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The Control of Induction Electromotor by the Resistance Change in Rotor Circuit

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ABSTRACT:*In this paper, we study the control algorithms of induction electromotor with wound rotor by the change of active resistance in rotor circuit. For the equations in per-units, we use nominal active values of current and voltage in stator windings.*

KEYWORDS*: Induction electromotor, resistance change, rotor circuit*

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I. INTRODUCTION

Induction motors are the most widely used electrical motors due to their reliability, low cost and robustness. However, induction motors do not inherently have the capability of variable speed operation. Due to this reason, DC motors found applications in the electrical drives. But the recent developments in speed control methods of the induction motor have led to their large scale use in almost all electrical drives.

Induction motors are a constant speed machines which account for 90% of the electrical drives used in Industry. Induction motors are usually constructed to work with a small value of slip, normally less than 5% at full load. Therefore the deviation of the motor speed from the synchronous speed is practically very small. However, there are certain applications that require enormous variation of the motor speed. With the increase in availability of high current power electronic devices, smooth and quick variation of external resistance introduced in the rotor circuit of slip ring induction motor to control its speed, can be accomplished electronically.

Schemes employing chopper control resistance can be used to obtain a constant torque, constant speed or any desired characteristics by using a proper feedback circuit along with it. Such circuits are widely used in industrial applications where the drive operation is intermittent such as hoists, cranes, conveyors, lifts, excavators and high starting torque are more important with low starting current to avoid voltage dip. The torque depends on motor resistance. Therefore, increasing the rotor resistance at a constant torque causes a proportionate increase in the motor slip with decrease in rotor speed. Thus, the speed for a given load torque may be varied by varying the rotor resistance.

The function of this resistance is to introduce voltage at rotor frequency, which opposes the voltage induced in rotor winding. Conventionally, the rotor resistance is controlled manually and in discrete steps. The main demerit of this method of speed control is that energy is dissipated in rotor circuit resistance. Because of the waste-fullness of this method, it is used where speed change are needed for short duration only.

The induction machine is a rugged, reliable and less expensive ac machine. It has been used for high performance drive applications. Different control methods of varying degrees of complexity have been proposed and used for the control of induction machines [I, 10, 11, 12, 13, 14].Stator voltage control of three-phase induction motor is a popular scheme used in industry for torque and speed control. A common method of controlling the stator voltage is by use phase angle control of thyristor circuit inserted in series between the supply and motor. Other methods use AC chopper with pulse width modulation PWM technique to control the applied voltage of the motor [2-4]. Method of the motor control based on the rotor circuit is used, such as using a thyristor-controlled resistive network in each rotor circuit [5-6]. This method will increase the rotor losses (heating).Operating the motor close to its rotor resonance by using reactive circuits in the rotor [7-9] gives high starting and breaking torque. This technique is limited as the rotor resonance is related to the varying motor speed.

II. MECHANICAL CHARACTERISTICS OF INDUCTION ELECTROMOTOR WITH ACTIVE RESISTANCE CHANGE IN ROTOR CIRCUIT

We assume that the rotor has a wound winding to which we can include additive resistance R (figure 1a).
This will influence the electromagnetic torque value and also the rotor rotation speed.

We consider that the stator winding is fed through three-phase sinusoidal e.m.f source with nominal parameters U_N and $\omega_1 \approx \omega_0$. Thus the notions of slip $S = \omega_2/\omega_1$ and rotor currents frequency $\omega_2^* = \omega_2/\omega_0$ in per-units are the same. To analyze the influence of R on mechanical characteristic, we can use the dependence of electromagnetic torque as a function of slip S:

$$M = \frac{2.M_K.(1 + bS_K)}{S/S_K + \frac{S_K}{S} + 2bS_K};$$

With $S = \omega_2/\omega_1$; $S_K = \omega_K/\omega_1$; $b = \omega_1^2.T_0^2/(1 + \omega_1^2.T_{01}^2)$
The parameters of mechanical characteristic are the critical torque and critical slip.
From the expression of critical torque
$M_k = m.U_N^2/(2\omega_1^2.L_K)$, it appears that its value very little depends on rotor circuit resistance R_2.
The critical slip $S_K = \pm R_2/(\omega_1.L_K)$, is proportional to rotor circuit resistance.
The plots of electromotor mechanical characteristics for various values of additive resistance R in rotor circuit are shown on figure 1b.

Obviously, the regulation of electromagnetic torque takes place because of energy losses on additive resistance R. The expression of power loss in rotor circuit is proportional to the slip and it is called the "slip power".
Very often the additive resistor with resistance R_d is attached to direct current diode bridge with endings connected to rotor windings. (Figure 2a).
In that case, it is necessary to change the rectified current circuit resistance R_d to equivalent resistance R in rotor alternative current circuit (Figure 2b)
Using the calculations coefficient:

$$K_{2d} = 3/K_{Ci}^2 = \pi^2/18 \approx 0{,}548;$$

$$R = K_{2d}.R_d \qquad (1)$$

For the regulation of additive resistance expression, we can use very technical solutions. One of the solutions is the discrete variation of rotor additive resistance by the shunt of its parts through contactors. The use of electronic contacts instead of contactors gives a particularly smooth regulation of resistor resistance value and a high quality of electromagnetic processing.

III. PULSE WIDTH CONTROL OF RESISTOR RESISTANCE TRANSISTOR IN ROTOR CIRCUIT

The change of resistance R_{d0} in rectified rotor current circuit can be done through the shunt of resistor with a key of given porosity γ. The circuit of resistor control for electromotor rotor rotation speed is done by the pulse width control as shown on figure 3.

The system is composed of additive resistor in rotor circuit R_{d0}, a transistor VT, a control system of the transistor CS VT, a current captor CC and a speed captor BR. The porosity $\gamma \in [0,1]$.
If the commutation's period is fixed, then the control is done by the change of transistor closed state. It is called "pulse width control".

The key commutations will lead to the change of equivalent resistance expression R_d in rotor rectified current circuit. We can prove that $R_d = \gamma.R_{d0}$ and $R = \gamma.R_0 = R_0/X^*$, with $R_0 = K_{2d}.R_{d0}$
With the variation of control variable $X^* = 1/\gamma$ the rotor resistance R will change. Consequently the rotor current and electromagnetic torque will vary.
The dynamic processes in this electromechanical system are characterized by the following equations:

$$\begin{cases} -\omega_2^*.L_K^*.i_{2v} + R_2^*.(T_K P + 1).i_{2u}^* = \omega_2^* - u_{2u}^*; \\ \omega_2^*.L_K.i_{2u} + R_2^*.(T_K P + 1).i_{2v} = -u_{2v}^* \end{cases}$$

With $u_{2u}^* = R^*.i_{2u}$; $u_{2v}^* = R^*.i_{2v}$
In general i_{2v} is very small and can be neglected.
And $(T_K.Pi_{2u}^* + i_{2u}^*).R_2^* = 1 - \omega^* - \gamma.R_0^*.i_{2u}^*$
With $\omega^* = 1 - \omega_2^*$.
If we add the movement equation

$T_{Mech}.P\omega^* = M^* - M_r^*$, the present system will be identical to direct current motor control with control of armature circuit resistance.

The dynamics construction of electromagnetic torque is done by a similar procedure as compared to direct current motor. The structural circuit for the subordinate control system is presented on figure 4.

The current loop regulator is a proportional element with amplified coefficient.

$$K_{sr}^* = 3.K_C^*.T_{Mech}/(\sqrt{2}.K_{Ci}.T_{r2})$$

With K_C^* – transfer coefficient of rotor rectified current captor.

IV. PULSE FREQUENCY CONTROL OF THYRISTORS BY THE RESISTOR RESISTANCE IN INDUCTION ELECTROMOTOR ROTOR CIRCUIT

The change of equivalent resistance in rotor circuit can be done by commutation of resistor R_{d0} through thyristor bridge rectifier (figure 5).

We assume that the control of rectifier is done through control pulses in all the thyristors simultaneously with period $T_G \in [\infty, 0]$ and asynchrously relatively to rotor voltage frequency ω_2.

Thyristors in that case are closed with control angle $\alpha \in [0, \pi/3]$. The medium value of control angle $\alpha_m = \pi/6$. Thrysistors are opened with the decrease of current to zero $\alpha_{op} = 2\pi/3$.

If we neglect electrical resistance R_2 and the inductance of rotor circuit L_K, then the middle voltage value added to resistor with resistance R_{d0},

$$E_{2d} = \frac{\omega_2^*.\sqrt{3}.U_B}{\omega_2.T_G}\int_{\pi/6}^{2\pi/3} cos(t-\pi/6).dt = \sqrt{6}.f^*.U_N$$

With $U_B = \sqrt{2}U_N$ – amplitude of stator phase voltage

$$\omega_2^* = \omega_2/\omega_1 - slip;$$

$$f^* = \frac{1}{\omega_1.T_G} \in [0, \infty] - controlvariable;$$

$$E_{2d}^* = \sqrt{6}.f^*$$

- For $\omega_2.T_G > (\alpha_{op} - \alpha_m) or f^* < f_0^* = 2\omega_2^*/\pi$, the current circulating in R_{d0} will have an interruption character and $I_d^* = \sqrt{6}.f^*/R_{d0}^*$.
- For $f^* = f_0^*$, the current will be limit continuous.

$$I_{d0}^* = \sqrt{6}.f_0^*/R_{d0}^* = 2.\sqrt{6}.\omega_2^*/(\pi.R_{d0}^*)$$

Therefore, the domain of interrupted currents is determined by inequality $I_d^* < I_{d0}^*$. For $f^* > f_0^*$, the current will depend on slip.

- For $f^* \to \infty$, the current I_d^* has a maximal value and is $I_{dm}^* = \omega_2^*.E_{20d0}^*/R_{d0}^* = 3\sqrt{6}.\omega_2^*/(\pi.R_{d0}^*)$,

With $E_{20d0}^* = K_{Ci} = 3.\sqrt{6}/\pi - emf$ of rectifier in per units for $\omega_2^* = 1$.

From the expressions of limit-continuity and maximal currents, the domain of interrupted currents is characterized by inequality:

$$I_d^* < (2/3)I_{dm}^*.$$

The aspect of electromechanical characteristics for various values of control frequency pulses f^* is shown on figure 6.

The electromagnetic torque in the zone of interrupted currents is proportional to pulses control frequency and can be expressed as equation (21):

$$M^* \approx K_{Ci}.I_d^*/3 = \sqrt{6}.K_{Ci}.f^*/(3.R_{d0}^*).$$

The dynamic characteristics of rectified current regulation are defined by the properties of thrysistor transducer. If we assume that the frequency of signals f^*- is input signal and the rectified rotor current I_d^* – is output signal, then the transfer function linking those signals can be an aperiodic element of first order with time constant $1/\omega_1$ and with a transfer coefficient $\sqrt{6}/R_{d0}^*$.

The construction of electromagnetic torque dynamics is done according to the structural circuit of subordinate system control as shown on figure 7.

The current loop regulator is an integral element with time constant $T_{r2} = 2.\sqrt{6}.K_C/(\omega_1.R_{d0}^*)$

The speed loop regulator is a proportional element with amplification coefficient.

$$K_{sr}^* = K_C^*.T_{Mech}/(\sqrt{2}.T_{r2}) \qquad (2)$$

For the increase of speed regulation diapason and the decrease of interrupted currents domain we use the circuit shown in figure 8.

The circuit is composed of three bridges with three cathodes (1,3,5) and three anodes (4,6,2) thyristor groups. The control of thyristor is done by control pulses simultaneously in pair of thyristors group cathode and anode. The sequence of control pulses is as follows: 1,2;2,3;3;3,4;4,5;5,6;6,1;1,2;…

The rotor rectified current is :

$$I_d = I_{d1} + I_{d3} + I_{d5} = I_{d2} + I_{d4} + I_{d6}$$

The minimal resistance value in rotor circuit for high control pulses frequency will be $(2/3).R_{10}$. Therefore, the maximal current value:

$$I^*_{dm} = \frac{3}{2}.\frac{E^*_{20d0}.\omega^*_2}{R^*_{10}} = \frac{9\sqrt{6}.\omega^*_2}{2\pi.R^*_{10}}$$

The value of limit-continuous current and maximal current are linked by the equation:

$$I^*_{d0}/I^*_{dm} = (2/9).R_{10}/(R_{10} + R_{20}).$$

V. PULSE PHASE CONTROL OF THYRISTORS IN INDUCTION ELECTROMOTOR ROTOR CIRCUIT

The regulation of rotor current can be done by thyristor bridge rectifier (figure 9), with the use of phase pulse control, whose direct current endings are closed on active inductance load.

The equivalent circuit of rotor rectified current with phase pulse control is shown on figure 10.

The rectified current is:

$$\mathrm{I_d} = \frac{\mathrm{E_{20d0}}.\omega^*_2.\cos(\alpha)}{2\mathrm{R_2} + \omega^*_2.\mathrm{X_{2d}} + \mathrm{R_{d0}}}$$

With:

$\mathrm{E_{20d0}}$ – Rectifier e.m.f for $\omega^*_2 = 1$ and $\alpha = 0$;
$\mathrm{R_2}$ − Active resistance of rotor windings;
$\mathrm{R_{d0}}$ − Active resistance of direct current circuit load;
$\mathrm{X_{2d}} = 3/\pi.\mathrm{X_K}$ − Commutation resistance of bridge rectifier for $\omega^*_2 = 1$;
$\mathrm{X_K} = \omega_1.\mathrm{L_K}$.

The angle of phase control α is a function of rotor currents frequency: $\alpha = \omega_2.\mathrm{t_0}$ with $\mathrm{t_0}$ − time delay.

$$\mathrm{t_0} = \arccos(\mathrm{u^*_0})\,/\omega_2, \mathrm{u^*_0} \in [0,1].$$

Thus, the rectified current in established regime will be:

$$\mathrm{I_d} = \frac{\mathrm{E_{20d0}}.\omega^*_2.\mathrm{u^*_0}}{2.\mathrm{R_2} + \omega^*_2.\mathrm{X_{2d}} + \mathrm{R_{d0}}} \approx \frac{\mathrm{E_{20d0}}.\omega^*_2.\mathrm{u^*_0}}{2.\mathrm{R_2} + \mathrm{R_{d0}}}$$

From that equation, it appears that the control signal $\mathrm{u^*_0}$ is approximately proportional to rotor rectified current and consequently to the electromagnetic torque.

The structural circuit of electrical part 1 of electric drive with phase pulse control resistor system according to equation $\mathrm{L^*_{2d}.PI^*_d + R^*_{2d}.I^*_d + \omega^*_2.X_{2d}.I^*_d + U^*_d = \omega^*_2.K_{Ci}}$ is shown on figure 11.

VI. CONCLUSIONS

The change of resistors resistance values in rotor circuit can be achieved through various technical solutions. We can distinguish the pulse and the phase control ways.

The pulse resistance regulation realized on total keys control permits to achieve high quality magnetic processes and smooth electromotor control. The pulse regulation will lead to low frequency current pulses in electromagnetic torque.

The variable of thyristor bridge resistance with phase control will lead to good quality electromagnetic processes but it leads to the increase of reactive currents components and additive heat to motor windings.

The control of electromotor by the change of resistors resistance in rotor circuit induces energy losses. The power of energy losses is proportional to the slip and resistance torque.

VII. FIGURES

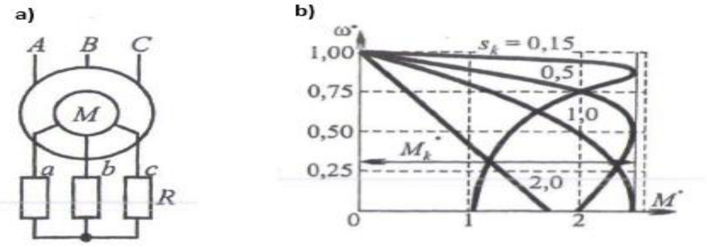
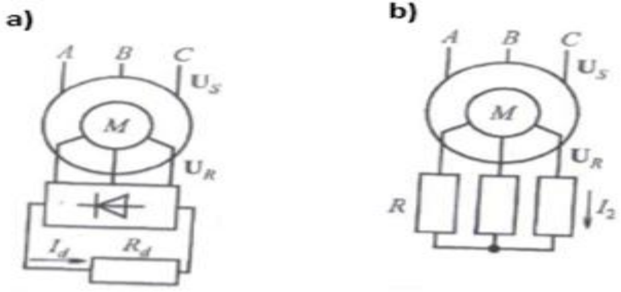


Figure 1: Torque regulation by introduction of additive resistance in rotor circuit:

a) Schematic circuit b) Mechanical caracteristics



Figures 2: Schematic circuits of resistors introduction:

a) For rectified current circuit b) For alternative current circuit

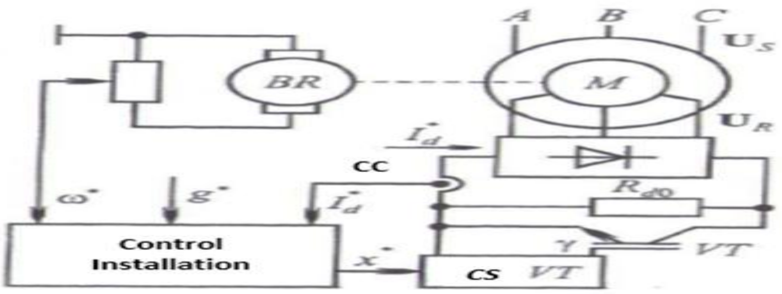


Figure 3: Schematic circuit of pulse-width resistor control of and induction electro-motor.

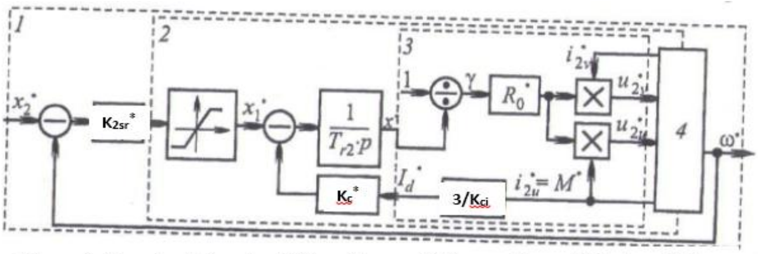


Figure 4 : Tructural circuit : 1) Speed loop 2) Current loop 3) Pulse-width resistor control 4) Electromotor

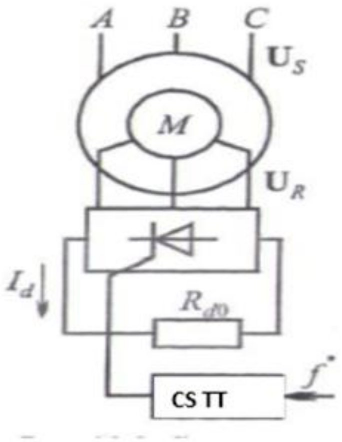


Figure 5 : Circuit of pulse frequency resistor control of thyristor bridge.

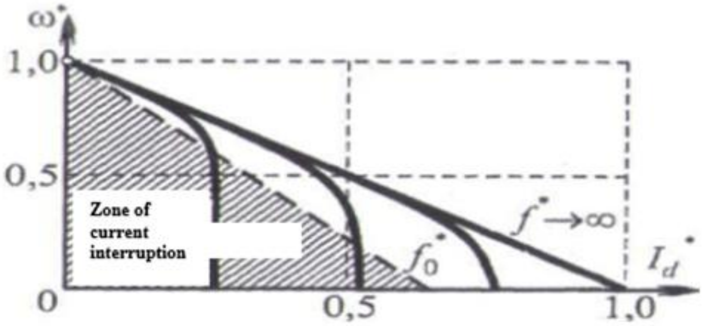


Figure 6 : Electromechanical characteristics for various frequency values of control pulses f* and $R_{d0}^* = 3\sqrt{6}/\pi$

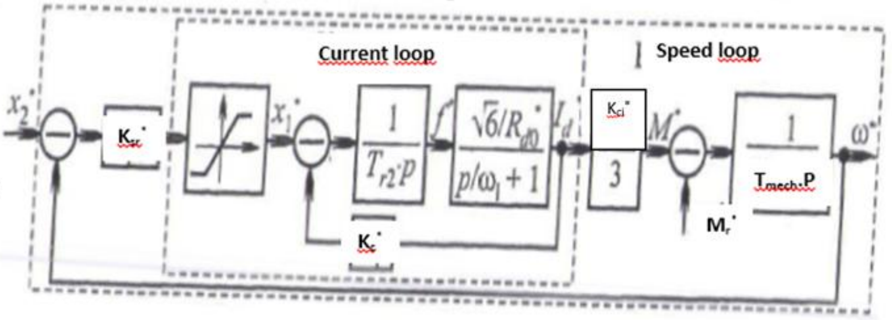


Figure 7: Structural circuit of pulse frequency resistor control system

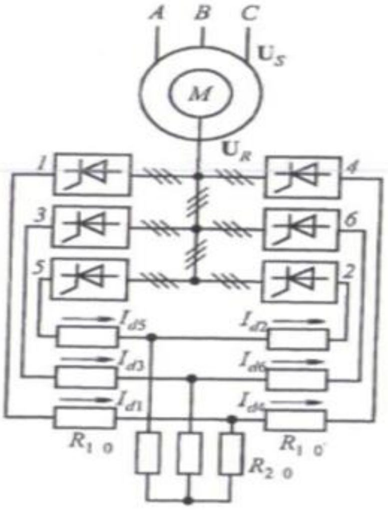


Figure 8 : Circuit of pulse frequency resistor control by three thyristor bridges

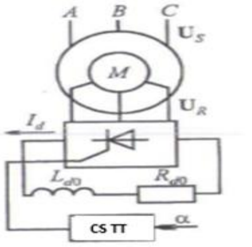


Figure 9 : Electric drive circuit with pulse phase resistor control.

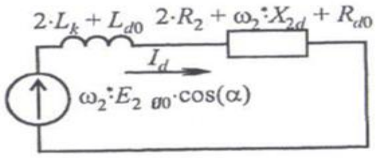


Figure 10: Equivalent circuit of rectified current network with pulse phase resistor control.

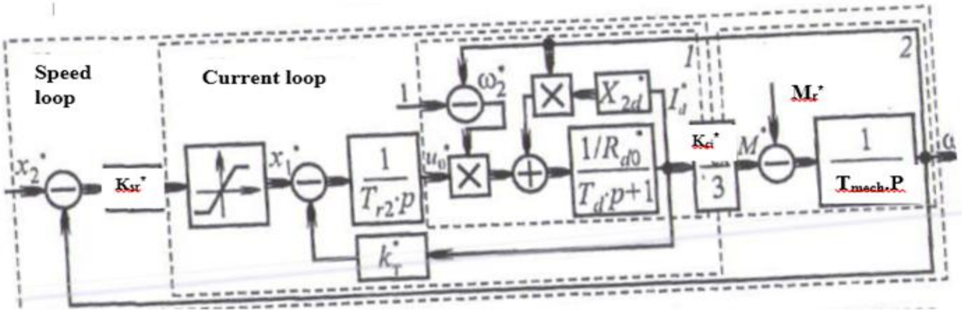


Figure 11: Structural circuit of pulse phase resistor control system: 1) For electrical part of drive 2) For mechanical part of drive.

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