

## Research of Cylindrical Linear Induction Motor with Unconventionally Connected Windings

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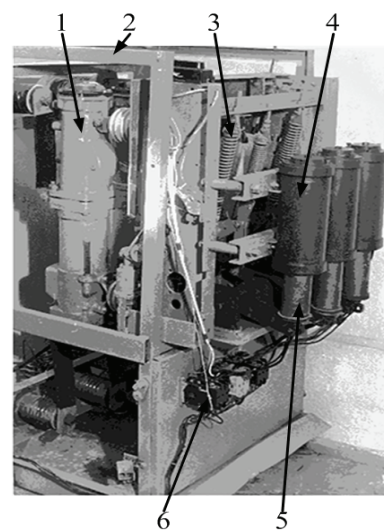
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### Introduction

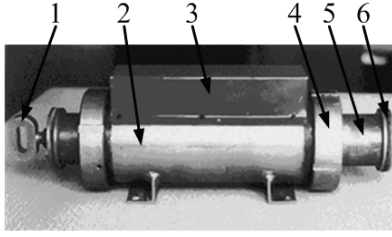
Cylindrical linear induction motors (CLIM) are often used in the drives of mechanisms operating in short-time duty modes, e.g. high-voltage circuit-breakers with separately controlled phases (Fig. 1) [1]. Such drives must ensure some certain velocity, when the secondary element of CLIM moves a predetermined distance (e.g. during connection of circuit-breaker contacts). If the drive does not satisfy the nominal characteristics of the mechanism, it is required to decrease or increase the starting force by changing the speed-torque characteristic of CLIM. The power parameters of short-time duty drive (efficiency and power factors, electrical power drawn from the supply line) are secondary in this case. Therefore the starting force required by CLIM can be obtained by connecting the three-phase winding of the CLIM inductor using unconventional methods. It was determined experimentally that it is possible to decrease or increase the CLIM starting force by changing the current direction in the separate coils of the polysolenoid winding of CLIM or by changing the number of coils in separate phases of the three-phase winding. By changing the current direction in separate winding conductors spaced apart by pole pitch  $\tau$  in the winding of the cylindrical linear induction machine (i.e. polysolenoid), it is possible to create required space functions of magnetomotive force, which are not possible to obtain in the electrical rotating induction or flat-type linear induction machines. It is impossible to change the current direction only in one side of the same coil of rotating or linear induction machine. We could not find any scientific references related to theoretical research of CLIM containing windings connected in a way mentioned above. In this paper the electromagnetic properties of CLIM with unconventionally connected windings are analyzed for the first time.

### Unconventional connection methods of the three-phase winding coils of CLIM and their research

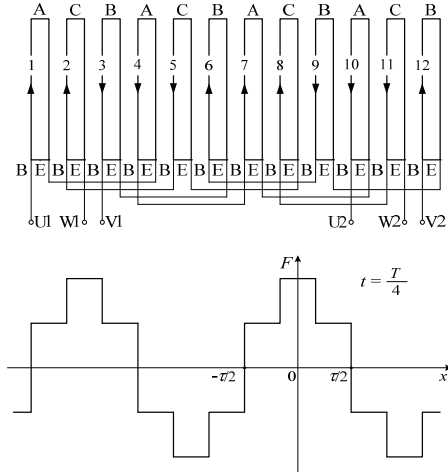
The general image of high-voltage oil circuit-breaker with separately controlled phases containing three CLIM is shown in Fig. 1. When the drive operates in a short-time duty, the motor can be assembled from monolithic parts of turned steel (Fig. 2). These are motors with two pole pairs ( $p = 2$ ). Inductor windings of such CLIM are usually laid as concentrated ( $q = 1$ ), furthermore, their span is not shortened ( $y = \tau$ ); here  $y$  – winding span,  $\tau$  – pole pitch. Therefore the symmetrical three-phase winding of CLIM (Fig. 3) is often called polysolenoid.



**Fig. 1.** High-voltage circuit breaker containing linear electrical drive with separately controlled phases: 1 – tank with circuit breaker contacts filled with transformer oil; 2 – frame; 3 – contact-opening springs; 4 – CLIM inductor; 5 – CLIM secondary element; 6 – contactors (magnetic starters)



**Fig. 2.** CLIM made from turned steel parts [1]: 1 – kinematical circuit; 2 – CLIM inductor; 3 – clamp box; 4 – inductor covers with friction bearings; 5 – secondary element of CLIM (steel core with copper coating formed by means of galvanoplastic process); 6 – shock absorber



**Fig. 3.** The layout of the three-phase symmetric CLIM winding ( $2p = 4$ ) and the space distribution of traveling magnetomotive force in time moment  $t = T/4$

Further we consider that under such winding connection type (Fig. 3) the CLIM creates the indicated starting force, which corresponds to relative force  $J_S^* = 1$ .

When a conventional three-phase winding connection is used (Fig. 3), the instantaneous space distributions of traveling magnetomotive force are symmetric in respect of coordinate axes. Such functions of magnetomotive force have only odd harmonics without multiples of three. The harmonic analysis of the traveling magnetomotive force function between space points  $-\pi/2$  and  $\pi/2$  (shown in Fig. 3) was performed according to the following expression [5, 6]

$$F_{\nu'} = \frac{4}{\pi \nu'} \sum_{i=1}^k F_i \sin\left(\nu' \frac{\beta_i}{2}\right); \quad (1)$$

here  $F_i$  – the apparent size of the  $i$ -th rectangle of magnetomotive force;  $\beta_i$  – the width of the  $i$ -th rectangle, expressed in electrical degrees of fundamental space harmonic;  $k$  – number of rectangles, which form the stair-shape curve of half-period of magnetomotive force;  $\nu'$  – number of odd space harmonic.

The parameters of the considered half-period of traveling magnetomotive force are the following:  $k = 2$ ;  $F_1 = 0,5$ ;  $F_2 = 0,5$ ;  $\beta_1 = 180^\circ$ ;  $\beta_2 = 60^\circ$ . The results of harmonic analysis are given in Table 1.

The electromagnetic efficiency factor of the three-phase winding is calculated according to such formula [5, 6]

$$k_{ef} = 1 - \sqrt{\sum_{\nu=1}^{\infty} f_{\nu}^2 - 1}; \quad (2)$$

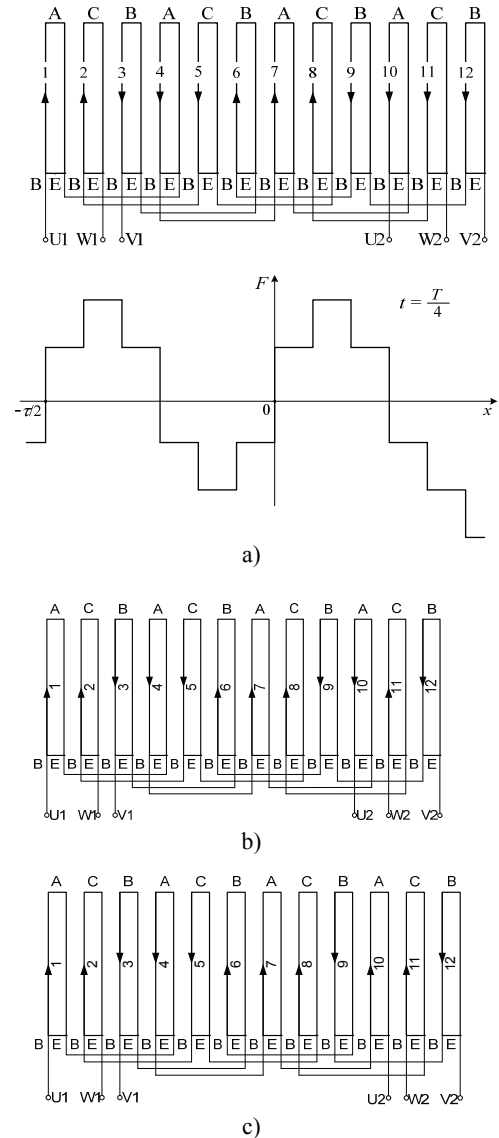
here  $f_{\nu}$  – relative magnitude of the  $\nu$ -th harmonic of magneto motive force.

The electromagnetic efficiency factor calculated using this formula is  $k_{ef} = 0,699$ .

**Table 1.** Harmonic analysis results of the traveling magnetomotive force created by three-phase symmetric CLIM winding

$\nu$	1	5	7	11	13	17	19
$F_{\nu}$	0,955	0,191	-0,136	-0,087	0,073	0,056	-0,050
$f_{\nu}$	1	0,2	0,142	0,091	0,076	0,059	0,052

By switching the terminals B and E of separate coils (Fig. 3), it is possible to reduce force  $J_S^*$  (Fig. 4).



**Fig. 4.** Coil connection diagrams for the reduction of CLIM starting force: a – up to  $J_S^* = 0,841$ , by changing the connection polarity of one coil; b – up to  $J_S^* = 0,825$ , by changing the connection polarity of two coils (connected to the windings of different phases); c – up to  $J_S^* = 0,81$ , by changing the connection polarity of two coils (connected to the windings of different phases)

After constructing the instantaneous space distribution of the traveling magnetomotive force created by CLIM inductor the windings of which are connected using one of the unconventional methods (Fig. 4, a), a function asymmetric in respect of coordinate axes is obtained. Such space function of magnetomotive force, under assumption that its half-period consists of the curve segment between space points  $-\tau/2$  and  $\tau/2$ , can be expanded into harmonics using the following expressions [5, 6]:

$$F_{v'} = \frac{4}{\pi v'} \sum_{i=1}^k F_i \sin\left(v' \frac{\beta_i}{2}\right) \cos(v' \gamma_i); \quad (3)$$

$$F_{v''} = \frac{4}{\pi v''} \sum_{i=1}^k F_i \sin\left(v'' \frac{\beta_i}{2}\right) \sin(v'' \gamma_i); \quad (4)$$

here  $\gamma_i$  – the asymmetry of  $i$ -th rectangle of the stair-shape half-period of magnetomotive force in respect of the selected coordinate axis, expressed in electrical degrees of the fundamental space harmonic;  $v'$  – the number of odd space harmonic;  $v''$  – the number of even space harmonic.

The parameters of the analyzed half-period of traveling magnetomotive force are such:  $k=9$ ;  $F_1=0,542$ ;  $F_2=0,5$ ;  $F_3=-0,458$ ;  $F_4=-0,5$ ;  $F_5=0,542$ ;  $F_6=0,5$ ;  $F_7=-0,458$ ;  $F_8=-0,5$ ;  $F_9=-0,5$ ;  $\beta_1=45^\circ$ ;  $\beta_2=15^\circ$ ;  $\beta_3=45^\circ$ ;  $\beta_4=15^\circ$ ;  $\beta_5=45^\circ$ ;  $\beta_6=15^\circ$ ;  $\beta_7=45^\circ$ ;  $\beta_8=22,5^\circ$ ;  $\beta_9=7,5^\circ$ ;  $\gamma_1=67,5^\circ$ ;  $\gamma_2=67,5^\circ$ ;  $\gamma_3=22,5^\circ$ ;  $\gamma_4=22,5^\circ$ ;  $\gamma_5=-22,5^\circ$ ;  $\gamma_6=-22,5^\circ$ ;  $\gamma_7=-67,5^\circ$ ;  $\gamma_8=-71,25^\circ$ ;  $\gamma_9=-78,75^\circ$ . The results of harmonic analysis are given in Table 2.

**Table 2.** The results of harmonic analysis of the traveling magnetomotive force created by CLIM with unconventionally connected coils

$v^*$	1	2	3	4	5	6	7
$F_v$	-0,002	0,095	0,093	-1,058	-0,069	0,054	0,030
$f_v$	0,002	0,09	0,088	1	0,065	0,051	0,028

**Table 2 (continued)**

	8	9	10	11	12	13	14	15
	-0,040	-0,052	0,085	0,104	-0,117	-0,102	0,077	0,034
	0,038	0,049	0,080	0,098	0,111	0,096	0,073	0,032

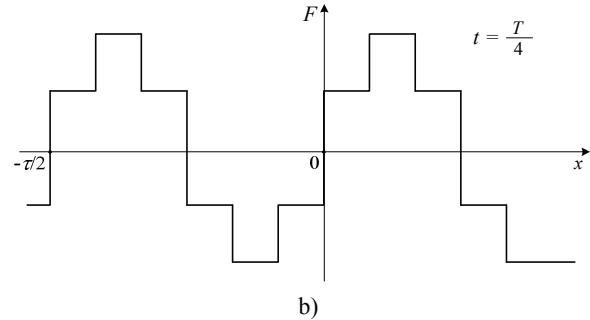
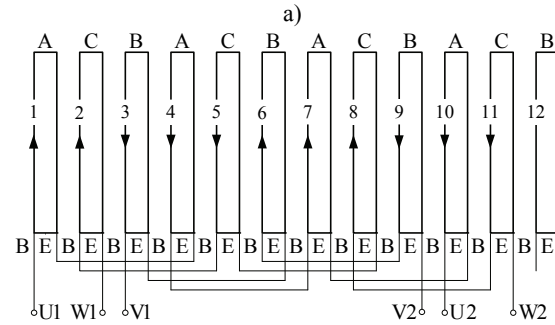
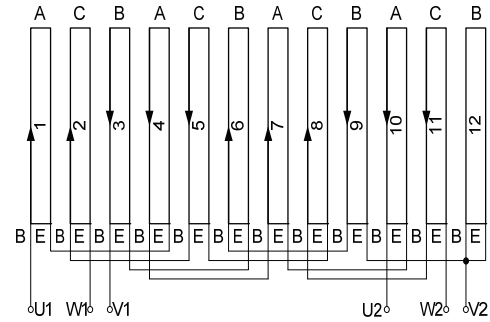
Electromagnetic efficiency factor of the three phase winding connected in this way (Fig. 4, a), calculated according to formula (2), is  $k_{ef} = 0,626$ .

When one coil of the CLIM inductor winding is short-circuited or it is removed from the phase winding, it is possible to increase the starting force generated by CLIM (Fig. 5).

After constructing the instantaneous space distribution of the traveling magnetomotive force created by CLIM inductor the windings of which are connected using one of the unconventional methods (Fig. 5, b), a function asymmetric in respect of coordinate axes is also obtained. This space function of magnetomotive force, under assumption that its half-period consists of the curve segment between space points  $-\tau/2$  and  $\tau/2$ , can be expanded into harmonics using the expressions (3) and (4).

The parameters of the analyzed half-period of traveling magnetomotive force are such:  $k=8$ ;  $F_1=0,521$ ;  $F_2=0,5$ ;  $F_3=-0,479$ ;  $F_4=-0,5$ ;  $F_5=0,521$ ;  $F_6=0,5$ ;

$F_7=-0,479$ ;  $F_8=-0,5$ ;  $\beta_1=45^\circ$ ;  $\beta_2=15^\circ$ ;  $\beta_3=45^\circ$ ;  $\beta_4=15^\circ$ ;  $\beta_5=45^\circ$ ;  $\beta_6=15^\circ$ ;  $\beta_7=45^\circ$ ;  $\beta_8=22,5^\circ$ ;  $\gamma_1=67,5^\circ$ ;  $\gamma_2=67,5^\circ$ ;  $\gamma_3=22,5^\circ$ ;  $\gamma_4=22,5^\circ$ ;  $\gamma_5=-22,5^\circ$ ;  $\gamma_6=-22,5^\circ$ ;  $\gamma_7=-67,5^\circ$ ;  $\gamma_8=-71,25^\circ$ . The results of harmonic analysis are given in Table 3.



**Fig. 5.** Coil connection diagrams for increasing of CLIM starting force: a – up to  $J_s^* = 1,032$ , when one coil terminals of the winding are short-circuited; b – up to  $J_s^* = 1,127$ , by removing one coil from the winding

**Table 3.** The results of harmonic analysis of the traveling magnetomotive force created by CLIM with unconventionally connected coils

$v^*$	1	2	3	4	5	6	7
$F_v$	0,019	0,016	0,014	-0,984	-0,029	0,038	0,036
$f_v$	0,019	0,016	0,014	1	0,029	0,039	0,037

**Table 3 (continued)**

	8	9	10	11	12	13	14	15
	-0,040	-0,036	0,036	0,029	-0,027	-0,018	0,014	0,005
	0,041	0,037	0,037	0,029	0,027	0,018	0,014	0,005

Electromagnetic efficiency factor of the three phase winding connected in this way (Fig. 5, b), calculated according to formula (2), is  $k_{ef} = 0,715$ .

Other ways of symmetric and asymmetric connection of windings are possible (especially in case of multipolar CLIM), which allow to change the starting force generated by CLIM. For example, by crossing terminals of two coils

in one phase winding, and one coil in other, it is possible to decrease the starting force down to  $J_s^* = 0,518$ .

Similarly, by switching the windings, it is possible to change the pressure generated by cylindrical magnetohydrodynamic liquid-metal pumps.

## Conclusions

1. The speed-torque characteristic of CLIM operating in short-time duty, and the starting force at the same time can be changed (selected, corrected) by differently connecting coils of the CLIM inductor three-phase winding (polysolenoid).

2. The Construction of CLIM permits changing of current direction in the conductors of inductor winding, equivalent to coil sides of rotating and linear plane-type induction machines.

3. Under conventional (symmetric) connection of phase winding coils, the investigated CLIM achieves the relative magnitude of starting force  $J_s^* = 1$ , and the electromagnetic efficiency factor of the winding connected in this way is  $k_{ef} = 0,699$ .

4. When the connection polarity of one coil was changed, the relative magnitude of CLIM starting force decreased down to  $J_s^* = 0,841$ , and the electromagnetic efficiency factor of this winding – down to  $k_{ef} = 0,626$ .

5. After one coil was removed from the winding, the relative magnitude of CLIM starting force increased up to  $J_s^* = 1,127$ , and the electromagnetic efficiency factor of this winding – up to  $k_{ef} = 0,715$ .

6. The electromagnetic efficiency of CLIM inductor winding indirectly indicates the starting force of this motor.

## References

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**A. J. Poska, J. Bukšnaitis. Research of Cylindrical Linear Induction Motor with Unconventionally Connected Windings // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 5(121). – P. 23–26.**

The changes of cylindrical linear induction motor (CLIM) starting force due to electric drive operation matching by changing the connection circuit of polysolenoid CLIM inductor winding coils are analyzed. The starting force measurements were carried out under different connections of CLIM winding coils and their relative magnitudes were determined. Also the research of electromagnetic properties of winding coils connected in some certain way was performed. It was determined that when changing phase winding polarities, it is possible to reduce the starting force by some certain amount, and when coil terminals are short-circuited or the coil is removed from the winding, the same force can be increased, compared to force generated by conventionally connected coils. The electromagnetic efficiency factor for conventionally connected winding coils was determined:  $k_{ef} = 0,699$ . When changing polarity of one coil of the winding, this factor decreased down to  $k_{ef} = 0,626$ , and when the coil is removed from the winding, factor increased up to  $k_{ef} = 0,715$ . This proves that the electromagnetic efficiency of CLIM inductor winding indirectly indicates the starting force of this motor. Ill. 5, bibl. 6, tabl. 3 (in English; abstracts in English and Lithuanian).

**A. J. Poška, J. Bukšnaitis. Cilindrinio tiesiaieigio asinchroninio variklio su netradiciškai sujungtomis apvijomis tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 5(121). – P. 23–26.**

Straipsnyje nagrinėjami cilindrinės konstrukcijos tiesiaieigio asinchroninio variklio (CTAV) paleidimo jėgos pokyčiai dėl elektros pavaros darbo suderinimo keičiant polisolenoidinės CTAV induktoriaus apvijų ričių sujungimo schemą. Esant įvairiems CTAV apvijų ričių sujungimams atlikti paleidimo jėgų matavimai, nustatyti jų santykiniai dydžiai. Taip pat atlikti kai kuriais būdais sujungtų apvijų ričių elektromagnetinių savybių tyrimai. Nustatyta, kad, keičiant fazinių apvijų ričių poliškumą, paleidimo jėgą galima norimu dydžiu sumažinti, o trumpai sujungiant ritės galus arba ritę iš apvijos pašalinant – tą jėgą galima padidinti normaliai sujungtų ričių sukuriamos paleidimo jėgos atžvilgiu. Esant normaliai sujungtomis apvijomis ritėms, nustatytas jos elektromagnetinio efektyvumo koeficientas  $k_{ef} = 0,699$ . Pakeitus apvijos vienos ritės poliškumą, šis koeficientas sumažėjo iki  $k_{ef} = 0,626$ , o pašalinus ritę iš apvijos – padidėjo iki  $k_{ef} = 0,715$ . Tai įrodo, kad CTAV induktoriaus apvijų elektromagnetinis efektyvumas netiesiogiai atspindi šio variklio sukuriamą paleidimo jėgą. Il. 5, bibl. 6, lent. 3 (anglų kalba; santraukos anglų ir lietuvių k.).