Speed Control of Vector Controlled Induction motor by Sliding Mode Control with Exponential Reaching Law

Jisha L K, A A Powly Thomas, Suresh Srivastava

***Abstract:** In this research work the performance of closed loop speed control of Indirect Field Oriented controlled Induction motor using Sliding Mode Controller is described. The phenomenon of chattering of the control signal, which is the major disadvantage of Sliding Mode Control is overcome by applying Exponential Reaching Law. In the proposed method an exponential function is used as the sliding variable which dynamically adapts with the variations of the controlled system. The mathematical modeling of complete system is done and the simulated results are compared with conventional sliding mode controller and classical PID controller. The simulation results verify the superior performance and chattering reduction by employing Sliding Mode Controller with Exponential Reaching Law..*

***Index Terms:** Sliding Mode Control; Chattering; Exponential Reaching Law; PID controller.*

I. INTRODUCTION

In the last few decades the classical PID controllers were widely used for the control of induction motor drives [1] due to its simplicity and satisfactory performance. But the behavior of the PID controller is still influenced by the uncertainties which can happen due to unpredictable parameter variations, external load disturbances and nonlinear dynamics. Therefore many studies such as adaptive control, Variable Structure control, artificial intelligence using fuzzy logic and neural control etc [2, 3, 4] have been implemented to increase the robustness and precision of Induction motor in the presence of uncertainties. Nowadays, the variable structure control using sliding mode controller has gained more attention regarding the control of Induction motor drives [5]. The most important feature of sliding mode control (SMC) is its robustness. The only limitation of SMC is the phenomena called chattering. It is the high frequency oscillations of the controller output due to the high speed switching required for the implementation of the sliding mode. As it involves high control activity and increase in power consumption, in practical applications chattering is highly undesirable. Recently different methods have been suggested to suppress the effect of chattering such as boundary layer method, using higher order SMC, adaptive algorithms etc [6, 7].

In this research work a sliding mode control strategy with exponential reaching law is considered. The proposed method uses an exponential term in the expression for sliding surface *S*. The exponential function smoothly adapts with the variation of *S*. The validity of the developed system has demonstrated through simulation. The results obtained have confirmed the superior performance by using exponential reaching law in the aspects of fast and good dynamic response and less control effort.

II. MATHEMATICAL MODEL OF VECTOR CONTROLLED INDUCTION MOTOR

The state equations of vector controlled Induction motor is described below [1]. The state variables selected are i_{ds}, i_{qs}, ψ_{dr}, ψ_{qr}.

$$\frac{di_{ds}}{dt} = -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma\tau_r}\right) i_{ds} + \omega_e i_{qs} + \frac{L_m}{\sigma L_s L_r \tau_r}\,\psi_{dr} + \frac{L_m\omega_r}{\sigma L_s L_r}\psi_{qr} + \frac{1}{\sigma L_s} V_{ds}$$

$$\frac{di_{qs}}{dt} = -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma\tau_r}\right) i_{qs} - \omega_e i_{ds} + \frac{L_m}{\sigma L_s L_r \tau_r}\,\psi_{qr} + \frac{L_m\omega_r}{\sigma L_s L_r}\psi_{dr} + \frac{1}{\sigma L_s} V_{qs}$$

$$\frac{d\psi_{dr}}{dt} = \frac{L_m}{\tau_r} i_{ds} - \frac{1}{\tau_r}\psi_{dr} + (\omega_e - \omega_r)\psi_{qr}$$

$$\frac{d\psi_{qr}}{dt} = \frac{L_m}{\tau_r} i_{qs} - \frac{1}{\tau_r}\psi_{qr} - (\omega_e - \omega_r)\psi_{dr} \qquad (1)$$

$$T_e = \frac{3P}{4}\,\frac{L_m}{L_r}\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right)$$

Where i_{ds} , i_{qs} are direct and quadrature axis components of stator currents, ψ_{dr} , ψ_{qr} are direct and quadrature axis components of rotor flux. R_s and R_r are stator and rotor resistance respectively.

L_s, L_r and L_m are stator, rotor and mutual inductances.

$\sigma = 1 - \frac{L_m^2}{L_s L_r}$ is the leakage coefficient of flux.

$\tau_r = \frac{L_r}{R_r}$ is the rotor time constant.

In the field oriented control, for decoupling of torque and flux, i_{ds} should be oriented in the direction of flux ψ_r and i_{qs} should be orthogonal to it.

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This condition is met if ψ_{qr} = 0,

then, $\psi_{dr} = \psi_r$

Then the above equations are simplified to

$$\frac{d\psi_{dr}}{dt} = \frac{L_m}{\tau_r} i_{ds} - \frac{1}{\tau_r}\psi_{dr}$$

$$\mathbf{0} = \frac{L_m}{\tau_r} \boldsymbol{i_{qs}} - (\boldsymbol{\omega_e} - \boldsymbol{\omega_r})\boldsymbol{\psi_{dr}} \tag{2}$$

$$T_e = \frac{3P}{4}\frac{L_m}{L_r}\left(\psi_{dr} i_{qs}\right)$$

$$T_e = K_T i_{qs} \tag{3}$$

Where,

$$K_T = \frac{3P}{4}\frac{L_m}{L_r}\psi^*_{dr}$$

Where ψ^*_{dr} is the command rotor flux

From (2), $\omega_{sl} = \omega_e - \omega_r = \frac{L_m}{\tau_r}\frac{i_{qs}}{\psi_{dr}}$ (4)

$\omega_e = \omega_r + \omega_{sl}$ and $\theta_e = \int \omega_e dt$

III. SLIDING MODE CONTROLLER AND EXPONENTIAL REACHING LAW

The sliding mode control is a nonlinear control strategy. The synthesis of SMC entails two stages. The first stage is the selection of suitable sliding surface *S(t)* and second stage is the design of control input *u(t)*. The *S(t)* is chosen as ,

$$S(t) = \lambda e + \dot{e} \tag{5}$$

Where $e = \omega_m - \overset{*}{\omega}_m$, is the tracking error (6)

ω_m and $\overset{*}{\omega}_m$ are the mechanical speed of induction motor and its reference speed respectively, λ is a positive constant. When the trajectory approaches the sliding surface, tracking error *e* converges to zero.

The second stage is to design the control law which directs the system trajectories towards the sliding manifold. It is possible if the condition,

$$S(t).\dot{S}(t) < 0 \ , \square \ t \tag{7}$$

is met. The above condition is called reaching law. In order to satisfy the above condition, in conventional SMC, $\dot{S}(t)$ is typically chosen as,

$$\dot{S(t)} = -\varepsilon Sign(S), \ \square t, \ \varepsilon > 0 \tag{8}$$

The term $-\varepsilon$ will drive the system trajectory towards the sliding surface rapidly. Therefore higher value of ε will reduce the time of reaching mode. But higher value of ε induces more chattering.

For Exponential Reaching Law [8] the $\dot{S}$ is chosen as

$$\dot{S} = -\varepsilon Sign(S) - KS, \ \square t, \ \varepsilon > 0, K > 0 \tag{9}$$

The term $-KS$ contributes to the exponential function as the solution of $\dot{S} = -KS$ is an exponential term which is of the form S = S(0)e^{-Kt}.

The electro-magnetic torque (T_e) equation of the Induction motor is given by

$$T_e = J\,\dot{\omega}_m + B\omega_m + T_L \tag{10}$$

T_L is the external load applied to the Induction motor.

From (3) and (10),

$$J\,\dot{\omega}_m + B\omega_m + T_L = K_T i_{qs} \tag{11}$$

As per (2) i_{qs} is the control input *u(t)* which controls the rotor speed.

Differentiating (5),

$$\dot{S} = \lambda\dot{e} + \ddot{e} \tag{12}$$

Where $\dot{e} = \dot{\omega_m} - \dot{\omega}^*_m$, $\ddot{e} = \ddot{\omega_m} - \ddot{\omega}^*_m$ (13)

$\dot{\omega}^*_m$, $\ddot{\omega}^*_m$ are zero as the reference speed is considered as constant.

Using (9),(10),(12) and (13),

$$i_{qs} = \left(-\varepsilon Sign(S) - KS - \ddot{\omega_m} + \frac{\lambda B}{J}\omega_m + \frac{\lambda}{J}T_L\right)\frac{J}{\lambda K_T} \tag{14}$$

It is seen that the control signal $u = i_{qs}$ has two parts, equivalent control u_{eq} and discontinuous control u_{disc}.

$$u = u_{eq} + u_{disc}$$

$$u_{eq} = \left(-KS - \ddot{\omega_m} + \frac{\lambda B}{J}\omega_m + \frac{\lambda}{J}T_L\right)\frac{J}{\lambda K_T}$$

$$u_{disc} = -\varepsilon Sign(S)\frac{J}{\lambda K_T}$$

The discontinuous control which has signum function (sign (.)) induces chattering [9,10]

As time tends to infinity speed tracking error, $e = \omega_m - \overset{*}{\omega}_m$ tends to zero.

Proof:

Let the Lyapunov candidate function is

$$V(t) = \frac{1}{2}S(t)^2$$

Substituting (12)

$$\dot{V}(t) = S(t)\,[\,\lambda\dot{e} + \ddot{e}\,]$$

$$= S(t)\dot{S}(t)$$

Substituting (13)

$$\dot{V}(t) = S(t)\,[\lambda(\dot{\omega_m} - \dot{\omega}^*_m) + (\ddot{\omega}_m - \ddot{\omega}^*_m)]$$

Using equation (9)

$$\dot{V(t)} = S(t)[-\varepsilon Sign(S) - KS]$$

$$= S(t)\dot{S}(t)$$

As per equation (7) $\dot{V(t)} < 0$, which shows that function $\dot{V(t)}$ is negative definite, V(t) tends to infinity as S(t) tends to infinity. Therefore the equilibrium at the origin is globally asymptotically stable and S(t) tends to zero as time approaches infinity[11,12]

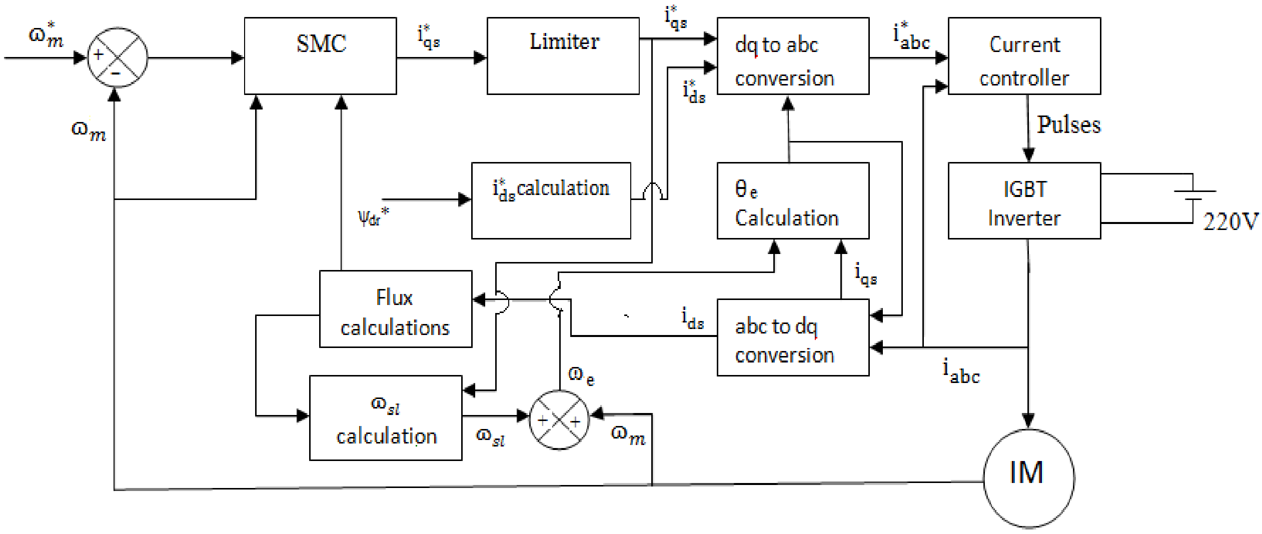

Figure 1. Block diagram representation of the system with SMC

Figure 1 shows the block diagram representation of the complete system described. As shown in fig.1, the power circuit consists of DC supply of 220V and IGBT two level inverter.The speed control loop generates the torque component of current i_{qs}^*. The flux component of current i_{ds}^* for the desired rotor flux ψ_{dr}^* is generated. The conversion of three phase stationary abc coordinates to two phase rotational dq system is done using Clarke's and Park's transformations. The current controller used is Hysteresis current control which takes the three phase reference and measured currents as input. Both the currents are compared and generate six PWM pulses, which is input to the IGBT inverter. The slip frequency ω_{sl} is generated from i_{qs}^* in the feedforward manner. Signal ω_{sl} is added with speed signal ω_m to generate the frequency signal ω_e. The signal θ_e is obtained by integrating ω_e.

IV. ILLUSTRATIVE CASE STUDY

The simulation of indirect field orient controlled induction motor is done using a 1HP (746W) three phase squirrel cage induction motor. The simulation is carried out with PID controller, conventional SMC and SMC with ERL. For simulation MATLAB (R2014a) /SIMULINK is used. The Induction motor parameters used for case study are 3A, 220V, 50Hz, 4Pole, $R_s = 6.37\Omega$, $R_r = 4.3\ \Omega$, $L_m = 0.24$H, $L_s = L_r = 0.26$H, $J = 0.0088$Kg/m^2. The PID controller is designed with Kp = 45, Ki = 0.1 and Kd = 0.5. For the design of conventional SMC, $\lambda = 100$ and $\varepsilon = 400$ are used. For SMC with ERL, $\lambda = 100$, $\varepsilon = 300$ and K =1500 are used. The reference speed of 120 rad/sec is selected.

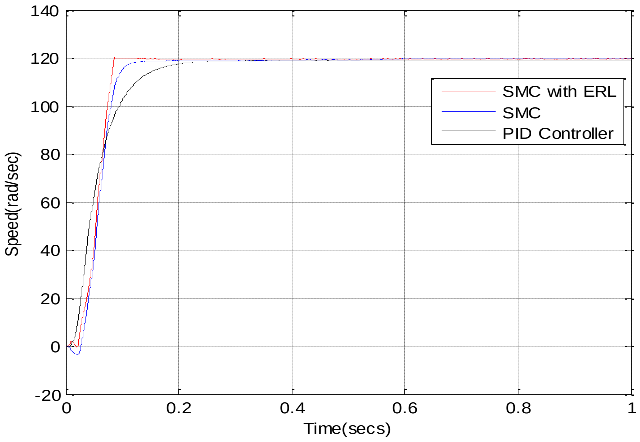

Figure 2. Speed - Time response of PID, SMC and SMC with ERL without applying external load.

Table 1
Performance comparison of different controllers

Controller description	Delay time in secs	Rise time in secs	Settling time in secs
SMC with ERL	0.02	0.08	0.08
SMC	0.05	0.09	0.09
PID	0.05	0.2	0.25

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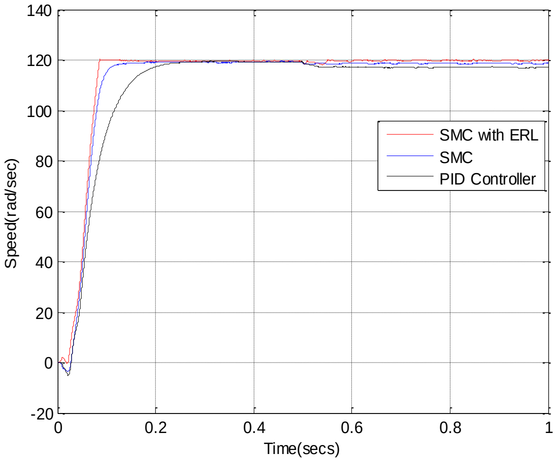

Figure 3. Speed - Time response of different ontrollers by applying external load of 6Nm after 0.5 secs.

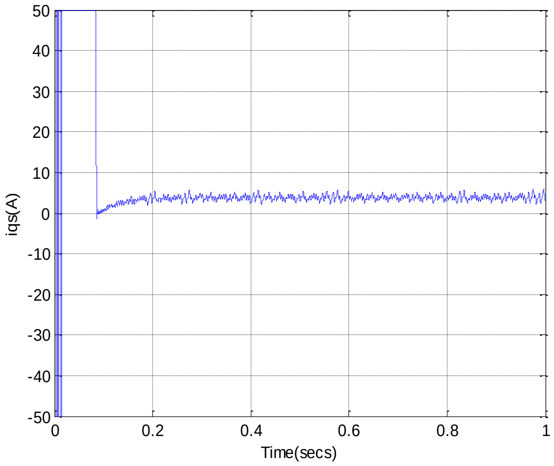

Figure 6. Control signal iqs of Sliding Mode Controller with ERL

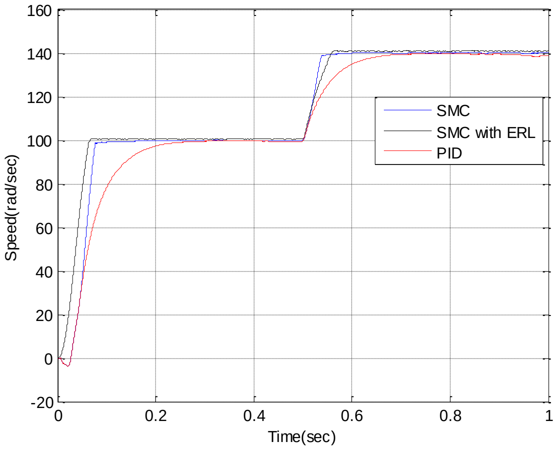

Figure 4. Speed - Time response of different controllers with Sudden change in speed at 0.5 secs.

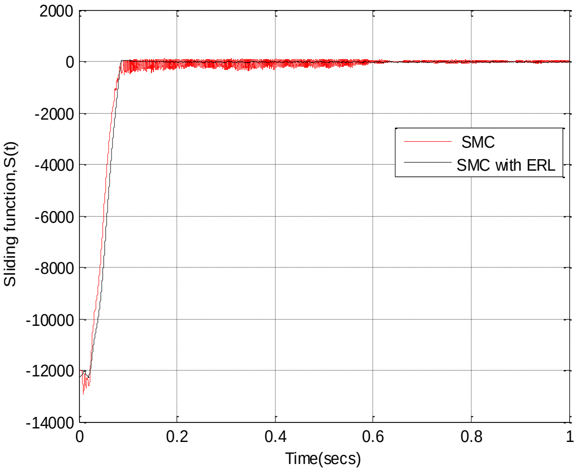

Figure 7. Sliding function of SMC and SMC with ERL

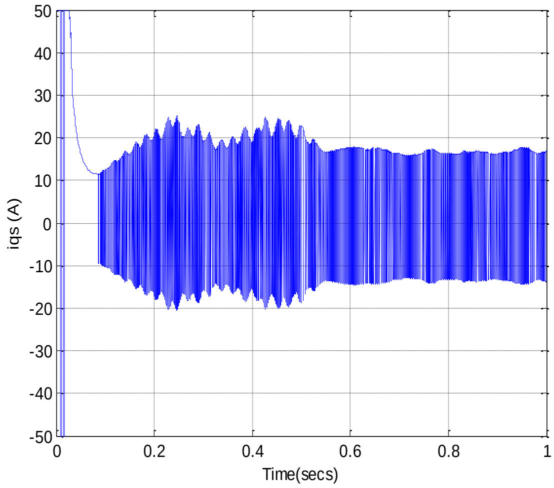

Figure 5. Control signal iqs with conventional Sliding Mode Controller.

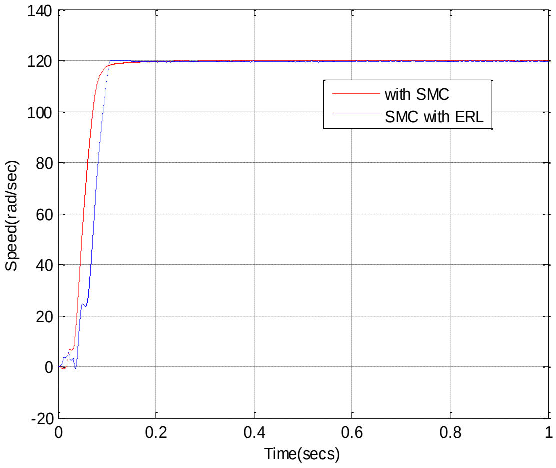

Figure 8 Speed – time response of SMC and SMC with ERL for 5% variation in rotor resistance

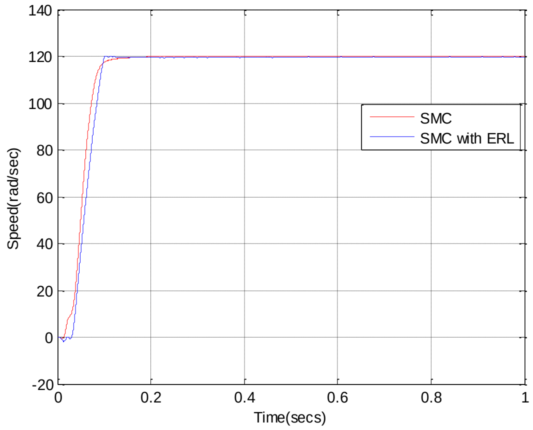

Figure 9 Speed – time response of SMC and SMC with ERL for 5% variation in rotor inductance

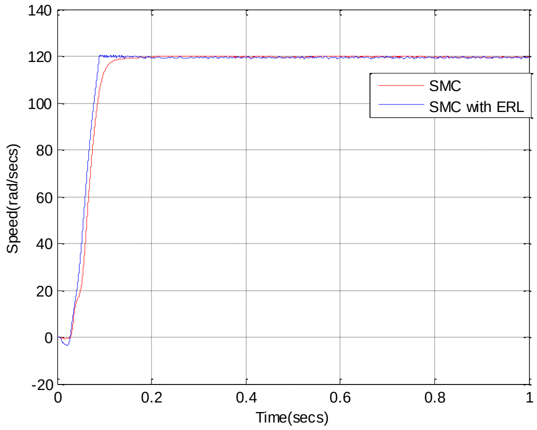

Figure 10 Speed – time response of SMC and SMC with ERL when continuously increasing load of 0 to 6Nm is applied from t=0 onwards.

Figure 2 shows the Speed - Time response of PID, SMC and SMC with ERL without applying external load. Table 1 shows the performance comparison of three controllers. It is seen that the rise time of PID controller is more compared to that of sliding mode controllers. Figure 3 shows the performance of different controllers in the presence of sudden external load of 6Nm applied after 0.5 secs. It is seen that SMC gives a robust control if there is sudden disturbance in the load. But for PID controller speed is suddenly reduced when sudden load is applied. In SMC with ERL approach apart from the robust control the transient behavior of the system is also improved. Figure 4 shows the Speed – Time response of PID, SMC and SMC with ERL when a step change in speed is applied after 0.5 secs. The reference speed is changed from 100rad/sec to 140rad/sec. The figure shows that the performance of SMC with ERL is superior than other controllers.

Figure 5 and 6 show the control input i_{qs} with conventional SMC and SMC with ERL respectively. The chattering of control signal is reduced when ERL is implemented compared to conventional SMC. Thereby it reduces the control effort and the power consumption of the system. Figure 7 shows the sliding function with SMC and SMC with ERL. It is observed that chattering is more in the sliding function of conventional SMC. The reaching time for SMC with ERL is slightly less than that of conventional SMC. Figure 8 shows the response of conventional SMC and SMC with ERL in the presence of parameter variations. The rotor resistance is varied by 5%.The figure shows that robustness is preserved in both the methods. Figure 9 shows the response of conventional SMC and SMC with ERL in the presence of parameter variations. The rotor inductance is varied by 5%.and it is seen that both the approaches are showing constant response. Figure 10 shows the performance of conventional SMC and SMC with ERL when a continuously increasing load is applied. The load varies from 0 to 6Nm with constant slope.

V. CONCLUSION

In this paper speed control for vector controlled induction motor is presented. The sliding mode controller with exponential reaching law is implemented for robust control. The mathematical model of indirect field orient controlled Induction motor with speed controller is described and numerical simulation is done. From the simulation results it is seen that performance of sliding mode control with exponential reaching law is superior to that of conventional PID controller and conventional sliding mode controller in the presence of uncertainties like parameter variations and load disturbances. The chattering phenomenon of sliding mode control is reduced by incorporating exponential reaching law.

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