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Design Characteristics of Permanent Magnet Linear Synchronous Motor for Short Reciprocating Trajectory

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Abstract

Design characteristics of PMLSM(Permanent Magnet Linear Synchronous Motor) considering the dynamic running condition under the limited input voltage and current for short reciprocating trajectory are presented. Particularly, the dynamic constraints resulted from the dynamic capability of PMLSM and the required motional performance of the repeated short stroke are applied to determine the design specification of PMLSM. In addition, optimal design flow based on the dynamic constraints is specified with the design parameters, such as coil resistances, the EMF constants, inductances, pole-pitch. Furthermore, proposed methods and results are validated by the experimental ones measured with the purpose-built prototype.

Key words: Permanent Magnet Linear Synchronous Motor, Short reciprocating trajectory, Dynamic constraints

I. Introduction

With rapid increase of required actuating force in such application as a machine tool or a factory automation, PMLSM(Permanent Magnet Linear Synchronous Motor) has been developed, and its smooth operation keeping high positioning accuracy has been realized thanks to precise manufacturing skill and position signal sensors with high resolution(less than micro-meter). Usually, industry field, where linear machine has been utilized most, will be the reciprocating short-stroke application, which needs high acceleration and velocity, low noise and little heat exhalation. In such applications, general design strategies considering steady-state condition are not agreeable because linear motor operates mostly under the accelerating or decelerating circumstances on short travel displacements [1]-[4]. Moreover, since the servo capability responding to various motional performance is recently regarded to be necessary, new plans considering dynamic constraints under the maximum input voltage and current must be made for better efficiency in machine sizing.

Generally, capability of PMLSM is defined by maximum input voltage and current, which expresses the maximum thrust force according to the specified mover velocity [5]-[7]. This capability, directly connected to the motor size, must be at least larger than required motional performance which are composed of jerk, acceleration, velocity, and mechanical parameters like mass, viscous damping coefficient and friction coefficient. Accordingly, dynamic constraints can be induced from a relation between such different dynamic capability and required motional performance under the limited input voltage and current. These dynamic constraints express the admissible design range from which design variables meeting the required trajectory can be obtained after all. In principle, dynamic constraints are associated with such parameters as resistance, inductance, pole-pitch and EMF constant. These parameters, also related with the machine dimension, will be the best criteria to evaluate the machine design results [8]-[12].

Based on the proposed design procedure considering the dynamic running condition, and supplementary design criteria, the purpose-built sample model of PMLSM with stroke-length of

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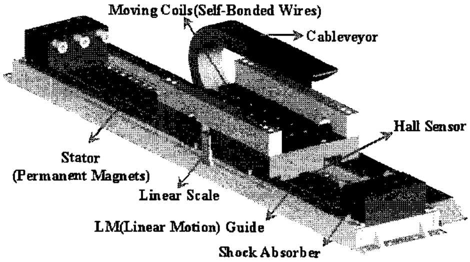
300[mm], maximum velocity of 4[m/s], maximum force/continuous force of 7500[N]/1500[N] under the input voltage of 220[V] and maximum peak current of 150[A], was designed and manufactured. Experimental results will be compared with analyzed ones to verify the successful implementation of design characteristics after all.

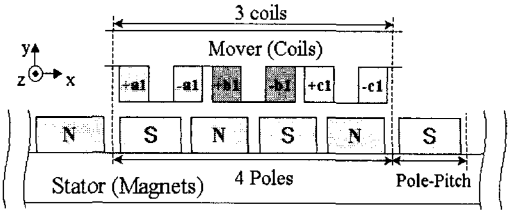
II. Dynamic capability of PMLSM and the required motional performance

2.1. PMLSM(Permanent Magnet Linear Synchronous Motor)

Conventional PMLSM is the moving-coil type one, which shows better controllability than moving magnet type one. In addition, PMLSM has been getting widely used mainly due to its large force productivity. In this paper, moving-coil type PMLSM producing the large force will be analyzed for our original intention to set up the design strategy for dynamic linear motional application.



(a) Assembled PMLSM



(b) Side view of PMLSM

Fig. 1. Moving coil type PMLSM(4poles, 3coils)

As shown in Fig. 1, PMLSM uses concentrated short-pitch winding on account of manufacturing easiness at work and compact treatment of end-winding, which has the combination of 4 poles and 3 coils(one module).

2.2 Dynamic capability and the required motional performance

PMLSM with limited input voltage($V_{\max}$) and current($I_{\max}$) has dynamic capability as follows, which is induced with commands as $i_d = 0$ (force maximization).

$$F_{e,\max} = \frac{3}{2} K_e \min\left(\frac{C_1 + \sqrt{C_2 - C_3}}{R_s^2 + (\pi/\tau)^2 L_s^2 \nu^2}, I_{\max} \right), \tag{1}$$

where, $C_1 \equiv - R_s \left\{ K_e \nu + \left(\frac{2L_s}{3K_e} \right) \left(m\frac{da}{dt} + Ba \right) \right\}$,

$$C_2 \equiv \left\{ \left(\frac{\pi}{\tau} \right)^2 L_s^2 \nu^2 + R_s^2 \right\} V_{\max}^2$$

$$C_3 \equiv \left(\frac{\pi}{\tau} \right)^2 L_s^2 \nu^2 \left\{ K_e \nu + \left(\frac{2L_s}{3K_e} \right) \left(m\frac{da}{dt} + Ba \right) \right\}^2$$

τ : Pole-Pitch[m], K_e : EMF constant[V/(m/sec)]

R_s : Resistance[Ω], L_s : Synchronous Inductance[H]

Equation (1) indicates the maximum thrust force at specified velocity under the maximum input voltage and current, and also includes the time-varying component, such as acceleration(a) and jerk ($J = da/dt$), available in dynamic analysis. The proposed dynamic capability has more meaning in linear machine than the conventional static capability under the acceleration and jerk set to be zero, which has been conventional approaches to the design process until now.

In Fig. 2, motional profiles of trapezoidal acceleration mode, most common in actual operation, and its relevant Force-Speed curve are shown.

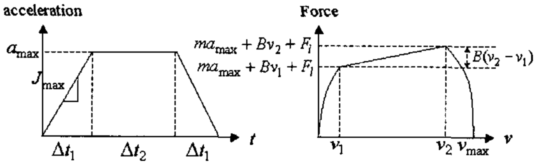


Fig. 2. Motional profiles of trapezoidal acceleration and Force-Speed curve of PMLSM

Force-Speed characteristics, which are obtained at each time interval, can be summarized as follows.

$$F_{e(\nu)}=\begin{cases} m\sqrt{\dfrac{2a_{\max}}{\Delta t_1}\nu}+B\nu+F_1 & (0<\nu\le\nu_1) \\ ma_{\max}+B\nu+F_1 & (\nu_1<\nu\le\nu_2) \\ m\sqrt{\dfrac{2a_{\max}(\nu_{\max}-\nu)}{\Delta t_1}}+B\nu+F_1 & (\nu_2<\nu\le\nu_{\max}) \end{cases} \tag{2}$$

where, $\nu_1=(a_{\max}/2)\cdot\Delta t_1,\nu_2=a_{\max}(\Delta t_1/2+\Delta t_2)$

III. Design characteristics of PMLSM applying dynamic constraints

3.1 Dynamic constraints of PMLSM design

In principle, dynamic capability shown in (1) should be larger than Force-Speed relation of required trajectory shown in (2). This constraint is shown in Fig. 3, where static and dynamic capability and the required motional trajectory are compared.

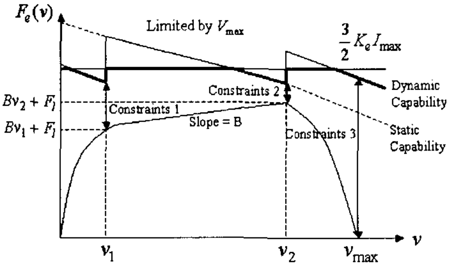


Fig. 3. Dynamic Constraints specified by required motional performance and dynamic capability

Particularly between two forces from maximum voltage and current respectively, the smaller one could be the final dynamic capability, which is based on (1). Therefore, heavy-line in Fig. 3 indicates the final capability of PMLSM, which should be larger than motional performance, and this conclusion gives effective design criteria referred as *dynamic constraints*. Therefore, it is reasonable that only dynamic capability at the velocity of ν_1, ν_2, $\nu_{\max}$ should be larger than the required one, which is summarized as follows.

<Constraint 1; $\nu=\nu_1$, $J=J_{\max}$, $a=a_{\max}$>

$$\frac{3}{2}K_e\frac{C_1+\sqrt{C_2-C_3}}{R_s^2+(\pi/\tau)^2L_s^2\nu^2}\gg ma_{\max}+B\nu_1+F_l \tag{3}$$

<Constraint 2; $\nu=\nu_2$, $J=0$, $a=a_{\max}$>

$$\frac{3}{2}K_e\min\left\{\frac{C_1+\sqrt{C_2-C_3}}{R_s^2+(\pi/\tau)^2L_s^2\nu^2},\ I_{\max}\right\}\gg ma_{\max}+B\nu_2+F_l \tag{4}$$

<Constraint 3; $\nu=\nu_{\max}$, $J=-J_{\max}$, $a=0$>

$$\frac{3}{2}K_e\frac{C_1+\sqrt{C_2-C_3}}{R_s^2+(\pi/\tau)^2L_s^2\nu^2}\gg 0 \tag{5}$$

In (3), the dynamic constraints only from voltage limitation are considered, because the other constraints from maximum input current can be neglected due to the same kind of constraints in (4). At velocity of ν_2 in (4), both of them must be satisfied at the same time, where dynamic capability($J=0$, $a=a_{\max}$) and static capability ($J=0$, $a=0$) show little difference which can be verified through (1). In constraints 3, it is sufficient to judge whether motor has an ability to produce the force or not. However, constraints 3 can be replaced by other different constraint like $\partial F_{e,\max}/\partial\nu\gg\partial F_e(\nu)/\partial\nu(at\ \nu=\nu_2)$ which means that, if the slope of dynamic capability are larger than that of required motional performance at $\nu=\nu_2$ (slope<0), constraint 3 at $\nu=\nu_{\max}$ are satisfied by itself. In addition to three basic constraints, such. a relations as $\nu_{\max}=V_{\max}/K_e$ and another constraint, $C_2\gg C_3$, should be obeyed also in all of dynamic constraints.

Meanwhile, major difference between constraints from conventional static capability and proposed dynamic capability would be noticed at $\nu=\nu_1$ and $\nu=\nu_2$. Although the properly designed machine can satisfy constraints given by static capability, required motional performance can not be realized due to the dynamic constraints, especially at $\nu=\nu_1$ (at $\nu=\nu_2$, there is little difference due to the zero jerk). Since discontinuous force change at $\nu=\nu_1$ and $\nu=\nu_2$results purely from jerk and acceleration, high accelerating PMLSM used in short traveling displacements should be designed along the dynamic constraints.

Defined design parameters in (1) will be τ, K_e, R_s, L_s which are strongly regulated by dynamic constraints, and used as decision criteria to the combination of the design variables judging that the dynamic constraints are fully satisfied, i.e. designed machine can be driven successfully satisfying the required motional performance. Actually, sensitivity to the design parameter variance is most serious to τ and K_e relatively than R_s , L_s which are occasionally neglected in simplified design flow. Accordingly, in addition to the dynamic constraints, more generalized design consideration at the primary stage should be done focusing on the influence of τ and K_e, which makes entire design process performing more effectively.

3.2 Generalized design consideration on the design parameters

Not only important to implement machine to satisfy the dynamic constraints, but basic design strategy based on the better efficiency should be established.

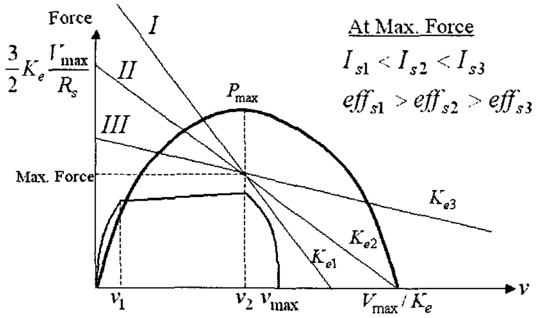


Fig. 4. Generalized Design Schematic Diagram (where *eff* denotes efficiency considering dominant copper loss, and $K_{e1} > K_{e2} > K_{e3}$ considering the difference of the magnetic flux density)

As shown in Fig. 4, design objectives and constraints are defined by maximum velocity($\nu_{\max}$), maximum force($F_{e,\max}$), running information in required motional performance, and the given inverter voltage($V_{\max}$) and current($I_{\max}$). Approximately, the point where maximum output power could be generated will be around $\nu = V_{\max}/K_e/2$(half to the no-load velocity). Likewise, maximum required mechanical power exists at $\nu = \nu_2$, therefore a design basis should be oriented as $\nu = V_{\max}/K_e/2$ $\nu_2 \approx V_{\max}/K_e/2$($K_{e2}$ model in Fig. 4). However, if required input current ($I_s = F_{e,\max}/(1.5 \cdot K_e)$) are considered, K_{e1} model needs smaller current(I_{s1}) than K_{e2} model(I_{s2}), which could be also interpreted as better efficiency. Accordingly, EMF coefficient, K_e[V/(m/s)], should be in the interval as follows.

$$V_{\max}/V_{\max} \le K_e \le V_{\max}/(2 \cdot \nu_{\max}) \tag{6}$$

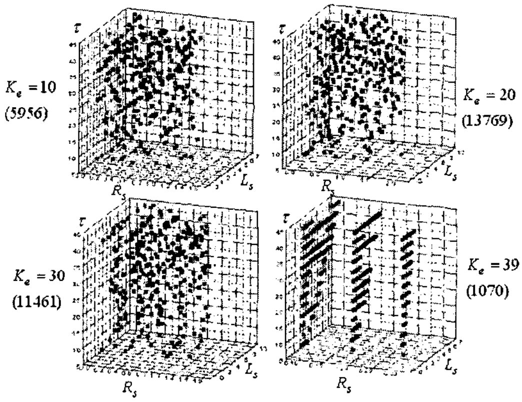
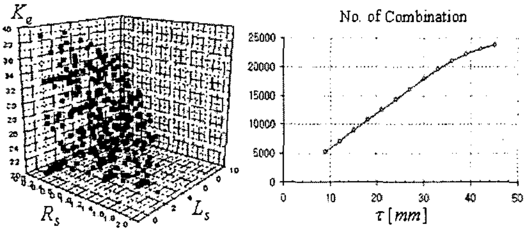


Fig. 5. Admissible design combination versus K_e (where, $V_{\max} = 160\,[V]$, $I_{\max} = 150\,[A]$, m=37[kg], B=100[N/(m/s)], F_l=50[N], $a_{\max} = 20\,[m/s^2]$, $\nu_{\max} = 4\,[m/s]$, $J_{\max} = 3000\,[m/s^3]$)

By changing the different combination of $\tau, K_g, R_s, L_s,$ we can regulate the admissible design region satisfying the dynamic constraints. In Fig. 5, distribution of design combination versus K_e is shown, which will be used as decision criteria to design variables in actual design flow. If it is applied to Fig. 4, $K_e = 20$ corresponds to K_{e2} model which shows the best design point from a viewpoint of size-effectiveness and usefulness in application. As the increase of K_e, better efficiency(lower input current) can be realized, and near the no-load speed($K_e = 20$), dynamic constraints strongly restricts the design combination which happen in the speed range of $\nu_2 \le \nu \le \nu_{\max}$. Particularly, the number of admissible design combination is maximum at the $K_e = 20$, which means the possibility to implement the machine successfully is highest at the best design point. In addition, the distribution of design combination changes noticeably along the EMF constant.



(a) Distribution at τ=30[mm] (b) Number versus τ

Fig. 6. Distribution and number of admissible design combination

Fig. 6(a) shows another distribution of design combination under τ=30[mm]. Distinguishably, it shows smaller combination at larger K_e, and irregularly discrete existence in the map. Number of admissible design combination shown in Fig. 6(b) increases gradually along the increased τ, which suggests such important design aspects that the machine with higher pole-pitch approaches favorably to the best solution.

Another sensitive design parameter, pole-pitch(τ), should be defined from the magnetic combination(4 poles and 3 coils), manufacturing feasibility, and detent force period. The one module length τ_m corresponding to $4 \cdot \tau$ and $3 \cdot \tau_c$ (where, τ_c is coil-pitch) should be multiplied with 12, which has validated itself compared with other combination. Hence, its minimum and maximum size are strongly restricted by the manufacturing feasibility and cost. Acceptable τ_m range for more than 1kW(in continuous operation) application is approximately from 36[mm](τ =9[mm]) to 180[mm](τ =45[mm]). Particularly, τ =30[mm] is most common statistically in large powered application. In addition, detent force, main cause to force ripple, are repeatedly arising against thrust force due to interaction between PM and ferromagnetic core. Such period and magnitude of detent force distribution are closely connected to the τ and τ_c, therefore much larger pole pitch causes some drawbacks in ripple free movements.

Actually, large τ indicates the smaller input frequency($\nu = 2\tau f$) showing the advantage in the point of core loss and inverter switching problem. However, since most of linear application can be possible with relatively low input frequency, smaller pole-pitch can be acceptable. That is the main reason why carbon-steel is generally used as the ferromagnetic core material. Also, instead of using large pole-pitch, increase of module number manifests the better approaches to the good design flow. In addition, since detent force period and magnitude are proportional to the pole-pitch, smaller pole-pitch is better for ripple-free operation. However, design point where the maximum efficiency can be guaranteed is obtained with the increased K_e which is overall proportional to pole-pitch. This says that the increase of machine height is inevitable for the compensation of deficient K_e under the smaller pole-pitch. Also, too small pole-pitch(likewise, too small coil-pitch) has big manufacturing problems of armature coil winding and machine assembly. Accordingly, it will be reasonable that such a sensitive component, pole-pitch, should be regarded as an independent design variable.

Design parameters(τ, K_e, R_s, L_s) are electrically and magnetically composed of design variables expressing the machine dimension, hence design process will be done by changing the design variables and checking the validity of sets of design variables under the criteria proposed by dynamic constraints. Particularly, pole-pitch(τ) will be sufficient to represent the moving directional (longitudinal) design aspects, because coil-pitch and one module-length are also determined accordingly. Then, the other variables can be summarized as air-gap length(g_0), height of magnet(h_m), height of slots(S_h)(or number of turns in slots), which are flexible to the normal direction. Particularly, there are some cases that air-gap length is fixed at first design stage, which is fully based on the manufacturing skill maintaining the constant air-gap length. In PMLSM, minimum air-gap length shows best results in efficiency and power factor, and the worst results in normal force and detent force. Height of magnets is closely dependent on the demagnetization effect, space harmonics in EMF due to the 4 poles and 3 coils combination, and the width of magnet to the pole-pitch. The height of slots matches perfectly to the number of turns in slots, where the constant slot-fill factor should be obtained previously with consideration of winding technique.

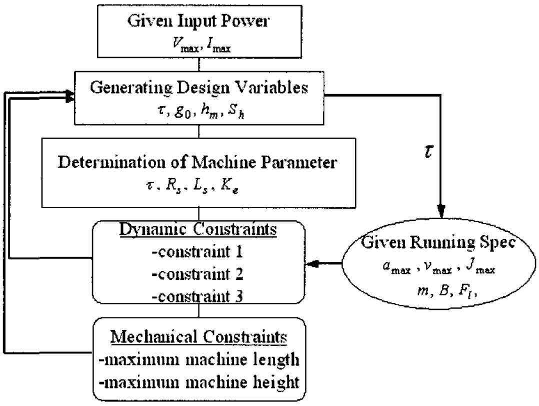


Fig. 7. Optimal design flow chart

With proposed design variables, optimization method can be applied to the design process under the constraints such as dynamic constraints, maximum mover length and maximum machine height, which are shown in Fig. 7 as a flowchart. For reference, another strong restriction imposed by thermal effect defines the maximum input current determined at the prior stage of the flowchart.

IV. Design, Manufacturing and Testing

Analogous to proposed design consideration, PMLSM for short reciprocating traveling displacement has been designed. Reciprocating linear motion is within 300[mm] and maximum force/continuous force is 7500[N]/1500[N], and the motor could run up to v_{max}=4[m/s], a_{max}=20[m/s^2] and J_{max}=3000[m/s^3] under the input voltage of 220[V] and maximum peak current of 150[A]. There is no restriction in total length and height, but ultimate goal is to minimize the machine size, satisfying the required performance at a same time. First of all, K_e should be from 20[V/(m/s)] to 40[V/(m/s)] as verified in (6), where $V_{max} \approx$160[V] in space vector PWM. Pole pitch is ranged around 30[mm] with difference of 12[mm]. Design variables are g_0, h_m, s_h(number of turns in slots are determined by fixed slot fill factor), and dynamic constraints are adopted with the force margin larger than 100[N].

Table 1. Purpose-designed PMLSM

	Specification	Dimension
General (Water Cooling)	Voltage/Current	220[V]/23.4[A]
	Stack length	100 [mm]
Stator (NdFeB, 45H)	Magnet height	9 [mm]
	Magnet width	27 [mm]
	Pole pitch	30[mm]
	Skew angle	30°(5[mm])
Mover (Coil size=1ϕ)	Slot width	14 [mm]
	Tooth height	16 [mm]
	Tooth width	10 [mm]
	No of turns	180 per coil
	Coil connection	3 parallel

(Three phase, Y-connection, 3 modules, Parallel Connection, K_e=34.63[V/(m/s)])

In Table I, one of optimal design results has been obtained through optimal design procedure shown in Fig. 7. In accordance, the prototype of PMLSM has been manufactured as shown in Fig.8, which will be tested for K_e to evaluate the dynamics operation.

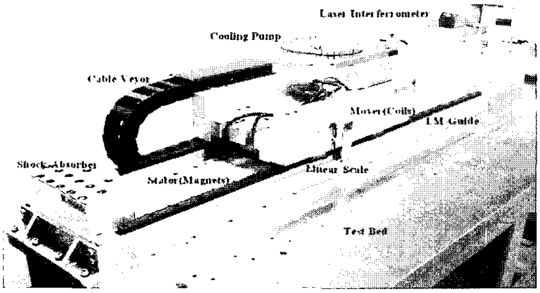


Fig. 8. Manufactured PMLSM

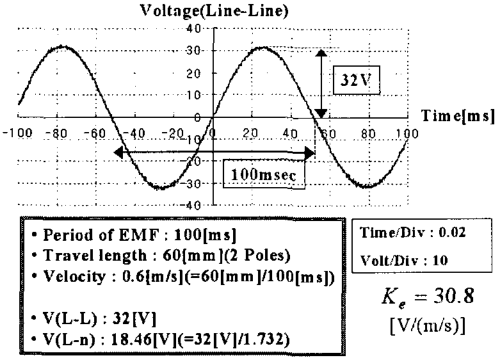


Fig. 9. Experimentally measured K_e

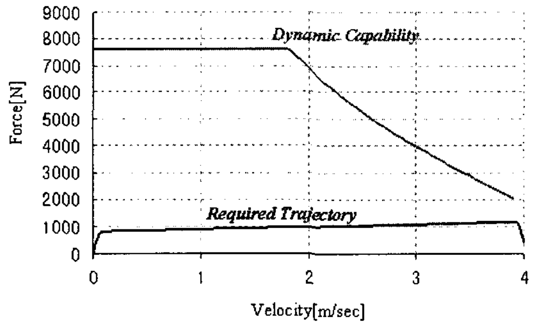


Fig. 10. Running characteristics of purpose-built PMLSM ($R_s=0.42[\Omega]$, L_s=3.5[mH], m=37[kg], B=100[N/(m/s)], $F_l=50[N]$, K_e=31.8[V/(m/s)])

K_e can be obtained by measuring line-to-line voltage under the constant speed. In Fig. 9, K_e=30.8 is obtained, but after iterative measurement, statistical K_e is changed to 31.8 which shows 8.2% error to the designed value of 34.63. Measured K_e as well as other parameter can prove the validity of the designed machine operation by comparing its capability with required trajectory along the given velocity, as shown in Fig. 10, which manifests rapid accelerating operation specified for the short reciprocating trajectory.

V. Conclusion

Design characteristics of PMLSM utilizing the dynamic constraints for satisfying the dynamic requirements under the limited input voltage and current in operation on short reciprocating trajectory has been considered in this paper. Dynamic constraints regulate the admissible region of design parameter expressed by design variables, and act as decisive criteria to each combination of design variables. Performances of the purpose-built PMLSM shows good agreements to the analyzed ones.

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