A Novel Direct Torque Control for Doubly Fed Induction Machine Based on Indirect Matrix Converter

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Abstract

This paper presents a novel Direct Torque Control (DTC) of Doubly-Fed Induction Machine (DFIM) based on Indirect Matrix Converter (IMC). The matrix converter allows many advantages compared to the conventional voltage or current source inverters. Functionally the IMC is very similar to the Direct Matrix Converter (DMC) but it has separate line and load bridges. Indirect matrix converter has no electrolytic capacitors in the DC link, which results that volume and size of converter reduced and increased longevity. The indirect modulation technique used in indirect matrix converter is able to provide practically sinusoidal waveforms of the input and output currents with venial harmonics amplitude. In the inverter stage, the classical DTC method is employed. In the rectifier stage, in order to reduce losses caused by circuit snubbr the rectifier four-step commutation method is employed. The simulation results of DTC system based on IMC confirms its effectiveness and accuracy.

1. Introduction

The Doubly-Fed Induction Machines (DFIM) are motor or generator that have winding on both stator and rotor and both winding transfer power between shaft and system. DFIM have clear superiority for the applications of large capacity and limited-range speed control case due to the partially rated inverter, lower cost and high reliability. These characteristics enable the doubly-fed wound rotor induction machine to have vast applications in wind-driven generation [1].

The Direct Torque Control (DTC) has been introduced in the 1980s by I. Takahashi and T. Noguchi as an alternative to field orientation control (FOC), with the twofold objective of simplifying the control algorithms and achieving similar or even better performance [2].

A number of papers appeared in literature improving the DTC of induction machines. Attentions were also paid to the DTC of doubly fed machine. The DTC strategies for brushless doubly-fed machines were studied, where the rotor flux based DTC method for cage induction machines was followed [1].

In this paper, a novel DTC strategy for doubly-fed induction machine (DFIM) based on Indirect Matrix Converter (IMC) is proposed to pursue a simple control structure and high efficiency. In recent years research on direct frequency conversion using Matrix Converters (MC) has become popular. Matrix converters have many desirable feature compared to the conventional voltage or current source inverter such as: No large energy storage components are needed, also compact size, longer lifetime, regeneration capability and unitary power factor for any load [2],[3].

DTC is commonly used with a voltage source inverter (VSI), where electrolytic capacitor is used on the dc link of the AC/DC/AC converter in order to smooth the dc voltage and store the energy recovered from the machine during regeneration braking. Large electrolytic capacitors in dc link causes that size and weight of converter considerably increased and longevity decreased [2].

There have been typical two current commutation methods proposed which are not required snubber circuits for a PWM rectifier of AC-to-AC converters without DC link components. The first method named rectifier zero current commutation and second method named rectifier four-step commutation [3]. In this paper we use the rectifier four-step commutation method in the rectifier stage, therefore the mechanisms involved in the commutation process are firstly described.

The paper is organized as follows: in section II, a review of conventional DTC for doubly-fed induction machine is presented; then, in section III, Indirect Matrix Converter (IMC) is introduced and its current commutation methods for rectifier stage (rectifier four-step commutation) is explained in section IV, in section V the DTC system based on IMC for doubly-fed induction machine is modeled and explained, simulation results of proposed model are available in section VI. Finally, the conclusions are exposed in section VII.

2. Direct torque control principle

The doubly-fed induction machine (DFIM) has been used for years, for variable speed drive. But, unlike the induction generator, induction motors have limited application. The stator winding of the doubly-fed induction machine is connected directly to the grid and the rotor is fed by a bidirectional converter that is also connected to the grid. A schematic diagram of the doubly-fed induction machine and its control system is shown in fig. 1.

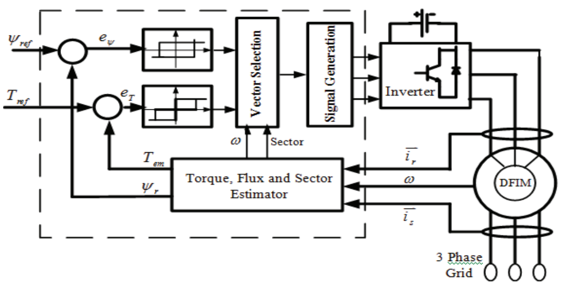

Fig. 1. The diagram of the DFIM direct torque control

The stator is supplied at constant frequency and constant three phase amplitude, since it is directly connected to the grid. The speed, Flux and torque are controlled by adjusting the amplitude, phase and frequency of the voltage introduced in the rotor.

The torque equation of doubly fed induction machine is as follows:

$$T_{em} = \frac{3}{2} p \frac{L_h}{\sigma L_s L_r} |\psi_r||\psi_s| \sin\theta \tag{1}$$

Where $\sigma = 1 - \frac{L_h^2}{L_s L_r}$ is the leakage coefficient. L_s and L_r are the stator and rotor inductance, L_h is mutual inductance and θ is phase angle difference between ψ_r and ψ_s. The expression for voltage and flux equations modeled the doubly fed induction machine in the stator reference frame is given by:

$$V_s = R_s i_s + \frac{d\psi_s}{dt} \tag{2}$$

$$V_r = R_r i_r + \frac{d\psi_r}{dt} - j\omega_m \psi_r \tag{3}$$

$$\psi_s = L_s i_s + L_h i_r \tag{4}$$

$$\psi_r = L_r i_r + L_h i_s \tag{5}$$

Where R_s and R_r are the stator and rotor resistance, and ω_m is mechanical speed.

As the stator winding of DFIM is connected to power grid, by ignoring the voltage drop of stator winding resistance and the fluctuation of supply voltage, one can appropriately consider the magnitude of the stator flux to be constant and rotate at synchronous speed [1]. Therefore, according to equation (1), we know that the torque/speed control of wound rotor doubly-fed machines can be realized through adjusting the rotor flux vector. Furthermore, in the case that the rotor flux $\overline{\psi_r}$ has a circular trajectory, T becomes the function of phase angle θ. T increases as θ increases. Conversely, T decreases as θ decreases. Therefore, the control of the torque/speed can be realized through adjusting the phase angle θ [4].

Fig. 2 shows the rotor voltage vector and rotor flux sector for motor and generator mode in rotor reference frame. Based on analysis above the selection of rotor voltage vector accomplished from table1.

Table 1. Switching table

H_Φ		1			-1		
H_{Te}		1	0	-1	1	0	-1
Rotor Flux Sector	1	V_6	V_0	V_2	V_5	V_7	V_3
	2	V_1	V_7	V_3	V_6	V_0	V_4
	3	V_2	V_0	V_4	V_1	V_7	V_5
	4	V_3	V_7	V_5	V_2	V_0	V_6
	5	V_4	V_0	V_6	V_3	V_7	V_1
	6	V_5	V_7	V_1	V_4	V_0	V_2

3. Indirect matrix converter

Indirect Matrix Converter (IMC) is an AC/DC/AC converter, but bulky DC link capacitor is eliminated in it and a filter in entrance is used instead. Also, bi-directional switch in rectifier stage are used (see fig. 3). Because it has converter configuration with two separate stages (rectifier and inverter stages), it has been considered more flexible to modify its topology. Pulse width modulation algorithms of conventional inverters can be utilized, which can greatly simplifies its control circuit. Furthermore commutation problem of DMC are considerably reduced by utilize specific current commutation methods [5],[6].

Regarding commutation strategies of MC, two main rules should be taken into account: 1) The incoming and outgoing switches should not be switched on together at any point in time 2) Also these switches should not both be switched off at the same time destroy the switches [8].

Typically two types of commutations methods have been proposed which don’t require snubber circuits for a PWM rectifier of AC-to-AC converters without DC link components.

The first method named rectifier zero current commutation and the second method named rectifier four-step commutation. In these methods, although the losses in snubber circuits and the switching losses in the PWM rectifier can be reduced, a

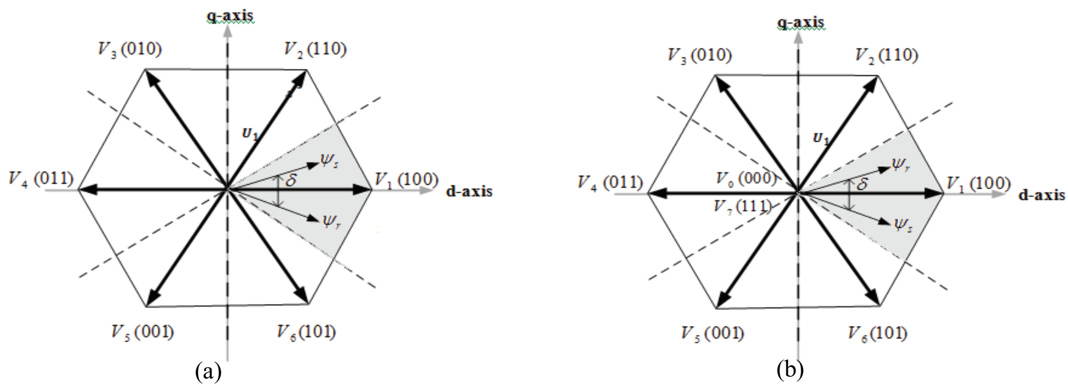

Fig. 2. Flux space vectors in the rotor reference frame, in motor and generator modes. (a) Motor mode, (b) Generator mode

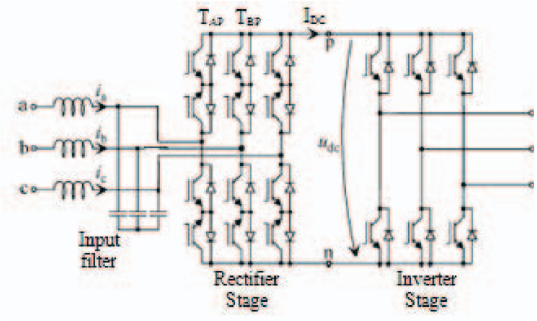

Fig. 3. General structure of indirect matrix converter

complicated control circuit must be added to synchronize the switching of both the PWM rectifier and the PWM inverter [3].

In this paper four-step commutation method in the rectifier stage is used, therefore the mechanisms involved in the commutation process are firstly described.

4. Four-step commutation strategy

The commutation process of matrix converter is more complicated compared with traditional AC-DC-AC converter due to having no natural free-wheeling paths [7]. Direction of output current and value of input voltage determine the sequence of switches that using four-step commutation strategy and commutation reliability depends on accuracy in detecting the direction of output current and two input-phase voltage differences [8].

The process of commutation is explained with Fig. 4. T_{AP} and T_{BP} are shown in Fig. 3. For example in this case the purpose is to show switching between phase A and B . phase A connects to rectifier output through IGBT of switch S_{11} and diode of switch S_{12}. At this point, as it is shown (dotted lines in fig. 4.a) current does not pass from other transistors and diodes. It has been supposed that commutation begins from phase A to phase B . When $i_{DC} > 0$ the following four-step switching sequence is: 1) turn off S_{12} ; 2) turn on S_{31} ; 3) turn off S_{11} ; 4) turn on S_{32} . When $i_{DC} < 0$, the following four-step switching sequence is: 1)turn off S_{11}; 2)turn on S_{32}; 3)turn off S_{12}; 4)turn on S_{31}.

5. Modeling Novel DTC Based on IMC for DFIM

In this section the suggested model of Direct Torque Control based on Indirect Matrix Converter for doubly-fed induction machine is presented and analyzed. The fig. 5 shows the related diagram block.

As its shown, input voltages are sensed and along with torque and flux error and rotor flux sector are applied to control block. Input voltage with current direction in DC link are employed to determination mode of implementation of four-step commutation, that explained in detail in last section. An indirect space vector modulation (ISVM) is often used for matrix converters, providing full control of both the output voltage vector and the instantaneous input current displacement angle. The proportion between the two adjacent vectors gives the direction and the zero-vector duty-cycle determines the magnitude of the reference vector.

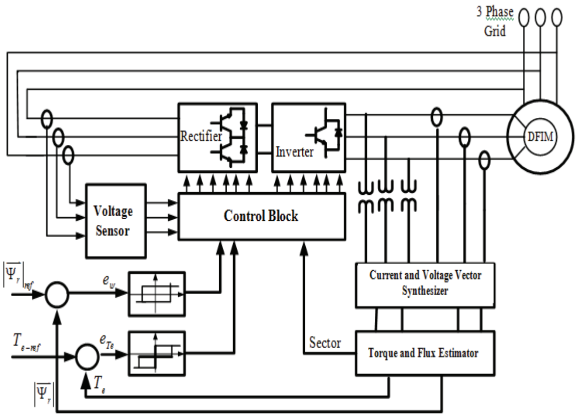

Fig. 5. Schematic diagram DTC based on IMC for DFIM

A. *Rectifier Stage*

The input voltage can be calculated using the following definition:

$$V_i = \frac{2}{3}(v_a + av_b + a^2 v_c) \tag{6}$$

Assuming that the displacement angle between the fundamental component of current and the input phase voltage is θ_i , therefore Phase current vector angle can be achieved with the following equation [2]:

$$I_x' = i_x' + ji_y' \tag{7}$$

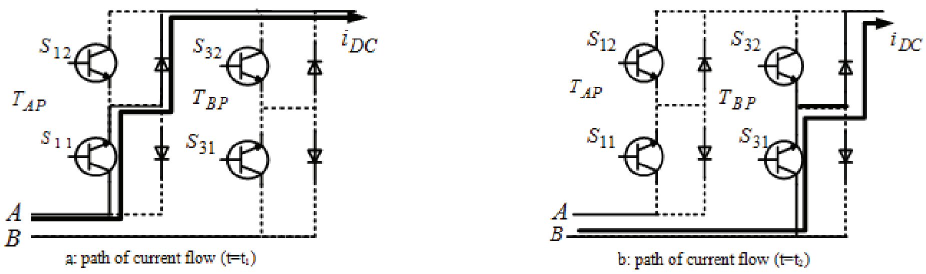

Fig. 4. Commutation from T_{AP} to T_{BP}

In which:

$$i_x' = v_x \cos\theta_i - v_y \sin\theta_i$$
$$i_y' = v_x \sin\theta_i + v_y \cos\theta_i \qquad (8)$$

The direction of $\overline{I_i}$ is given by:

$$\measuredangle \overline{I_i} = \arctan \frac{i_y'}{i_x'} \qquad (9)$$

Fig. 6 shows that there are six active current space vectors, each of them is related to a certain switching configuration.

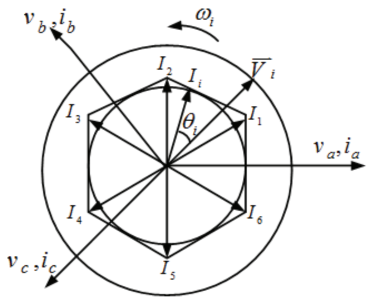

Fig. 6. Input voltage and current vectors

As presented in Fig. 7 it is possible to obtain the input current vector by synthesize two adjacent fixed active vectors [2]:

$$I_i = d_\gamma i_\gamma + d_\delta i_\delta \qquad (10)$$

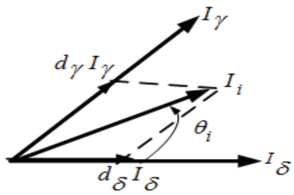

Fig. 7. Synthesis of input current vector

Where the relative duration of current vectors are:

$$d_\delta = \sin(60^\circ - \theta_i)$$
$$d_\gamma = \sin\theta_i \qquad (11)$$

B. *Inverter Stage*

The space vector of IMC output line-to-line voltage V_{oL-L} may be defined [9]:

$$V_{oL-L} = (\frac{2}{3})(v_{AB} + a v_{BC} + a^2 v_{CA}) \qquad (12)$$

The output line-to-line voltage vector V_{0L-L} is synthesized by two adjacent fixed active vectors, as shown in Fig. 8.

$$V_{oL-L} = d_\alpha v_\alpha + d_\beta v_\beta \qquad (13)$$

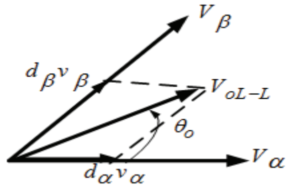

Fig. 8. Synthesis of output voltage

Where the relative duration of voltage vectors are:

$$d_\alpha = \sin(60^\circ - \theta_o)$$
$$d_\beta = \sin\theta_o \qquad (14)$$
$$d_0 = 1 - d_\alpha - d_\beta$$

C. *Two-Stage Matrix Converter*

To balance the input currents and the output voltages properly in the same switching period, the modulation pattern should combine the rectification and inversion vectors uniformly, producing the following switching pattern: α γ-α δ-β γ-0. The combined duty-cycles of the rectification and inversion stages, using the previously presented switching pattern, are obtained as a cross product of their independent duty-cycles as shown in (15a), (15b), (15c) and (15d) [9].

$$d_{\alpha\gamma} = d_\alpha d_\gamma = \sin(60^\circ - \theta_o)\sin(\theta_i) \qquad (15a)$$
$$d_{\beta\gamma} = d_\beta d_\gamma = \sin(\theta_o)\sin(\theta_i) \qquad (15b)$$
$$d_{\alpha\delta} = d_\alpha d_\delta = \sin(60^\circ - \theta_o)\sin(60^\circ - \theta_i) \qquad (15c)$$
$$d_{\beta\delta} = d_\beta d_\delta = \sin(\theta_o)\sin(60^\circ - \theta_i) \qquad (15d)$$

The zero-vector duty-cycle is determined as the complement of all active states combined. During the rest of the period all output phases are shorted and load voltage is zero, i.e. zero vector is taken:

$$d_0 = 1 - d_{\alpha\gamma} - d_{\alpha\delta} - d_{\beta\gamma} - d_{\beta\delta} \qquad (16)$$

The switching pattern for an IMC is presented in Fig. 9. $d_{\beta(\delta+\gamma)}$ and $d_{0\gamma}$ that shown in fig. 9 is given by [9]:

$$d_{\beta(\delta+\gamma)} = (d_\delta + d_\gamma).d_\beta \qquad (17)$$
$$d_{0\gamma} = d_0 d_\gamma = d_\gamma.(1 - (d_\gamma + d_\delta).(d_\alpha + d_\beta)) \qquad (18)$$

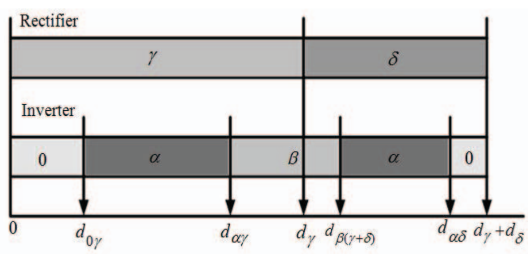

Fig. 9. Switching pattern for an IMC

6. Simulation results

In order to validate the justness of the proposed control strategy, the developed control system, shown in Fig. 5, is implemented in MATLAB/SIMULINK. The machine parameter are provided by Matlab 7.8 as follows:

$250V$ stator line-line voltage, $P_N = 15kW$, $f = 50Hz$,

The input voltage V_r and current I_r of the IMC are shown in Fig.10. This indicates that the unity power factor of the rotor winding has been achieved. Fig.11 shows the network voltage and the network current. The obtained sinusoidal current waveform demonstrates one of the important advantages of the proposed control strategy. Fig.12 shows the trajectory of rotor flux vector obtained using the proposed DTC control. It can be seen that the round locus of rotor flux has been achieved. Fig. 13 shows the torque control process. It indicates that the direct torque control of DFIG based on IMC offers satisfying torque control performance.

Fig.14, 15 and 16 shows rotor current, stator current and network current respectively. Also, Fig.17 and 18 shows flux response and rotor flux sector that determine accuracy of proposed model. Finally Fig.19 shows the DC link voltage of IMC.

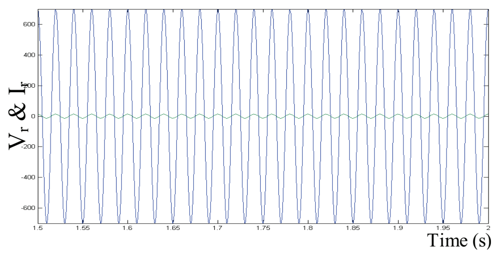

Fig. 10. Input voltage and current of IMC

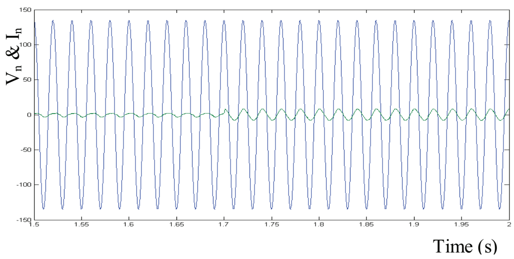

Fig. 11. Network voltage and current

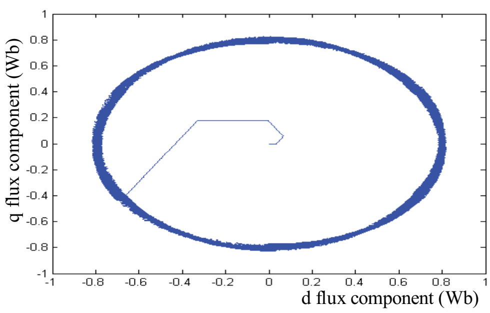

Fig. 12. Trajectory of rotor flux vector in DTC

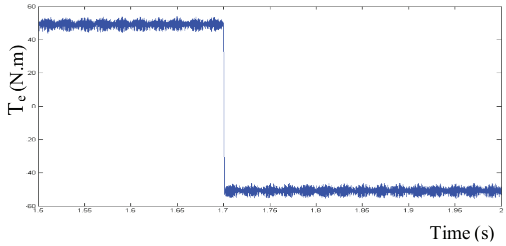

Fig. 13. Torque response

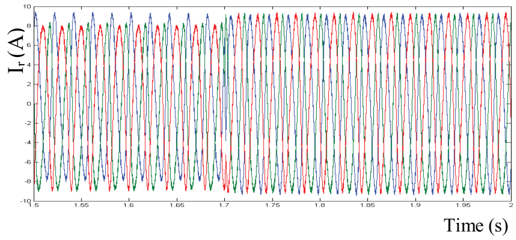

Fig. 14. Rotor current

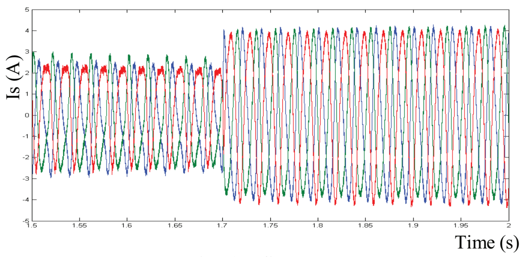

Fig. 15. Stator current

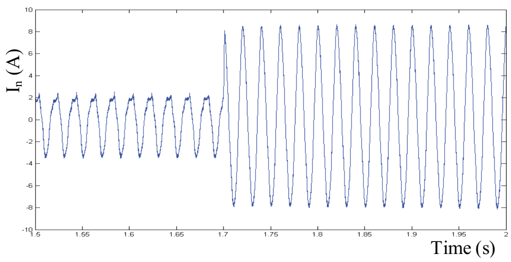

Fig. 16. Network current

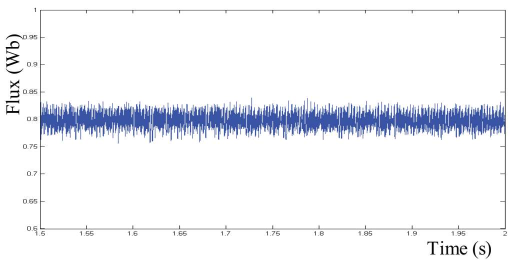

Fig. 17. Flux response

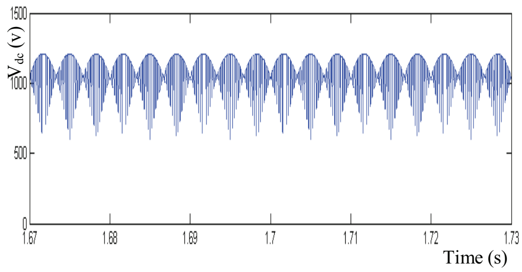

Fig. 18. DC link voltage of IMC

7. Conclusions

In this paper for enjoyment of the benefits of matrix converters and direct torque control at the same time (such as small size, fast response in torque control, near sinusoidal input current and long life-time) direct torque control based on indirect matrix converter is proposed. Doubly-fed induction generator is used extensively in wind power plant to generate energy. Proposed model improving current injection into the network. On the other hand, DC link electrolytic capacitor problems such as limited lifetime and bulky size have been limited. To reduce problems, snubbers were excluded from the converter and Four-step commutation strategy was used instead. Simulation results obtained from SIMULINK/MATLAB simulation software verify the effectiveness of the strategy proposed in this paper.

8. References

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