An Approach of Position and Torque Estimation for Induction Motor based Sensor-less Drive

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Abstract:— This paper presents a new approach with stability analysis, simulation and experimental investigation of a sliding mode based estimator for rotor-position and torque-load calculation in high performance speed-sensor-less AC motor drive. The proposed algorithm is built based on the induction motor (IM) fluxes equations for two rotationg referential frames. The First equation calculates the stator flux vector while the second gives the rotor flux vector. Moreover, the stator flux equation is linked to a stator-flux rotating referential frame and the rotor flux equation is linked to a rotor-flux rotating referential frame. Among merits of the proposed technique is no necessity to rotor-speed measurement and adaptation. Thus, it is well suitable to the fully speed-sensorless scheme. The whole observer stability is verified by using of Lyapunov's principle. Simulations are done by using Matlab-Simulink and experimental implementation is performed in order to prove the feasibility of proposed algorithm. The illustrated results are shown by using a DS1104 controller board.

Keywords— Sliding Mode Observer (SMO), Direct Torque Control (DTC), Induction Motor, Lyapunov Stability Criterion.

I. INTRODUCTION

In today's industry, many applications use induction motors in order to convert the electric power to mechanical work, due to their high performance and low cost. Moreover, in the majority of cases, this using needs the accompaniment of a power static converter in order to guarantee their feeding in various operating conditions. For that, the classical six-switch two-level voltage source inverter (VSI) has been heavily opted. Furthermore, the unprecedented development in power electronics components (i.e,. IGBT transistors, Diodes…) and high speed microcontrollers (i.e,. DSP, FPGA…) has contributed to the enhancing of their performances. However, the use of these control boards and circuits needs at least an electronics interface card with sensors and some measurements which increase the cost of the whole system. Thus, the economic and good quality sensor-les solutions are more and more researched. Therefore, much algorithms and research works has been introduced and performed in order to improve these products. Among works, the introducing of new and complex algorithms or techniques for control and estimation, such as fuzzy logic controllers, sliding mode observers (SMO) and model reference adaptive systems (MRAS) [1]- [5]. The DTC using space vector modulation (SVM) is one of the high dynamic and reliable drives; owing to it focuses basically on the direct control of the stator flux without any inner loops [6]- [8]. Often, the speed sensor-less approach is preferred to decrease the drive cost and increase its robustness. However, the elimination of speed sensor may cause serious problems in the flux estimation especially when the estimation algorithm dependents to the rotor speed quantity and when an inaccurate estimation method is selected. In this context, many researchers have given suggestions to obtain high accuracy speed estimation [9]–[18]. From the magnetic-saliency based methods, which demonstrated their limitations in term of precision in measurement and their using with low saliently motors [12]-[14], to the observer based methods [15]-[16], which suffer of the model parameters variation especially at very low speeds and standstill operations. The artificial intelligence (AI) approach has been introduced to solve the model parameters mismatch problem but its exigencies in real time implementation are more and more complex [17]-[18]. Thus, speed sensor-less flux estimation algorithms are more robust and reliable to achieve high performance drives. Among these algorithms, the adaptive sliding mode observer based flux and electromagnetic torque estimation which is based on variable structure control theory.

In this paper, a speed sensor-less sliding mode observer is introduced to rotor position and Load torque estimation in induction motor DTC Drive. The principle of sliding mode observer based flux and electromagnetic torque is adopted wherein the variable structure control is used to develop new sensor-less estimation which neglects all rotor speed and position dependence. Furthermore, the concept of Lyapunov in stability theory is used to framing the stability low of the whole system. Since the observer robustness should be confirmed, a stator and rotor resistances variation tests are opted. Therefore, a model reference adaptive control (MRAC) based stator resistance online adaptation is discussed. The

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simulation results are done using Matlab-Simulink and experimental implementation which demonstrate the feasibility of this types of estimation are shown using DS1104 controller board which based on Texas Instruments TMS320F240 digital signal processor.

II. Sliding Mode Fluxes Observers based Stator Current Estimation

For IM model, in arbitrary rotating reference frame, denoted by (e), the stator flux vector $\underline{\lambda}_s$ can be given by the following differential equation

$$\frac{d}{dt}\underline{\lambda}_s^{(e)} = \frac{R_s}{\sigma L_s}\left(\frac{L_m}{L_r}\underline{\lambda}_r^{(e)} - \underline{\lambda}_s^{(e)}\right) - j\omega_e \underline{\lambda}_s^{(e)} + \underline{u}_s^{(e)} \tag{1}$$

Where, $\underline{\lambda}_r$ is the rotor flux vector which represent the flux-linkage of rotor armatures, it is expressed by the following equation

$$\frac{d}{dt}\underline{\lambda}_r^{(e)} = \frac{R_r}{\sigma L_r}\left(\frac{L_m}{L_s}\underline{\lambda}_s^{(e)} - \underline{\lambda}_r^{(e)}\right) - j(\omega_e - \omega_r)\underline{\lambda}_r^{(e)} \tag{2}$$

Where, ω_e is the angular speed of the rotating reference frame and ω_r is the rotor angular speed. In addition, $\underline{u}_s^{(e)}$ represents the applied voltage vector and both of R_s, R_r, L_s, L_r, L_m and σ represent the IM-model parameters given in Tab. 1.

Tab. 1. The used Motor-Data

Rated power	900 W
Voltage	380/660 V
Current	2.6 A
Frequency	50 Hz
Rated torque	6N·m
Rated speed	1420 rpm
P	2
Rs	21.00 Ω
R'r	22.63 Ω
Ls	1.052 H
L'r	1.081 H
Lm	0.996 H

In the proposed estimator model, the rotor angular speed ω_r should be omitted in order to build a sensor-less scheme. In fact, it will be considered as disturbance for the whole system. For that, the stator flux estimator in Equation (3) is developed based on Equation (1) in stator-flux rotating reference-frame denoted by (sf).

$$\frac{d}{dt}\hat{\underline{\lambda}}_s^{(sf)} = \frac{R_s}{\sigma L_s}\left(\frac{L_m}{L_r}\hat{\underline{\lambda}}_r^{(sf)} - \hat{\underline{\lambda}}_s^{(sf)}\right) - j\omega_{sf}\hat{\underline{\lambda}}_s^{(sf)} + \underline{u}_s^{(sf)} + \underline{k}_1^{(sf)}\underline{\mu}^{(sf)} \tag{3}$$

The rotor flux estimator in Equation (4) is also given based on Equation (2) in rotor-flux rotating reference-frame denoted by (rf)

$$\frac{d}{dt}\hat{\underline{\lambda}}_r^{(rf)} = \frac{R_r}{\sigma L_r}\left(\frac{L_m}{L_r}\hat{\underline{\lambda}}_s^{(rf)} - \hat{\underline{\lambda}}_r^{(rf)}\right) - j\left(\omega_{sf} - \omega_r\right)\hat{\underline{\lambda}}_r^{(rf)} + \underline{k}_2^{(rf)}\underline{\mu}^{(rf)} \tag{4}$$

The sup-script (^) denotes the estimated value of variables, k_1 and k_2 are the Estimator gains and $\underline{\mu}$ is the correction vector.

On the other hand, in stator-flux reference-frame, only the direct component of the stator-flux vector is considered ($\lambda_s^{(sf)} = \lambda_{sd}^{(sf)}$) and ($\lambda_{sq}^{(sf)} = 0$). Thus, the stator flux equation in (3) becomes

$$\frac{d}{dt}\hat{\underline{\lambda}}_{sd}^{(sf)} = \frac{R_s}{\sigma L_s}\left(\frac{L_m}{L_r}\hat{\underline{\lambda}}_{rd}^{(sf)} - \hat{\underline{\lambda}}_{sd}^{(sf)}\right) + \underline{u}_{sd}^{(sf)} + \underline{k}_{1d}^{(sf)}\underline{\underline{\mu_d}}^{(sf)} \tag{5}$$

Similarly, in rotor-flux reference frame only the direct component of the rotor-flux vector is considered ($\lambda_r^{(rf)} = \lambda_{rd}^{(rf)}$) and ($\lambda_{rq}^{(rf)} = 0$), the rotor-flux equation (4) becomes

$$\frac{d}{dt}\hat{\underline{\lambda}}_{rd}^{(rf)} = \frac{R_r}{\sigma L_r}\left(\frac{L_m}{L_r}\hat{\underline{\lambda}}_{sd}^{(rf)} - \hat{\underline{\lambda}}_{rd}^{(rf)}\right) + \underline{k}_2^{(rf)}\underline{\underline{\mu_d}}^{(rf)} \tag{6}$$

The correction mechanism can be of fuzzy-sliding-mode [2] type based on the error between the actual stator-current value and its estimated value. The main idea of this hybrid observer is the fuzzification, by using Takagi-Sugeno fuzzy controller, of the observer's discontinuous-part in order to generate a reached-part. Hence the following surface (s) is used as input in stationary reference frame

$$\underline{s} = \underline{i}_s^{(s)} - \hat{\underline{i}}_s^{(s)} \tag{7}$$

And

$$\hat{\underline{i}}_s^{(s)} = \frac{1}{\sigma L_s}\left(\frac{L_m}{L_r}\hat{\underline{\lambda}}_r^{(s)} - \hat{\underline{\lambda}}_s^{(s)}\right) \tag{8}$$

Where, the sup-script (s) denotes the stationary reference frame. In order to verify the sliding mode conditions, the Lyapunov function based stability was selected. From (4) and (5), the derivative of the error equation, with assumption that non mismatch in all model parameters, is

$$\frac{d}{dt}\underline{s} = \frac{1}{\sigma L_s}\left(\frac{L_m}{L_r}\frac{d}{dt}\left(\underline{\lambda}_r^{(s)} - \hat{\underline{\lambda}}_r^{(s)}\right) - \frac{d}{dt}\left(\underline{\lambda}_s^{(s)} - \hat{\underline{\lambda}}_s^{(s)}\right)\right) \tag{9}$$

Similarly for the stator flux error

$$\begin{aligned}&\frac{d}{dt}\left(\underline{\lambda}_s^{(sf)}-\hat{\underline{\lambda}}_s^{(sf)}\right)=\frac{R_s L_m}{\sigma L_s L_r}\left(\underline{\lambda}_r^{(sf)}-\hat{\underline{\lambda}}_r^{(sf)}\right)\\&-\frac{R_s}{\sigma L_s}\left(\underline{\lambda}_s^{(sf)}-\hat{\underline{\lambda}}_s^{(sf)}\right)-j\omega_{sf}\left(\underline{\lambda}_s^{(sf)}-\hat{\underline{\lambda}}_s^{(sf)}\right)-\underline{k}_1\underline{\mu}^{(sf)}\end{aligned}\tag{10}$$

And the stator flux error

$$\begin{aligned}&\frac{d}{dt}\left(\underline{\lambda}_r^{(rf)}-\hat{\underline{\lambda}}_r^{(rf)}\right)=\frac{R_r L_m}{\sigma L_r L_s}\left(\underline{\lambda}_s^{(sf)}-\hat{\underline{\lambda}}_s^{(sf)}\right)\\&-\frac{R_r}{\sigma L_r}\left(\underline{\lambda}_r^{(rf)}-\hat{\underline{\lambda}}_r^{(rf)}\right)-j\left(\omega_{rf}-\omega_r\right)\left(\underline{\lambda}_r^{(rf)}-\hat{\underline{\lambda}}_r^{(rf)}\right)-\underline{k}_2\underline{\mu}^{(rf)}\end{aligned}\tag{11}$$

Both of candidate Lyapunov's function and attractivity condition, used to reflect the characteristic of the estimator, are given by

$$V(\underline{s})=\frac{1}{2}\left(\underline{i}_s^{(s)}-\hat{\underline{i}}_s^{(s)}\right)^T\left(\underline{i}_s^{(s)}-\hat{\underline{i}}_s^{(s)}\right)\tag{12}$$

It is noticed that, when the system reaches the sliding mode surface, the inequality condition will be

$$\underline{k}_1\frac{L_r}{L_m}-\underline{k}_2\rangle MAX\left|-C_1+C_2\right|\tag{13}$$

With C1 and C2 are two coefficients given by

$$C_1=\frac{R_s}{\sigma L_s}\left(\frac{L_r}{L_m}-\frac{L_m}{L_r}\right)\hat{\underline{\lambda}}_s$$

$$C_2=j\omega_r+\frac{R_r}{\sigma L_r}\left(\frac{L_r}{L_s}-\frac{L_m}{L_r}\right)\hat{\underline{\lambda}}_r$$

III. Torque and Rotor Position Calculation

The estimated electromagnetic torque is derived from the estimated flux and measured currents in stationary reference frame as

$$T_{em}^{(s)}=\frac{3P}{4}\left(\hat{\lambda}_{sd}^{(s)}i_{sq}^{(s)}-\hat{\lambda}_{sq}^{(s)}i_{sd}^{(s)}\right)\tag{14}$$

In adjustable speed sensor-less drives, the rotor speed is auto generated via the software. It has been estimated by using

$$\hat{\omega}_r^{(s)}=\hat{\omega}_s^{(s)}-\hat{\omega}_{slip}^{(s)}\tag{15}$$

Where, ω_{slip} represents the slip speed and ω_s is calculated using the following expression

$$\hat{\omega}_s^{(s)}=\frac{\dfrac{d\hat{\lambda}_{rd}^{(s)}}{dt}\hat{\lambda}_{rq}^{(s)}-\dfrac{d\hat{\lambda}_{rq}^{(s)}}{dt}\hat{\lambda}_{rd}^{(s)}}{\hat{\lambda}_r^{(s)2}}\tag{16}$$

And

$$\hat{\lambda}_r^{(s)}=\frac{L_r'}{L_m}\left(\hat{\lambda}_s^{(s)}-\sigma L_s i_s^{(s)}\right)\tag{17}$$

The slip speed can be calculated by dividing the estimated electromagnetic torque by the square of the rotor flux

$$\hat{\omega}_{slip}^{(s)}=\frac{2\hat{R}_s\hat{T}_{em}^{(s)}}{3P\lambda_r^{(s)2}}\tag{18}$$

Overall, the rotor position is given as follow

$$\hat{\theta}_r^{(s)}=\frac{d\omega_r^{(s)}}{dt}\tag{19}$$

The block scheme with inputs, state variables and estimated quantities is given in Fig.1

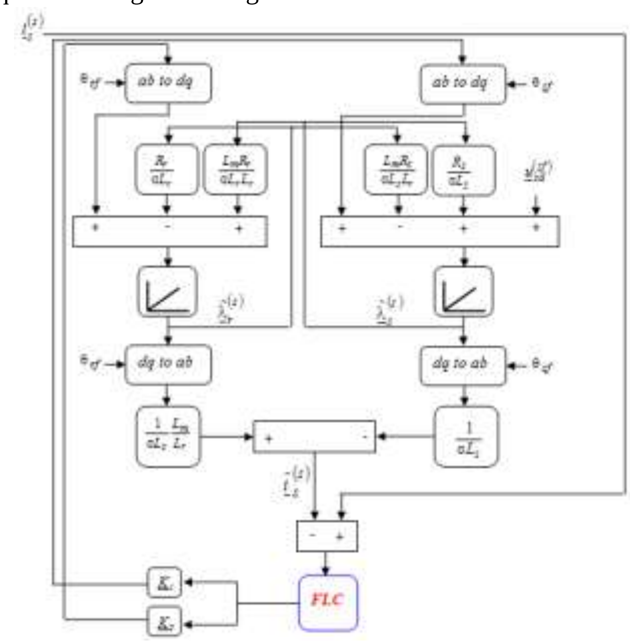
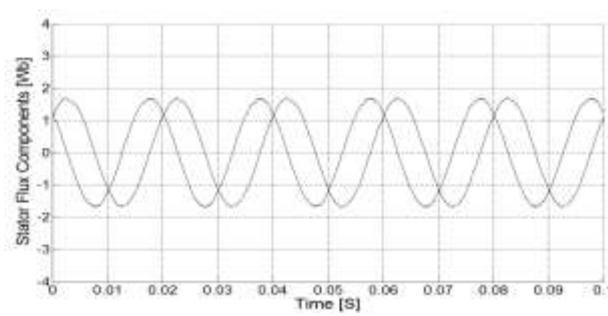


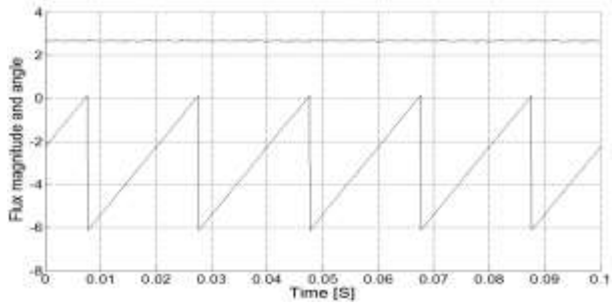
Fig. 1. The proposed sliding mode observer based state estimation.

IV. Simulation Results

In this section, the proposed scheme is verified by simulation in Simulink/Matlab environment. Firstly, the IM-model is simulated in stationary reference frame based on the specifications and data as listed in Tab. 1. The DTC technique is opted in order to drive the IM under various operation modes.



(a)



(b)

Fig. 2. Estimated stator flux using the proposed method
a) *d-q* flux components b) Flux magnitude and angle (offset=-3)

Fig. 2 shows the estimated flux components when the rotor speed reaches its nominal value, the amplitude and angle are shown in the same figure.

In second step, the performance of the proposed algorithm is verified by simulation for two different speeds as in Tab. 2.

Tab. 2. Simulation Setup.

	Unit	Time [S]			
		[0 2]	**[2 4]**	**[4 6]**	**[6 8]**
T_Load	N.m	0.000	**6.000**	6.000	6.000
ω_Rotor	rad/s	62.80	62.80	**0.628**	0.628
R_Stator	Ω	21.00	21.00	21.00	**30.00**

.

In Fig. 3 the estimation error between reel and estimated flux magnitude is illustrated for high and very low speed ranges.

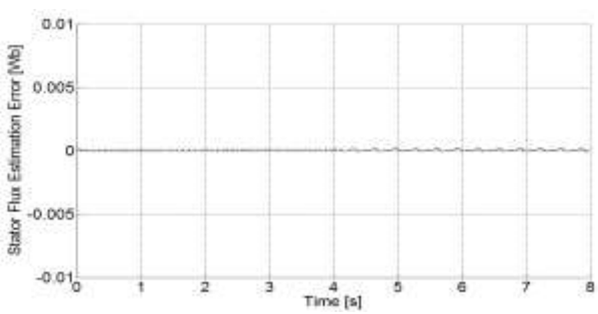
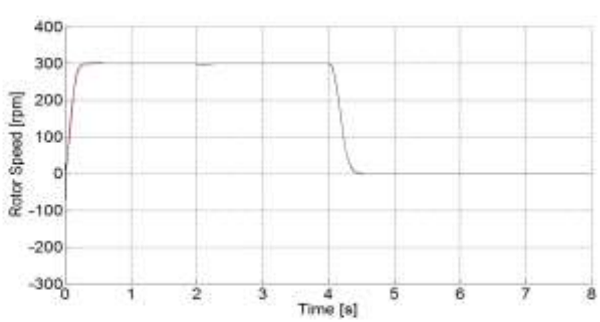
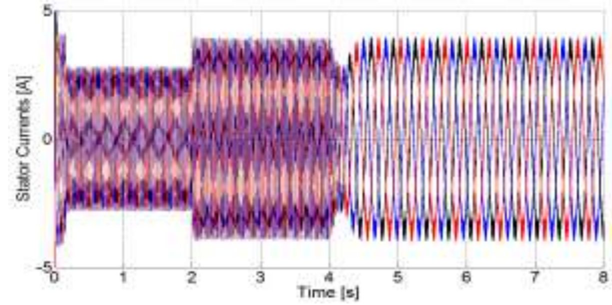


Fig. 3. Error of estimation under different operating modes.



(a)



(b)

Fig. 4. a) Estimated speed Vs reference value b) Three phase stator currents

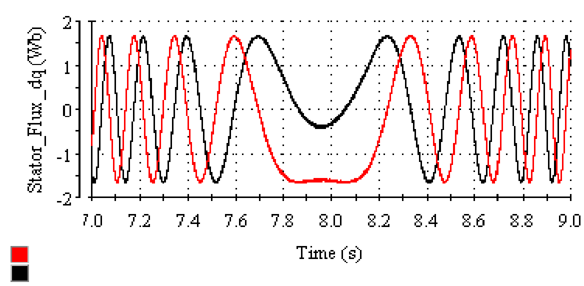
Since the speed error converges to zero, we can conclude the accurate rotor flux estimation, and therefore, the high performance of the proposed scheme. Fig. 4 shows the reference and the estimated rotor speed. In the same figure, the three phase stator currents are illustrated at various operating modes.

V. Experimental Results

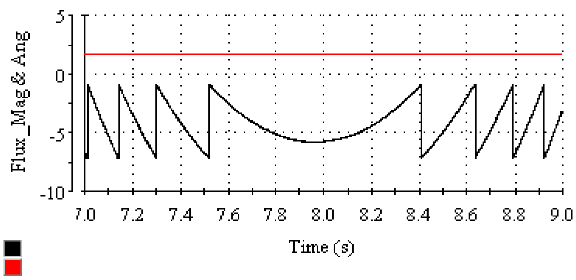
The feasibility of the proposed algorithm is also verified by experimental setup by using a DS1104 controller board. A 900W squirrel cage induction motor (specifications and data are given in Table 1) is employed to drive a mechanical load which consists of a MAGTROL motor test-bench. The whole system uses a SEMITOP three phases inverter manufactured by SEMIKRON. The switching frequency was set at 9kH, while the sampling frequency was fixed to 1kH. The software features are MATLAB/Simulink and control desk version 4.3.

In the experimental phase, both of high and very low speeds are considered. Firstly, in order to verify the feasibility of the proposed method, the motor was run without load. As illustrated in Fig. 5, the estimated stator flux components and both of stator flux magnitude and phase are presented.

Since the no availability of flux sensor, the error signal between reel and estimated flux cannot be evaluated, therefore, the merits of the proposed scheme cannot be directly known. One of the solutions is to use the rotor speed or position error signals, since (16) is heavily depends of the estimated flux.



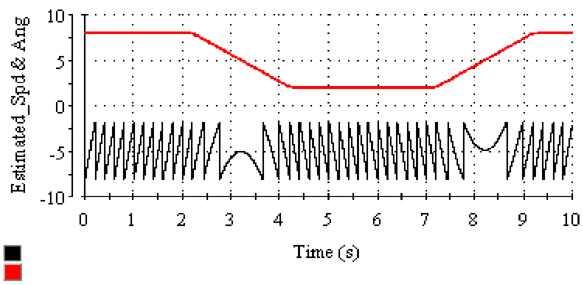
(a)



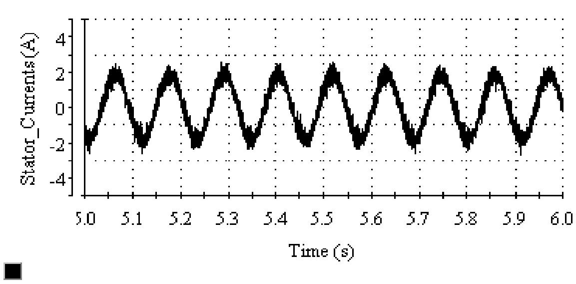
(b)

Fig. 5. Estimated stator flux
a) *d-q* flux components b) Flux magnitude and angle (offset=-4).

In the second step, the proposed estimation algorithm was susceptible to several tests to prove its merits not only when the motor run at no load and high speeds, but even at full load and low speeds, which represents in fact, a reel challenge to all speed-sensorless drives [7].



(a)



(b)

Fig. 6. a) Estimated rotor speed (offset = +5) and angle (offset=-5) at ±10% of its synchronous speed. b) One phase stator current.

Fig. 6 shows the estimated rotor speed at ±10% of its synchronous speed, in the same figure we can see the evolution of a one phase stator current.

VI. Conclusion

In this work, new sliding mode based estimator has been proposed to calculate the rotor position and the electromagnetic torque in speed sensor-less IM based drive. The direct torque control DTC technique has been opted in order to generate the switching signals. An accurate and inherently speed-sensor-less technique has been performed in two rotating reference frames. The stability of the proposed scheme has been verified by using Lyapunov theorem. The feasibility of the whole algorithm has been verified by simulation and experimental setup by using DS1104 controller board associated to a MAGTROL motor test-bench.

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

Aimad Ahriche carried out the simulation and the Experimental.

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