Inverter-Fed Multiphase AC Linear Motor under Non-Traditional Control

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ABSTRACT: The over-phase control method of inverter multiphase (i.e. having number of phases more than four) AC linear drives is developed by the authors of this paper. Its application allows improving considerably a number of the drive technical-and-economic characteristics (speed of response, reliability, mass-and-overall dimensions, etc.).

1 INTRODUCTION

The increase of the phase number m more than four allows not only to improve a number of technical-and-economic characteristics of the inverter-fed linear AC motors, but also to open the way for the design of the linear drives having radically new properties and possibilities. It is conditioned by the possibility for the use of some non-traditional motor control modes in the AC drive system which appears when $m \geq 5$. These non-traditional control modes can not in principle be used when the inverter-fed linear motor phase number is equal to three or four.

2 NON-TRADITIONAL CONTROL METHODS

In particular, the over-phase control method (OPM) is one of the above-mentioned non-traditional ones. It was developed by the authors of this paper for the use in the field of both linear and non-linear inverter multiphase (i.e. having the phase number $m \geq 5$) AC drives. Its detailed description was presented in (Belozyorov et al. 2008, Brazhnikov 1993, Brazhnikov & Dovzhenko 1994, 1997, 1998, Brazhnikov et al. 1995, 1996, 2005, Brazhnikov & Belozyorov 2011a, b).

The essence of the control according to OPM is that in this case the electrical angles α between the voltages (or currents) of the nearest phases of inverter are increased by a factor of H (in comparison with any traditional control method) without any change of the inverter voltage (or current) amplitude and frequency, i.e. in this case $\alpha_H = H \cdot \alpha_T$, where H is some whole number, α_T is the value α when some traditional control method is used ($\alpha_T = 2\pi / m$), and α_H is the value α when OPM is used (see Figures 1 and 2).

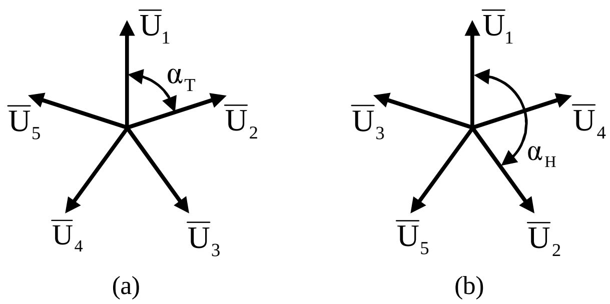

Figure 1. 5-phase system of the inverter output voltages:
a) – H = 1; b) – H = 2.

H is the major parameter of OPM that characterizes the type of this control method (the value H = 1 corresponds to any traditional control method, and the value H > 1 corresponds to OPM).

The range of the parameter H (including its maximal value), which can be achieved in the given drive system, depends on the phase number of the system and on a motor stator winding type.

The change of the parameter Hresults in the change of the filtering properties of the inverter multiphase AC drive. In particular, the numbers of the harmonics, which take part in the creation of the magnetic field in a motor air gap, are described by the following equation:

$$H \cdot c \pm \frac{n}{p} = b \cdot m\,, \qquad (1)$$

where c is the number of the phase voltage (or current) harmonic (i.e. the number of the time harmonic), n are the numbers of the harmonics of the functions which describe a space distribution of the mutual inductances between motor phase windings (i.e. the numbers of the space harmonic), and the coefficient b = 0, ± (1, 2, 3, …).

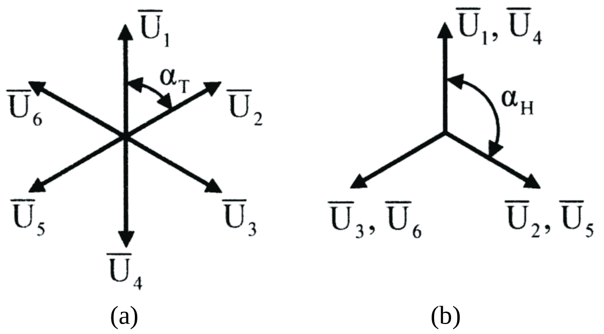

Figure 2. 6-phase system of the inverter output voltages:
a) – H = 1; b) – H = 2.

The magnetic fields created in a motor air gap by the harmonics, numbers of which does not satisfy equation (1), cancel each other.

OPM has two kinds – over-synchronous control method (OSM) and phase-pole control one (PPM). The use of these OPM kinds allows achieving the following two effects:

– the increase of the linear motor movable secondary element motion speed over its synchronous value V_S which is conditioned by the inverter output voltage frequency and the motor pole number (OSM).
– the increase of the motor linear forces without any change in the amplitude and frequency of the inverter output voltage (PPM).

OSM differs from PPM in the following: when OSM is used, the spectrum of the function, which describes the space distribution of the mutual inductances between motor phase windings, does not change for all parameter H values which have to be realized in the given drive system. When PPM is used, the spectrum of the above-mentioned function changes during H value changing process.

3 APPLICATION OF OSM

When OSM is used, the linear motor movable secondary element motion speed V may be increased by a factor of some whole number C_0 over its synchronous value V_S, i.e. $V = C_0 \cdot V_S$, where

$$C_O = \frac{m \pm 1}{H}\,. \qquad (2)$$

The values of the parameter C_0, which can be achieved for $m \in [5; 24]$ in the case when OSM is used, are given in Table 1.

Table 1. Values of the parameter C_O.

m	H								
	2	3	4	5	6	7	8	9	10
5	3* / 2**	2	–	–	–	–	–	–	–
7	3	2	2	–	–	–	–	–	–
8	–	3	–	–	–	–	–	–	–
9	5	–	2	2	–	–	–	–	–
10	–	3	–	–	–	–	–	–	–
11	5	–	3	2	2	–	–	–	–
13	7	–	3	–	2	2	–	–	–
14	–	5	–	3	–	–	–	–	–
15	7	–	–	–	–	2	2	–	–
16	–	5	–	3	–	–	–	–	–
17	9	–	–	–	3	–	2	2	–
19	9	–	5	–	3	–	–	2	2
20	–	7	–	–	–	3	–	–	–
21	–	–	5	–	–	–	–	–	2
22	–	7	–	–	–	3	–	–	–
23	11	–	–	–	–	–	3	–	–
24	–	–	–	5	–	–	–	–	–

* – When the spectrum of the inverter output voltage contains only odd harmonics.
** – When the spectrum of the inverter output voltage contains both even and odd harmonics

As an example mechanical characteristics of a multiphase linear inverter-fed induction motor are shown in Figure 3 on a per-unit basis for the cases when the traditional control method (1) and OSM (2) are used, where F is a linear traction force (or torque, when the motor stator is bow-shaped).

Theoretically (when $m \to \infty$) the use of OSM allows to increase the motion speed V over the value V_S without limit. However the use of OSM is accompanied by considerable decrease of the motor energy efficiency. In spite of this, it is indubitable that some peculiar fields of OSM application may be found both on the nano-level and on the macro-level (in the cases when the possibility of attaining the ultra-high motion speeds is the most important of all).

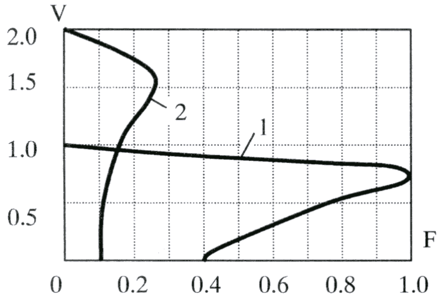

Figure 3. Mechanical characteristics of a multiphase linear inverter-fed induction motor on a per-unit basis: (1) natural characteristic, when the traditional control method is used (H = 1), and (2) when OSM is used (H = 2).

OSM can be used both for flat, and for tubular design types of the multiphase linear motor. However in the case of a flat design type it is necessary to use the phase stator windings having number of slots per a pole and a phase no less than two to ensure the possibility of OSM application.

4 APPLICATION OF PPM

4.1 Peculiarities of PPM

During PPM application process, when the parameter H changes, the effect adequate to the synchronous change of the drive phase number and number of motor poles appears.

PPM being used, the following equation is fulfilled:

$$p_E \cdot m_E = p \cdot m = \text{const}\,, \qquad (3)$$

where m is real value of the phase number of the inverter multiphase AC drive system, m_E is equivalent (observed) value of the drive system phase number, p is real value of the motor pole number, and p_E is equivalent (observed) value of the motor pole number ($p_E = p \cdot H$).

The values of parameter p_E for $m \in [6; 30]$, which can be achieved when PPM is used, are given in Table 2 for the case when p = 1.

PPM can be used both for flat, and for a tubular design types of the multiphase linear motor.

Designing motor winding, it is necessary to consider, that the following necessary conditions must be fulfilled for attaining the opportunity of PPM realization without any deterioration of drive system technical-and-economical characteristics (in particular, system efficiency) in comparison with the case when H = 1:

– Condition 1: The space harmonics having numbers n = p · H must be contained in the spectrum of the function describing the space distribution of the mutual inductances between motor phase windings for all parameter H values which have to be realized in the given drive system.
– Condition 2: When H > 1, the amplitudes of the above mentioned space harmonics (i.e. having numbers n = p · H) must have the values being not less than those at H = 1.

Table 2. Values of the parameter p_E for given values m and p =1.

m	p_E								
	2	3	4	5	6	7	8	9	10
6	■								
8	■								
9		■							
10	■								
12	■	■	■						
14	■								
15		■		■					
16	■		■						
18	■	■			■				
20	■		■	■					
21		■				■			
22	■								
24	■	■	■		■		■		
25				■					
26	■								
27		■						■	
28	■		■			■			
30	■	■		■	■				■

A number of the design versions of linear and non-linear motors and their windings, the use of which allows to provide the above-mentioned conditions, has been worked out by the author of this paper. Some of these designs are described in (Belozyorov et al. 2008, Brazhnikov & Dovzhenko 1998, Brazhnikov et al. 2005, 2011, Brazhnikov & Belozyorov 2010, 2011b). They can be easily realized both on the nano-level and on the macro-level.

The combined application of PPM and the classical frequency control method allows obtaining the following advantages over the traditionally controlled drive systems without any rise in the motor magnetic circuit magnetization magnitude.

4.2 Increase of motor maximal and starting linear forces

The set of motor mechanical characteristics, which differ in their magnitudes of the synchronous motion speed, and maximal and starting linear traction forces (or torques, when the motor stator is bow-shaped) from each other, are obtained by the regulation only of the parameter H without any change in the frequency and amplitude of inverter output voltage or current (see lines (2) and (3) in Figure 4).

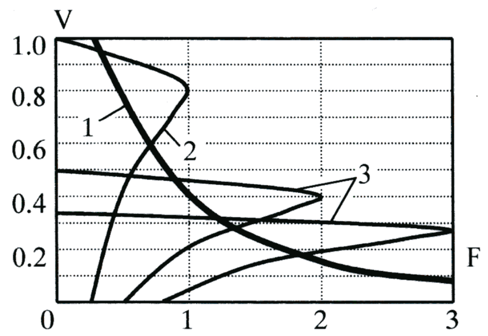

Figure 4: Descending mechanical characteristic of motor load (1) and mechanical characteristics of a multiphase linear inverter-fed induction motor on a per-unit basis: (2) natural characteristic, when the traditional control method is used (H = 1), and (3) when PPM is used (H = 2 and H = 3).

In this case the synchronous speed value V_S and maximal linear traction force (torque) F_M of an AC motor are described by the following formulae:

$$V_{S.H} = \frac{60 \cdot c_M \cdot f_O}{n_M} = \frac{V_{S.T}}{H}, \quad (4)$$

$$F_{M.H} = h_M \cdot H \cdot F_{M.T}, \quad (5)$$

where $V_{S.T}$ is the synchronous motion speed when the traditional control method is used (i.e. when H = 1), $V_{S.H}$ is the same parameter when PPM is used (i.e. when H > 1), $F_{M.T}$ is maximal value of motor linear traction force (torque) when the traditional control mode is used (i.e. when H = 1), $F_{M.H}$ is the same parameter when PPM is used (i.e. when H > 1), f_0 is the frequency of the inverter output voltage,

$$h_M = \frac{m^2 - A_M \cdot H^2}{m^2 - B_M}, \quad (6)$$

A_M = 0 for even values of phase number m_E = p × × m / p_E, A_M = 1 for odd values of the parameter m; B_M = 0 for even values of m, B_M = 1 for odd values of m, c_M is the least value of c satisfying equation (1), n_M is the least value of n satisfying equation (1) at c = c_M.

Formula (6) is true for the case when the type of a motor stator phase windings connection is "the star without a neutral conductor".

If this connection type is "the star with a neutral conductor", h_M = 1 for all values of the parameters m, H, and m_E.

Thus in the case when PPM is used the considerable increase of the maximal and starting forces (or torques, when the motor stator is bow-shaped) of a multiphase AC linear motor can be provided. This effect may be obtained in all the range of motor secondary element speed regulation, but in this case the frequency and amplitude of inverter output voltage must be increased by a factor the value of which depends on the parameter H value.

4.3 Optimal values of PPM parameter H

The application of PPM allows increasing the reliability (strictly speaking, survivability) of the multiphase AC linear drive in spite of the fact that the number of wires between the inverter and linear motor is increased when the phase number m is extended.

The optimal value H_0 of PPM parameter H for the given phase number m was found by the authors of this paper. When the equation H = H_0 is obtained, both the drive system mass-and-overall dimensions decrease and its survivability increase are achieved. The value H_0 is determined as follows:

$$H_O = \begin{cases} [A_{H.O}] & \text{if} \quad \{A_{H.O}\} \le 0.5; \\ [A_{H.O} + 1.0] & \text{if} \quad \{A_{H.O}\} > 0.5; \end{cases} \quad (7)$$

$$A_{H.O} = \frac{-K_A \pm \sqrt{K_A^2 + 4 \cdot K_A \cdot H_M}}{2}, \quad (8)$$

where $[A_{H.0}]$ is the integer part of the number $A_{H.0}$, $\{A_{H.0}\}$ is the fractional part of the number $A_{H.0}$, H_M is the maximal value of parameter H for the given value of phase number m, $H_M = [B_M]$, $[B_M]$ is the integer part of the number B_M = m / 3.

The parameter K_A shows, in how many times the decrease in drive mass-and-overall dimensions is more important than the increase of its survivability for the drive system developer (i.e. the parameter K_A establishes the compromise between the above-mentioned mass-and overall dimensions decrease and the linear drive survivability increase).

For example, at the previous design stage the developer has chosen value of phase number m = 30 (in this case $H_M = 30 / 3 = 10$). If he has taken an interest in both the motor mass-and-overall dimensions minimization and its survivability enlargement to the same extent, he chooses the value $K_A = 1.0$. In this case the value of the parameter $H_0 =$ $= 3$.

In a number of cases (for example, in the field of oil deep-well pumps) it is especially important to obtain at once the linear drive mass-and-overall dimensions decrease and its survivability enlargement.

4.4 Molten metals electromagnetic stirring intensity enlargement

It is common knowledge that at present linear stators are in considerable use for the electromagnetic stirring of molten metals in melting furnaces, ladles, castings, etc.

The application of the phase-pole-controlled (i.e. when PPM is used) multiphase inverter-fed linear stators allow to increase (in comparison with the case when the phase number m is equal to three or four) the intensity of electromagnetic stirring of molten metals by providing with continuous change of the quantity, space location, and configuration of the vortex areas in the metal mass during the process of the above-mentioned stirring. The range of this intensity increase may be wide, and its limit depends on the phase number m.

Besides that the use of PPM allows to prevent the intensity decrease of molten metal electromagnetic stirring when the metal viscosity increases in the consequence of the change in metal temperature or typical composition of alloy. In this case the change of the parameter H makes according to the principle $H / \mu = \text{const}$, where μ is viscosity coefficient of a molten metal.

5 CONCLUSION

The received results show once again that the multiphase non-traditional controlled electromechanical AC systems have prospects for the use in different fields of industry and transport, as on the nano-level and on the macro-level.

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