International Journal of Power Electronics and Drive System (IJPEDS)
Vol.1, No.1, September 2011, pp. 58~64
ISSN: 2088-8694

RNN Based Rotor Flux and Speed Estimation of Induction Motor

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Abstract

Speed control of induction motor can be obtained by closed loop system which require speed sensor. Speed sensor system is less effective for wide plant system, because the sensor location is too far from the main control system and measurement result is less accurate. This paper presents the development of speed sensorless field oriented control (FOC) of induction motor by using the rotor flux and speed observers. The observers only required the stator voltage and current of induction motor to obtain the rotor flux and speed estimation. The observers based on recurrent neural network (RNN) methods are implemented. Finally, the effectiveness of the proposed method is verified by simulation. Simulation results show that RNN observer can produce well the rotor flux and speed estimation. MSE values of the rotor flux estimation are between 0.000087 and 0.000264, whereas MSE values of the speed estimation are between 43.0552 and 156.0798.

Keywords*: field oriented control, induction motor, observer, and recurrent neural network.*

1. Introduction

Recently, induction motors are the most used electrical motor in industries since they are simply in construction, reliable, flexible, inexpensive, high efficiency and free maintenance [1]. However, the induction motors have disadvantage of difficulty in maintaining a constant speed when the load changes. Basically, the induction motor speed regulation is rather difficult, but after the field oriented control (FOC) or vector control method is found, this problem can be solved. FOC method of induction motor is widely recognized and becomes popular amongst the speed control technique. There are many methods proposed in this field [2,3]. FOC is a field regulation method of ac motor by changing coupled system to decoupled system. By this method, excitation and load current can be separately controlled; hence flux and torque also can be separately controlled as in dc motor. In industrial application, the induction motor is required to operate in various speeds. These variable speeds can be obtained by using closed loop system which requires speed sensor. However, the speed sensor has disadvantage in terms of less accurate measurement result if the sensor location is too far from the main control system for wide plant, therefore speed sensor system is less effective for this plant system [1,4-9].

Speed sensorless control methods of induction motor using speed estimation to replace speed sensor has been developed since 1980. With this method, the induction motor speed is estimated from instantaneous value of stator voltage and current. Recently, the other methods approach such as model reference adaptive system (MRAS), extended Kalman filter (EKF) algorithm, etc., are already applied to achieve the accurate and robust speed estimation performance [2-9]. However, an induction motor is a nonlinear dynamic plant type and its parameter depends on time and condition of operation. Therefore, it is very difficult to achieve good performance for overall scale speed and transient condition using previous methods.

To solve this constraint, the artificial intelligent techniques, such as fuzzy logic control, neural network (NN) are very promising for the identification and control of nonlinear dynamical systems. These methods are powerful to achieve a desired wide margin of nonlinear functions without requirement to acknowledge the internal system behavior. In case of artificial neural network, there have been several investigations of NN applications to power electronics and ac drives [4,6-9]. In this paper, observer using recurrent neural network (RNN) method is utilized to estimate the speed of induction motor according to the speed reference. Basically, the RNN method is similar to feed-forward neural network except the fact that they contain feedback loops around their neurons. The feedback loops also contain unit delay operators (z-1) [10]. By this approach, RNN can approximate dynamic input output mappings either linear or nonlinear.

2. Research Method

2.1. Induction Motor Model

Dynamic model of a three phase induction motor can be described by d-q coordinate system in state space equation form as [5]

Received Jun 29th, 2011; Revised Sept 3rd, 2011; Accepted Sep20th, 2011

$$\frac{d}{dt}\begin{bmatrix} \mathbf{i}_s \\ \lambda_r \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} \\ \mathbf{A}_{21} & \mathbf{A}_{22} \end{bmatrix}\begin{bmatrix} \mathbf{i}_s \\ \lambda_r \end{bmatrix} + \begin{bmatrix} \mathbf{B}_1 \\ 0 \end{bmatrix}\mathbf{v}_s \quad (1)$$

where,

$\mathbf{i}_s = \begin{bmatrix} \mathbf{i}_{sd} & \mathbf{i}_{sq} \end{bmatrix}^T$: stator current

$\lambda_r = \begin{bmatrix} \lambda_{rd} & \lambda_{rq} \end{bmatrix}^T$: rotor flux

$\mathbf{v}_s = \begin{bmatrix} v_{sd} & v_{sq} \end{bmatrix}^T$: stator voltage

$\sigma = 1 - \frac{M^2}{L_s . L_r}$: linkage coefficient

$\tau_r = \frac{L_r}{R_r}$: rotor time constant

$$\mathbf{A}_{11} = -\{R_s/(\sigma L_s) + (1-\sigma)/(\sigma\tau_r)\}\mathbf{I} = a_{r11}\,\mathbf{I}$$

$$\mathbf{A}_{12} = M/(\tau L_s L_r)\{(1/\tau_r)\mathbf{I} - \omega_r\,\mathbf{J}\} = a_{r12}\,\mathbf{I} + a_{i12}\,\mathbf{J}$$

$$\mathbf{A}_{21} = (M/\tau_r)\,\mathbf{I} = a_{r21}\,\mathbf{I}$$

$$\mathbf{A}_{22} = -(1/\tau_r)\mathbf{I} + \omega_r\,\mathbf{J} = a_{r22}\,\mathbf{I} + a_{i22}\,\mathbf{J}$$

$$\mathbf{B}_1 = 1/(\tau L_s)\mathbf{I} = b_1\,\mathbf{I}$$

$$\mathbf{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \;;\; \mathbf{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

Electromagnetic torque (*Te*) can be obtained by equation (2) as

$$Te = \frac{3}{2}\frac{p}{2}\frac{M}{L_r}\left(\lambda_{rd} i_{sq} - \lambda_{rq} i_{sd}\right) \quad (2)$$

Rotor speed as function load torque and electromagnetic torque can be expreesed as

$$\frac{j}{p}\frac{d\omega_r}{dt} + K_g\omega_r = T_e - T_L \quad (3)$$

where,
K_g = friction constant (kg.m^2/s)
J = inertia moment (kg.m^2)
ω_r = rotor speed (rad/s)

2.2. Field Oriented Control Strategy

Field Oriented Control (FOC) is a field regulation method of ac motor by changing coupled system to decoupled system. This system refer to induction motor model by separating between current i_{qs}* and current i_{ds}* through a coordinate transform. By this approach, flux and torque of induction motor can be separated and induction motor can be operated as in dc motor. Block diagram of induction motor by regulation of field and torque current is shown in Figure 1.

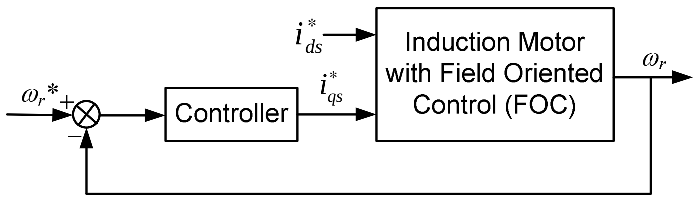


Figure 1. Speed Control of Induction Motor Drives

2.3. Recurrent Neural Network

Recurrent neural network (RNN) is similar to feed-forward neural network (FNN), however RNN consist of feedback loop around neuron. Feedback loop also consist of unit delay operator (z^{-1}) [9,10]. By this approach, RNN can approximate dynamic input output mappings either linear or nonlinear.

One of popular RNN structure was introduced by Elman and called Simple Recurrent Network (SRN). The architecture is shown in Figure 2.a. Input layer is called recurrent or context neuron and carry out activation of hidden layer from previous time step through unit delay operator. Other popular structures are modified Elman structure (Figure 2.b), Jordan structure (Figure 2.c) and Bengio structure (Figure 2.d) [10].

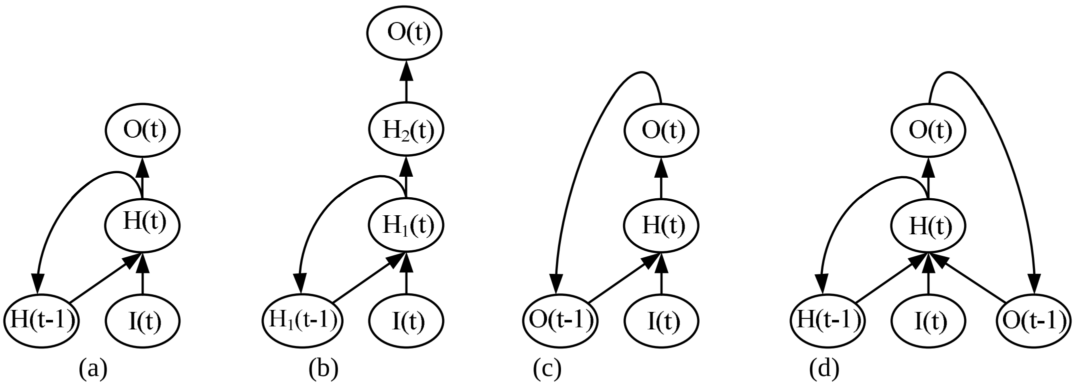


Figure 2. RNN Structures

Learning term of artificial *neural network* is regulation process of weights connection between nodes by particular method, so that obtained desired weights. Learning process must be performed to guarantee the output of neural network according to desired output (target). If connection weights are not able to produce desired output, weights will be regulated by particular method through continuous training. By this way, weights will have new composition and better. By this new weight composition, different between neural network output and desired output will be small. Hence, the output of neural network will be equal with desired output. After neural network is trained, the neural network is ready to be validated and used. Validating process is said success if neural network can receive input and obtain output according to output target.

Based on providing of input and output data, learning method of neural network has two types: supervised learning and unsupervised learning. One of popular supervised learning methods is back-propagation.

2.4. Modeling of RNN Observer

The block diagram of model system is shown in Figure 3. The observer is used to estimate the rotor flux and speed of induction motor. The observer inputs only require the stator voltage and current. The proposed method observer is recurrent neural network (RNN).

RNN observer is used to estimate the speed of induction motor contain of rotor flux observer and rotor speed observer. The observer is based on dynamic equation of induction motor for following the induction motor behavior. RNN observer is learned by using data from induction motor model such as stator voltage, current voltage and rotor speed. By this way, the observer can estimate the rotor flux and speed of induction motor. The learning process of the RNN observer is shown in Figure 4.

The configuration of the observers after completion of learning process to estimate the rotor speed of induction motor is provided in Figure 5. The rotor flux observer inputs are the stator voltage and current, whereas its output is rotor flux estimation. The speed observer input are stator current and rotor flux estimation from rotor flux observer, whereas its output is rotor speed estimation.

RNN observer is begun with composing of RNN architecture which is considered complexity such as the number of hidden layers and the number of neurons in hidden layers. In the learning process, the number of hidden layer will be added if the learning error is still larger than target error. The numbers of input and output data for training process are taken from induction motor model. The number of neurons in every hidden layer, learning rate, maximum error, and maximum epochs are respectively 10 neurons, 0.5, 0.001, and 1000 epoch. Learning algorithm uses back-propagation.

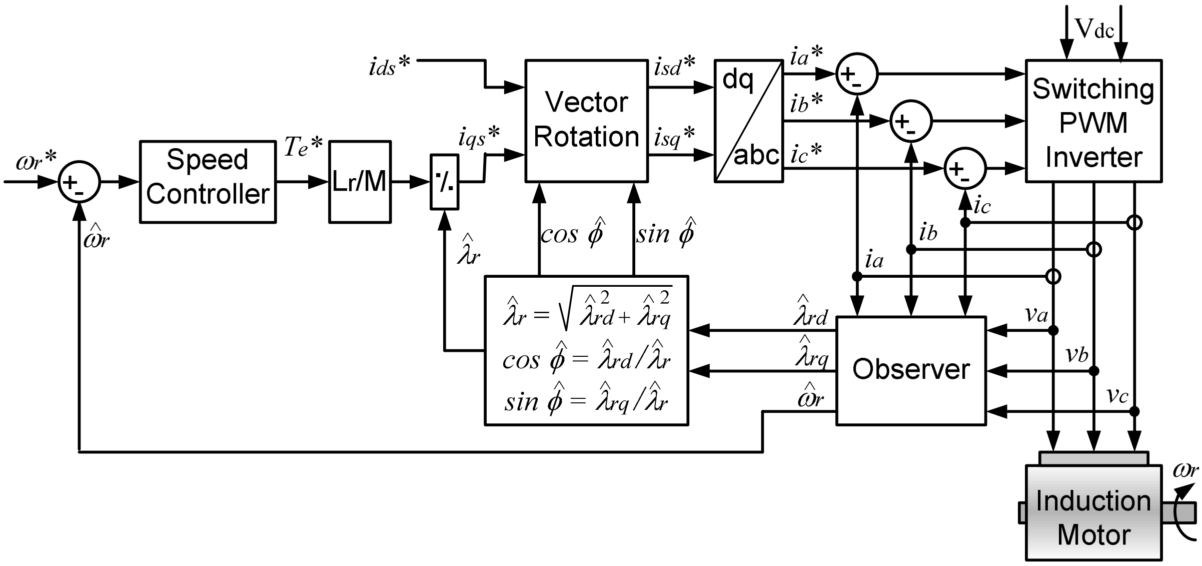
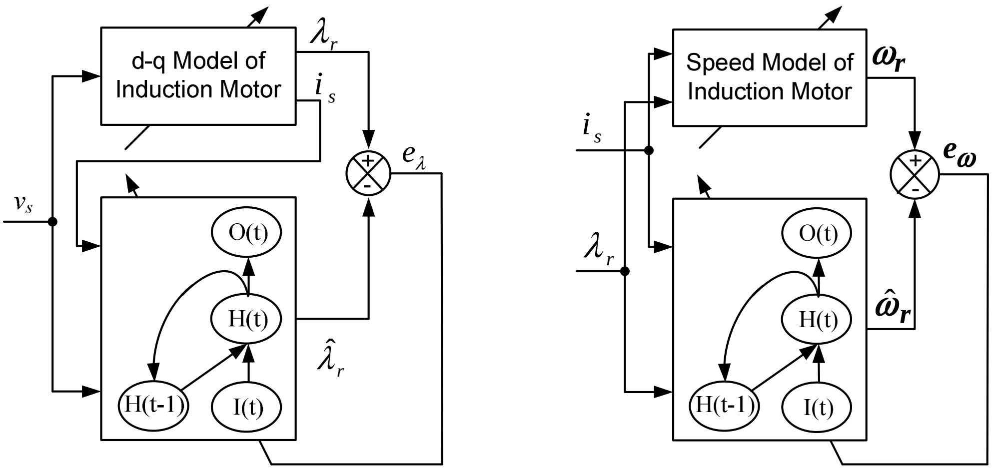


Figure 3. Block Diagram of Model System



a. Rotor Flux Observer b. Speed Observer

Fig. 4. Learning Process of RNN Observer

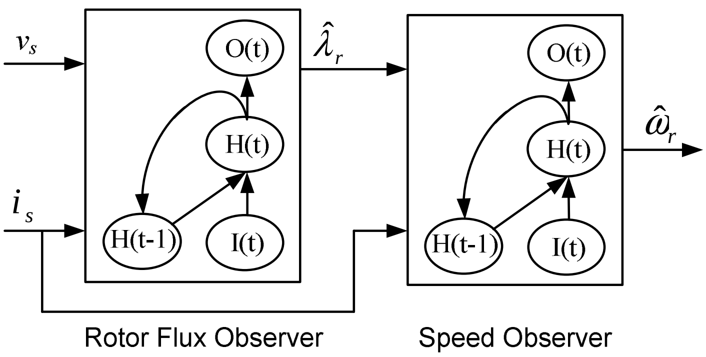


Figure 5. Diagram Block of RNN Observer

5. Results and Analysis

The efectiveness of proposed method is verifed by using simulation. Simulation is performed by comparing the results of the rotor flux and rotor speed from induction motor model with the rotor flux and speed estimation from RNN observer. Quality of estimation results are determined by mean square error (MSE). MSE can be calculated by equation (4).

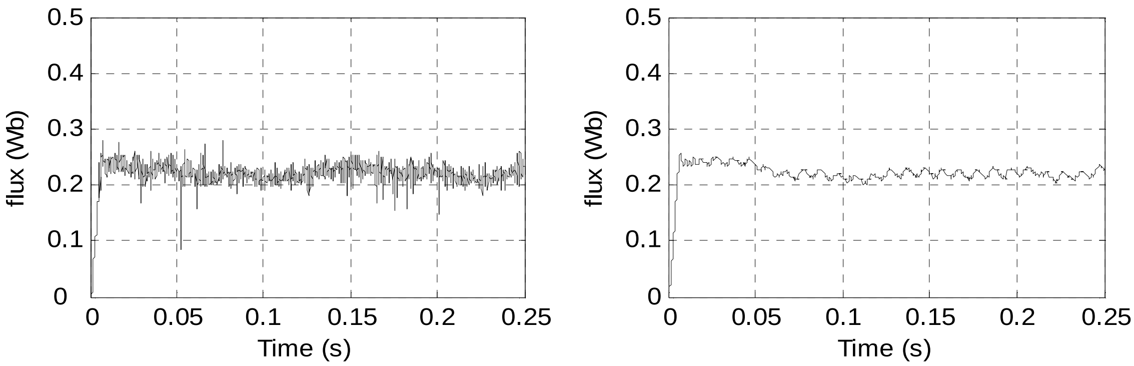
$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(y_i - y'_i\right)^2 \qquad (4)$$

where, n, y_i, and y'_i are respectively number of data, actual values and estimation values.
The induction motor parameters are as follows: rated voltage of 115V, 2 poles, 60Hz, stator resistance of 176Ω, rotor resistance of 190Ω, stator inductance of 3.79H, rotor inductance of 3.31H, mutual inductance of 3.21H, inertia moment of $10.5e^{-6}$ $Kg.m^2$, and friction coefficient of $1.9e^{-5}$ $Kg.m^2/s$.

The simulation results are sequentially presented in Figure 6-9. Figure 6 and 8 shows the rotor flux estimation from RNN observer and rotor flux actual from induction motor model for speeds of 250 rpm and 1250 rpm, respectively. In these results, RNN rotor flux observer can produce rotor flux estimation according to rotor flux from induction motor model. MSE value of the rotor flux estimation for speeds of 250 rpm and 1250 rpm are respectively 0.000141 and 0.000087.

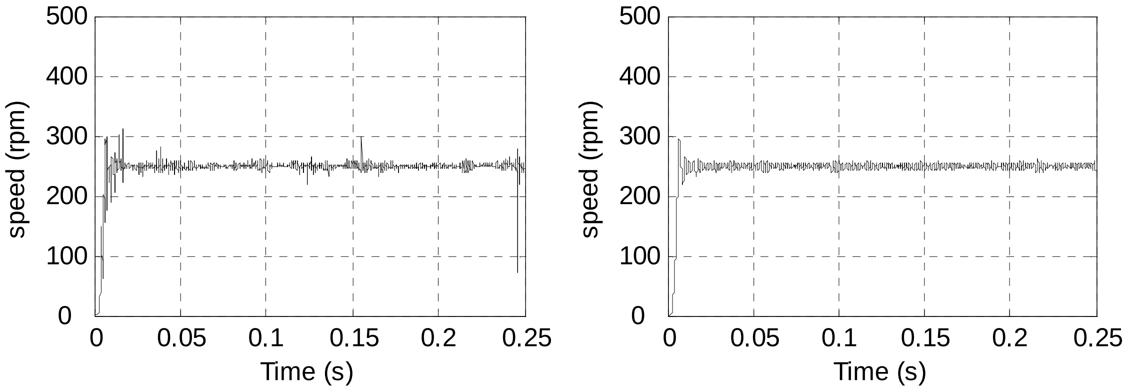
Figure 7 and 9 shows the speed estimation of induction motor from RNN speed observer and speed actual from induction motor model under speeds of 250 rpm and 1250 rpm, respectively. RNN speed observer can also produce the speed estimation of induction motor according to speed of induction motor model. MSE value of the speed estimation for speeds of 250 rpm and 1250 rpm are respectively 43.0552 and 156.0798.

Table 1 show calculation result of the MSE values for rotor flux and speed estimation from RNN observer under different speed conditions. MSE values of the rotor flux estimation are between 0.000087 and 0.000264 when speed of 1250 rpm and speed of 500 rpm. MSE values of the speed estimation are between 43.0552 and 156.0798 when speed of 250 rpm and speed of 1250 rpm.



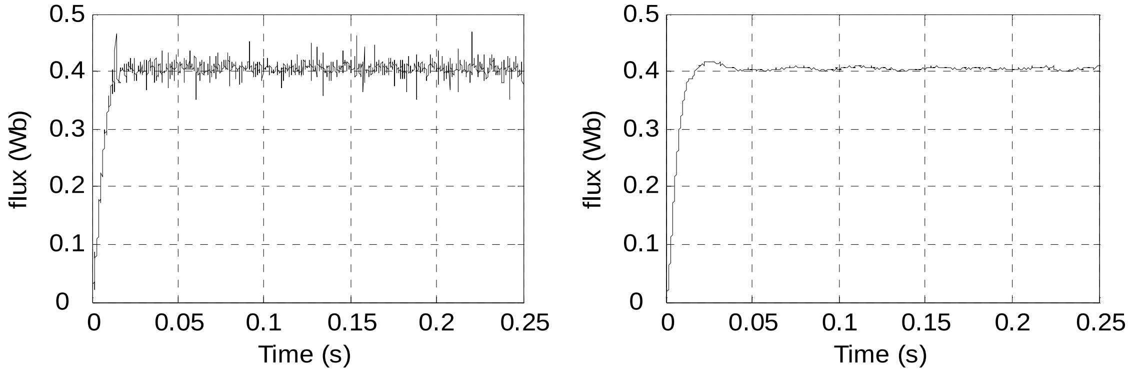
a. Estimation b. Model

Figure 6. Rotor Flux Estimation for Speed of 250 rpm



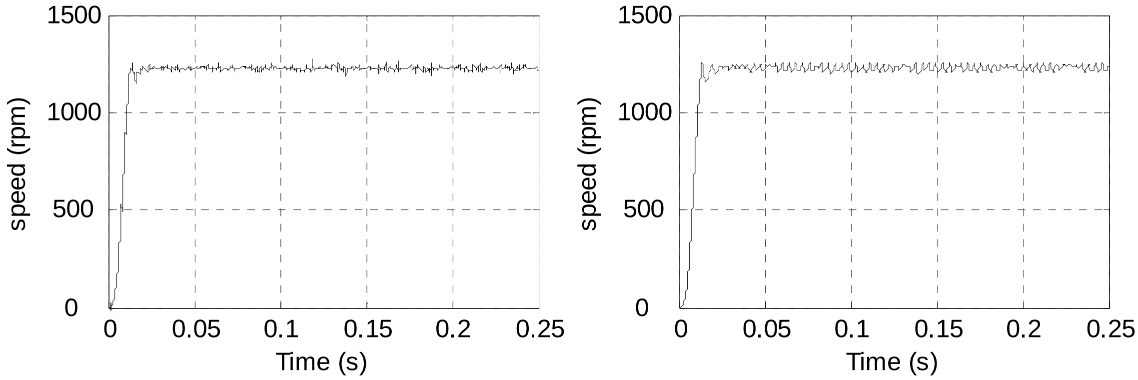
a. Estimation b. Model

Figure 7. Speed Estimation for Speed of 250 rpm



a. Estimation b. Model

Figure 8. Rotor Flux Estimation for Speed of 1250 rpm



a. Estimation b. Model

Figure 9. Speed Estimation for Speed of 1250 rpm

Table 1. Calculation Result of MSE values for RNN Observer

Speed (rpm)	Mean Square Error (MSE) Values	
	Rotor Flux Estimation	Speed Estimation
250	0.000141	43.0552
500	0.000264	52.1471
750	0.000174	126.4367
1000	0.000123	99.9148
1250	0.000087	156.0798

6. Conclusion

The development speed sensorless control field oriented control (FOC) method has been presented. The rotor flux observer and speed observer were described to estimate the rotor flux and speed of induction motor. The RNN observer requires only the stator voltages and currents of induction motor for the input signals. RNN observer is effectively used to estimate the rotor flux and speed of induction motor following the rotor flux and speed from induction motor model. Simulation results show that RNN observer can produce well the rotor flux and speed estimation. MSE values of the rotor flux estimation are between 0.000087 and 0.000264, whereas MSE values of the speed estimation are between 43.0552 and 156.0798.

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