Research on Permanent Magnet Synchronous Motor Rotor Information Control Based on MRAS Algorithm

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ABSTRACT: *Because of its excellent performance and combination with high precision control method, permanent magnet synchronous motor (PMSM) has wider applications in such areas as industry, social life, aerospace and national defense. This paper introduces the structure of the PMSM. Then, it gets the mathematical model that PMSM rotates on the* $x-y$ *coordinate system under the stator flux linkage according to the theory of direct torque analysis coordinate systems which involves the coordinate transformation, combined with the coordinate system and a mathematical model of PMSM in a three-phase PMSM stationary coordinate system. Afterwards, it analyses the basic principles of MRAS control, and designs an adaptive location identifier based on stator flux reference to realize identification of rotor speed and position, which can avoid the introduction of the speed sensor with complex system and high maintenance costs.*

Subject Categories and Descriptors
B.1.2 [Control Structure Performance Analysis and Design Aids]: Hardware Control
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General Terms : Mathematical Model, Hardware Control

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1. Introduction

PMSM takes the advantages of simple structure, small volume, low weight, low loss and high efficiency. It does not need mechanical commutator and brush, which is quite different from the DC motor. Its large rotor gap, good control performance, the measurable rotor parameters, and the lack of reactive excitation current, makes the characters of high power factor, the stator current, small resistance loss different from asynchronous motor [1, 2]. As its excellent performance and combination with high precision control method, permanent magnet synchronous motor (PMSM) has wider applications in such areas as industry, social life, aerospace and national defense. This article firstly gives a brief review on the control method of AC motor, including Variable Voltage Variable Frequency (VVVF) Control, Vector Control, and Direct Torque Control (DTC). It needs detection of the rotor position and speed, no matter DTC or Vector Control, and the traditional motor speed control system can be finished by mechanical sensor like photoelectric encoder [3]. The existence of speed sensor increases the system cost and difficulties of installation and maintenance, lower system reliability and restricts the high temperature and high humidity application under bad circumstances. Therefore, scholars and researchers gradually put more attention on the control of PMSM speed sensorless. Li Xiangwei, Tianjin University, makes a research on PMSM control method [4] based on MRAS. With the object PMSM, he further studies the DTC of speed sensorless, mathematical model of MRAS and applies the instantaneous reactive power to the rotor speed identification. Researchers like Zhang Hongshuai, come up with a fuzzy PI model reference adaptive observer to realize the implementation of the PMSM rotor position detection, which is based on its high speed and wide range of speed.

2. The Structure Of PMSM and Its Mathematical Model

2.1 The Structure of PMSM

The Electro Magnetic Field of PMSM approaches to sine, the purity of which is determined by the magnetization quality of permanent magnet material. When properly placed in the permanent magnet rotor, PMSM air gap density is pure sinusoidal. Practically, as the stator windings can not precisely district like sine, so its gap density is not purely sinusoidal, just close to it. Just like Figure 1 illustrates, according to the rotor structure, PMSM can be divided into three structures: veneer, plug-in and built-in in accordance with the installation form.

The simplest and most common structure of PMSM is surface protruding rotor structure in Figure 1. The dynamo of this structure owns small rotor diameter and motor inertia, as is always applied to the Servo System. Meanwhile, armature of this kind motor has little reaction, which makes the permanent magnet role like air. Thus, permanent magnet has low inductance and larger effective gap length. Plug-in rotor structure, like Figure 1 (b), placed in the permanent magnet rotor surface to make it more stable. Its advantage is to increase leakage flux but also increase the q-axis inductance, the armature reaction and the polar angle, so that it reduces the electromagnetic torque. Built-in structure, like Figure 1 (c), is complex and expensive, but owns the merits of high air gap magnetic flux density to produce more torque compared with surface mounted motor. Dynamo illustrated in Figure 1(a) belongs to non-salient pole generator, featured by tiny difference between d axis and q axis inductance. Plug-in and Built-in dynamo in Figure 1(b) and Figure 1(c) are all salient pole machines, with large difference between d axis and q axis inductance, which can generate reluctance torque.

2.2 Mathematical Model of PMSM in the stator flux rotation x-y coordinate system

Theoretical analysis of direct torque refers to the coordinate transformation of coordinate system diagram, just like what illustrated in Figure 2, among which A, B, C is three phase stator static coordinate system; α, β is two phase static stator coordinate system, α axis is defined on the A axis relative to the stator winding; x, y is two phase stator (w_c) rotating coordinate system, among them x axis is defined in the permanent magnet rotor axis d, q is two phase rotor rotating coordinate system. Among them, d axis is defined in the axis of the permanent magnet of rotator. ψ_f is rotator PM flux, ψ_s is stator flux. In the picture, θ_r is the angle rotor flux ψ_f with respect to α axis, θ_s is the angle stator flux ψ_s with respect to α axis, δ is intersection angle between stator flux vector and rotor flux vector, which is torque angle.

PMSM direct torque control always adopts stator flux oriented, so the mathematical model has to be transformed into stator flux linkage rotating reference frame. Combine Figure 2 and mathematical model of PMSM on three phase stator static coordinate system, we can get mathematical model of PMSM on stator flux linkage rotating coordinate system $x - y$.

Space vector of stator voltage on three-phase coordinate system ABC can be:

$$\vec{U}_{ABC} = R\vec{I}_{ABC} + d\vec{\psi}_{ABC}/dt \tag{1}$$

Here,

$$\vec{U}_{ABC} = \frac{2}{3}(U_A + aU_B + a^2U_c), \vec{I}_{ABC} = \frac{2}{3}(\vec{I}_A + a\vec{I}_B + a^2\vec{I}_c),$$

$$\vec{\psi}_{ABC} = \frac{2}{3}(\vec{\psi}_A + a\vec{\psi}_B + a^2\vec{\psi}_c)$$

When vector S revolves at speed v relative to three-phase coordinate system A axis, it can be Euler resolved into:

$$\vec{S} = |S|(\cos\theta_v + j\sin\theta_v)\,|S|\,e^{j\theta v} \tag{2}$$

Here, θ_v is phase angle between vector S and A axis, when (1) is processed like (2), it can be

$$\vec{U}_v = R\vec{I}_v + \frac{d\vec{\psi}_v}{dt} + j\omega_v\vec{\psi}_v \tag{3}$$

let $\omega_v = \omega_s$, $\theta_v = \theta_s$, $\delta = -(\theta_v - \theta_s)$, here ω_s is electrical angular velocity that coordinate system xy revolves relative to A axis, then gets the expression of space vector on xy rotating coordinate system:

$$\vec{U}_{xy} = R\vec{I}_{xy} + \frac{d\vec{\psi}_{xy}}{dt} + j\omega_{xy}\vec{\psi}_{xy} \tag{4}$$

Then replaces $\vec{U}_{xy} = U_{xy} + jU_{xy}$, $\vec{I}_{xy} = I_{xy} + jI_{xy}$, $\vec{\psi}_{xy} = |\psi_s|$, and expresses real and imaginary components separately, we will get Voltage Equation's scalarization form of dynamo on stator $x - y$ coordinate system:

$$\begin{cases} U_x = R_s I_x + \dfrac{d\psi_s}{dt} \\ U_y = R_s I_y + \omega_s \psi_s \end{cases} \tag{5}$$

Under the rotor $d - q$ axis coordinate system, it can be represented by mathematical model of systematic dynamo as:

Flux linkage equation: $$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \tag{6}$$

Torque equation: $$T_e = \frac{3}{2} p[\psi_f i_q + (L_d - L_q) i_d i_q] \tag{7}$$

Here $i_d, i_q, \psi_d, \psi_q, L_d, L_q$ respectively are current on axis $d - q$, flux components and inductance.

We can know from Figure 2, if transform the physical quantity on rotor $d - q$ axis coordinate system into stator xy coordinate system, we can use rotating transformation equation:

$$\begin{bmatrix} f_x \\ f_y \end{bmatrix} = \begin{bmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} f_d \\ f_q \end{bmatrix} \tag{8}$$

Make use of (8) and replace i_d, i_q with i_x, i_y, then substitute into equation(6) respectively, it is the expression stator flux linkage ψ_s on $x - y$ axis:

$$\begin{bmatrix} \psi_{sx} \\ \psi_{sy} \end{bmatrix} = \begin{bmatrix} L_d\cos^2\delta \; L_q\sin^2\delta & -L_d\sin\delta\cos\delta + L_q\sin\delta\cos\delta \\ -L_d\sin\delta\cos\delta + L_q\sin\delta\cos\delta & L_d\cos^2\delta + L_q\sin^2\delta \end{bmatrix} \begin{bmatrix} i_x \\ i_y \end{bmatrix} + \psi_f \begin{bmatrix} \cos\delta \\ -\sin\delta \end{bmatrix} \tag{9}$$

Torque equation:

Make use of (8) and replace i_d, i_q with i_x, i_y then substitute into equation (6) and (7) respectively, it is the expression torque T_e on $x - y$ axis:

$$T_e = \frac{3}{2}\, p\, [\psi_d (i_x \sin\delta + i_y \cos\delta) - \psi_q (i_x \cos\delta + i_y \sin\delta)] = \frac{3}{2}\, p\, |\psi_s|\, i_y \tag{10}$$

Equation (10) proves that the electromagnetic torque of MSM is proportional to stator current y component i_y on condition that amplification $|\psi_s|$ of stator flux linkage remains constant.

3. Controls Over No-speed Sensor of PMSM Based on MRAS

3.1 Basic Principles of MRAS Control

The main idea of MRAS is: if we call equation with parameter to be evaluated variable model, then the equation without unknown parameter can be called reference model. These two models enjoy the same output quantity with physical meanings. If work simultaneously, we can realize the purpose that controlled member output and follow reference model by adjusting variable model parameter in the laws that the output error constitutes an appropriate adaptive. Its structure chart is Figure 3 [6, 7].

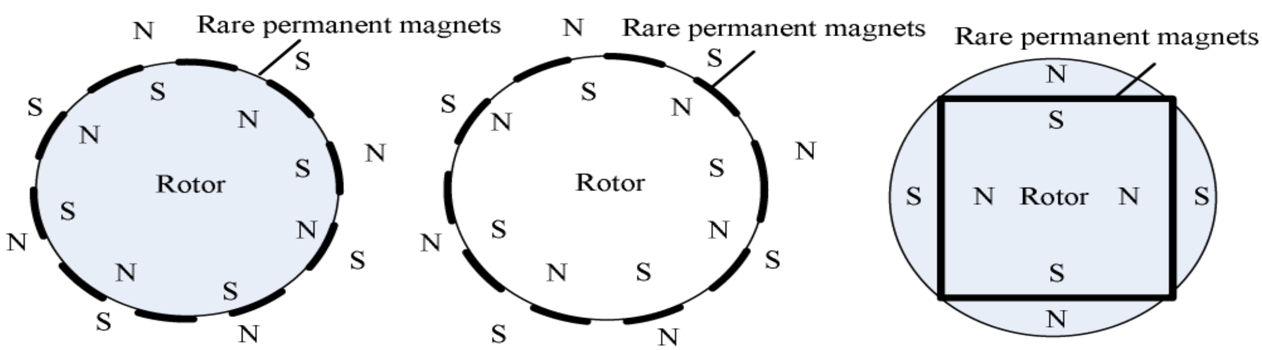

Figure 1. Rotor Structure of PMSM

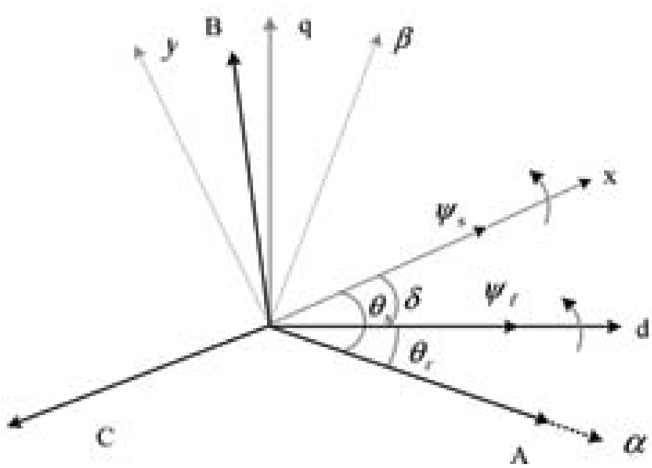

Figure 2. Relations of Four Coordinate Systems

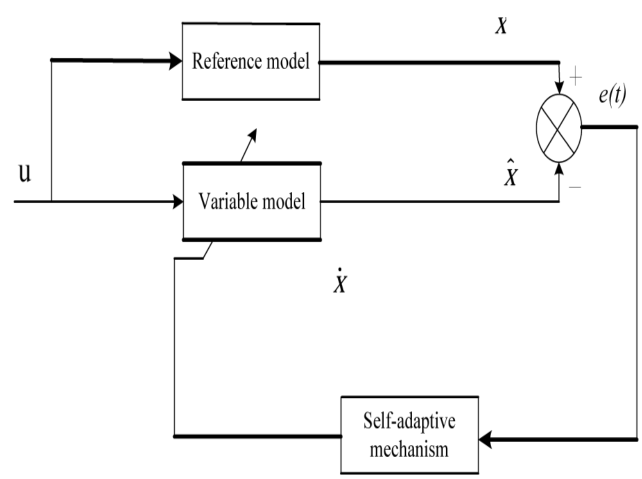

Figure 3. Control principles of MRAS

It can be known that variable model and reference model are stimulated by the same outside input quantity and x and $\hat{x}$ are state vectos of variable model and reference model in respect.

By regarding x of reference model as given performance index, Adjustable system corresponding performance and given performance of x in variable model can be obtained with an error comparison. This error value $e(t)$ can make the variable model $\hat{x}$ stable and rapidly approach to x, which is to make the error value $e(t)$ close to zero, by take advantage of the self-adaptive mechanism. This mechanism can have a modification over the parameter of variable model.

3.2 No-Speed Sensor Controller Strategies of PMSM Based on MRAS

Stator flux model of PMSM under $d-q$ coordinate system:

$$\frac{d\psi_d}{dt} = u_d + \omega\psi_q - R_s i_d$$
$$\frac{d\psi_q}{dt} = u_q - \omega\psi_d - R_s i_q \tag{11}$$

Put (6) into (11), it can be:

$$\frac{d\psi_d}{dt} = u_d + \omega\psi_q - \frac{R_s}{L_s}\psi_d + \frac{R_s}{L_s}\psi_f$$
$$\frac{d\psi_q}{dt} = u_q - \omega\psi_d - \frac{R_s}{L_s}\psi_q \tag{12}$$

We can see that, motor flux model is connected with the speed, so the flux linkage model can be adjustable model. However, motor itself can be regarded as reference model, with parallel form structure as identification of rotating speed. The expression (12) can be changed into:

$$\left[\frac{d}{dt}\right]\begin{bmatrix}\psi_d\\ \psi_q\end{bmatrix}\begin{bmatrix}\frac{R_s}{L_s} & \omega\\ -\omega & -\frac{R_s}{L_s}\end{bmatrix}\begin{bmatrix}\psi_d\\ \psi_q\end{bmatrix}+\begin{bmatrix}u_d+\frac{R_s}{L_s}\psi_f\\ u_q\end{bmatrix} \tag{13}$$

As $\psi'_d = \psi_d$, $\psi'_q = \psi_q$, $u'_d = u_d + \frac{R_s}{L_s}\psi_f$, $u'_q = u_q$ thus the recognition process is

$$\frac{d}{dt}\begin{bmatrix}\psi'_d\\ \psi'_q\end{bmatrix}=\begin{bmatrix}-\frac{R_s}{L_s} & \omega\\ -\omega & -\frac{R_s}{L_s}\end{bmatrix}\begin{bmatrix}\psi'_d\\ \psi'_q\end{bmatrix}+\begin{bmatrix}u'_d\\ u'_q\end{bmatrix} \tag{14}$$

Simplified: $\frac{d}{dt}\ \psi' = A\psi' + Bu'$ (15)

Express (15) as estimated value, parallel adjustable model can be:

$$\frac{d}{dt}\begin{bmatrix}\hat\psi'_d\\ \hat\psi'_q\end{bmatrix}=\begin{bmatrix}-\frac{R_s}{L_s} & \hat\omega\\ -\hat\omega & -\frac{R_s}{L_s}\end{bmatrix}\begin{bmatrix}\hat\psi'_d\\ \hat\psi'_q\end{bmatrix}+\begin{bmatrix}u'_d\\ u'_q\end{bmatrix} \tag{16}$$

Simplified: $\frac{d}{dt}\ \hat\psi' = \hat A\hat\psi' + Bu'$ (17)

ω In parallel adjustable model is adjustable parameter which needs recognition, while keep the others invariant. Definition state variable error:

$$e_{\psi d} = \psi'_d - \hat\psi'_d$$
$$e_{\psi d} = \psi'_q - \hat\psi'_q \tag{18}$$
$$e_\omega = \omega' - \hat\omega'$$

(15) Subtract (17), and simplify:

$$\frac{d}{dt}e = \frac{d}{dt}\begin{bmatrix}e_{\psi d}\\ e_{\psi q}\end{bmatrix}=\begin{bmatrix}\psi'_d\\ \psi'_q\end{bmatrix}-\begin{bmatrix}\hat\psi'_d\\ \hat\psi'_q\end{bmatrix}$$

$$=\begin{bmatrix}-\frac{R_s}{L_s} & \omega\\ -\omega & -\frac{R_s}{L_s}\end{bmatrix}\begin{bmatrix}\psi'_d\\ \psi'_q\end{bmatrix}-\begin{bmatrix}\frac{R_s}{L_s} & \hat\omega\\ -\hat\omega & -\frac{R_s}{L_s}\end{bmatrix}\begin{bmatrix}\hat\psi'_d\\ \hat\psi'_q\end{bmatrix}$$

$$= (A\psi' - A\hat\psi')$$
$$= (\hat A\hat\psi' - \Delta\hat A\psi')\hat A\hat\psi'$$
$$= \hat A\,(\psi' - \hat\psi')\,\Delta\hat A\psi'$$
$$= \hat A e + \Delta\hat A\psi'$$
$$= A\hat e + W$$

$$\left[\frac{d}{dt}\right] e = Ae - Iw$$
$$v = De$$
$$w = (\hat A - A)\,\hat\psi'$$

let $D = I$, then: $v = Ie = e$ (21)

According to Popov's super stability theorem, expression transitivity $D = (sI - A)^{-1}$ expressed by (21) is strictly positive real matrix. Popov's integral inequality:

$$\eta(0, t_0) = \int_0^{t_0} v^T w dt \geq -\gamma_0^2, \qquad \forall t_0 \geq 0,\ \gamma_0^2$$

can be any finitude positive number. Thus, MRAS is gradual and steady. A converse-solving to Popov's integral inequality can get the identification algorithm:

$$\hat\omega = \int_0^{t_0} k(\psi'_d\hat\psi'_q - \psi'_q\hat\psi'_q)\,d\tau + k\,(\psi'_d\hat\psi'_q - \psi'_q\hat\psi'_d) + \hat\omega(0) \tag{22}$$

Here $k_1, k_2 \geq 0$. Change (22) into:

$$\hat\omega = \left(k_p + \frac{k_i}{s}\right)\varepsilon_\omega \tag{23}$$

Among. $\varepsilon_\omega = \psi'_d\,\hat\psi'_q - \psi'_q\hat\psi'_d$ It follows that ε_ω depends on the error information of $\psi' \times \hat\psi'$, Speed signal ω generated by PI regulator will make estimated and practical flux value of adjustable model unanimous; further get stator flux vector error approach to zero and the rotate speed estimated value to practical value. The whole recognition operation diagram is as Figure 4:

4. Conclusion

PMSM take a prior advantage over asynchronous machine and continuous current dynamo [8, 9], like high power factor, high power density and energy efficiency, so that it have a wider application over fields like elevators, transportation, aerospace and industrial and agricultural production. The combination of quick control response and simple structure of DTC and no-speed sensor lack of various disadvantages of mechanical transducer gradually becomes one of the hotspot in the modern communication field [11, 12]. This paper makes a research on the no-speed sensor direct torque control of MRAS. It also has a further study of mathematical model that no-speed sensor's direct torque control over MRAS, and applies instantaneous reactive power into recognition of rotor

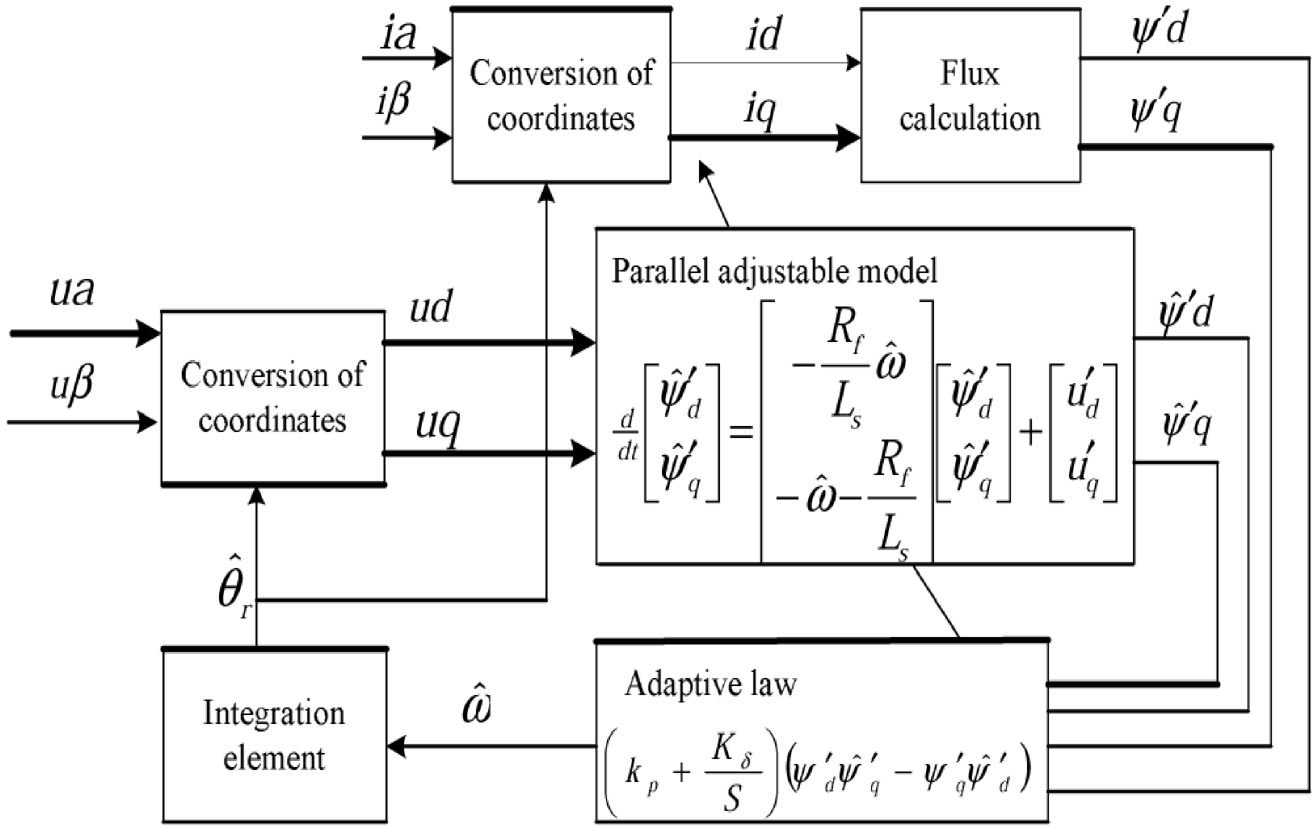

Figure 4. MRAS's rotate recognition operation diagram of PMSM

speed. This method seems more precise formula, relatively simple calculation and can be easily accomplished in digital chip.

Our nation is rich in abundant permanent magnet material, especially rare earth permanent magnetic material like neodymium, iron and boron. Its developed reserves of rare earth accounts for as much as 80% of the world total, called "*rare earth kingdom*". Therefore, PMSM sees a good development and application prospect in our country. What we should do is to give full play to the advantages of rare earth, strengthen various researches of PMSM based on rare earth material and vigorously promote its practical application, which can definitely bring about vital theoretical meanings and practical values in socialist modernization.

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