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Military Technical College
CAIRO - EGYPT

VARIABLE FREQUENCY STARTING OF A SYNCHRONOUS MOTOR FED FROM A VOLTAGE SOURCE INVERTER

S.S.ROWIHAL ** M.H.OMRAN * S.A.GAWISH **

ABSTRACT

The starting methods of synchronous motors are discussed generally. A new technique based on an open loop control starting system of a synchronous motor fed from a voltage source inverter emplementing Gate Turn Off thyristors (G.T.O) and a single phase half controlled bridge rectifier is presented. An accurate model of the Rectifier-Inverter-Motor set is developed to simulate the motor response during start-up. A comparison between the fixed frequency starting and the variable frequency starting is presented.

1. Introduction :

The starting methods of synchronous motors depend very much on the requirements and conditions. However, the static starting devices have proved a very efficient way not only in starting the motor to the required predetermined speed; but also in driving the motor at variable speeds.

The methods of start-up employed for synchronous motors may be classified as shown in Fig. 1.

The use of mechanical methods of start-up is limited due to economical and practical reasons [1] (in addition to the space they occupy, they continue running after they had fulfilled their task).

The asynchronous starting at a fixed frequency as an induction motor by the help of damper winding is advantageous in shortening the starting time, but a high reactive current is drawn which affects the supply circuit. Moreover, the inrush current imposes stresses on the motor.

The rotary frequency starting and Unger connection have their own drawbacks such as, the usage of several machines (Induction motor + Asynchronous generator in Unger connection, for example).

The static frequency starting employing current source inverter where the machine is supplied with variable frequency-variable voltage, reduces the transient loading on the supply

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* Col.Eng. Department of Electrical Power Engineering M.T.C.

** Col.Dr. Department of Electrical Power Engineering M.T.C.

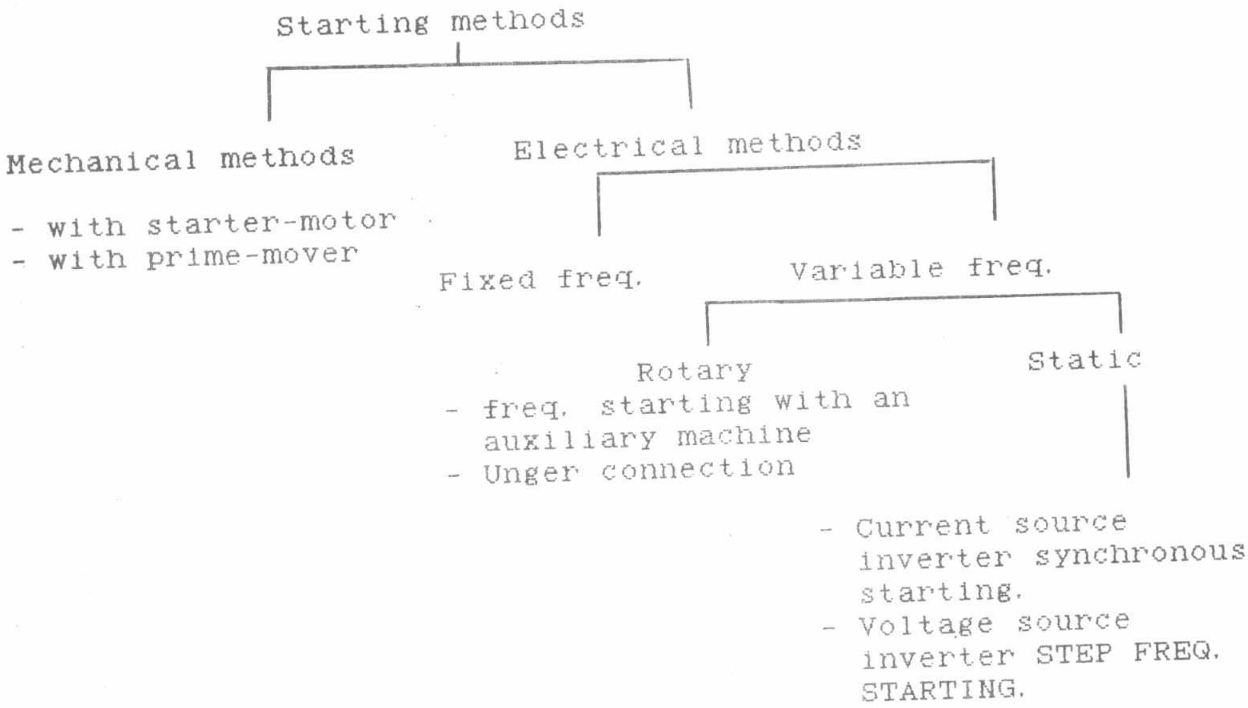


Fig. 1. Classification of starting methods of synchronous motors

and avoids large dips in the voltage. In this method, the frequency rises continuously from zero to the operating frequency and the rotor is synchronised with the rotating field of the stator. The relief being substantial compared to synchronous start at a fixed frequency. The synchronous starting which employs static frequency starting system is particularly economic when the same system is used to start-up several machines one after another. This scheme is justified only for large synchronous motors without damper windings or with damper windings intended solely for damping and do not contribute to the starting process. So it is not used in most of small or medium synchronous motors provided with damper windings. Moreover, the starting time is increased substantially and excitation is to be connected even from standstill. Thus special means of excitation must be available. The load torque at starting must be very small otherwise the machine will not be able to start-up.

2. Variable Frequency Start-up

Since most of small and medium size synchronous motors and majority of synchronous condensers are provided with damper windings for start-up purposes, an alternative technique is to be used rather than the synchronous starting.

A variable frequency starting scheme with a voltage source inverter, offers a simple and reliable alternative.

In this scheme, the machine is started-up as an induction motor with constant voltage per cycle. As a matter of fact the technique may be called "STEP FREQUENCY ASYNCHRONOUS STARTING TECHNIQUE".

The frequency is increased in steps starting from a value which is reasonably low (typically 10% of the rated frequency). Once the speed of the rotor approaches the speed of the stator rotary magnetic field (95%), the input frequency is increased by a step (5-10Hz). In order to keep the torque constant, the air-gap flux must be maintained constant as the frequency increases. This is achieved by keeping the ratio between the counter emf. produced by the resultant air-gap flux and the frequency, constant. As the stator leakage impedance is very small (2-15%) [1], so the counter emf is nearly equal to the supply voltage, and the torque is kept constant by keeping the ratio of the supply voltage to the frequency constant, which is known as constant voltage per cycle control.

Increasing the frequency in steps and consequently the input voltage, the motor will speed up. When the speed approaches the sinchronous speed (95%), the machine is synchronised by supplying the field winding from suitable dc source.

The Open Loop Frequency and Voltage Control

The desired frequency of the inverter is controlled by a low power master generator that generates train of pulses. These pulses are directed to the gating circuits of the G.T.Os of the voltage source inverter to switch the required thyristor On or OFF according to a switching pattern determined by a microprocessor and logic circuits.

The voltage control is achieved by controlling the firing angle of the rectifier bridge. The value of the firing angle is determined by the microprocessor in such a way to keep the constant voltage per cycle ratio.

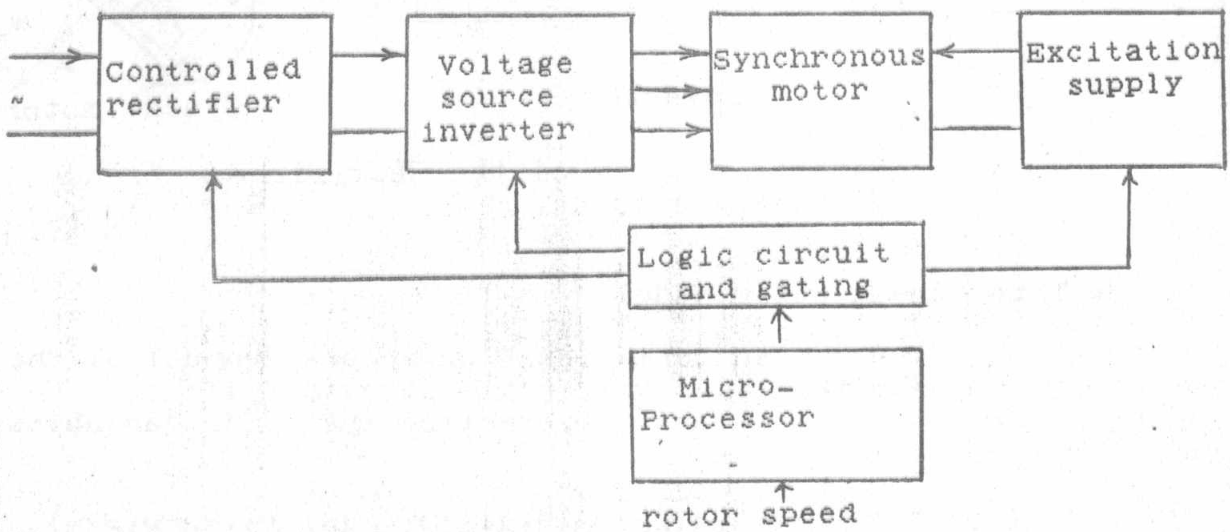


Fig. 2. A simplified block diagram of an open loop variable frequency start-up system

The switching on of the field excitation is achieved also by a signal from the microprocessor and logic circuit when the speed reaches 95% of the synchronous speed.

A simplified block diagram of the control scheme is shown in Fig. 2.

3. Digital Model

The digital model of the system is intended to simulate accurately a three phase synchronous motor fed from a three phase voltage source inverter and a single phase half controlled rectifier bridge.

The circuit diagram of the Rectifier-Inverter-Motor set is shown in Fig. 3. The triggering circuits are eliminated for simplification.

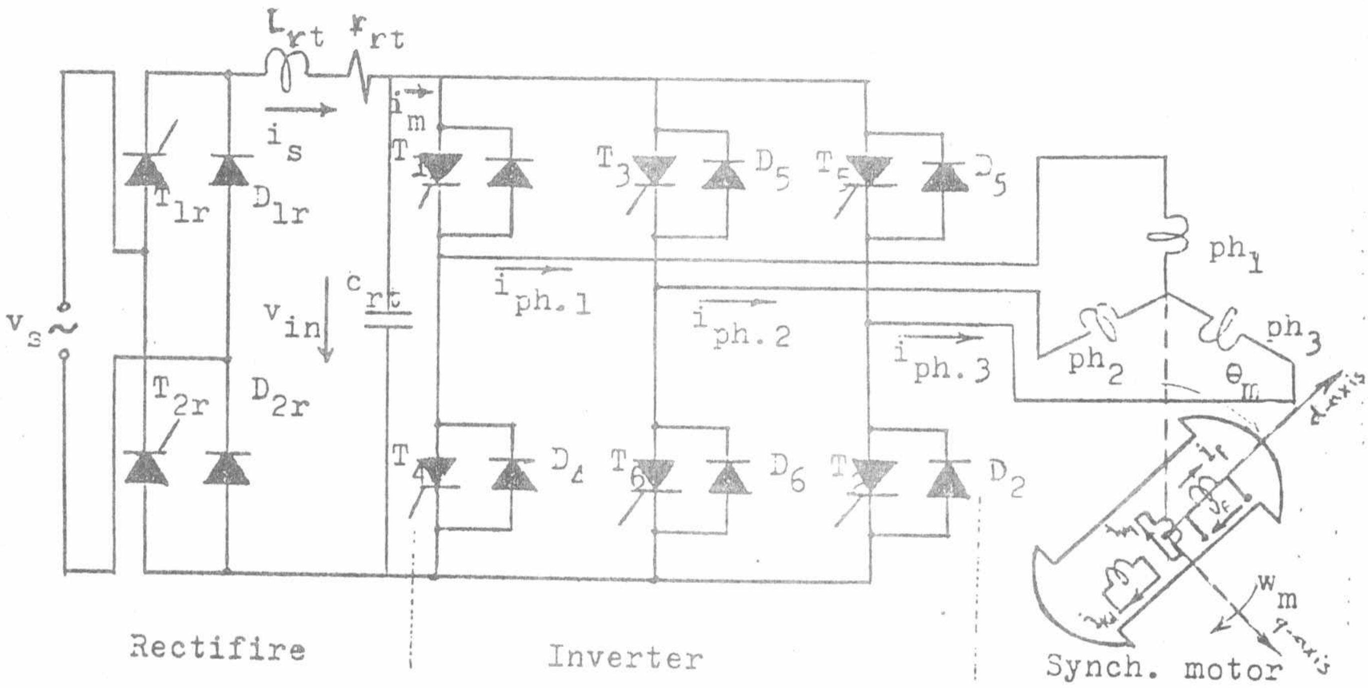


Fig.3. Circuit diagram of the Rectifire-Inverter-Motor set

The Synchronous Motor Model

Based on PARK's transformation, an accurate model of the synchronous motor with damper winding is developed [1].

The state space equations representing the motor variables can be written as following

$$pi_d = w_b[-a_{11}i_d+a_{12}i_f+a_{13}i_{kd}+w_m(a_{14}i_q+a_{15}i_{kq})-b_{11}v_d-b_{12}v_f]$$

$$pi_f = w_b[\ a_{21}i_d+a_{22}i_f+a_{23}i_{kd}+w_m(a_{24}i_q+a_{25}i_{kq})-b_{21}v_d-b_{22}v_f]$$

$$pi_{kd} = w_b[\, a_{31}i_d + a_{32}i_f + a_{33}i_{kd} + w_m(a_{34}i_q + a_{35}i_{kq}) + b_{31}v_d - b_{32}v_f]$$

$$pi_q = w_b[-w_m(a_{41}i_d + a_{42}i_f + a_{43}i_{kd}) - a_{44}i_q + a_{45}i_{kq} + b_{44}v_q]$$

$$pi_{kq} = w_b[\, w_m(a_{51}i_d + a_{52}i_f + a_{53}i_{kd}) + a_{54}i_q - a_{55}i_{kq} - b_{54}v_q]$$

$$pi_o = w_b(- r_s i_o + v_o/L_o)$$

and,

$$pw_m = -D'w_m + (1/2H)[(KM_f i_f i_q + (L_d L_q) i_d i_q - KM_{kd} i_q i_{kd} - KM_{kq} i_d i_{kq})/3 - T_L]$$

$$p\theta = w_b\, w_m$$

Where a_{11}, a_{12} ....a_{55} and b_{11} b_{12}.........b_{54}

depend on the motor parameters (Appendix A).

The set of first order nonlinear differential equations is completely representing the synchronous motor in both transient and steady state.

Voltage Source Inverter Model

The inverter under consideration is a three phase bridge inverter with six Gate Turn Off thyristors (Th_1 - Th_6) and six diodes (D_1 - D_6). Each thyristor and corresponding diode is considered as a bidirectional switch. The use of the G.T.Os may allow us to assume an ideal switching with instantaneous commutation. The gating signals to switch on and switch off the thyristors are assumed to be automatically available.

To simplify the analysis the following assumptions are considered :

1) Ideal switching devices
2) Instantaneous commutation
3) Automatically available gating signals to the thyristors (on and off)
4) The mode of operation of the inverter is 180^{o} conduction

The following logic variables are assigned to the thyristors, diodes and bidirectional switches :

- Thyristor : "1" and "0" for conduction and nonconduction respectively.
- Diodes : "0" and "1" for nonconduction (corresponding thyristor is conducting) and conduction (corresponding thyristor is non conducting) respectively
- Bidirectional switches "1", "-1" and "0" for positive, negative and zero current respectively.

The values of the logic variables are determined each time step and hence, the output voltage to each of the motor phases is determined.

The switching pattern of the inverter and the corresponding phase voltage as a function of the angle θ where $\theta = wt$ ($w = 2\pi f$) can be summerised as following :

θ	Th_1	Th_2	Th_3	Th_4	Th_5	Th_6	V_{ph1}	V_{ph2}	V_{ph3}
0^0-60^0	1	0	0	0	1	1	1/3	-2/3	1/3
60^0-120^0	1	1	0	0	0	1	2/3	-1/3	-1/3
120^0-180^0	1	1	0	1	0	0	1/3	1/3	-2/3
180^0-240^0	0	1	1	1	0	0	-1/3	2/3	-1/3
240^0-300^0	0	0	1	1	1	0	-2/3	1/3	1/3
300^0-360^0	0	0	1	0	1	1	-1/3	-1/3	2/3

The values 1/3, 2/3, -1/3, -2/3 are given here as a ratio of the input of the inverter (v_{in}).

Model of The Rectifier

The single phase half controlled rectifier is represented by two more differential equations. The two equations differ according to the mode of operation of the rectifier [3].

Mode I

One thyristor and one diode are conducting

$$pi_s = -(r_{rt}/L_{rt})i_s + (1/L_{rt})v_s - (1/L_{rt})v_{in}$$

$$pv_{in} = (1/C_{rt})i_s - (1/C_{rt})i_m$$

Mode II

Two diodes are freewheeling

$$pi_s = -(r_{rt}/L_{rt})i_s - (1/L_{rt})v_{in}$$

$$pv_{in} = (1/C_{rt})i_s - (1/C_{rt})i_m$$

Mode III

The current i_s equals to zero (if negative, it will be zero due to the diodes)

$$pv_{in} = -(1/C_{rt})i_m$$

The current i_m will be the current of one of the motor phases according to the mode of the inverter.
The mode of the rectifier is determined according to the angle of firing as following :

Mode I $\pi > w_s t > \alpha$

Mode II $\alpha > w_s t >$ zero

Mode III $i_s \leq$ zero

The equations of the rectifier are combined with those of the motor to form a complete set of nonlinear differential equations which, together with the time dependant switching pattern of the inverter, completely describes the system of the Rectifier Inverter Motor set. The equations are solved using the numerical integration technique to analyze both the dynamics and statics of the motor in the time domain.

Here the modified Runge Kutta-Gill (RKG) is used.

Simulation of the Step Frequency Asynchronous Starting :

This is achieved using the digital model developed by changing the input frequency from an initial value (f_o) chosen to be 10% of the rated frequency, in steps each of a value Δf which is chosen to be 5hz till reaching the final rated frequency (f_{end}).

The increase of the input frequency from a certain value f to another value f + Δf is accomplished when the speed of the rotor reaches a value w_m = 95% ($2\pi f$).

Each increase in the input frequency is accompanied by a decrease in the firing angle α in such away to keep the ratio v/f constant.

When the rotor speed reaches 95% of the rated value, the field excitation is applied to synchronise the motor.

4. Simulation Results

The transient response as well as the steady-state waveforms are shown in Fig.4.a and Fig.4.b for the variable frequency starting and fixed frequency starting respectively.

The waveforms, except the speed waveform, are observed at three intervals corresponding to start-up, synchronisation and steady-state. Each interval spans 0,2 second. The speed waveforms are observed throughout the whole range.

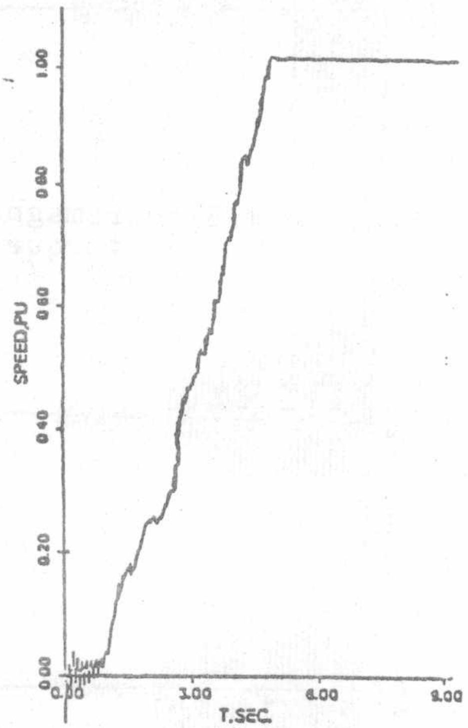


Fig.4.a.1. Speed waveform

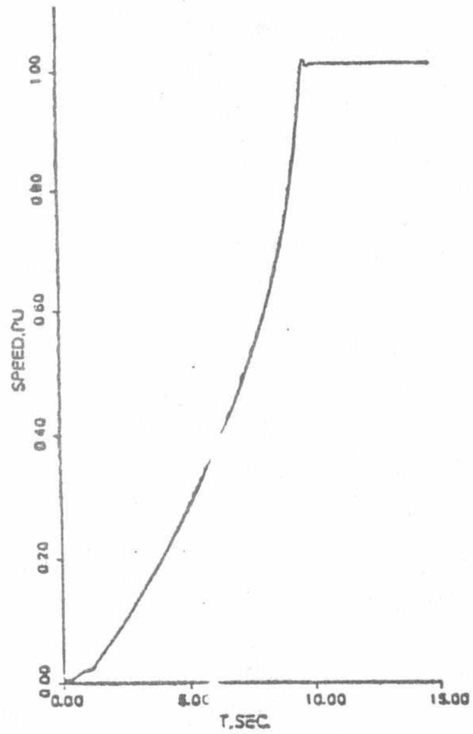


Fig.4.b.1.Speed waveform

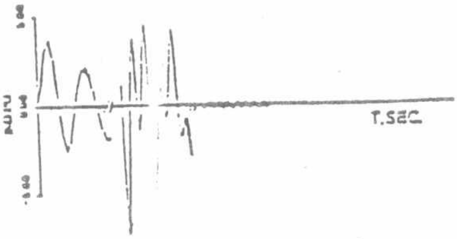


Fig.4.a.2.Direct axis current

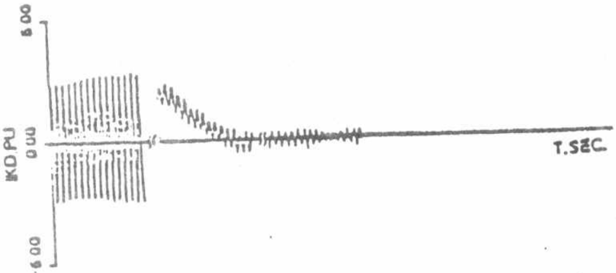


Fig.4.b.2.Direct axis current

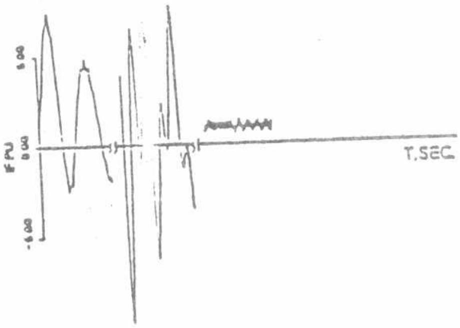


Fig.4.a.3 Field current

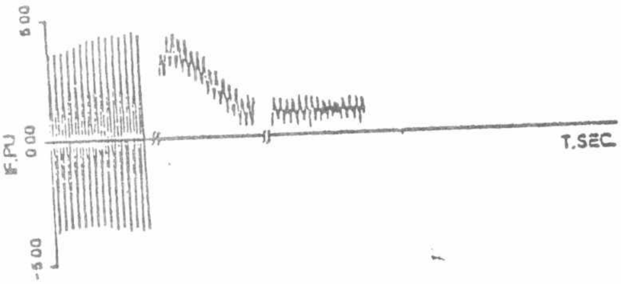


Fig.4.b.3.Field current

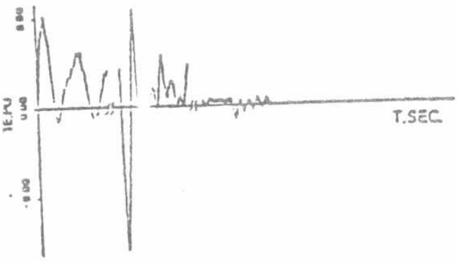


Fig.4.a.4.Electromagnetic torque

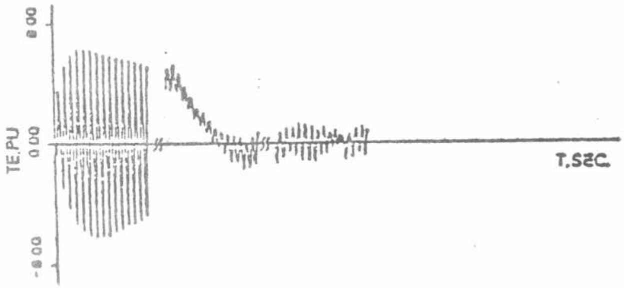
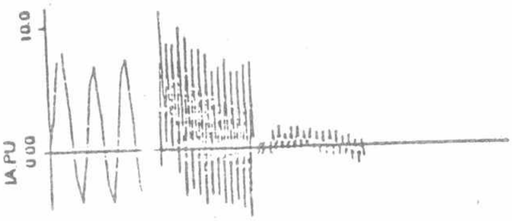
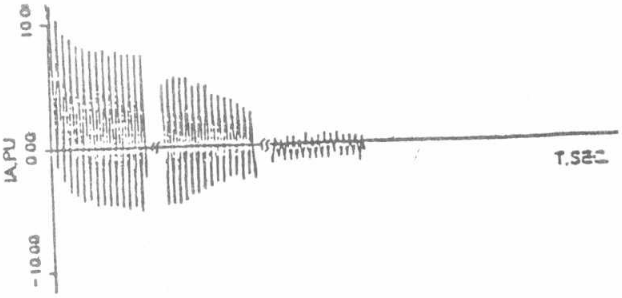
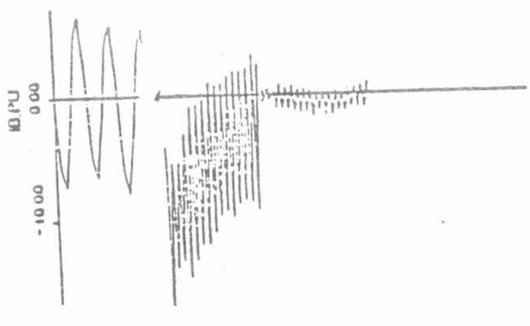
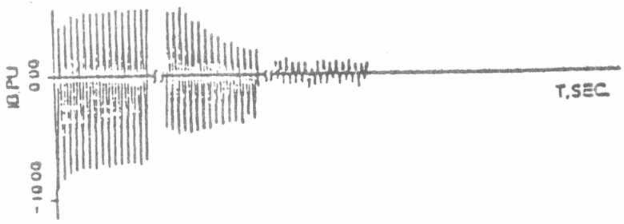


Fig.4.b.4.Electromagnetic torque









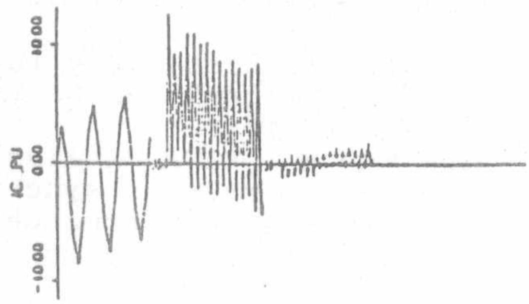


Fig.4.a.5.Phase currents

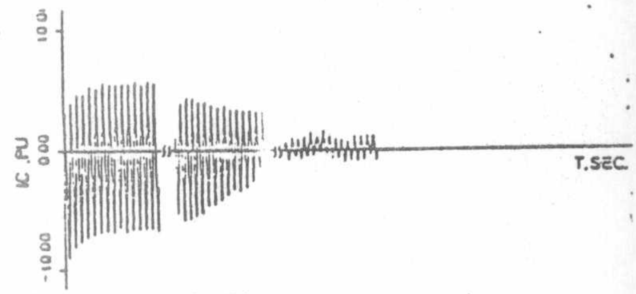


Fig.4.b.5.Phase currents

5. Comparison Between Fixed Frequency and Variable Frequency Starting Techniques :

The use of the variable frequency technique reduces the starting time approximately to half the time when the start up is performed at fixed frequency.

At low frequencies and voltages, the rectifier output-due to the increase of the firing angle-contains ripples representing the harmonics (double frequency and multibles) which affects slightly the starting performance in the variable frequency method.

The inrush current may be reduced in the variable frequency technique, thanks to the emplementation of the microprocessor which may be programming to obtain the optimum frequency, voltage and switching pattern throughout the starting period.

The effect of the initial rotor angle position is more soundy when variable frequency technique is used, rather than when fixed frequency method is used which must be taken into consideration.

6. Conclusions :

The open-loop variable frequency starting technique with voltage source inverter is simple and reliable Moreover, the technique reduces substantially the starting time.

The use of the microprocessor will lead us to more improvement in the starting performance.

The effect of the rectifier harmonics may be decreased if a three phase bridge is used instead of the single phase bridge used.

The initial rotor angle position must be taken into consideration due to its pronounced effect on the starting performance.

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List of Symboles :

v_{sd} , i_{sd}	direct-axis voltage and current, pu
v_{sq} , i_{sq}	quadrature-axis voltage and current, pu
v_f , i_f	field voltage and current, pu
r_s	stator resistance per phase, pu
r_f	field resistance, pu
r_{kd} , r_{kq}	d-axis and q-axis damper winding resistance, pu
L_{sd}	d-axis synchronous inductance, pu
L_{sq}	q-axis synchronous inductance, pu
L_{ff}	field self inductance, pu
L_{kd} , L_{kq}	d-axis and q-axis damper winding self inductance, pu
M_f	mutual inductance "stator & field winding", pu
M_{kd}	mutual inductance"stator & d-axis damper winding", pu
M_{kq}	mutual inductance"stator & q-axis damper winding", pu
M_r	mutual inductance"stator field & d-axis windings", pu
H	inertia constant, sec
T_{EM}	electromagentic torque, pu
T_L	load torque, pu
w_b	base angular frequency, rad/sec
w_m	motor speed, pu
θ_m	rotor angle, electrical radians
i_m	motor current, pu

6

K	constant = 3/2.
r_{rt} , L_{rt}	series resistance and inductance, pu
c_{rt}	perallel capacitance, pu
v_s	supply voltage ($vs = V_{sm} \sin w_s t$), pu
w_s	supply frequency, rad/sec
i_s	supply current, pu
$T_1 - T_6$	inverter thyristors (Gato Turn Off thyristors)
$D_1 - D_6$	inverter diodes
T_{r1} , T_{r2}	rectifier thyristors
D_{r1} , D_{r2}	rectifier diodes
θ_o	initial rotor angle, electrical radians

Appendix A

$a_{11} = r_s/\sigma_1 \sigma_5 L_d$

$a_{12} = r_f(KM_f/L_d - \mu_1 M_r/\sigma_3 L_{kd})/\sigma_1 \sigma_5 L_f$

$a_{13} = \mu_1 r_{kd}/\sigma_1 \sigma_3 \sigma_5 L_{kd}$

$a_{14} = L_q/\sigma_1 \sigma_5 L_d$

$a_{15} = KM_{kq}/\sigma_1 \sigma_5 L_d$

$a_{21} = r_s(KM_f/L_f - \mu_2 M_r/\sigma_3 L_f)/\sigma_1 \sigma_5 L_d$

$a_{22} = r_f/\sigma_3 L_f + a_{12} a_{21}/a_{11}$

$a_{23} = r_{kd} M_r/\sigma_3 L_f L_{kd} + a_{13} a_{21}/a_{11}$

$a_{24} = a_{14} a_{21}/a_{11}$

$a_{25} = a_{15} a_{21}/a_{11}$

$a_{31} = r_s \sigma_2/\sigma_1 \sigma_3 \sigma_5 L_d$

$a_{32} = r_f M_r/\sigma_3 L_{kd} L_f - a_{12} a_{21}/a_{11}$

$a_{33} = r_{kd}/\sigma_3 L_{kd} + a_{13} a_{31}/a_{11}$

$a_{34} = a_{14} a_{31}/a_{11}$

$a_{35} = a_{15} a_{31}/a_{11}$

$a_{41} = L_d/\sigma_2 L_q$

$a_{42} = KM_f/\sigma_2 L_q$

$a_{43} = Km_{kd}/\sigma_2 L_q$

$a_{44} = r_s/\sigma_2 L_q$

$a_{45} = r_{kd} KM_{kq}/\sigma_2 L_q L_{kq}$

$a_{51} = KM_{kq} L_q/\sigma_2 L_q L_{kq}$

$a_{52} = KM_f KM_{kq}/\sigma_2 L_q L_{kq}$

$a_{53} = KM_{kd} KM_{kq}/\sigma_2 L_q L_{kq}$

$a_{54} = r_s KM_{kq}/\sigma_2 L_q L_{kq}$

$a_{55} = r_{kq}/\sigma_2 L_{kq}$

$b_{11} = 1/\sigma_1 \sigma_5 L_d$

$b_{12} = (KM_f/L_d - \mu_1 M_r/\sigma_3 L_{kd})\sigma_1 \sigma_5 L_f$

$b_{21} = b_{11} a_{21}/a_{11}$

$b_{22} = a_{22}/r_f$

$b_{31} = b_{11} a_{31}/a_{11}$

$b_{32} = a_{32}/r_f$

$b_{44} = 1/\sigma_2 L_q$

$b_{54} = KM_{kq}/\sigma_2 L_q L_{kq}$

and

$\sigma_1 = 1 - (KM_f)^2/L_f L_d$

$\sigma_2 = 1 - (KM_{kq})^2/L_q L_{kq}$

$\sigma_3 = 1 - (M_r)^2/L_f L_{kd}$

$\sigma_4 = 1 - (KM_{kd})^2/L_d L_{kd}$

$\sigma_5 = 1 - (1-\sigma_4 + (1-\sigma_1)(1-\sigma_3) - 2KM_f KM_{kd} M_r/L_f L_d L_{kd})/\sigma_1 \sigma_3$

$\mu_1 = (KM_{kd} - KM_f M_r/L_f)/L_d$

$\mu_2 = (KM_{kd} - KM_f M_r/L_f) L_{kd}$

Appendix B

The synchronous motor parameters (per unit)

L_d	1.106
L_f	1.2422
L_{kd}	1.36422
L_q	0.642
L_{kq}	0.7182
KM_f , KM_{kd} & M_r	1.00
KM_{kq}	0.536
r_s	0.00366
r_f	0.000804
r_{kd}	0.03803
r_{kq}	0.03548
H	3 KW. sec/KVA

and,

V_{sm}	2.45
θ_o	180^o (3.14 rad.)
T_L	0.0
r_{rt}	0.001
L_{rt}	0.02
C_{rt}	0.25