) Induction motor speed control by static control of rotor resistance.

2.1. Principle of operation

When the thyristors are gated, the rotor is virtually shorted via a resistor R, through which the rotor current flows as shown by Figure (2). This current interacts with airgap flux to produce torque. The motor shaft accelerates towards a set speed, and when it reaches the target speed the error signal goes negative and the gate signals are removed. The thyristors do not cease conduction immediately after the removal of gate signals, they must wait till commutation takes place naturally. With the rotor circuit open, no torque is provided and the motor coasts its load, by virtue of stored energy in its inertia and at the expense of a drop in speed. Once the speed goes below the demand speed, the error control sees a positive error and orders the firing circuit to produce a train of gate pulses. The thyristor resistance can be segmented into two or three components for a better control over different regions of the torque speed characteristic.

The thyristors are connected in delta via resistors, to the slip rings. Gate pulses are provided to allow the thyristors, which are forward biased by the induced emf in the rotor, to conduct. Only two thyristors can carry the rotor current at a time because the third will be reversed biased by the forward voltage drop across the other two.

Figure 3 shows the block diagram of the closed loop system of the bang-bang scheme.

2.2 Assumptions

(i) The power source may be considered to be a set of balanced sinusoidal three phase voltages. Source resistances and reactances may be added to corresponding values of stator windings of the machine.

(ii) The three thyristors have identical characteristics and may be replaced in the blocking mode by a high resistance and by zero resistance when the forward or anode — to — cathode voltage changes from positive to negative. The impedance becomes zero, whenever a trigger pulse is applied, provided the forward voltage is positive.

(iii) The induction machine is an idealized machine in which the stator and rotor windings are distributed so as to produce a single sinusoidal mmf wave in space when balanced sets of currents flow in the stator and rotor circuits.

(iv) All parameters of the machine are assumed to be constant and saturation of magnetic circuit is neglected.

(v) The firing circuit is perfect i.e. it provides the triggering signal when the speed is below the set speed and stops it when the speed is above that.

2.3 System Modes

(i) Any two of the three thyistors are ON. The three phases will be then short circuited together and the machine works like a normal balanced rotor of induction motor with the three phases connected to a single rotor neutral point.

$I_{ra} \neq 0 \quad I_{rb} \neq 0 \quad I_{rc} \neq 0$ (See Figure 4a).

(ii) One of the three thyristors is ON and two are OFF. In such a case two phases carry currents (equal and opposite in sign), while the third phase has zero current Three possibilities emerge from this case:-

(a) Thyristor 1 is ON hence $i_b = -i_c$ and $i_a = 0$ (See figure 4c)

(b) Thyristor 2 is ON hence $i_c = -i_a$ and $i_b = 0$ (See Fig 4b)
(c) Thyristor 3 is ON hence $i_a = -i_b$ and $i_c = 0$ (See Fig 4d)
(iii) All thyristors are OFF hence $i_a = i_b = i_c = 0$ (See Fig 4e)

2.4 State Variable Analysis

In the analysis of problems involving induction machinery, it has proved useful to transform the equations which describe the behaviour of the machine to d-q axes fixed either on the stator or on the rotor, or rotating in synchronism with the applied voltages. This causes variable coefficients to appear in the resulting differential equations owing to the sinusoidal variation of mutual impedance with displacement angle. However a transformation of voltage and current variables to d-q axes results in a set of constant coefficients in the resulting differential equations when the rotor speed is constant. These performance equations can be written in matrix from as

$$\begin{bmatrix} V_{d1} \\ V_{q1} \\ V_{d2} \\ V_{q2} \end{bmatrix} = \begin{bmatrix} r_{d1} + pL_{d1} & 0 & pL_m & 0 \\ 0 & r_{q1} + pL_{q1} & 0 & pL_m \\ pL_m & \Omega L_m & r_{d2} + pL_{d2} & \Omega L_{q2} \\ -\Omega L_m & pL_m & -\Omega L_{d2} & r_{q2} + pL_{q2} \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} \quad \ldots$$

The subscript d is for the direct axis, q for the quadrature axis, 1 for the stator, 2 for the rotor & 'm' refers to the mutual inductance. These four differential equations contain the differential operator (p) implicitly. In order to put them in a form suitable for direct programming using a continuous system simulation language, they have to be put in a from with the differential operator term on the left hand side (such a form is also the from suitable for simulation on an analogue computing):

$$Pi_{d1} = \{V_{d2}L_m - L_{d2}V_{d1} + r_{d1}L_{d2}i_{d1} - \Omega L_m^2 i_{q1} - \Omega L_{q2}L_m i_{q2} - r_{d2}L_m i_{d2}\} / \{L_m^2 - L_{d1}L_{d2}\}$$
$$Pi_{q1} = \{V_{q2}L_m - V_{q1}L_{q2} - L_m r_{q2} i_{q2} + \Omega L_m L_{d2} i_{d2} + r_{q1}L_{q2}i_{q1}\} / \{L_m^2 - L_{q1}L_{q2}\}$$
$$Pi_{d2} = \{V_{d2}L_{d1} - V_{d1}L_m + r_{d1}L_m i_{d1} - \Omega L_m L_{d1} i_{q1} - L_{d1} r_{d2} i_{d2} - \Omega L_{d1}L_{q2}i_{q2}\} / \{L_{d1}L_{d2} - L_m^2\}$$
$$Pi_{q2} = V_{q2}L_{q1} - V_{q1}L_m + r_{q1}i_{q1}L_m + \Omega L_{q1}L_m i_{d1} + \Omega L_{q1}L_{d2}i_{d2} - L_{q1}r_{q2}i_{q2}\} \{L_{q1}L_{q2} - L_m^2\}$$

....(2)

$$\begin{bmatrix} V_{d1} \\ V_{q1} \\ 0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \times \begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \end{bmatrix} \quad (3)$$

Equations (2) are the basic equations required however the torque equation is also essential for the solution. Such an equation can be put in the form:

$$T_m = L_m (\text{[illegible]}) - T_l \qquad \ldots(3)$$

Where T_m is the inertia torque, which is equal to the electomagnetic torque minus the load torque T_l. The intertia equation hence is $P\Omega = T_m/J_m$ ...(4)

Where J_m is the moment of inertia.
The d-q /phase transformation is also needed.
The phase voltages may be written:

$$V_{a1} = V_m \sin wt$$

$$V_{b1} = V_m \sin(wt + \frac{2\pi}{3} \qquad \ldots(5)$$

$$V_{c1} = V_m \sin(wt + \frac{4\pi}{3}$$

These values have to be transformed into d-q variables using the tranformation:-

The rotor voltage V_{d2} and V_{q2} equal to zero when the rotor termainals are short circuited. However when all three thyristors are off, the rotor circuit is open and hence these two voltages do not equal to zero. In order to give them their correct values reference to their corresponding values in the phase configuration should be made. The three rotor voltages are

$$V_{a2} = R_1 i_{a2}$$
$$V_{b2} = R_2 i_{b2}$$
$$V_{c2} = R_3 i_{c2} \qquad (7)$$

The three equivalent resistances R_1 and R_2 and R_3 are the values indicated in Figure (4) and he currents i_{a2}, i_{b2} and i_{c2} are the rotor phase currents which are related to the d-q rotor currents by:

$$\begin{bmatrix} i_{a2} \\ i_{b2} \\ i_{c2} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \sin\theta & \frac{1}{\sqrt{2}} \\ \cos(\theta + \frac{4}{3}\pi) & \sin(\theta + \frac{4}{3}\pi) & \frac{1}{\sqrt{2}} \\ \cos(\theta + \frac{2}{3}\pi) & \sin(\theta + \frac{2}{3}\pi) & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_{d2} \\ i_{q2} \\ 0 \end{bmatrix} \quad \ldots (8)$$

The relationship between V_{a2}, V_{b2}, V_{c2} and V_{d2} and V_{q2} is similar to that of equation 6 i.e.

$$\begin{bmatrix} V_{d2} \\ V_{q2} \\ 0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \times \begin{bmatrix} V_{a2} \\ V_{b2} \\ V_{c2} \end{bmatrix} \quad \ldots (9)$$

If the stator phase currents are requiredthey may be calculated from the equations:

$$\begin{bmatrix} i_{a1} \\ i_{b1} \\ i_{c1} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & +\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & +\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix} \times \begin{bmatrix} i_{d1} \\ i_{q1} \\ \; \end{bmatrix} \quad \ldots (10)$$

Hence the motor preformance can be obtained using equations (2) to (10) provided that the switching of the delta connected thyristors is properly programmed in terms of the three resistances R_1, R_2 and R_3. These are equivalent resistances so as to show the inter terminal equivalent resistances of the actual thyristor connections. Note that R is very big resistance near to infinity.

2.5 Modes Switching

When the motor speed is under the required speed, the motor operates in mode 5 i.e all the three phases short circuited. See Figure 4a.

When the speed is above the required speed, the change from one mode to another depends upon the present mode and the moment when one of the phase currents cross through zero.

If the mode is 1, i.e. the rotor is open circuit then the only change which can occur is that the speed drops under the required speed due to the load torque, hence the next mode must be mode 5

Modes 2, 3 and 4 may continue as they are If any of the three phase currents crosses through zero, than the mode changes to the open circuit rotor condition i.e mode 1. This is because for these three modes, one phase current equals zero whilst the other two phases are equal and opposite Hence when any of these two currents passes throught zero, the three currents must then equal zero

If the system is in mode 5 and the speed is above the required speed, and a crossing of zero in one of the three phases occured then one of three things may happen:

(a) If i_a goes through zero in either directions with $i_c>0$, then thyristor 3 blocks, hence mode 2 will result. If $i_a<0$ no change occurs.

(b) If i_b goes through zero in either directions with $i_a>0$ than thyristor 1 blocks hence mode 3 will result. If $i_b<0$ no change occurs.

(c) If i_c goes through zero in either directions with $i_b>0$ then thyristor 2 blocks hence mode 4 will result. If $i_c<0$ no change occurs.

Finally it should be noted that in the simulation the compensation network, the amplifier, the comparator, the logic circuit, the oscillator and the firing circuit are all considered to be ideal If the exact transfer functions for these blocks are known they may be easily added to the computer program.

3. Digital Computer Simulation

The system equations as described above are suitable for solution a digital computer using one of the continuous system simulation languages One of the most suitable languages is DARE -p. A flow chart for the program is shown in figure 5.

The program consists of three sections: the system description section, the initial conditions section and the output reqnest section.

In the initial conditions section three types of constants are defined: the initial values of all the dependant variables in the system, e.g initial speed and currents, constants of the system e.g. resistances and inductances of the motor, and some of the parameters of DARE-P e.g. the maximum time for integration, the maximum integration increment, number of points requested by the output, etc

In the output section, the form of the output can be specified in the form of a listing, a plot on the line printer, or a plot on the graph plotter

The main part of the program, i e the system description section, consists of two main blocks. The derivative block and the logic block A third block may also be added to define the method of integration A choice of one of 12 integration methods is available The logic block is the first block to which the control is directed. Some of the system constants or prameters may be included in this block and then the control is transferred to the main block in the program i.e the derivative block In this block the statements of main equations describing the system is introduced These equations may be introduced in any order and can contain some procedural sections for complicated logical operations or calculations In our case equations 2 to 10 above can be introduced directly with the differential operator (p, replaced by a of ;) after the term The logical operations shown in Figure 5 decides whether there is a change in the node of operation If there is, then the integration is stopped and the control is returned to the logical block where new mode parameters are introduced If there is no change in the mode, the process of integration is continued with the same parameters.

The decision as to which of the modes of operation is the next, is performed according to the flow chart of Figure 5 taking account of the modes switching logic given in section 2.5.

In the process of reinitialization of parameters after the selection of a new mode of operation care should be observed in initializing the dependant variables of the differential equations. This is because the values of the parameters at the end of the last mode of operation may be far from those needed for the starting of the new mode. This may be due to exessive values of integration increment.

4. Discussion of Results

The motor used for the experiment had the following parameters:
$r_1 = 6.5$, $x_1 = 8.1$, $x_m = 135.4$
$r_m = 1020$, $r_2 = 7.2$ the turns ratio = 0.955
$J = 0.003$ kg m^2 , $v = 150V$ per phase

Figure 6 and 7 show the expermental results[4] i.e. the waveforms of stator and rotor currents respectively. Trigger signals are shown as well.

When the machine was simulated, two target speeds were tried, the 40% and the 80% of the synchronous speed. For each of these two traget speeds, the case of inclusion of external rotor resistance of 10Ω per phase and the case for no such resistances were considered. Two values of moment of interia were tried, 0.003 kgm^2 i.e. the motor inertia alone and 0.01 kgm^2, i.e. the motor with the load. The combination of these different parameters resulted in 8 cases. Plots for torque, speed stator currents, rotor currents and mode changes were obtained. Figure 8 shows those for the case of external rotor resistance, loaded motor and with a target speed of 80% of the synchronous speed. This case simulates theexperimental set up very closely.

Table (1) Calculated Results

Case	J	R_e	Ω_1/Ω_m	Reg. Speed	Min Speed	Max Speed	Change%	Time of Switching
1	0.003	0	0.4	125.7	119.2	131.9	10.1	0.299
2	0.01	0	0.4	125.7	123.2	127.6	3.5	0.976
3	0.003	10	0.4	125.7	125.6	131.4	4.7	0.273
4	0.01	10	0.4	125.7	125.1	127.3	1.7	0.832
5	0.003	0	0.8	251.3	251.2	269.0	7.1	0.558
6	0.01	0	0.8	251.3	251.2	255.8	1.8	1.804
7	0.003	10	0.8	251.3	251.3	251.1	1.7	0.682
8	0.01	10	0.8	251.3	251.3	253.0	0.7	2.194

Table (1) shows the list of parameters corresponding to these figures with the speed variation noticed during the run.

From the table it is noticed that the worse case is when there is no external resistance low inertia and at low speed limit. When an external resistance is inserted, the variation decreases to 4.7% at low speed limit and to 1.7 at high speed limit.

The effect of inertia can be noticed by comparing the results of cases 1 and 2, the percentage speed variation decreases from 10.1% to 3.5%.

The best speed control is achieved when the speed limit is high, the inertia is high and with external resistance in the rotor circuit

The relationship between the time to the first switching to occur, the inertia and the target speed is evident.

From the torque/time curves, high pulsating torque is noticed at low target speeds (not shown). It decrases with the increase of inertia and with increase in external rotor resistance. For high target speeds the tarque pulsation is not very severe (see figure 8 a)and for long period of times there is no torque due to the rotor being open circuited. This is seen clearly from figure 8c which show the mode variations It was noticed that at low target speeds the average number of switchings per second is higher than the number at high target speed. After some time the seqence of peration becomes stable

Before the desired speed is reached the operation is according to mode 5 When it reaches the limit speed, the system changes to modes 3,2 or 4. In switching from each of these modes to another, the operation passes through mode 1 or mode 5 (as is hown in figure 8c) or through both modes 1 and 5

When examining the rotor current waveforms it is clear that they agree, with the experimental results. for low target speeds and low inertia, the currents may be as high as the starting current or even higher. When the target speed is high the levels of the currents are low compared to the starting current.

With regard to the stator currents the same trend may be observed An analysis of the harmonics contained in the stator current waveform might reveal some useful information.

5. Conclusions

In conclusion the peculiar performance of the bang-bang control of rotor impedance has become clear. The simulation of such set up although possible by traditional methods. the use of continuous simulation languages proved to be easy to use. accurate enough and suitable for such dynamic problems Experimental and the oratical results proved to be near enough to validate the model used Wider eaise of thyristors applications may be simulated using the technique mentioned e.g. H V.D C applications or thyristors in control of electric machines.

6. Acknowledgements

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