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The Mechanical Transient Process at Asynchronous Motor Oscillating Mode

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Abstract - The research object is squirrel-cage asynchronous motor connected to single-phase sinusoidal. There are shown, that by connecting to the stator windings a certain sequence of half-period positive and negative voltage, a motor rotor is rotated, but three times slower than in the three-phase mode. Changing the connecting sequence of positive and negative half-period voltage to stator windings, motor can work in various oscillating modes. It is tested experimentally. The mechanical transient processes had been researched in rotation and oscillating modes.

I. INTRODUCTION

There are many national economic sectors where are devices with tools that perform oscillating motions in widely applied mechanisms of vibrotransporting, vibrosorting, prepacking, dye mixing, polishing machine tools, etc. In these devices rotary movement of the electric motor will be transformed in oscillatory by means of various cinematic parts.

The task for reduction of metal consumption, weight and size parameters, simplification of operating system is to search for the ways to obtain oscillations without the mechanical running gears. In practice for providing oscillation the different types of motors (asynchronous, synchronous, step and direct current motors) and operating methods are used [1].

II. PRINCIPLE OF OPERATION

An object of our researches is three-phase squirrel-cage asynchronous machines in oscillating mode, which are supplied with single-phase voltage.

In 80th of the last century in RPI (now RTU) the staff of the Electric Drive department patented the control method of three-phase asynchronous motor, which is connected to single-phase sinusoidal voltage supply [2]. The positive or negative half-periods of the voltage are connected to the stator phase windings of motor, through the semiconductor switch in a certain sequence. This sequence is shown in Fig. 1. In the beginning of the positive half-period of voltage, motor is connected to A phase winding, winding of phase B is switched when negative half-cycle starts, but next positive half-cycle is switched to winding of phase C. The next negative, positive and negative voltage is switched accordingly to windings of phases A, B and C. In the time of 3 half-cycles of voltage one full cycle is complete. The next such cycles are following. In such regime current that flows in stator windings creates pulsing rotating magnetic field in rotor windings. In time of each half-cycle direction of magnetic flow is perpendicular to plane of respective winding and value of flow changes by sinus law. In next half-cycle the value of flow is changing according to sine low, but the direction is changing by 60^0. In the time of six half-cycle (3 periods) magnetic flow make full turn on 360^0. This rotating field induces EMF in rotor windings. Electromagnetical torque that is created by the interaction of rotor current and magnetic flow makes rotor to turn. In this regime magnetic field rotates three times slower than drive switched to three-phase voltage supply. Respectively also rotor turns three times slower. To change the rotation direction of rotor of asynchronous drive, magnetic field rotating direction should be changed on opposite direction. In three-phase system it can be done by changing over two wires that are connected to stator windings. Also in this case it is possible to act similarly by changing the voltage half-cycle switching order to stator phase B and C windings of motor (Fig. 1).

Experiments are executed with squirrel-cage asynchronous motor with two magnetic pole pairs, for three-phase alternating voltage (frequency=50 Hz) the rotation frequency at no-load mode is 1500 min $^{-1}$, but connecting single-phase voltage – 500 min $^{-1}$[4,5].

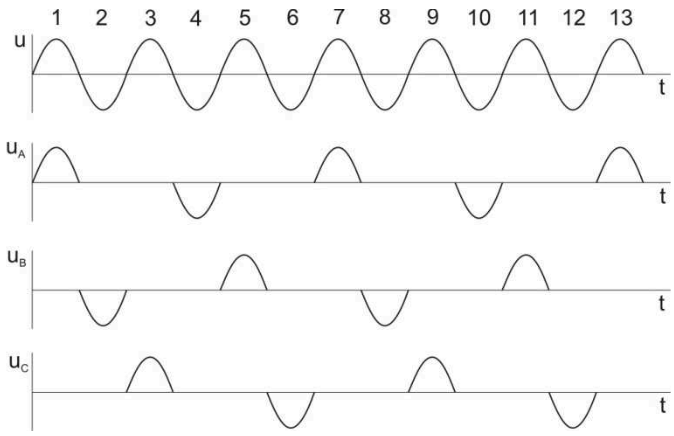

Fig. 1. The distribution of stator windings voltages

The considered operating method can be modified so that the rotor of motor was not revolved, but operated in the oscillating mode [3]. For the above-described operating method a sequence of half-period voltage was: **A – B` - C – A` - B – C`**. Here „`" means, that according to winding the negative half-period of voltage is connected. During the time of these three periods the direction of the magnetic flux changes for 360 electric degrees, but the rotor turns for 180^0. The next three periods (6 half-periods) a voltage connects sequence: **A – C` - B – A` - C – B`**, and the magnetic field and also rotor rotate in the opposite direction. In the time of six voltage half-cycles rotor makes one full oscillation with rotation angle of 180^0 on each direction. Oscillation frequency is $f_{os} = 50/6 = 8.33$ Hz, but period is $T_{os} = 6T = 120$ ms. Oscillation frequency can be changed, by changing rotor turning angle. Reducing rotating angle, oscillation frequency increases and oscillation period decrease. Increasing turning angle, oscillation frequency f_{os} decreases and period T_{os} increases. For example, if supply voltage half-cycles to stator are delivered in following order: $\mathbf{A^+ - B^- - C^+ - A^- - B^+ - A^- - C^+ - B^- - A^+ - C^- - B^+ - A^- - C^+ - A^- - B^+ - C^-}$, one oscillation continues 8 voltage periods, oscillation frequency $f_{os} = 6.25$ Hz and rotating angle is 240^0. For constant turning angle the oscillation frequency could be reduced if the voltage is not connected to any stator winding for single or multiple periods at the end of each oscillation. Certainly, the period of oscillation can be regulated also changing frequency of the supply voltage or using the motors with other number of pole pairs.

Return to the motor rotation mode analysis. Asynchronous motor one stator winding connection to input voltage $u = U_m \sin \omega t = U_m \sin \alpha$ is described with a differential equation:

$$U_m \sin \alpha = iR + \omega L di / d\alpha \ , \tag{1}$$

which solution, if the voltage is connected at the beginning of half-period, is the following:

$$i = \frac{U_m}{\varpi L} \frac{1}{1+k^2} \left(\exp(-k\alpha) - \cos\alpha + k \sin\alpha \right). \tag{2}$$

where i - stator winding current instantaneous value, A;
u –input sinusoidal voltage instantaneous value, V;
L – inductance of asynchronous motor single-phase winding at standstill rotor and given voltage frequency, Hz;
R – asynchronous motor stator phase active resistance, Ω;
$\omega = 2\pi f$ –input network angular frequency, *rad/s*;
$k = R/\omega L$ – coefficient.

The current continues to flow at voltage decreasing to zero value and changing polarity. The certain angle α_N value, when winding current stops to flow, can be expressed from equation:

$$e^{-k\alpha} - \cos\alpha + k \sin\alpha = 0 \ . \tag{3}$$

One stator winding active power in single pulse period time can be determined as:

$$P = \frac{1}{T} \int_0^T uidt \tag{4}$$

where: T – clock pulse period.
The stator winding output electromagnetic power in one clock cycle differs for a value $\Delta P_{CUI} = i^2 R$. The power during one clock cycle is a constant value at the given loading.

III. THE INDUCTION MOTOR MECHANICAL TRANSIENT PROCESS

The transient process begins at the asynchronous motor starting moment. At the beginning of start the rotation speed is equal with zero and only after some time this speed is reaching the steady state value. The movement torque for rotation movement if the inertia torque J is constant is

$$M_m - M_s = J d\Omega/dt \ , \tag{5}$$

where M_m – motor developed torque, Nm;
M_s – static resistance torque, Nm;
$M_m - M_s = M_{dyn}$ – dynamic torque, Nm;
J – inertial torque, kgm^2
Ω – rotation frequency, *deg/s*;
$d\Omega/dt$ – angular acceleration, deg/s^2.

Assuming, that M_s is proportional to rotation frequency Ω $M_s = C\Omega$ and M_m is approximately constant $M_m = K\Omega_S$, the expression (5) could be rewritten:

$$K\Omega_S - C\Omega = Jd\Omega / dt \tag{6}$$

Dividing all sides of equation by K, the following expression is obtained

$$(J/K) d\Omega / dt + (C/K)\Omega = \Omega_S \ , \tag{7}$$

where K and C – constants;
Ω_S – steady state rotation frequency, *deg/s*.

The non-uniform first order linear differential equation had been obtained for the rotation frequency calculation. The solution of such equation could be expressed as the sum of given non-uniform first order linear differential equation partial solution (steady state or driven mode) with corresponding uniform equation generalized solution (free mode).

$$\Omega = \Omega_S + \Omega_h = \Omega_S + A \exp(pt) \tag{8}$$

where Ω_h - rotation frequency free mode component, grad/s;
p – root of the characteristic equation, *1/s*;
A – integration constant, *grad/s*.
The characteristic equation of equation (7) is $(J/K)p + C/K = 0$ and its root is $p = -C/J$. At the

begining of start $t = 0$, and $\Omega(0) = 0$, and from (8) follows, that $A = -\Omega_S$.
The solution of equation (7) in finite way is

$$\Omega = \Omega_S\left[1 - \exp(pt)\right] = \Omega_S\left[1 - \exp\left(-t / T_{meh}\right)\right] \qquad (9)$$

where $T_{meh} = |1/p| = J/C$ - transient process mechanical time constant, s.

IV. EXPERIMENTAL AND CALCULATION RESULTS FOR OSCILLATING MODES

The experiments are provided with 0.55 *kW* power АИР71А4У3 type three phase induction motor with cage rotor, which inertial torque is $\mathrm{J} = 0.0013\ \mathrm{kgm}^2$ and idle rotation speed 1500*rpm*. In single phase operation mode the stationery rotation frequency is 500 *rpm* or $\Omega_S = 3000\,\Omega_S$ *deg/s.*

Operating drive in oscillating regime the frequency of oscillations is the same as calculated but oscillating angle is much smaller than it is calculated theoretically. There is torque of inertia for real drives. During switching in rotation regime there is transient process and only after some time the drive is rotating with steady-state rotation frequency Ω_S. The rotation frequency changes by exponent in constant load case (9). Processing data of starting process for rotating case there is calculated the mechanical time constant value $T_{meh} = 0.14$ *s*.

If rotor is oscillating, the drive is all the time in braking or starting regime and rotation frequency Ω_S is newer reached. When regime becomes quasi-stable in one oscillation half - period rotation frequency changes by exponent within $-\Omega_{os}$ till Ω_{os} value, but in next half period within Ω_{os} till $-\Omega_{os}$ (Fig. 2). It is assumed that $\Omega_{os} = \Omega_S / k$, where $k > 1$. In first half-period

$$\Omega(t) = \Omega_S\left[1 - (k+1)\exp\left(-t/T_{meh}\right)/k\right] \qquad (10)$$

Taking into account that: $\Omega(0) = -\Omega_{OS}$, but $\Omega(T_{OS}/2)$, we get

$$\Omega(t) = \Omega_S\left[1 - \left(2\exp\left(-t/T_{meh}\right)\right)/\left(1 + \exp\left(-t/2T_{meh}\right)\right)\right] \qquad (11)$$

During the time interval from 0 till *t'* the moment the asynchronous machine rotor is braked, but in interval from *t`* till $T_{os}/2$ is turned on opposite direction.

During time interval from *t`* till $T_{os}/2 + t'$ rotor turns by angle α_{os}, that is named oscillating angle

$$\alpha_{os} = \int_{t'}^{T_{os}/2 + t'} \Omega(t)dt\,. \qquad (12)$$

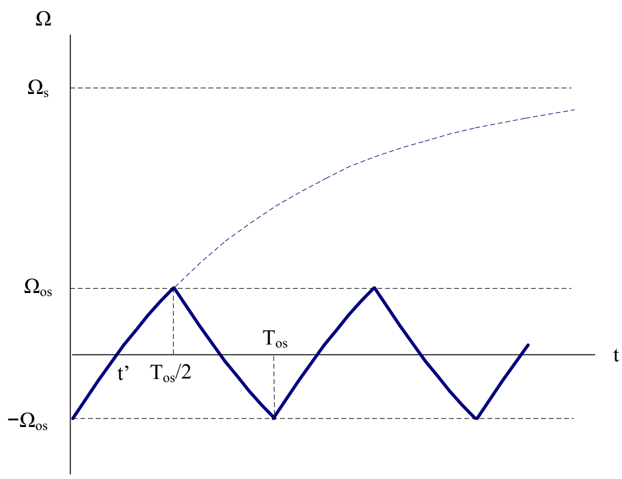

Fig. 2. The changes of rotation frequency in oscillating regime

Here *t`* is less than $T_{os}/4$. The longer is oscillating period $T_{os}$, the smaller is *t`* (relatively). Experimentally, oscillating period was changed by changing the length of pause when voltage half-cycles are not connected to stator windings (table 1.)

TABLE 1
VOLTAGE SUPPLY TO STATOR WINDINGS DURING OSCILLATING REGIMES

T_{os}, s	0,08	0.12	0,16	0,20	0,24	0,28
1	A^+	A^+	A^+	A^+	A^+	A^+
2.	B^-	B^-	B^-	B^-	B^-	B^-
3.	C^+	C^+	C^+	C^+	C^+	C^+
4.	B^-	-	-	-	-	-
5.	A^+	-	-	-	-	-
6.	C^-	B^-	-	-	-	-
7.	B^+	A^+	-	-	-	-
8.	C^-	C^-	B^-	-	-	-
9.		B^+	A^+	-	-	-
10.		-	C^-	B^-	-	-
11.		-	B^+	A^+	-	-
12.		C^-	-	C^-	B^-	B^-
13.			-	B^+	A^+	A^+
14.			-	-	C^-	C^-
15.			-	-	B^+	B^+
16.			C^-	-	-	-
17.				-	-	-
18.				-	-	-
19.				-	-	-
20.				C^-	-	-
21.					-	-
22.					-	-
23.					-	-
24.					C^-	-
25.						-
26.						-
27.						-
28.						C^-

If oscillating period T_{os} increases, ratio *k* decreases, increases rotation frequency Ω_{os} and oscillation angle α_{os} grows.

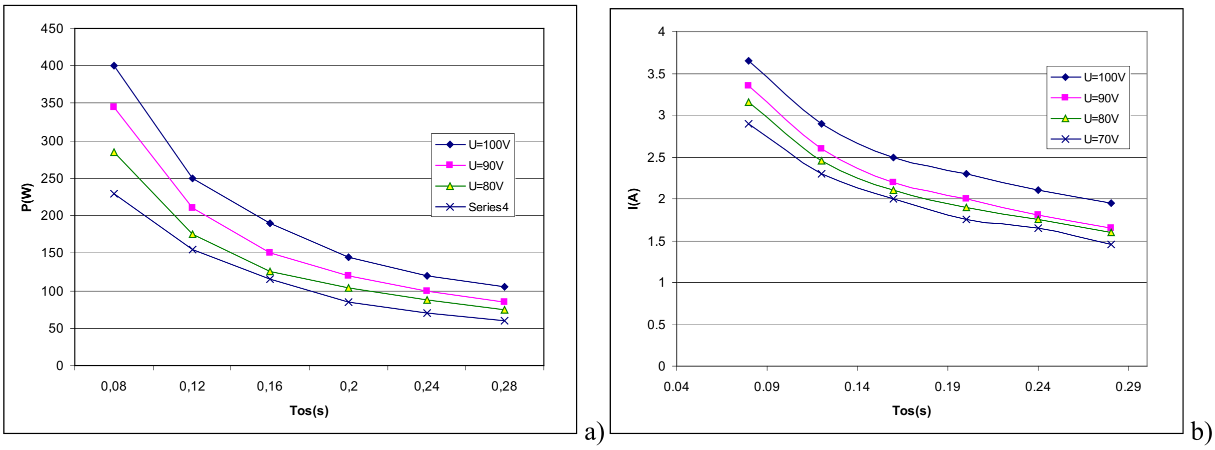

Fig.3. Consumed power P and current I dependent on oscillation period T_{os}: a) $P = f(T_{os})$; b) $I = f(T_{os})$

Ω_{os} and α_{os} calculation results are generalized in table 2.

TABLE 2
OSCILLATING ANGLE α_{OS} DEPENDENCE ON OSCILLATING PERIOD T_{OS}

T_{os}, s	0,08	0,12	0,16	0,20	0,24	0,28
Ω_{os}, deg/s	425	633	834	1028	1212	1386
α_{os}, deg	8,5	19,1	33,8	52,5	73,7	106,5

Operation of drive in oscillating regime is experimentally proved to unloaded drive. There is measured consumed power *P* of drive and current *I* dependent on oscillation period T_{os} at 4 different supply voltage *U* values [6]. Result is given in Fig.3.
If oscillating period T_{os} grows, consumed power *P* and current *I* decrease. Also *P* and *I* decrease if supply voltage *U* is decreased.

V. CONCLUSIONS

1. During the transient process the cage rotor induction motor rotation frequency Ω increases exponentially at condition $M_s = C\Omega$ or $M_s = \text{const}$.
2. It is useful to utilize motor in quasi-stable oscillating mode.
3. The drive system ensures frequency and amplitude changing in wide range.

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