# Particle Swarm Optimization Based Energy Efficiency Method for High Speed IPMSM Drives

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*Abstract*— **This paper describe a novel method for increasing energy efficiency of interior permanent magnet synchronous motor (IPMSM) drives. In order to minimize the controllable electrical losses of IMPSM the *dq*-axes armature current is calculated based on particle swarm optimization (PSO). The method are tested for the wide speed range and different load condition. Simulation results of high speed IPMSM drives are presented and discussed.**

***Keywords- IPMSM, high speed, PSO, energy efficiency***

## NOMENCLATURE

| | |
|---|---|
| $v_d$ ,$v_q$ | – stator *d*- and *q*- axis input voltages |
| $v_{od}$ ,$v_{oq}$ | – stator *d*- and *q*- axis airgap voltages |
| $i_d$, $i_q$ | – stator *d*- and *q*- axis input currents |
| $i_{do}$, $i_{qo}$ | – stator *d*- and *q*- axis airgap currents |
| $i_{dc}$, $i_{qc}$ | – stator *d*- and *q*- axis equivalent iron loss currents |
| $R_s$ | – stator phase resistance |
| $R_c$ | – iron losses resistance |
| $\Psi_m$ | – permanent magnet flux |
| $L_d$ ,$L_q$ | – stator *d*- and *q*- axis self inductances |
| $\omega$ | – actual rotor angular speed |
| $m_{el}$ | – electromagnetic torque |
| $m_m$ | – load torque |
| $J$ | – motor inertia |
| $p$ | – number of pole pairs |
| $\rho$ | – saliency ratio ($L_q/L_d$) |
| $T$ | – torque |
| $P_{Cu}$ ,$P_{Fe}$ | – copper and iron losses |
| $P_L$ | – total electric power losses |

## I. INTRODUCTION

The 60% of electric energy generated in industrialized countries is expended on electromechanical conversion. Losses occur during any such conversion, and optimization is required for their minimization [1]. Energy conservation and profitability are the basis of a faster development of digitally regulated electrical drives in a wide range of speeds, which are seeing more and more use in industrial processes.

Last decade the permanent magnet synchronous motor (PMSM) are widely used. PMSM combine a high power density, good heat transfer, and, lastly, a greater efficiency compared to other types of motors used for energy conversion. At the same time, synchronous motors boast favorable control characteristics, making them suitable for various applications, such as hybrid vehicles, servo-drives, household appliances etc [2]. The past few decades experienced rapid development of microcontrollers of vast capabilities, enabling full digital control of electromechanical conversions. Great effort has been expended in resolving problems of digital electrical drives. Synchronous motor energy efficiency can be further increased with improvements in digital control algorithms, while additional expenses can be reduced by increasing the rotor revelation speed [3], [4].

Drive losses are consisted of converter losses and motor losses. Motor losses are consisted of losses in stator windings, mechanical losses, and iron losses. The past several years saw the development of a number of loss optimization methods for regulated permanent magnet synchronous motor drives. These methods can be divided into two basic groups: methods based on search algorithms [1] - [3], and model-based methods [4] - [14]. The first group is independent on the motor model used, and includes inverter losses, but may, in some cases, cause ripples to appear in steady-state torque. The second group requires the knowledge of motor (as well as converter) parameters during drive operation.

In search algorithms, the input power is measured, and then minimized through alteration of system variables. A required property for optimization is constant output power. Search algorithms are most often used in steady-state operation, but, optionally, can be combined with model-based methods during transient states. Authors in [1] have, based on measured currents and DC circuit voltage, estimated input power, and use algorithms to determine the optimal *d*-axis current vector component for steady-state operation. An adaptive algorithm for on-line IPMSM loss optimization is presented in [2]. The algorithm functions in steady-state only. The authors of [3] present an algorithm suitable for scalar PMSM control in battery powered electric vehicle drives. Input power calculations utilize DC current and voltage. The minimal power is achieved through regulating output voltage.

Model-based algorithms require the modeling of motor and converter losses and utilization of those models during optimization. Parameters must be known, and in most cases necessitate the consideration of magnetic core saturation [4]. In [8], the authors utilize the stator flux vector as an independent variable both the torque equation and the voltage equations, and propose loss reduction through voltage angle correction. The proposed solution takes into consideration both voltage and current limitations, also expressed through the stator flux vector. In addition to loss optimization, flux estimation is necessary to improve the control algorithm dynamic performance [9]. The choice of optimal currents is enabled by look-up tables, generated off-line using various program suites.

This paper will consider the synchronous motor constructed in such a way that the induced electromotive force is sinusoidal, while the permanent magnets ate imprinted into the

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iron core. High magnetic anisotropy is a staple of such motor, that is to say, such construction greatly reduces the amount of iron in the d-axis, making the $L_d$ inductance significantly lesser than $L_q$ inductance ($L_d$<$L_q$). The optimization was performed by using particle swarm optimization (PSO) algorithm. PSO algorithm is a swarm intelligence optimization technique that has found its basis in natural, special in interactions of flocks of birds and swarms of insects. It was first introduced by Kennedy and Eberhart (1995) [15]. The proposed PSO algorithm attempts to reduce copper and iron losses both in constant field and field weakening areas of operation. Optimal currents are recorded in look-up tables. For a given speed and torque, optimal currents are read and used as input for current regulators. The proposed algorithm is compared a standard $i_d$= 0 control.

## II. EQUIVALENT CIRCUIT AND BASIC EQUATION

Fig. 1 shows the *d*- and *q*-axis equivalent circuits of IPMSM.

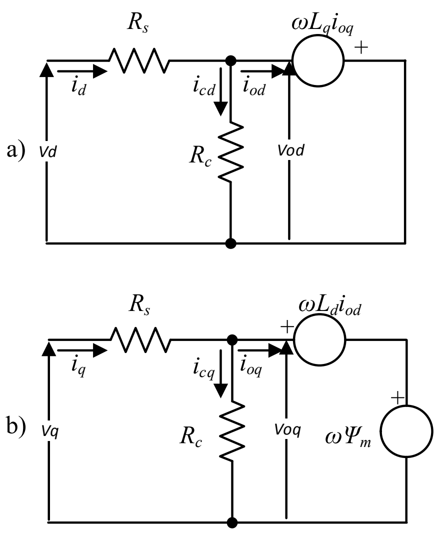


Figure 1. d- and q-axis equivalent circuits of IPMSM a) d-axis equivalent circuit, b) q-axis equivalent circuit

Based on Fig. 1 the mathematical equations of the equivalent *dq* axis model of IPMSM in the rotor reference frame are expressed as [7]:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \left(1 + \frac{R_s}{R_c}\right) \begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega \rho L_d \\ \omega L_d & 0 \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_m \end{bmatrix} \tag{2}$$

where,

$$i_{od} = i_d - i_{cd}, i_{oq} = i_q - i_{cd} \tag{3}$$

$$i_{od} = -\frac{\omega \rho L_d i_{oq}}{R_c}, i_{oq} = \frac{\omega\left(\Psi_m + L_d i_{od}\right)}{R_c} \tag{4}$$

### A. Torque production

The electromagnetic torque of the IPMSM has two components: fundamental magnetic torque (which is proportional to the product of the magnet flux and *q*-axis stator current), and the reluctance torque (which is dependent on the saliency ratio and to the product of *dq*-axis stator current components). Based on Fig.1 torque can be expressed as:

$$T = \frac{3}{2} p\left(\Psi_m i_{oq} + (1 - \rho) L_d i_{od} i_{oq}\right) \tag{5}$$

### B. Controllable losses

The copper losses are proportional to square of current and can be estimated using circuit in Fig.1:

$$P_{Cu} = \frac{3}{2} R_s \left(i_d^2 + i_q^2\right) \tag{6}$$

The iron losses in the machine consist of two components: hysteresis and eddy current losses. The entire no-load losses are assumed to be dominantly due to the iron losses and are modeled by a parallel resistance called $R_c$ (which is function of speed) [4]:

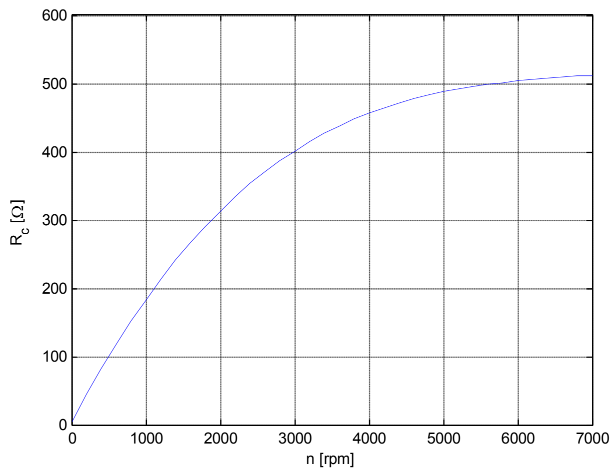


Figure 2. $R_c$ estimation

The iron losses can be estimated using circuit in Fig.1:

$$P_{Fe} = \frac{3}{2} R_c \left(i_{cd}^2 + i_{cq}^2\right) \tag{7}$$

The mechanical losses are not controllable. The electrical losses are controllable by means of current vector control. The electrical losses are consisted of copper and iron losses:

$$P_L = P_{Cu} + P_{Fe} \tag{8}$$

The electrical losses can be expressed as function of $i_{od}$, $T$ and $\omega$. Minimal electrical losses can be derived by differentiating function of electrical losses with respect to $i_{od}$ and equating the derivates to zero. For IPMSM there is no analytical solution [4].

$$P_L = f\left(i_{od}, T, \omega\right) \tag{9}$$

### III. PARTICLE SWARM OPTIMIZATION

The PSO main goal is to explore the search space of interest using groups made of particles. A group of particles makes swarm, which is identified with a population in evolutionary terms. Each particle is characterized with its position which representing the potential solution of the optimization problem and velocity. Velocity is the difference between the current and previous positions. Particle remembers its best personal position in the history of the search, while swarm remembers best global position. The basic idea of the PSO algorithm is that the particles move guided by the personal and global best position through search space, while calculating a new value of velocity in each iteration. A new position of the particle is described by the following expressions:

$$v[k+1] = w \cdot v[k] + cp \cdot rp[k] \cdot (p[k] - x[k]) + cg \cdot rg[k] \cdot (g[k] - x[k]) \quad (10)$$

$$x[k+1] = x[k] + v[k+1] \quad (11)$$

The parameters $w$, $cp$ and $cg$ represent inertial, cognitive and social component. Their value is changed in order to improve performance which led to different modifications of the PSO algorithm [16] - [18]. In this analysis the Generalized PSO (GPSO) was used [18]. GPSO is inspired by linear control theory. The authors have identified particles swarm with dynamical system of second order with two inputs and one output and then analyzed its stability. The input represented by personal and global position of the particle, and the output of system is the current position of the particle.

### IV. SIMULATION RESULTS

As described in Section II the electrical losses $P_L$ are controllable by current vector control. If the electrical losses can be driven to a minimum value by the optimal current vector control, the efficiency becomes maximum. So, optimal problem is to find value of current components that minimalizes the loss.

Fig. 3 shows a block diagram of optimal model-based method for wide range speed control of IPMSM. Rotor speed and position are estimated or measured using a rotary encoder. Speed regulator output is the torque required for the requested speed. Based on the current speed and required torque, the model-based loss optimization block (PSO) generates the optimal reference currents that are further routed to an current regulated voltage source inverter (CRVSI).

Fig. 4 and 5 show the sum of controllable losses dependent on $i_{od}$ current for a given speed and multiple various load torques. The diagram displays the existence of such $i_{od}$ currents that will produce optimal controllable losses. As there is no analytical solution of equating the derivates of (9) to zero, a PSO is used to generate currents that will result in minimal losses.

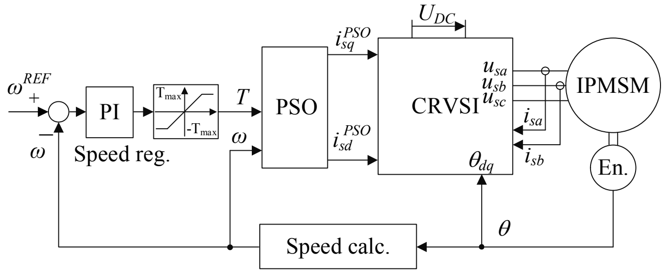


Figure 3. PSO based energy efficient IPMSM drive

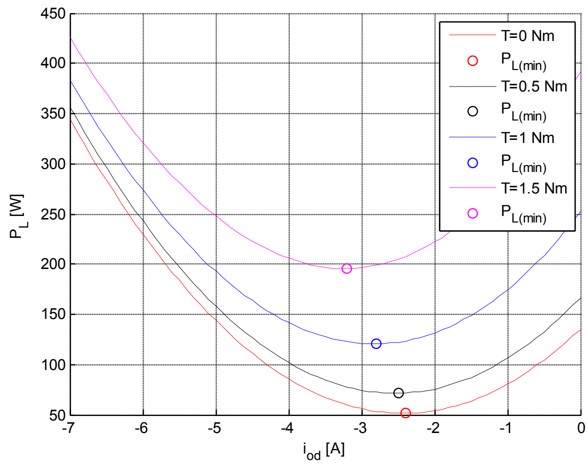


Figure 4. Electrical losses as function of $i_{od}$ and T at 7000rpm

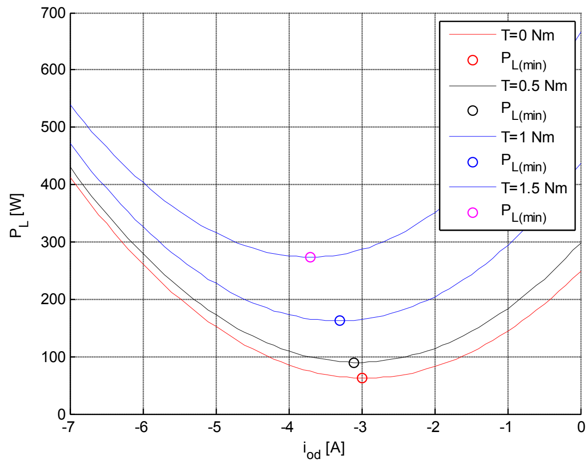


Figure 5. Electrical losses as function of $i_{od}$ and T at 14000rpm

Optimal values of current for wide speed and torque range (speed: 0 - 14000rpm, with step 100rpm; torque: 0 - 1.5Nm, with step 0.1Nm) are found by using GPSO modification [18] of the typical PSO algorithm. One algorithm running find optimal current value for fixed speed and torque, and (9) is used as fitness (criteria) function of optimization algorithm. Number of iteration used in optimization process was 40 and number of the particles in populations was 25. Initial populations are random numbers on the interval (-10, 0). Algorithm is evaluated 2256 times, and the number of calculated optimal current values are the same. The flowchart of algorithm is shown in Fig 6.

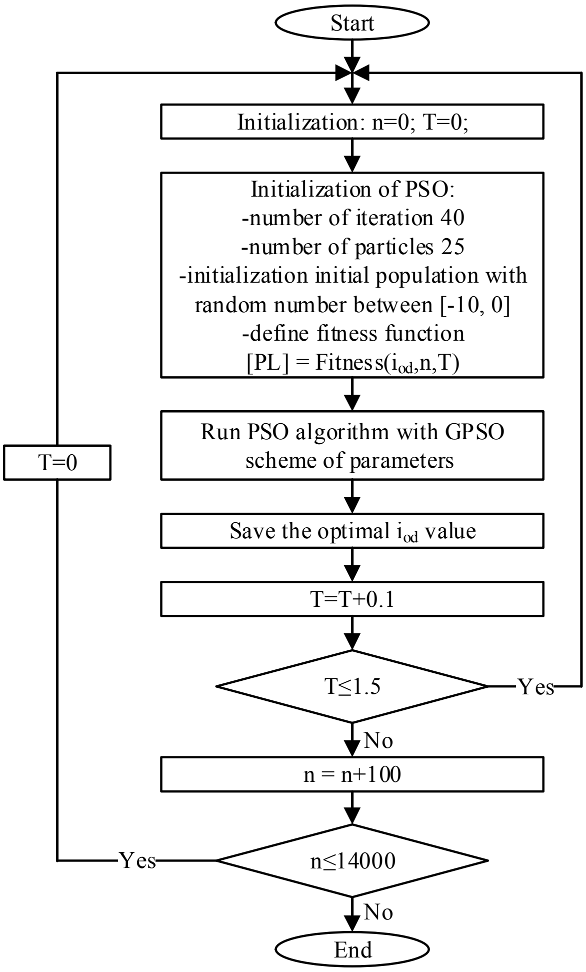


Figure 6. Optimal $i_{od}$ for wide speed and load range

Calculated results presented optimal *d*-axis current component value for wide speed and torque and there are shown in Fig. 7.

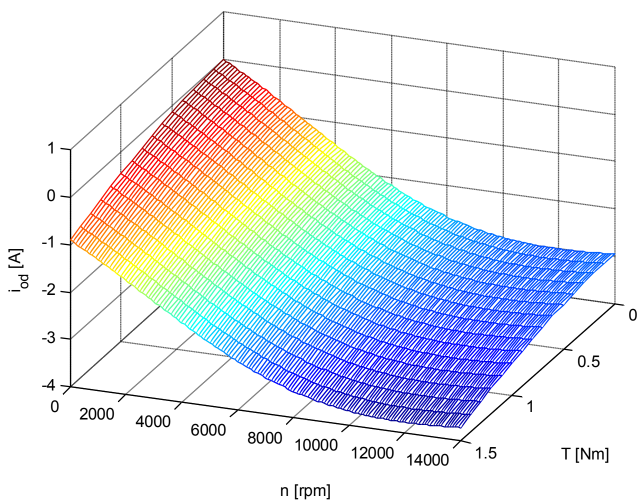


Figure 7. Optimal $i_{od}$ for wide speed and load range

Fig. 8 shows electrical losses as a function of load at given speed for the two control types: the standard, $i_{od}$ = 0 (blue, dashed), and the PSO algorithm (red, solid). The decreased controllable losses of the new algorithm can be noted. The existence of the negative d axis current causes a reduction in motor flux, and, thus, the iron losses. As such losses are exacerbated by high speeds, the PSO algorithm yields greater benefits in high speed operation.

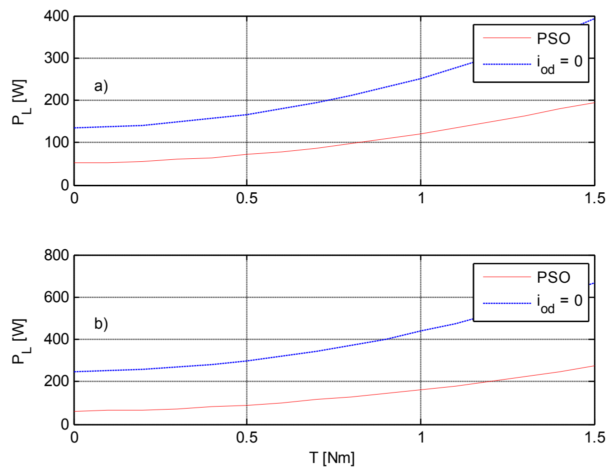


Figure 8. Electrical losses for wide load range at a) 7000 rpm, b) 14000 rpm

TABLE I. MOTOR PARAMETERS

| Parametrs | IPMSM | |
|---|---|---|
| | ***Value*** | ***Unit*** |
| $P$ | 1 | kW |
| $\Psi_m$ | 0.080074 | Wb |
| $L_d$ | 20.33 | mH |
| $L_q$ | 30.54 | mH |
| $R_s$ | 3.575 | Ω |
| $p$ | 4 | - |

Fig. 9 shows copper and iron losses ratio as a function of load for two different speed, 7000rpm (red, solid) and 14000rpm (blue, dashed). The PSO algorithm (Fig.9b) providing higher copper losses and lower iron losses, compared with standard $i_{od}$ algorithm (Fig. 9a), but total losses are lower at the end.

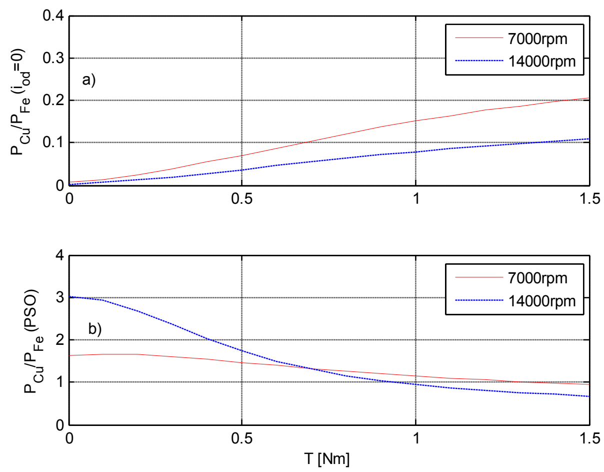


Figure 9. $P_{Cu}/P_{Fe}$ ratio for wide load range at 7000 rpm and 14000 rpm: a) standard $i_{od}$ = 0 algorithm, b) PSO algorithm

Fig. 10 shows electrical losses as a function load and speed for the $i_{od} = 0$ algorithm. Fig. 11 shows electrical losses as a function load and speed for the PSO algorithm. With increasing the speed at given load losses are increased as expected, but unlike the $i_{od} = 0$ control these electrical losses are optimal.

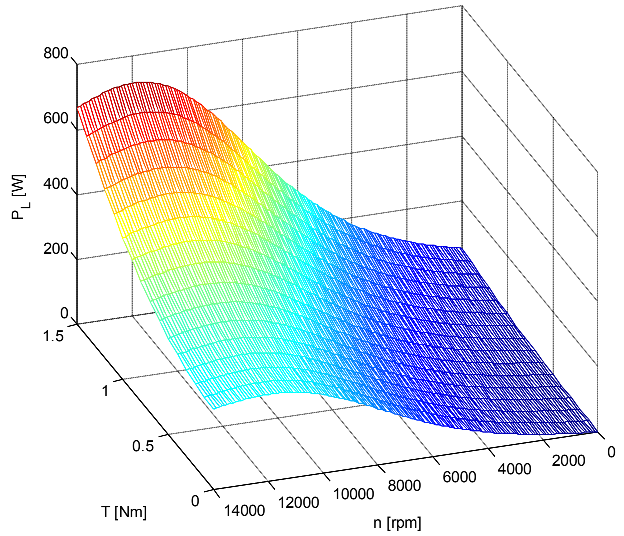


Figure 10. Electrical losses for wide speed and load range with $i_{od}=0$

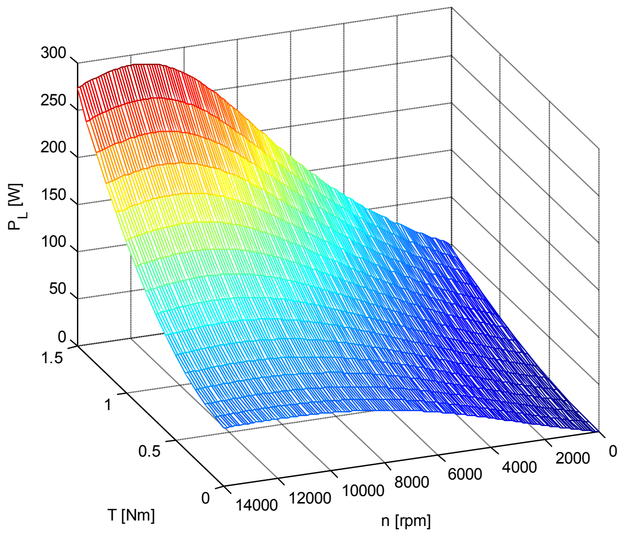


Figure 11. Optimal electrical losses for wide speed and load range

## V. Conclusion

The paper proves that controllable electrical losses of IPMSM can be minimized by the optimal control of current vector angle. In particular, the proposed particle swarm optimization drastically minimizes controllable electrical losses. The lookup table is generated offline and can be easily implemented in existing IPMSM control algorithm. This method can be further improved by including *dq*-axis inductance dependences on current magnitudes during the lookup table creation. Generated lookup table can be implemented in the DSP-based digital control system with the enough memory space.

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