

# Online Rotor Resistance Estimation Based on MRAS-Sliding Mode Observer for Induction Motors

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**Abstract-** This paper deals with rotor resistance estimation for induction motors drives purpose. A novel MRAS structure for rotor resistance adaptation is proposed. It is based mainly on the use of a very robust sliding mode flux observer as reference model, which gives robustness to the whole parameter estimation operation. Unlike to classical MRAS structure, based on the use of pure integrators, which have initial value and drift problems.

By using the proposed MRAS-Sliding mode observer, system has a better performance and robustness. Effectiveness of this proposed estimation structure is verified by experiment under critical disturbance conditions.

**Keywords-** Induction motor; MRAS; Rotor resistance estimation; Sliding mode flux observer.

## I. INTRODUCTION

It is well known that control laws quality for controlling induction motor requires a good knowledge of state variables required and parameters involved in the model. Access to these quantities requires state measured by sensors whose accuracy is crucial for performance level required by some industrial applications. The cost of these sensors and their lack of precision, make this task very difficult. To solve these problems, it is essential to use software sensors through observers and estimators design.

In induction machine control, problem of observation arises especially for rotor flux, which is not accessible state.

For parametric variations, rotor and stator resistances are most critical machine parameters, because their influence is crucial as it is for the control or observation. These parameters can vary up to 100% of their nominal values, due to temperature variation.

Several types of observers and estimators exist in the literature. Among techniques used may be mentioned: high gain observer [1], observer of Luenberger [2], techniques of extended Kalman filter (EKF) [3], adaptive observers [4], techniques based on adaptive systems reference model (MRAS) [5], and techniques based on sliding mode [6]. Each of these techniques has advantages and disadvantages.

The techniques that have attracted most attention in literature are: extended Kalman filter, which is based on solving Riccati equation from the linearized mathematical model of the machine, and takes into account parametric variations and noise measurements. This technique has been used both to observe flux and speed [7] for parameter estimation [8]. This technique has advantage of robustness and drawback of calculations intensity and the need of proper initialization.

The second attractive technique is based on an MRAS structure in which an error vector is formed from outputs of two independent models. This error is brought to zero by adjusting estimated variable through an adaptation mechanism. This variable influences one model and not the other. The influenced model is called adjustable model and the other is called reference model. MRAS structure differs from another by choice of output variable of the two models, as well as the choice of the adaptation mechanism. The most common choice of output variable of the two models is the rotor flux. The MRAS structure based on such a choice has advantage of estimating angle of the rotor flux, which can be used as part of a field oriented control. The disadvantage of such a structure is sensitivity at low speeds, variation of stator resistance and drift of the integrator. Other choices of output variable have been proposed and are based on the electromotive force (EMF) or reactive power [9,10]. Unfortunately, these techniques have not led to satisfactory solutions for structures based on those choices are always problems at low speed.

MRAS structure approach has been used both to estimate the speed in a sensorless control and for parameter estimation in real time [11]. It has advantage of having a direct physical interpretation, because of its easy implementation.

Sliding mode technique has also an extensive development in recent years. This approach is based on a discontinuous control to force system state to reach a sliding surface in a first step, and then drag it to the surface to an equilibrium point in a second step. This technique has advantage of being very robust against uncertainties and disturbances, and disadvantage of high-frequency called "chattering." To reduce effect of this drawback, several

versions of higher-order sliding mode have been proposed [12]. This technique has been used both to observe flux, speed and for parameter estimation [13].

In this paper, we have integrated a robust sliding mode observer in an MRAS structure. The use of this robust flux observer based on the principle of sliding mode allowed us to design new MRAS structure for rotor resistance estimation.

The rest of this paper is organized as follows: in section II, we present the sliding mode flux observer, which will be used later in section IV, in section III, we present the classical MRAS observer, in section IV the RF-MRAS sliding mode observer is presented, in section V the Load torque observer is detailed and in section VI the experimental results are discussed.

## II. SLIDING MODE FLUX OBSERVER

The proposed observer is based on a current model [14, 15]. This observer has advantage of not requiring speed and rotor time constant as inputs, unlike other flux observers. Therefore, any variation of these quantities will no effect on current and flux estimation. In addition, the use of sliding mode method for the design of this observer guarantees both robustness with respect to various disturbances, and good dynamic performance over all speed range. The equations of the stator currents and rotor flux can be written in the fixed reference as:

$$\begin{aligned} \dot{i}_{s\alpha} &= \frac{1}{\sigma L_s} \frac{L_m}{L_r} \frac{1}{T_r} \phi_{r\alpha} + \frac{1}{\sigma L_s} \frac{L_m}{L_r} \omega \phi_{r\beta} - \frac{1}{\sigma L_s} \left( R_s + \frac{L_m^2}{L_r T_r} \right) i_{s\alpha} + \frac{1}{\sigma L_s} u_{s\alpha}, \\ \dot{i}_{s\beta} &= \frac{1}{\sigma L_s} \frac{L_m}{L_r} \frac{1}{T_r} \phi_{r\beta} - \frac{1}{\sigma L_s} \frac{L_m}{L_r} \omega \phi_{r\alpha} - \frac{1}{\sigma L_s} \left( R_s + \frac{L_m^2}{L_r T_r} \right) i_{s\beta} + \frac{1}{\sigma L_s} u_{s\beta}, \\ \dot{\phi}_{r\alpha} &= -\frac{1}{T_r} \phi_{r\alpha} - \omega \phi_{r\beta} + \frac{L_m}{T_r} i_{s\alpha}, \\ \dot{\phi}_{r\beta} &= -\frac{1}{T_r} \phi_{r\beta} + \omega \phi_{r\alpha} + \frac{L_m}{T_r} i_{s\beta}, \end{aligned} \quad (1)$$

These equations can be represented in matrix form by

$$\begin{bmatrix} \dot{i}_{s\alpha} \\ \dot{i}_{s\beta} \end{bmatrix} = k_1 \left( \begin{bmatrix} \eta & \omega \\ -\omega & \eta \end{bmatrix} \begin{bmatrix} \phi_{r\alpha} \\ \phi_{r\beta} \end{bmatrix} - \eta L_m \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \right) - k_2 \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} + k_3 \begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix}, \quad (2)$$

$$\begin{bmatrix} \dot{\phi}_{r\alpha} \\ \dot{\phi}_{r\beta} \end{bmatrix} = - \left( \begin{bmatrix} \eta & \omega \\ -\omega & \eta \end{bmatrix} \begin{bmatrix} \phi_{r\alpha} \\ \phi_{r\beta} \end{bmatrix} - \eta L_m \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \right) \quad (3)$$

With

$$k_1 = \frac{k_3 L_m}{L_r}, \quad k_2 = \frac{R_s}{\sigma L_s}, \quad k_3 = \frac{1}{\sigma L_s}, \quad \sigma = 1 - \frac{L_m^2}{L_s L_r}, \quad \eta = \frac{1}{T_r} = \frac{R_r}{L_r},$$

We define the matrix S by

$$S = \left( \begin{bmatrix} \eta & \omega \\ -\omega & \eta \end{bmatrix} \begin{bmatrix} \phi_{r\alpha} \\ \phi_{r\beta} \end{bmatrix} - \eta L_m \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \right) \quad (4)$$

We can note that the matrix S appears simultaneously in the equations of currents and flux. This implies that design of current and the flux observer can be based on replacing the common term, which is the matrix S by the proposed sliding mode functions  $\psi_{r\alpha\beta}$

$$\begin{bmatrix} \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix} = \hat{S} = \left( \begin{bmatrix} \eta & \hat{\omega} \\ -\hat{\omega} & \eta \end{bmatrix} \begin{bmatrix} \hat{\phi}_{r\alpha} \\ \hat{\phi}_{r\beta} \end{bmatrix} - \eta L_m \begin{bmatrix} \hat{i}_{s\alpha} \\ \hat{i}_{s\beta} \end{bmatrix} \right) \quad (5)$$

Current and flux observers became

$$\begin{bmatrix} \dot{\hat{i}}_{s\alpha} \\ \dot{\hat{i}}_{s\beta} \end{bmatrix} = k_1 \begin{bmatrix} \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix} - k_2 \begin{bmatrix} \hat{i}_{s\alpha} \\ \hat{i}_{s\beta} \end{bmatrix} + k_3 \begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} \dot{\hat{\phi}}_{r\alpha} \\ \dot{\hat{\phi}}_{r\beta} \end{bmatrix} = - \begin{bmatrix} \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix} \quad (7)$$

Where

$$\psi_{r\alpha} = -u_0 \text{sign}(S_{s\alpha}), \quad \psi_{r\beta} = -u_0 \text{sign}(S_{s\beta}), \quad (8)$$

And

$$\begin{aligned} S_{s\alpha} &= \bar{i}_{s\alpha} = \hat{i}_{s\alpha} - i_{s\alpha} \\ S_{s\beta} &= \bar{i}_{s\beta} = \hat{i}_{s\beta} - i_{s\beta} \end{aligned} \quad (9)$$

$\hat{i}_{s\alpha}, \hat{i}_{s\beta}$  and  $i_{s\alpha}, i_{s\beta}$  are respectively, observed and measured components of stator current.

When the estimated current converges to the measured current, the flux estimation is a simple integration of sliding mode functions without having to know either the speed or the rotor time constant.

Selection of  $u_0$  in (8) will ensure convergence of the observation of the current by the Lyapunov stability analysis.

It should be noted that we have assumed that the equivalent control of sliding mode observer is obtained by a simple low-pass filtering of the discontinuous control.

$$\psi_{r\alpha\beta}^{eq} = \frac{1}{\mu p + 1} \psi_{r\alpha\beta} \quad (10)$$

$\mu$  is time constant of the low-pass filter

Now the rotor flux can be estimated by

$$\begin{bmatrix} \dot{\hat{\phi}}_{r\alpha} \\ \dot{\hat{\phi}}_{r\beta} \end{bmatrix} = - \begin{bmatrix} \psi_{r\alpha}^{eq} \\ \psi_{r\beta}^{eq} \end{bmatrix} \quad (11)$$

“Fig.1” illustrates the overall scheme of the observer

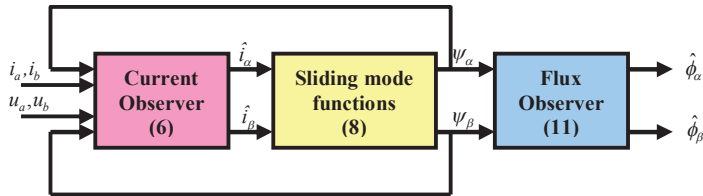


Fig. 1. Overall scheme of sliding mode flux observer

### III. CLASSICAL MRAS ESTIMATION

Model reference adaptive system (MRAS) is one of the most popular methods used for observing the parameters and states of the induction machine. Using stator and rotor equations in the fixed frame, we can estimate the rotor flux in two different forms [16]

$$\begin{bmatrix} \dot{\phi}_{r\alpha} \\ \dot{\phi}_{r\beta} \end{bmatrix} = \frac{L_r}{L_m} \begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix} - \begin{bmatrix} (R_s + \sigma L_s p) & 0 \\ 0 & (R_s + \sigma L_s p) \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} \dot{\phi}_{r\alpha} \\ \dot{\phi}_{r\beta} \end{bmatrix} = \begin{bmatrix} (-1/T_r) & -\omega \\ \omega & (-1/T_r) \end{bmatrix} \begin{bmatrix} \phi_{r\alpha} \\ \phi_{r\beta} \end{bmatrix} + \frac{L_m}{T_r} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \quad (13)$$

“Fig.2” illustrates structure of classical MRAS. It is based on the use of output error between two independent flux observer models. This error is driven to zero through adjustment of the parameter by an adaptive mechanism.

The first is based on the equation (12), and is called the reference model because it does not depend on the rotor time constant ( $\beta_r = 1/T_r$ ).

The second is based on the equation (13), and is called adjustable model, as through adaptation of rotor time constant, it shall be recalibrated on the first model.

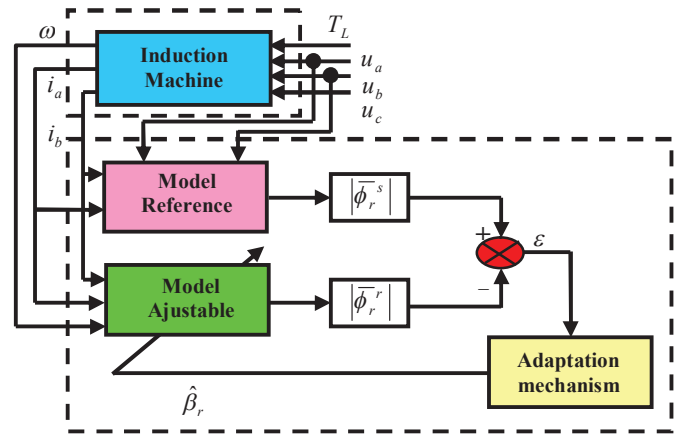


Fig. 2. Rotor time constant estimator structure

The estimated rotor time constant is obtained from the mechanism of adaptation following

$$\hat{\beta}_r = \left( K_p + \frac{K_i}{p} \right) \left( |\phi_r| - |\hat{\phi}_r| \right) \quad (14)$$

The appropriate adaptation mechanism is deduced using the Popov hyperstability criterion.

### IV. RF-MRAS-SLIDING MODE ESTIMATION

New MRAS structure is proposed for rotor resistance estimation. The idea is to use the flux observer presented in section I as a reference model with its performance especially in terms of robustness, and recalibrated the current model on this model in order to estimate  $R_r$  [17]. The diagram of the structure is shown in “Fig.3”.

The adaptive mechanism, which is a simple PI controller, relies on an error quantity that represents the difference between the instantaneous positions of the two rotor flux estimates by the two models (reference and adjustable).

Using sliding mode observer, as reference model gives a big advantage to the whole MRAS structure. The rotor resistance MRAS estimation scheme, developed in this section, will make use of this advantage to achieve estimation of the two quantities. The role of reference and adjustable model will be interchanged for this purpose, since the rotor flux estimate of (11) is independent of rotor resistance.

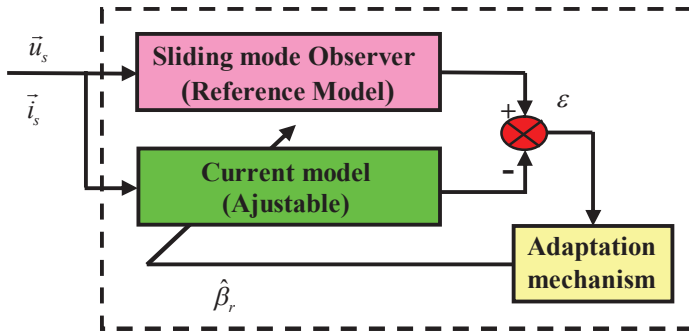


Fig. 3. RF-MRAS observer structure for  $R_r$  estimation

The rotor flux oriented control scheme for an induction motor, utilized in the paper in experimental investigation, is illustrated in “Fig. 4”. It includes, apart from a speed controller, rotor flux and currents controllers as well.

The required feedback quantities for the rotor flux closed loop control are obtained from the reference model (12).

Induction motor data are given in the Appendix. A DSP system, based on DS1104 controller board from dSPACE, is used for experimental investigation. Motor stator currents are measured, while stator voltages are reconstructed from the known PWM pattern and the measured dc voltage.

$\hat{i}_L$  is the observed load torque,  $\tau_0$  is the observer time constant and  $z$  is the observer state.

VI. EXPERIMENTAL RESULTS

In order to validate our MRAS structures for rotor resistance estimation, we have used an experimental setup, consisting of a wound rotor induction machine connected to a rheostat-phase so that they can act the apparent resistance of the rotor circuit.

The block schematic of the experimental setup is shown in “Fig. 5”. Experimental setup consists of a wound rotor induction motor of rating: Star/Delta 380V/220V AC, 8.9 A/15.5 A, 4 kW, p.f. 0.82, 1440 r.p.m, 50 Hz and is coupled with a powder brake. The rotor shaft of the induction motor is fitted with an optical position encoder with 1024 lines per rotation for measuring angular position and speed. The induction motor receives power from an SVPWM inverter of 1000 V, 30 A rating. The dSPACE interface generates the SVPWM pulses for the inverter and takes the signals of the measured currents for phase “a” and “b” through ADCs and angular position signals through encoder. It takes also the speed command from the dSPACE “controldesk” and generates the voltage command for the SVPWM inverter. The signal for angular positions are sampled for every 750 microsecond interval and the current signals are sampled for every 200 microsecond interval. The computation for control algorithm is done within a time step of 200 microseconds. The inverter switching frequency is kept at 10 kHz using the slave DSP. The control and estimation algorithms need as inputs (1) the stator currents and (2) the encoder position. For that filters are used:

- Digital low pass filter is used for filtering encoder position signal.
- Digital synchronous resonating filter [19] is used for reducing high-frequency noise in the stator current signals arising out of SVPWM and electrical grid.

A sudden change in resistance was caused during motor operation to test the performance of the two methods described above.

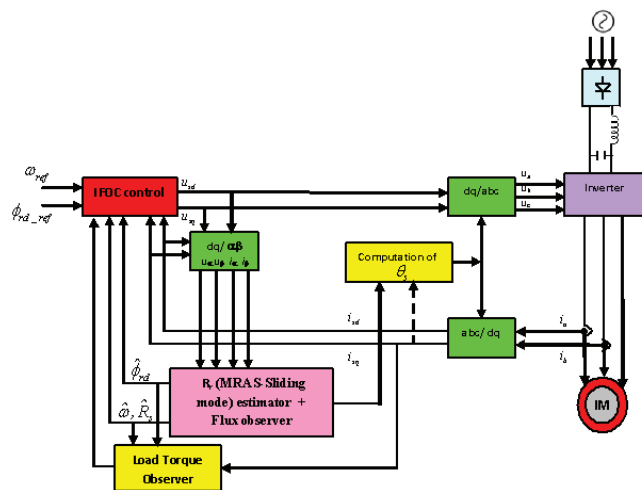


Fig. 4. Rotor flux oriented control scheme

V. LOAD TORQUE OBSERVER

To observe the load torque, we use the observer proposed in [18]

$$\hat{t}_L = \frac{1}{\tau_0} \left( z - \frac{J}{n_p} \omega \right) \tag{5}$$

$$\frac{dz}{dt} = n_p \frac{2}{3} L_m \lambda_{2d} i_{1q} - \hat{t}_L$$

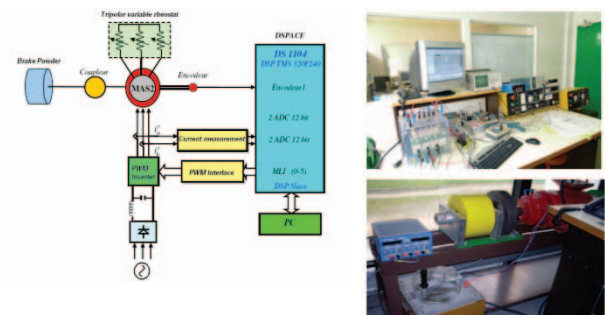


Fig. 5. The experimental setup

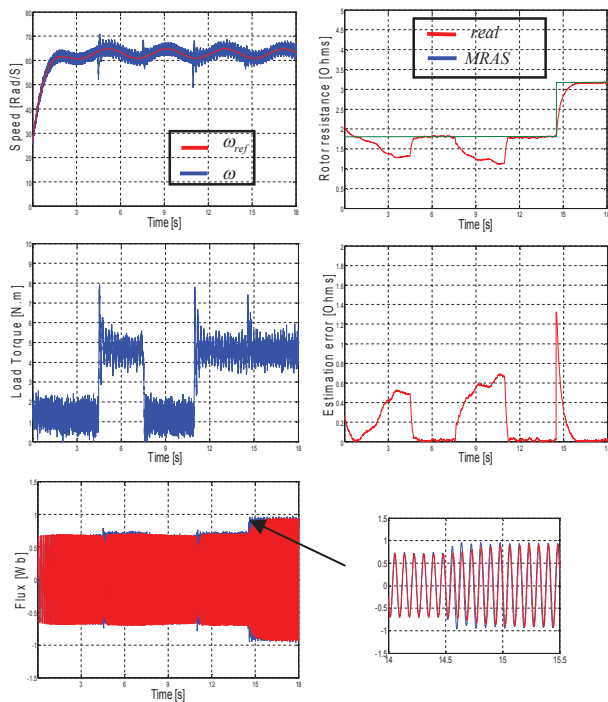


Fig. 6. Estimation performance (experimental results) Classical MRAS

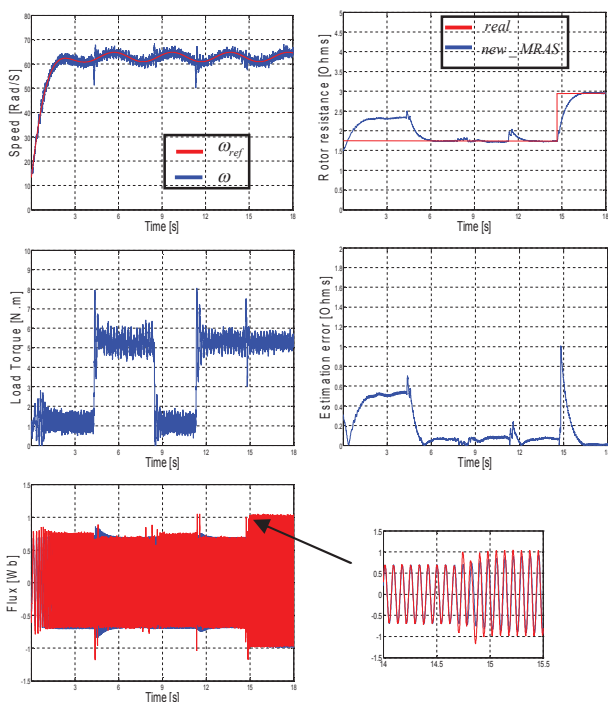


Fig. 7. Estimation performance (experimental results) RF-MRAS-Sliding mode

## DISCUSSION

The experimental results are illustrated by “Fig.6 and 7”. The results were obtained under an indirect field oriented induction machine control. The motor started without load to

reach a certain speed steady. After a few seconds, a torque was applied. For the two structures, the estimate is efficient and converges very quickly (in less than one second) to a value very close to the nominal value. By variation on the variable resistor connected to the rotor, the apparent value of the rotor resistance has been changed deliberately. According to the “Fig.6 and 7”, the two methods follow exactly what change and converge quickly to the new value. The profile of the variable speed was chosen in order to judge the performance of the estimation with respect to the change in speed. We find that the two proposed approaches for the identification provide good performance when the speed is constant or varies slowly. Note that both versions of the identifier MRAS provide better performance in terms of accuracy and robustness. Note also that in the absence of load torque, the first method is unable to give an accurate estimate of the rotor resistance, while the second still provides a good estimate of this parameter, as shown in “Fig.7”.

## VII. CONCLUSION

Using a robust flux observer based on the principle of sliding mode allowed us to design new MRAS structure for rotor resistance estimation. The experimental validation has confirmed the effectiveness of these methods. A comparative study was conducted on several axes. MRAS-sliding mode observer gives the best performance in terms of accuracy and robustness to external disturbance. The other interesting feature of the proposed structure is that it is simple and easy to implement in real time.

## APPENDIX

### INDUCTION MOTOR DATA

Stator resistance	1.34 ohms;
Rotor resistance	1.18 ohms;
Mutual inductance	0.17 H;
Rotor inductance	0.18 H;
Stator inductance	0.18 H;
Number of pole pairs	2
Motor load inertia	0.0153 kgm <sup>2</sup> ;

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