DYNAMIC BEHAVIOUR OF THE THREE PHASE INDUCTION MOTOR USED IN THE SLIP ENERGY RECOVERY DRIVE

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Summary *:In the case of injection of a voltage to the rings, the produced torques with high amplitude and the related stator currents are constituted a dangerous situation during the dynamic behaviour of the 3 phase induction machine used in the slip power recovery system (Kramer System)*

Therefore, in this paper, these torques and current are examined. In the analysis, the motor is modelled in d-q axes revolving with syncronous speed.

Key Words: *Wound Induction Machine, Slip Power, Recovery Of The Slip Power, Mathematical Model, Numerical Analysis, Injected Voltage*

1-INTRODUCTION

One of the method to get a variable speed is the power recovery system. Since some partion of the energy drawn by stator is recovered, the efficiency of the system is high compared to the other method used for the speed control. By this method, the speed control is done only in the under-syncronous speed region[1]

On this topics, some research has been done. In the reference [2], the behaviour of the machine has analysed using a hybrid model including rectifier and inverter. In [2], emphasised that with an appropriate rectifier-inverter circuit, a speed adjustment can be realised in the sub syncronous speed region using the slip energy recovery system.

In reference [3], an alternative starting method which includes two coppers placed between rectifier and inverter is examined.

In reference [4], a method similar to the method given in reference [3] has been developed and this method, the harmonics in the power recovered has been reduced.

In figure 1, Kramer System recovering the slip power is shown with a similar system in which the rectifier changes place with inverter, power can be injected to the rotor, so the motor can be worked in the supersyncronous region.

The injected voltage may have positive or negative polarity with respect to the voltage applied to the stator [5,6]. If the voltage in phase with the stator voltage is injected the power recovered will increase. This causes the slip to increase and hence, the speed to decrease. Thus, it will be possible to adjust the speed under the syncronous speed.

In a similar way, if a voltage opposite in phase with the stator voltage is injected the speed can be adjusted above the syncronous speed since some power will be injected to the rotor[5]

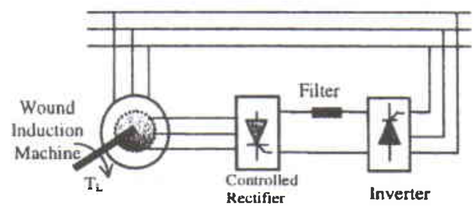

Fig. 1. The slip power recovery system

In this work, first, for the analysis required the induction motor will be modeled in the d-q axes revolving with syncronous speed. Then, the differential equations obtained will be solved taking the operation conditions in to consideration.

2-MATHEMATICAL MODEL OF THE INDUCTION MACHINE

The voltage equation of the induction machine in *abc* axes are

$$V_{abc,s} = r_s\, i_{abcs} + p\,\lambda_{abcs} \quad (1)$$

$$V_{abc,r} = r_r\, i_{abcr} + p\,\lambda_{abcr} \quad (2)$$

where $p=d/dt$ [7]

Since the inductance in equations (1) and (2) are function of θ which depends on time the solution of these are very difficult. Therefore, applying the phase transformation successively the equations (1) and (2) are referred to the d-q axes. Thus, by these transformation the inductances become independent from time and the equations (1) and (2) become

$$v_{qd0s} = r_s\, i_{qd0s} + \omega\lambda_{dqs} + p\lambda_{qd0s} \quad (3)$$

$$v'_{qd0r} = r'_r\, i'_{qd0r} + (\omega - \omega_r)\lambda'_{dqr} + p\lambda'_{qd0r} \quad (4)$$

where;

ω :the speed of the referred axes

ω_r : the speed of the rotor

ω may have three different values as fallow

a) $\omega=0$; reference frame axes are fixed on stator and called as "Stationary Axes"

b) $\omega = \omega_r$; reference frame axes are fixed on rotor and called as " Axis system revolving with rotor speed"

c) $\omega = \omega_s$; reference frame axes are fixed on rotating magnetic field and called as " Axis system revolving with syncronous speed"

These axis system are shown in figure 2.

In the drive system under the consideration, since the voltage applied to the stator and rotor are both symmetric, the axis system revolving with syncronous speed will be adequate to model the machine [7].

After transformation, the stator and rotor currents can be expressed as fallow depending on fluxes.

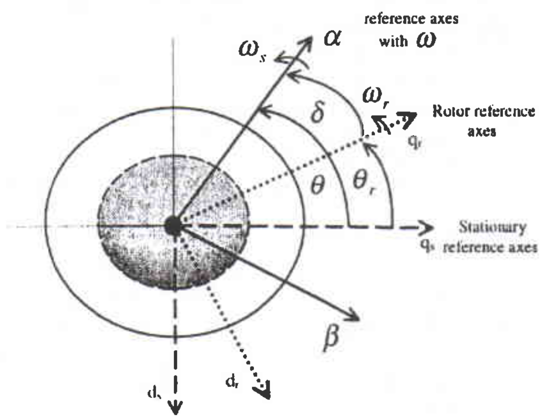

Fig. 2. Reference axes system

$$\begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \\ i'_{qr} \\ i'_{dr} \\ i'_{0r} \end{bmatrix} = \frac{1}{D} \begin{bmatrix} X'_{rr} & 0 & 0 & -X_M & 0 & 0 \\ 0 & X'_{rr} & 0 & 0 & -X_M & 0 \\ 0 & 0 & \frac{D}{X_{ls}} & 0 & 0 & 0 \\ -X_M & 0 & 0 & X_{ss} & 0 & 0 \\ 0 & -X_M & 0 & 0 & X_{ss} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{D}{X'_{lr}} \end{bmatrix} \begin{bmatrix} \varphi_{qs} \\ \varphi_{ds} \\ \varphi_{0s} \\ \varphi'_{dq} \\ \varphi'_{dr} \\ \varphi'_{0r} \end{bmatrix} \quad (5)$$

where

$$D = X_{ss} X'_{rr} + X^2_M \quad (6)$$

The voltage equation of the system

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{0s} \\ v'_{qr} \\ v'_{dr} \\ v'_{0s} \end{bmatrix} = \begin{bmatrix} \frac{r_s X_{rr}}{D} + \frac{p}{\omega_b} & \frac{\omega}{\omega_b} & 0 & -\frac{r_s X_M}{D} & 0 & 0 \\ -\frac{\omega}{\omega_b} & \frac{r_s X_{rr}}{D} + \frac{p}{\omega_b} & 0 & 0 & -\frac{r_s X_M}{D} & 0 \\ 0 & 0 & \frac{r_s}{X_{ls}} + \frac{p}{\omega_b} & 0 & 0 & 0 \\ -\frac{r_r X_M}{D} & 0 & 0 & \frac{r_r X_{ss}}{D} + \frac{p}{\omega_b} & (\frac{\omega - \omega_r}{\omega_b}) & 0 \\ 0 & -\frac{r X_M}{D} & 0 & -(\frac{\omega - \omega_r}{\omega_b}) & \frac{r_r X_{ss}}{D} + \frac{p}{\omega_b} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{r_r}{X_{lr}} + \frac{p}{\omega_b} \end{bmatrix} \begin{bmatrix} \varphi_{qs} \\ \varphi_{ds} \\ \varphi_{0s} \\ \varphi'_{dq} \\ \varphi'_{dr} \\ \varphi'_{0s} \end{bmatrix} \quad (7)$$

Since it includes less terms the fluxes are chosen as state variables in equation (7). Hence, the torque produced expresses in fluxes as fallow

$$T_e = (\frac{3}{2})(\frac{p}{2})(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}) \quad (8)$$

Equation (7) and (8) are not enough to solve the differential equations. Therefore, the motion equation;

$$p\omega_r = \left[(\frac{1}{j})(\frac{2}{P_T})(T_E - T_L - B.\omega_r) \right] \quad (9)$$

is used as a additional equations

3. INJECTION OF A VOLTAGE TO THE RINGS

In order to analysis the effect of the injected voltage the equivalent circuit shown in figure 3 is examined.

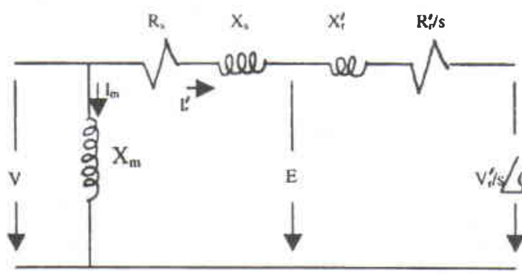

Fig. 3. Approximate equivalent circuit referred to stator

Taking the direction s in this circuit positive and denoting the voltage ratio $(\frac{E_s}{E_r})$ by k the slip and speed for the ideal no-load operation ($T_L \cong 0 \rightarrow I_r \cong 0$) are expressed as below

$$s = (kV_r / E) \quad (10)$$

$$\omega_{m0} = [1 - (kV_r / E)]\omega_{ms} \quad (11)$$

where V_r is in phase with E.

According to equation (11) the no-load speed can be changed from syncronous sped to standstill by varying V_r from 0 to (E/k). Further, if V_r is reversed, from equation (10) slip will be negative and thus, no-load speed will be higher then syncronous speed. That means, according to the polarity of the injected voltage (V_r) two different situation appear [5]. These are;

a) If V_r is positive with respect to stator voltage the motor starts working subsyncronous region since some power will be recovered from rotor.

b) If V_r is negative with respect to stator voltage the motor starts working supersyncronous region

Changing the polarity of V_r and the load torque T_L the following operation modes appear.

a) $\omega_m < \omega_{mc}$ subsyncronous motoring *b)* $\omega_m < \omega_{mc}$ subsyncronous braking

c) $\omega_m > \omega_{mc}$ supersyncronous motoring

d) $\omega_m > \omega_{mc}$ supersyncronous braking

where ω_{mc} is the speed for V_r=0. On the other hand, denoting

P_e : the rotor circuit electrical power
P_g : air-gap power
P_m : mechanical power produced
ω_{ms} :syncronous speed

where produced torque and related mechanical power

$$T = (P_g / \omega_{ms}) \tag{12}$$

$$P_m = T.\omega_m = \frac{P_g}{\omega_{ms}}(1-s)\omega_{ms} = (1-s)P_g \tag{13}$$

Hence,

$$P_e = P_g - P_m = P_g - (1-s)P_g = sP_g \tag{14}$$

and

$$sP_g = P_e = P_r + P_{cr} \tag{15}$$

where

P_r : the power related to V_r
P_{cr} : rotor circuit losses

In the case of power recovery

$$P_m = P_g - P_r - P_{cr} \tag{16}$$

From to above equation the rotor speed is

$$\omega_m = \omega_{ms} - \frac{P_r + P_{cr}}{T} \tag{17}$$

it is obvious that P_r which is injected to or recovered from rotor circuit is affected the rotor speed.

4. SOLUTION OF THE STATE EQUATIONS

The plate values of the motor under the consideration are 3 phase, 220 V, 3 Hp, 60 Hz, 4 Pole, wound-rotor and the equivalent circuit parameters of this machine

R_s=0,435 ohm　　X_{ls}=0,754 ohm
R_r=0,816 ohm　　X_{lr}=0,754 ohm
J = 0,089 kg.m　　X_M=26,13 ohm
B=0,005 Nm/rad/sn

And the load of the machine T_L=10 Nm. The value of the injected voltage V_r are given in Table 1.

Table 1. Various values of V_r versus time

t (sn)	0	2	4	6	8	10	12	14	16	18
V_r (V)	0	20	40	60	0	-20	-40	-60	0	

From the solution of the state equation of the drive system for the values of the V_r in table 1. The following figures can be obtained. Now, let us analysis the behaviour of the system evaluating these figures. In figure 5;

a) In the time interval (0-2 s) the motor works with a short-circuited rings (V_r=0) after transient state it starts working in the subsyncronous motoring mode.
b) In the same figure in the time interval (2-8s) a positive voltage (+V_r) is injected to the rings decreasing the value of the V_r step by step. Under the constant torque, some power will be recovered from rotor, hence speed will be reduced. In this case, again the motor continues working in subsyncronous motoring mode. As understood well, the speed of the motor will be adjusted by changing the value of the positive voltage V_r.
In this mode of operation, if the +V_r is applied with a large step, some pulses with high amplitude may occure in stator currents and hence in the torque produced. This pulses of torque with negative polarity may create a dangerous situation from mechanical point of view. They may cause some mechanical troubles. So, the attentions must focus on the step value of +V_r. Large pulses in the stator currents may affect the power supply and cause some trouble in windings of the stator.
c) In the time interval (8-10s) the rings are short-circuited, the speed starts increasing since the power recovery is not present.
d) In the time interval (10-16 s) a negative V_r is injected to the rings and thus some power is injected to the rotor. This causes to speed to increase and to work in supersyncronous region.
e) In the time interval (16-18 s) the rings are again short-circuited, hence, the speed starts decreasing since the injected power is not present

The speed-torque characteristic including the above points is given in figure 7. From this figure it is seen that the motor can be work in subsyncronous and supersyncronous braking mode as well as motoring mode using rectifier-inverter or inverter-rectifier

Since some power is recovered from rotor the breaking by this method increases the efficient. Therefore the speed control of the wounded induction motor with large power is implemented by this method.

5-CONCLUSION

In the injection of the voltage to the rings in the slip power recovery drive system.

a) The injected voltage (+V_r) should be in small step length.
b) A large increase in (+V_r) causes some pulses with large amplitude in the stator currents and torque produced. In the powerfull system these current pulses may affect the supply and burn the winding of the machine. The positive pulses in torque causes the machine load to display an irregular performance. The negative pulses in torque creates more dangereous mechanical situations. For instance, it causes the shaft of the motor to be broken or to be twisted. Also, it causes the load to display an irregular performance.
c) Adjustment of (+V_r) with smoll step length provides a fine speed control.

Some negative aspects of this method such as current and torque pulses with large amplitude can be overcome

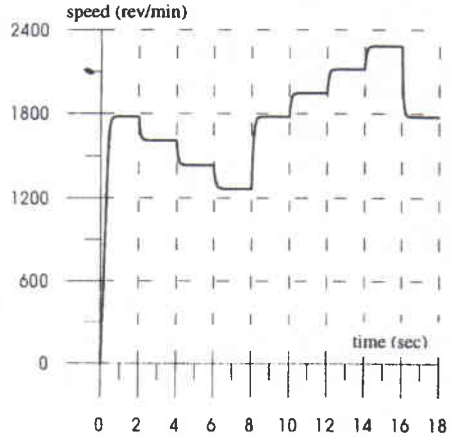

Fig. 5. Speed-Time variation

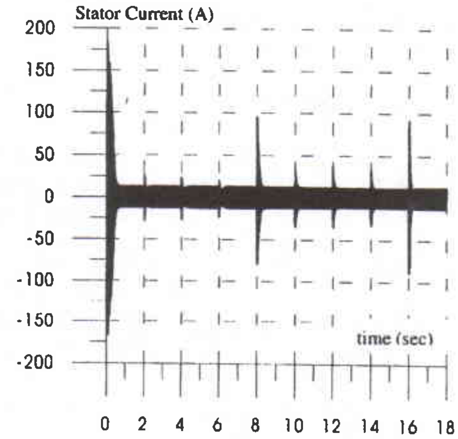

Fig. 8. Current-Time variation

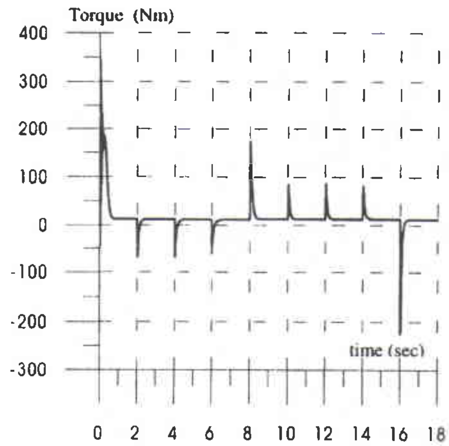

Fig. 6. Torque-Time variation

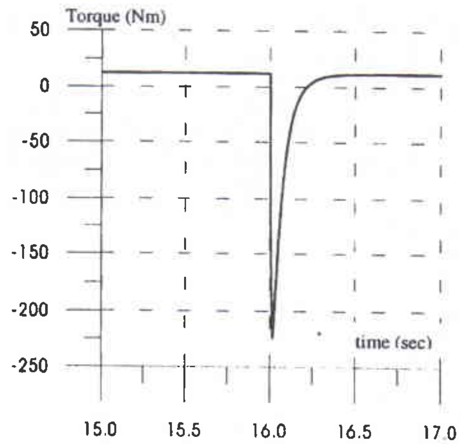

Fig 9. Negative torque pulse

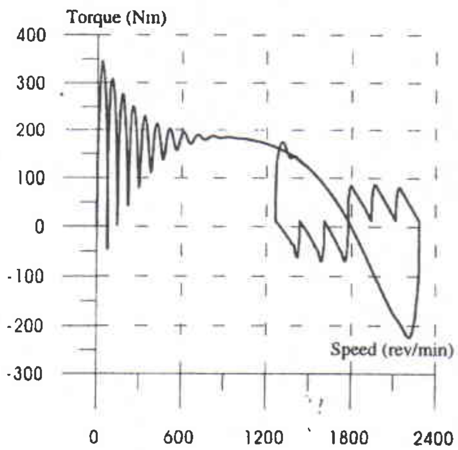

Fig 7. Torque-Speed variation

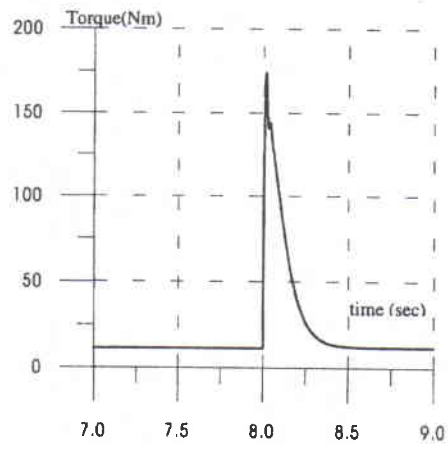

Fig 10. Positive torque pulse

employing modern control method such as Fuzzy Control or Neural Network Control.

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