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NEW PERFORMANCES OF CSI-FED INDUCTION MOTOR BY FIELD STEPPING OF 30 DEGREES

INTRODUCTION

There is the advent of variable-speed induction motor drives in industry taking the excellent performances of inverter-fed induction motor drives into account. Thus, a new current-source inverter (CSI) fed induction motor drive has been developed, designed and put into practice by the authors above. It is well worth mentioning that the first industrial product was exhibited at the Budapest International Fair in May 1988 (Figure 1).

The first step was to develop a four-quadrant drive working in a fully automatic way /1, 2/. The second degree was to put the drive into operation without reactor in the d-c link accompanied by new thyristor firing control strategy /3, 4/. The third phase was to reduce torque ripple and to maintain the revolving magnetic field even in that case when the current conduction in the stator winding is discontinuous /5/. In the fourth step an advanced inverter-fed drive was developed which needs neither reactor nor capacitor in the d-c link /6/. In addition, commutating elements such as commutating diodes and capacitors can be eliminated when the drive is equipped with a chopper in the d-c link /7, 8/. Particular regard was given to harmonics, therefore a harmonic analyzer-aided drive has also been developed and designed /9/.

The fifth phase of research work, which is the topic of this paper is to present the newest inverter-fed variable-speed drive equipped with new inverter control electronics plus aided by chopper in order to minimise torque ripple and to improve the performances of the drive.

Revolving magnetic field is being maintained in the airgap of induction motor with constant speed while the current is standing for a duration equivalent to 60 degrees. It is a consequence coming from the vectorial multiplication of the flux and the current that there is a big difference between the momentary values of the initial and the final torque, thus unfavourable torque-ripple appears. This phenomenon can be observed particularly at low speed, therefore it is a must to reduce torque-ripple. The new method is that the resultant current field will be stepping around by 30 degrees instead of the previous steps of 60 degrees. In this way not only torque-ripple is reduced but the variation of torque-angle will also be decreasing.

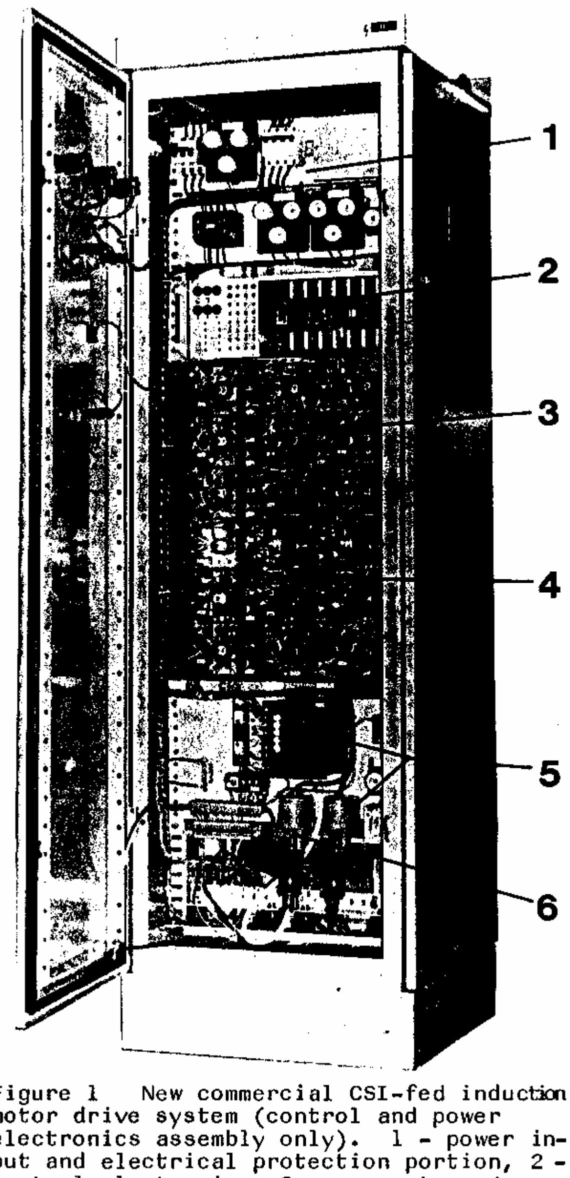

Figure 1 New commercial CSI-fed induction motor drive system (control and power electronics assembly only). 1 - power input and electrical protection portion, 2 - control electronics, 3 - converter, 4 - inverter with chopper, 5 - emergency power supply, 6 - induction motor connection.

The dimensions of the cabinet which incorporates power electronic devices, control logic, analog and digital circuits, etc. are: height x width x length = 1700 x 600 x 600 millimetres, total weight of the cabinet is approx. 200 kilograms. This assembly is suitable up to 200 kW.

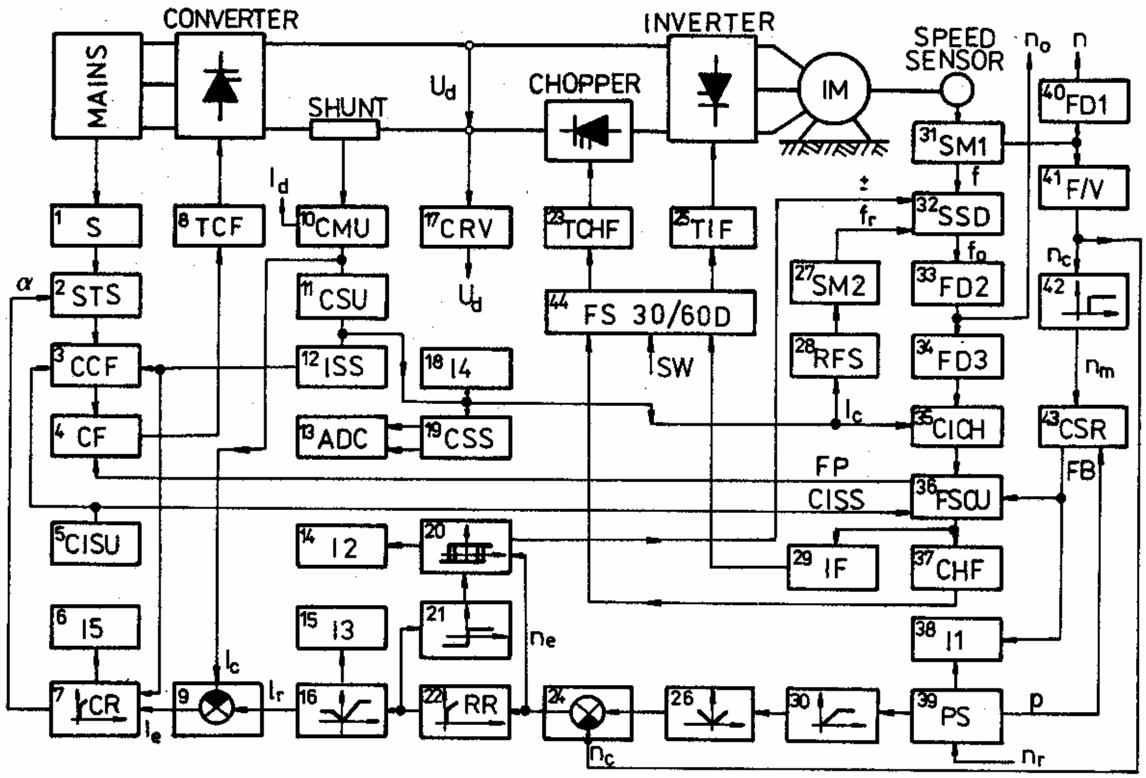

Figure 2 Block-diagram of current-source inverter-fed induction motor

IM - Induction Motor, 1 S - synchronous signal generator, 2 STS - saw-tooth signal creating circuit, 3 CCF - coding device for converter firing signal, 4 CF - converter thyristor firing pulse producing circuit, 5 CISU - converter-inverter synchronizing signal, 6 I5 - indicating circuit for firing angles of converter thyristors, 7 CR - current regulator, 8 TCF - transformer for converter thyristor firing, 9 - subtracting junction i.e. error signal device, 10 CMU - current signal matching unit, 11 CSU - current signal monitoring unit, 12 LSS - logic circuit for motor starting and stopping, 13 AOC - auxiliary and other circuits e.g. power supplies, selection circuits, etc. 14 I2 - motor/generator action indicating circuit, 15 I3 - current-limit indicating circuit in motor/generator action, 16 - absolute value producing circuit equipped with current-limit, 17 CRV - circuit creating indication of rectified voltage signal, 18 I4 - circuit for indicating possible starting or stopping, 19 CSS - circuit for control strategy selection, 20 - circuit of hysteresis, 21 - positive/negative sign producing circuit, 22 RR - r.p.m. regulator, 23 TCHF - transformer for chopper thyristor firing, 24 - subtracting junction i.e. error signal device, 25 TIF - transformer for inverter thyristor firing, 26 - absolute value producing circuit, 27 SM2 - signal modification unit for signal coming from rotor frequency generator, 28 RFS - rotor frequency signal generator, 29 IF - inverter thyristor firing pulse producing circuit, 30 - reference signal retardation circuit, 31 SM1 - signal modification unit for signal coming from rotation-sensing device, 32 SSD - summing and subtracting device for two digital signal-series modifying their frequencies in analog way, 33 FD2 - frequency dividing circuit, providing the indication of revolving magnetic field in r.p.m., 34 FD3 - frequency dividing circuit, 35 CICH - code network for inverter-chopper control, 36 FSCU - firing sequence coding unit, 37 CHF - chopper firing pulse creating circuit, 38 I1 - reference signal sign for forward/backward rotation and indicating circuit for firing sequence of inverter thyristors, 39 PS - reference signal producing circuit, 40 FD1 - frequency dividing circuit for indication of rotor rotation in r.p.m., 41 F/V - frequency to voltage converter, 42 - comparator circuit for detecting threshold rotation, 43 CSR - logic circuit for prohibiting reference signal and reversing rotational direction, 44 FS 30/60 D - field stepping of 30/60 degrees.

α - firing angle adjustment signal, I_c - current control signal, I_c' - current control digital signal, I_e - current error signal, I_r - current reference signal, CISS - converter-inverter synchronous signal, FB - forward/backward rotation specified signal, FP - firing pulse, f - digital signal proportional to speed, f_o - digital signal proportional to synchronous speed, f_r - digital signal proportional to rotor frequency, n - actual speed in r.p.m., n_c - r.p.m. control signal, n_e - r.p.m. error signal, n_m - r.p.m. zero or minimum signal, n_r - r.p.m. reference signal possibly either positive or negative, n_o - speed of revolving magnetic field, p - rotational direction control signal, SW - electronic switch signal indicating 30 or 60 degrees of field stepping.

The new drive can be equipped with computer control, too: reference signal needed for the accurate operation can be provided by a process control computer.

NEW ERA FOR VARIABLE-SPEED INVERTER-FED INDUCTION MOTOR DRIVES

The outstanding characters of the new drive can be observed particularly in the variable-speed range where not only any speed profile but r.p.m. reversal and plugging are required, too. The new system can be put into operation in an economic, efficient and precise technological way.

The application fields of this drive are, among others, as follows: to drive various machine tools, forwarding machines, conveyors in machine industry, cannery, food and deep-freezing industry, paint workshops, to operate pumps and fans, to drive production machines in automobile and electrical machine industry, too. In addition, there are several industries where only squirrel-cage induction motors can be employed because the drive is exposed to possible explosions of various gases and chemical materials, nuclear and other radiations, underwater areas, etc.

The block diagram of the drive is given in Figure 2. There are 4 closed-loop controls working simultaneously such as speed control with subordinate current control, slip-frequency and torque-angle control as well.

There is another auxiliary device in the circuits "the vector monitoring instrument" i.e. vector monitor which contributes to the optimal setting of the drive while monitoring the actual state of the vectors concerned.

The schematic diagram of the inverter-fed 3-phase induction motor provided with chopper (T7) in the d-c link is presented in Figure 3.

There are four significant new results achieved by the introduction of advanced control electronics such as

(1) reactor is not needed in the d-c link because it is replaced by control electronics and both d-c voltage and d-c current have not to be filtered;

(2) the commutating devices such as commutating capacitors and diodes are also not needed in the inverter if the drive is equipped with a chopper in the d-c link. The chopper can be built by power transistors, conventional thyristors or GTOs.

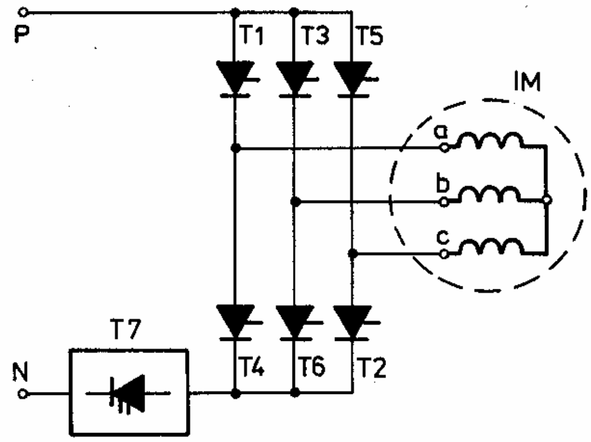

Figure 3 Schematic diagram of inverter-fed 3-phase induction motor equipped with chopper in the d-c link

(3) Discontinuous conduction is being maintained by control electronics and revolving magnetic field can exist continuously even in that case when the conduction in the stator winding of the motor is discontinuous.

(4) Logic control ensures 4-quadrant operation of the drive under the existence of the facts/phenomena described in para. (1 , (2) and (3). To present energy-saving character there can be surplus energy recuperated into the mains during generator action and required torque can be provided with minimised current-input.

NEW THYRISTOR FIRING CODE NETWORKS FOR INVERTER AND CHOPPER CONTROL

There has been such logic circuit developed which fires the appropriate thyristors in any required time and stops firing signal of all thyristors in the time concerned.

The schematic diagram of the new thyristor firing code networks developed especially for the inverter and chopper control is presented in Figure 4.

The logic functions of code network are:

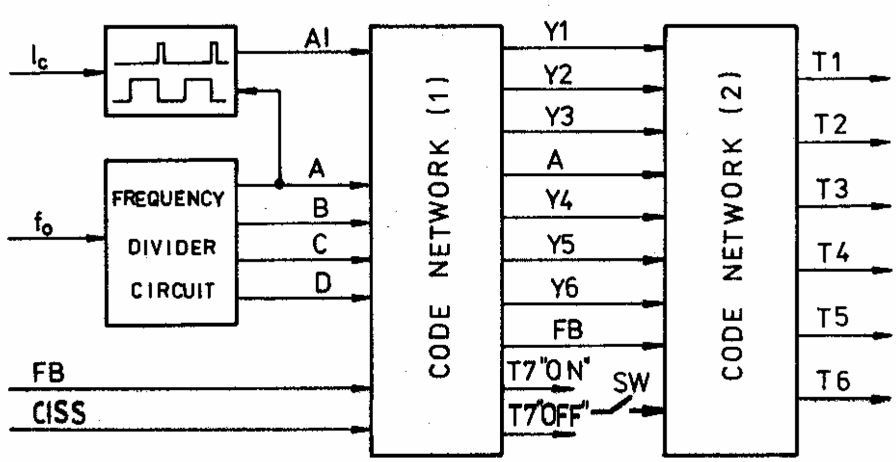

Figure 4

New thyristor firing code networks for inverter and chopper control.

Input signals are indicated in Figure 2 and output signals are available from logic functions given in the next page.

$Y1=\overline{D}\cdot\overline{C}\cdot CISS\cdot\overline{AI}$

$Y2=(\overline{D}\cdot(\overline{C}\cdot B+C\cdot\overline{B})\cdot FB+\overline{B}\cdot(\overline{D}\cdot\overline{C}+D\cdot C)\cdot\overline{FB})\cdot CISS\cdot\overline{AI}$

$Y3=(\overline{B}\cdot(\overline{D}\cdot C+D\cdot\overline{C})\cdot FB+D\cdot(\overline{C}\cdot B+C\cdot\overline{B})\cdot\overline{FB})\cdot CISS\cdot\overline{AI}$

$Y4=D\cdot\overline{C}\cdot CISS\cdot\overline{AI}$

$Y5=(D\cdot(\overline{C}\cdot B+C\cdot\overline{B})\cdot FB+\overline{B}\cdot(\overline{D}\cdot C+D\cdot\overline{C})\cdot\overline{FB})\cdot CISS\cdot\overline{AI}$

$Y6=(\overline{B}\cdot(\overline{D}\cdot\overline{C}+D\cdot C)\cdot FB+\overline{D}\cdot(\overline{C}\cdot B+C\cdot\overline{B})\cdot\overline{FB})\cdot CISS\cdot\overline{AI}$

$T7\text{"ON"} = CISS\cdot\overline{AI}$

$T7\text{"OFF"} = CISS\cdot AI$

The output logic functions of code network (2) can be determined in the following way:

$T1=Y1+SW\cdot(FB\cdot A+\overline{FB}\cdot\overline{A})\cdot Y5\cdot Y6$

$T2=Y2+SW\cdot(FB\cdot A+\overline{FB}\cdot\overline{A})\cdot Y1\cdot Y6$

$T3=Y3+SW\cdot(FB\cdot A+\overline{FB}\cdot\overline{A})\cdot Y1\cdot Y2$

$T4=Y4+SW\cdot(FB\cdot A+\overline{FB}\cdot\overline{A})\cdot Y2\cdot Y3$

$T5=Y5+SW\cdot(FB\cdot A+\overline{FB}\cdot\overline{A})\cdot Y3\cdot Y4$

$T6=Y6+SW\cdot(FB\cdot A+\overline{FB}\cdot\overline{A})\cdot Y4\cdot Y5$

REVOLVING CURRENT FIELD STEPPING AROUND BY 60 OR 30 DEGREES WITHOUT CURRENT COMMUTATION

The objectives to be implemented by control electronics are as follows:

(a) Field stepping around by 60 degrees:
- the first step is to break the current carrying in the windings concerned,
- the 2nd step is to prepare the current path of the required windings,
- the 3rd step is to provide the current in the required windings by the synchronous firing of the appropriate thyristors.

(b) Field stepping around by 30 degrees:

To carry out the previous steps in such a way that in the 3rd step the appropriate thyristors should be fired in order to carry the current in two windings for the time equivalent to 30 degrees then to carry the current in all the 3 windings for also 30 degrees.

In both cases the current is broken by switch-off state of the d-c chopper. The chopper circuit incorporates a capacitor which receives considerable portion of energy existing in motor windings after the switch-off position and the current-break occurs at the current commutation.

The rotation of the phasor indicating current field (Figure 5) can be stepped around by 60 degrees e.g. in backward directional rotation in the following way:

(a) after switching off the chopper the thyristors T1, T6 are fired, then

(b) after duration equivalent to 60 degrees the current is broken by the chopper and

(c) switching on the chopper the thyristors T5, T6 are fired. To continue this process according to the thyristors firing indicated in Figure 5 the revolving field is provided.

Figure 6 presents that case when after the length of time equivalent to 30 degrees all 3 thyristors T1, T5 and T6 will be fired during the other 30 degrees left. This additional process creates a revolving field stepping around now by 30 degrees.

INFLUENCE OF CURRENT FIELD STEPPING BY 30 DEGREES ON TORQUE DEVELOPMENT

Assuming identical current and flux fields plus torque angle it is evident from Figures 7 and 8 that torque-ripple is far lower at field stepping by 30 degrees than by 60 degrees and in addition, the induction has surplus torque in some respects. The result is that the new drive works with less current-input, less losses

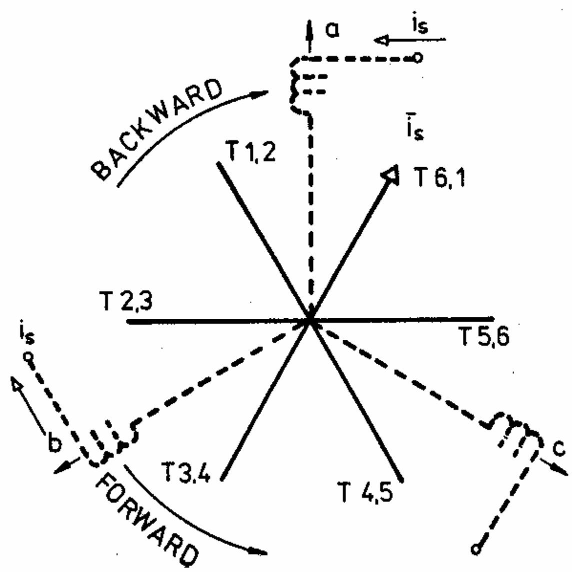

Figure 5 Current space phasor by field stepping of 60 degrees

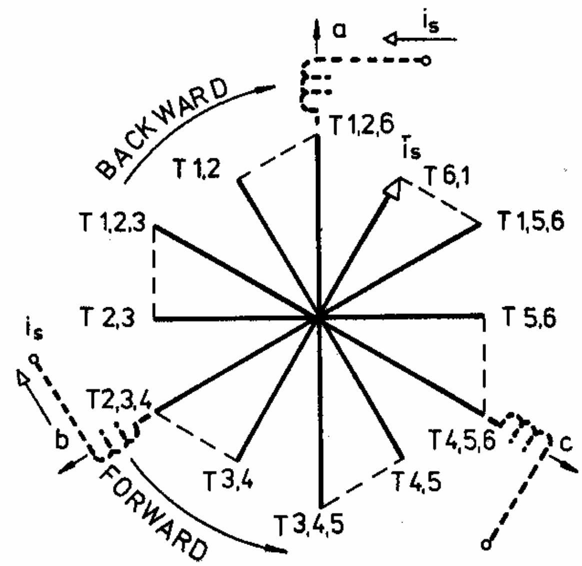

Figure 6 Current space phasor by field stepping of 30 degrees

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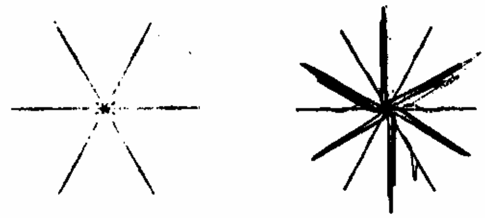
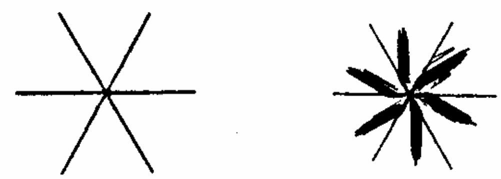
OSCILLOSCOPE RECORDS

Field Stepping of		Field Stepping of	
60	30	60	30 Degrees



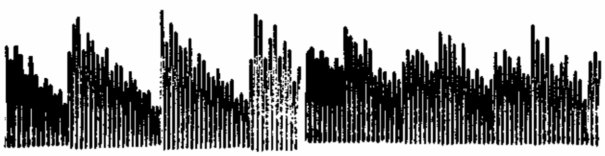
Current space phasors
Small load
50 r.p.m.



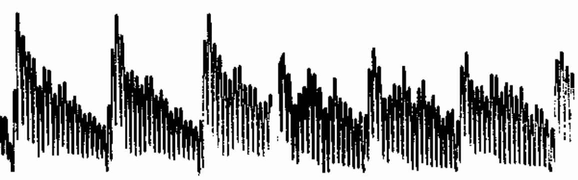
Current space phasors
Medium load
50 r.p.m.

Current versus time functions
Small load
50 r.p.m.

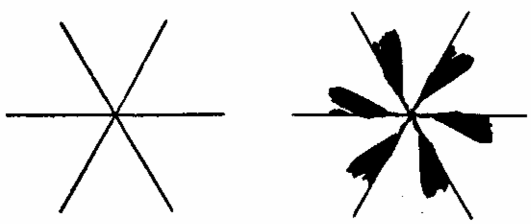
Current versus time functions
Medium load
50 r.p.m.



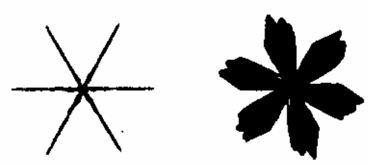
Torque versus time functions
Small load
50 r.p.m.



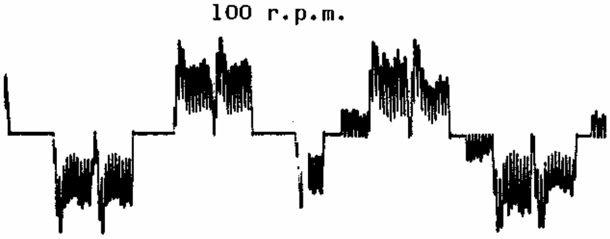
Torque versus time functions
Medium load
50 r.p.m.



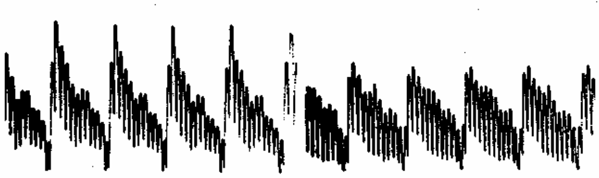
Current space phasors
Rated load
100 r.p.m.



Current space phasors
Small load
720 r.p.m.



Current versus time functions
Rated load
100 r.p.m.



Torque versus time functions
Rated load
100 r.p.m.

Remarks:

(1) Oscilloscope records are presented here in order to compare the current space phasors plus the current versus time and the torque versus time functions recorded at field stepping of 60 and 30 degrees as well.

(2) The current space phasors at rotational speed 720 r.p.m. are recorded by very long-term storage, therefore all possible current-paths can be observed.

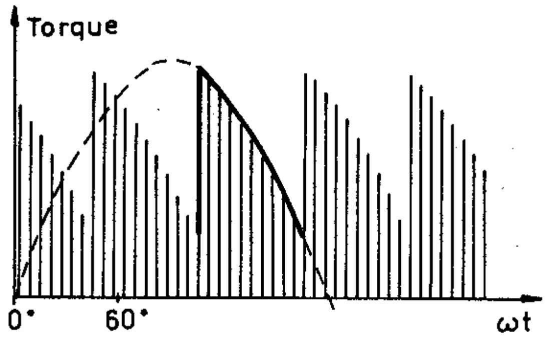


Figure 7 Torque versus time function by field stepping of 60 degrees

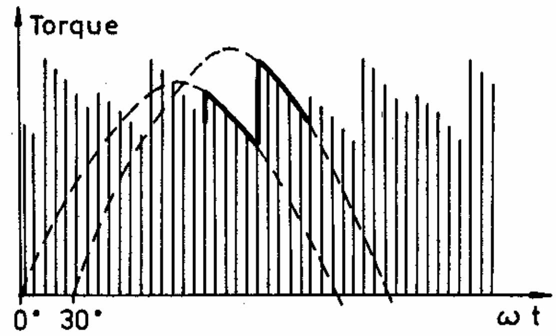


Figure 8 Torque versus time function by field stepping of 30 degrees

and even with higher efficiency. The oscilloscope records presented on the previous page verify theoretical considerations and present favourable dynamic performances of the drive.

CONCLUSIONS

The paper presents a newly developed CSI-fed induction motor drive and compares the performances of a CSI-fed induction motor by field stepping of 60 degrees with the other one of 30 degrees.

There can be a brief account on the new performances verified by the appropriate oscilloscope records given as follows:

(a) the fundamental of the current by the field stepping of 30 degrees can aproach the sinusoidal wave in a more precise way than by the 60 degrees stepping.

(b) The current phasor is standing only for the duration equivalent to 30 degrees instead of the previous 60 degrees and torque is being developed during this length of time by the aid of the revolving magnetic flux. Therefore, particularly at low speed torque-ripple is far more favourable than before even without amplitude-modulation, too.

The patented main circuit and firing logic provide outstanding technical parameters verified by long term tests performed recently on the first industrial product.

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