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Actor-Critic Modulation Index Controller for Improved Power Factor of Slip Energy Recovery Drive

Anyin Paul¹, Akpama James², Ohiero Peter³

¹University of Cross River State (UNICROSS), anyinpnp@gmail.com ² University of Cross River State (UNICROSS), akpama_eko1@unicross.edu.ng ³ University of Cross River State (UNICROSS), <u>peterohiero@unicross.edu.ng</u>

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Abstract: Poor power factor has been projected as the most limiting factor of the slip controlled Wound Rotor Induction Motor also known as Slip Energy Recovery Drive (SERD). Despite it slip energy recovery capabilities. However, the limitation of poor power factor in the performance of SERD constitutes torque pulsation, misfiring, high investment cost and so on. Thus, making it inapt in applications that require improved power factor and optimum drive performance, resulting from significant reactive power and in-rush current harmonics drawn by the inverter on the dc-link. This paper presents an intelligent Modulation index-controlled system using policy improved proximal policy optimization algorithm and a space vector pulse width regulated boost chopper. This policy improved proximal policy optimization algorithm examines and adjust the drive speed and power factor through the feedback channel and manifest intelligent pulse width switching aptitudes on the boost chopper. This made use of Insulated Gate Bipolar Transistors (IGBT) as a boost chopper switch, and IGBT bridge inverter as the ac means recovery inverter. Switching aptness being a necessity in balancing the dc-link ripples, the actor-critic is hybridized with a callback in the algorithm training sessions, after every training timestep of 200 in a total time step of 1,000. This was simulated on Matlab SIMULINK, and compared with the Traditional SERD under fuzzy logic controlled schemes.

Keywords-dc-link, power factor, actor-critic, SERD, and slip power.

1. INTRODUCTION

Industrial revolution has birth a new research interest, especially in applications where power electronics are concentrated. Induction motor being the workforce of every motion industry is characterized with series of inventions in it control and drive application [1]. One rugged type of induction motor is wound rotor induction motor which is characterized with high starting torque, low inrush current, and high power lost, hence inapt in applications of high power demand, due to the slip power that is exhausted in the slip rings, which intensify during speed control [2]. The improved wound rotor induction motor scheme is the Slip Energy Recovery Drive (SERD), which is an energy conservative scheme that recoups the slip power that is produced in the slip rings of a wound rotor induction motor and feeds back to the ac mains supply through static converters and 3-phase optional step up transformer [1]. SERD is made up of the dc-link and wound rotor induction motor. The dc-link serving the purpose of the recovery channel and speed control, comprising; rectifiers, inverters and other basic dc-link components. This scheme however is confronted with poor power factor and complex control circuitries, resulting from high inrush current, poor reactive power control, and complicated speed control techniques. This

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is generally due to poor system dc-link formation [3]. Several researchers have suggested techniques of adjusting the drive speed and monitoring the corresponding performance, such as; an energy efficient variable speed high power factor three phase induction motor drive using PWM system, was designed. This technique was deployed to obtain independent control of speed and power factor of the three hase induction motor, using four semiconductor controllable switches. The technique although was complicated, but was realized using ac freewheeling switches. Result showed that, speed control and power factor of induction motor depend not only on the load parameters, but also on the complex engagement of the inverter in controlling the drive speed and modulating the inverter output. As such, resulting in more inrush current and increased stator copper losses. Increased stator copper losses of induction motor causes reduction in power factor and efficiency [4]. A simple SERD was introduced with an improvement in drive efficiency, using the inverter to control the drive

there was no evidence of the speed performance [8]. An energy efficient variable speed high power factor SERD using combined PWM and extinction angle control system, was designed, this involved a GTO-thyristor as a dc-link chopper, which functioned as a speed and inrush current controller. The power factor and the drive performance was improved [9].

However, recent innovations using dc-link configurations consist of a boost chopper inverter, which is often used for the drive speed control, especially in systems where the inverting converters are basically used for modulating and controlling the ac output of the dc-link [9]. Thus, following the trend of dc-link chopper control technique, an investigation of its modulation index behavior and effect on the precise drive overall performance prediction is very necessary. Thus, this system uses a simple SERD with a robust dc-link configuration, and an IGBT as a switch and the dc-link boost chopper fired with actor critic reinforcement learning algorithm. The IGBT is preferably used over the GTO-thyristor because of the advantage of it switching frequency [2]. This illustration is presented in Figure 1.



Fig. 1. Schematic block diagram of SERD

speed, but there was no distinctive effect on the inverter parameters on the drive speed performance [5] [6]. Similarly, the transformer ratio controlled slip power recovery scheme was introduced. The aim was to get better overall harmonics distortion with speed control of the rotor through changing the turn's ratio of the transformer. The power factor was not presented and control circuit was complicated [7]. Also, performance analysis of slip power recovery scheme was presented, employing two inverter topologies. Although there was an overall improvement in the drive performance, but

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II. METHOD

A. Induction Motor Dynamic Model

The dynamic model of the induction motor is displayed as follows [7] [8] [9];

From Figure 2, the stator and rotor voltage equations are given as:

$$V_{sa} = R_s i_{sa} + l_s p i_{sa} + M_s p i_{sb} + M_s p i_{sc} + M_{sr} p'(i_{ra} \cos \theta + i_{rb} \cos \theta_1 + i_{rc} \cos \theta_2)$$
(1)

$$V_{sb} = M_s p i_{as} + R_s i_{sb} + l_s p i_{sb} + M_s p i_{sc} + M_{sr} p'(i_{rc} \cos \theta_2 + i_{ra} \cos \theta + i_{rb} \cos \theta_1)$$
(2)

$$V_{sc} = M_s p i_{sa} + M_s p i_{sb} + R_s i_{sc} + l_s p i_{sc} + M_{sr} p'(i_{rb} \cos \theta_1 + i_{rc} \cos \theta_2 + i_{ra} \cos \theta)$$
(3)

$$V_{rr} = M_{rr} p'(i_{rr} \cos \theta + i_{rr} \cos \theta_{r} + i_{rr} \cos \theta_{r}) +$$

$$R_{r}i_{ra} + l_{r}p'i_{ra} + M_{r}p'i_{rb} + M_{r}p'i_{rc}$$
(4)

$$\begin{split} V_{rb} &= M_{sr} p' (i_{sc} \cos \theta_2 + i_{sa} \cos \theta + i_{sb} \cos \theta_1) + \\ M_r p' i_{ra} &+ R_r i_{rb} + l_r p' i_{rb} + M_r p' i_{rc} \end{split}$$

Thus the matrix equations are:

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \begin{bmatrix} R_s + l_s p^{,} & M_s p^{,} & M_s p^{,} \\ M_s p^{,} & R_s + l_s p^{,} & M_s p^{,} \\ M_s p^{,} & M_s p^{,} & R_s + l_s p^{,} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + p^{,} M_{sr} \begin{bmatrix} \cos \theta & \cos \theta_1 \\ \cos \theta_2 & \cos \theta & \cos \theta_1 \\ \cos \theta_1 & \cos \theta_2 & \cos \theta \end{bmatrix} \begin{bmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix}$$
(7)



Fig. 2. The three-phase diagram of induction motor in normal operation

$$\begin{bmatrix} V_{ra} \\ V_{rb} \\ V_{rc} \end{bmatrix} = pM_{sr} \begin{bmatrix} \cos\theta & \cos\theta_2 & \cos\theta_1 \\ \cos\theta_1 & \cos\theta & \cos\theta_2 \\ \cos\theta_2 & \cos\theta_1 & \cos\theta \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \begin{bmatrix} R_r + l_r p' & M_r p' & M_r p' \\ M_r p' & R_r + l_r p' & M_r p' \\ M_r p' & M_r p' & R_r + l_r p' \end{bmatrix} \begin{bmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix}$$
(8)

Where,

$$L_{\rm sr} = M_{\rm sr} \begin{bmatrix} \cos\theta & \cos\theta_1 & \cos\theta_2\\ \cos\theta_2 & \cos\theta & \cos\theta_1\\ \cos\theta_1 & \cos\theta_2 & \cos\theta \end{bmatrix}$$
(9)

Where, V_s is stator voltage and V_{sa} , V_{sb} , and V_{sc} are stator phase A, B, and C voltages respectively. Measured in Volts.

 V_r is rotor voltage and V_{ra} , V_{rb} , and V_{rc} are rotor phase A, B, and C voltages respectively. Measured in Volts.

 i_s is stator current and i_{sa} , i_{sb} , and i_{sc} are stator phase A, B, and C currents respectively. Measured in Ampere.

 i_r is rotor current and i_{ra} , i_{rb} , and i_{rc} are rotor phase A, B, and C currents respectively. Measured in Ampere.

 R_{s} and R_{r} are the stator and rotor resistances. Measured in Ohms.

 M_{sr} is the stator and rotor mutual inductance, while M_s and M_r are the stator and rotor inductances respectively. Measured in Henry.

 $L_{\rm s}$ and $L_{\rm r}~$ are the self-leakage inductances of stator and rotor, Measured in Henry

 $\psi_{qr}, \psi_{qs}, \psi_{dr}$ and ψ_{ds} are the quadrature and direct fluxes of the rotor and stator respectively

Equation (9) is the mutual coupling matrix L_{sr} , it is dependent on the rotor phase angle θ . However, equation (7) and (8) requires the inductance matrix to be computed and be inverted continuously. This model can be successfully simplified by applying packs transformation [5]. And this leads to equation (10).

$$\begin{bmatrix} V_{dr} \\ V_{dr} \\ V_{dr} \\ V_{dr} \\ \end{bmatrix} = \begin{bmatrix} \frac{W_{dr} r}{w_{s}} & -(\omega - \omega_{r})M_{sr} & \frac{I_{dr} p + M_{sr} p + R_{dr} \omega_{b}}{\omega_{b}} & \frac{-(\omega - \omega_{r})(I_{dr} + M_{sr}) & 0}{\omega_{b}} \\ -(\omega - \omega_{r})M_{sr} & \frac{M_{sr} p}{\omega_{s}} & -(\omega - \omega_{r})(I_{dr} + M_{sr}) & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{dr} \\ I_{dr}$$

Where:

$$V_{ds} = \frac{1}{\omega_s} (l_s p i_{ds} + M_{sr} p i_{ds} + M_{sr} p i_{dr}) - \omega (l_s i_{qs} + M_{sr} i_{qs} + M_{sr} i_{qs}) + R_s i_{ds}$$
(13)

(12)

$$V_{qs} = \frac{1}{\omega_s} \left(l_s p i_{qs} + M_{sr} p i_{qs} + M_{sr} p i_{qr} \right) - \omega \left(l_s i_{ds} + M_{sr} i_{ds} + M_{sr} i_{dr} \right) + R_s i_{qs}$$
(14)

$$V_{0s} = \frac{1}{\omega_{s}} (l_{s} p i_{0s} + M_{sr} p i_{0s}) + R_{s} i_{0s}$$
(15)

And;

$$V_{dr} = \frac{1}{\omega_s} (l_{dr} p i_{dr} + M_{sr} p i_{dr} + M_{sr} p i_{ds}) - (\omega - \omega_r) (l_{dr} i_{qr} + M_{sr} i_{qr} + M_{sr} i_{qs}) + R_{dr} i_{dr}$$
(16)

$$V_{qr} = \frac{1}{\omega_s} \left(l_{dr} p i_{qr} + M_{sr} p i_{qr} + M_{sr} p i_{qs} \right) - (\omega - \omega_r) \left(l_{dr} i_{dr} + M_{sr} i_{dr} + M_{sr} i_{ds} \right) + R_{dr} i_{qr}$$
(17)

$$V_{0r} = \frac{1}{\omega_s} (l_{dr} p i_{0r} + M_{sr} p i_{0r}) + R_{dr} i_{0r}$$
(18)

The flux equations is;

$$L_{ss} = l_s + M_{sr}$$
$$L_{drr} = l_{dr} + M_{sr}$$
And

$$\psi_{ds} = \mathcal{L}_{ss} \mathbf{i}_{ds} + \mathcal{M}_{sr} \mathbf{i}_{dr} \tag{19}$$

$$\psi_{qs} = \mathcal{L}_{ss}i_{qs} + \mathcal{M}_{sr}i_{qr} \tag{20}$$

$$\psi_{0s} = L_{ss} i_{0s} \tag{21}$$

$$\psi_{dr} = \mathcal{L}_{drr} \mathbf{i}_{dr} + \mathcal{M}_{sr} \mathbf{i}_{ds} \tag{22}$$

$$\psi_{qr} = L_{drr}i_{qr} + M_{sr}i_{qs} \tag{23}$$

$$\psi_{0r} = \mathcal{L}_{drr} \mathbf{i}_{0r} \tag{24}$$

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{os} \end{bmatrix} = \begin{matrix} \psi_{ds} \\ \psi_{qs} \end{matrix}$$

$$\begin{bmatrix} \frac{l_{sp} + M_{sr}p + R_s \omega_s}{\omega_s} & -\omega(l_s + M_{sr}) & \frac{M_{sr}p}{\omega_s} & -\omega M_{sr} & 0 \\ -\omega(l_s + M_{sr}) & \frac{l_{sp} + M_{sr}p + R_s \omega_s}{\omega_s} & -\omega M_{sr} & \frac{M_{sr}p}{\omega_s} & 0 \\ 0 & 0 & 0 & 0 & \frac{l_{sp} + M_{sr}p + R_s \omega_s}{\omega_s} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ i_{qo} \end{bmatrix}$$

$$And$$

(10)

Therefore, equation (13), (14), (15), (16), (17) and (18) becomes

$$V_{ds} = \frac{1}{\omega_s} p \psi_{ds} - \omega \psi_{qs} + R_s i_{ds}$$
(25)

$$V_{qs} = \frac{1}{\omega_s} p \psi_{qs} - \omega \psi_{ds} + R_s i_{qs}$$
(26)

$$V_{0s} = \frac{1}{\omega_s} p \psi_{0s} + R_s i_{0s}$$
(27)

$$V_{dr} = \frac{1}{\omega_s} p \psi_{dr} - (\omega - \omega_r) \psi_{qr} + R_{dr} i_{dr} \qquad (28)$$

$$V_{qr} = \frac{1}{\omega_s} p \psi_{qr} - (\omega - \omega_r) \varphi_{dr} + R_{dr} i_{qr}$$
(29)

$$V_{0r} = \frac{1}{\omega_s} p \psi_{0r} + R_{dr} i_{0r}$$
(30)

With the supply voltages V_{sa} , V_{sb} , and V_{sc} set as;

$$\begin{split} V_{sa} &= V_m \cos \omega_e t \\ V_{sb} &= V_m \cos \left(\omega_e t - \frac{2\pi}{3} \right) \\ V_{sc} &= V_m \cos \left(\omega_e t + \frac{2\pi}{3} \right) \\ \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} &= \sqrt{\frac{3}{2}} V_m \begin{bmatrix} \cos(\omega_e t - \theta_r) \\ \sin(\omega_e t - \theta_r) \end{bmatrix} \end{split}$$

Finally, the equation associated with the mechanical motion is given by

$$p\omega_{\rm r} = \frac{N\left(Te - TL - (\frac{2}{N})Bwr\right)}{2J}$$
(31)

Where the electromagnetic torque T_e is determined by equation (32) and TL representing the load torque.

$$T_{e} = \frac{3N}{4} (\psi_{ds} i_{qs} - \psi_{qs} i_{ds})$$
(32)

B. Modulation Index Control of Induction Motor

For safe commutation of these drives, Pulse Width Modulations (PWM) are used in drive control system. This is the process of modifying the width of the pulses in a pulse train in direct proportion to a small control signal [10]. The greater the control voltage the wider the corresponding pulses generated [6]. This process of modifying the pulse width requires a modifying ratio which determines the period of the generated pulses. This modifying ratio is referred as modulation index [6]. Modulation index plays a vital role in the conducting cycle of converters. As a simple variation in modulation index results in an obvious change in the system performance. Hence, in this scheme, the modulation index of the boost chopper will be varied continuously from zero to one. An IGBT switch is connected in the dc-link of SERD between the rectifier and the inverter,

which recoups the slip power back to the ac source through the fixed-frequency inverter [7]. Therefore, the input and output of the IGBT boost chopper becomes [9];

$$V_{LL} = m \times \frac{Vdc}{2} \times \frac{\sqrt{3}}{\sqrt{2}}$$

$$m = \frac{(2\sqrt{2})V_{LL}}{(\sqrt{3})V_{dc}}$$
(33)

C. Actor Critic Reinforcement Learning

Actor-Critic Reinforcement Learning (ACRL) is a popular technique in the field of reinforcement learning that combines both actor and critic networks to learn optimal policies in complex environments [10-13]. In this context, it is applied to select the best modulation index for a slip energy recovery scheme (SERS). The SERS is a technique used to recover energy from wheel-rail sliding during braking or deceleration [2-4]. The modulation index is a parameter that determines the level of modulation applied to the traction current during braking, which affects the amount of energy that can be recovered. The goal of this ACRL algorithm is to learn the optimal modulation index that maximizes the energy recovery and improve power factor while minimizing the impact on the overall system performance [14-20].

Problem formulation

The slip energy recovery scheme involves converting excess mechanical energy in an induction motor into electrical energy. The modulation index determines the efficiency of this process. The goal is to find the optimal modulation index that maximizes energy recovery [7-8].

State Space (S)

Define the state space, which includes the relevant features describing the system. This might include the motor's operating conditions, load, and electrical parameters [20-24].

$$S = \{s_1, s_2, \dots, s_n\}$$
 (35)

Action Space (A)

Define the action space, representing the possible modulation index values [21].

$$A = \{a_1, a_2, \dots, a_m\}$$
(36)

Policy Function (π)

The policy function determines the probability distribution of selecting each action given the current state [15].

$$\pi(a|s,\theta^{\pi}) \tag{37}$$

Here, $\theta\pi$ represents the policy parameters.

Value Function (V)

The value function estimates the expected cumulative reward of being in a certain state.

$$V(s,\theta^{V}) \tag{38}$$

Here, θ^{v} represents the value function parameters.

Advantage Function (A)

The advantage function measures how good or bad an action is compared to the average action in a given state.

$$A(s,a,\theta^{\pi},\theta^{V}) \tag{39}$$

Objective Function

Define the objective function that the RL algorithm aims to maximize.`

$$J(\theta^{\pi}, \theta^{V}) = E_{\pi}[\sum_{t=0}^{\infty} \gamma^{t} R_{t}]$$

$$\tag{40}$$

Where R_t is the reward at time t and γ is the discount factor.

Actor and Critic Updates

Update the actor and critic parameters using policy gradient methods for the actor and temporal difference (TD) learning for the critic.

$$\theta^{\pi} \leftarrow \theta^{\pi} + \alpha_{\pi} \nabla \theta^{\pi} J(\theta^{\pi}, \theta^{V})$$
(41)

$$\theta^{\mathrm{V}} \leftarrow \theta^{\mathrm{V}} + \alpha_{\mathrm{V}} \nabla \theta^{\mathrm{V}} J(\theta^{\pi}, \theta^{\mathrm{V}}) \tag{42}$$

Where α_{π} and α_{V} are the learning rates for the actor and critic, respectively.

Exploration-Exploitation

Implement a strategy for balancing exploration and exploitation during action selection. This could involve using an epsilon-greedy strategy.

Training

Train the Actor-Critic model by interacting with the slip energy recovery system, observing states, taking actions, and receiving rewards.

Testing

Evaluate the trained model on unseen scenarios to ensure generalization.

Selection of Best Modulation Index

Choose the modulation index associated with the action that maximizes the expected cumulative reward.



Table 1. Motor Specification

	Rated power	4 HP
	Rated stator	460 V
	voltage	
	Rated frequency	50 Hz
	Rated slip	0.046
	Rated speed	1500 rpm
	Maximum	19.006 N-m
	torque	
	Number of pole	2
	pairs	
	Stator	Wye/Wye
	connection	
	Stator resistance	0.435 Ω/phase
Fig. 3.	Rs	
	Stator	0.004 H/phase
	inductance L _s	
	Rotor resistance	0.816 Ω/phase
	R _r	
	Rotor	0.027 H/phase
	inductance L _r	
	Mutual	0.06931 H/phase
	inductance M _{sr}	
	Rotor mass	0.089 Kgm²
	moment of	
	inertia J	
	dc-link	0.2 mH
	inductance	
	Transformer	1:2
	turn ratio	

Simulation model of SERD in SIMULINKS

III. RESULTS AND DISCUSSION

This simulation is conducted in Matlab/SIMULINK environment using actor-critic reinforcement learning algorithm. The complete SIMULINK simulation diagram is presented in Figure 3. The modulation index values used are set within the range of 0 to 1.2.





Fig. 5. Plot of Modulation Index versus Speed

Fig. 4. Episode Reward for Actor Critic Model

MODULATION INDEX	SPEED (rpm)
	(1)
0.1	800
0.2	960
0.3	1100
0.4	1240
0.5	1330
0.6	1380
0.7	1400
0.8	1470
0.9	1488
1	1502
1.1	1503
1.2	1509

Table 2: Table of Modulation index versus speed



Fig. 6. Speed Response at Different Modulation Indexes



IV. DISCUSSION/CONCLUSION

From Figure 4, the actor critic algorithm was trained and the reward per episodes were presented. The agent progressed from -5,000 to -1,000 within 42 episodes. The optimal modulation index with the unity (1) power factor was presented to be 0.8823 (Approximately = 0.88). Hence this system was validated using different modulations index within 0.1 to 1.2 as seen in Table 2, the drive speed was seen to be highest at a modulation index of one and lowest at a modulation index of 0.1. Which validate the optimality of reinforcement learning algorithm for availing optimal gain [10-24]. And this is demonstrated in the modulation index versus speed plot in Figure 5. Thus, at a modulation index of one, the speed is 1502rpm, and at a modulation index of 0.1, the speed is 800rpm. This gives a speed control range of 800rpm to 1502rpm. Moreover, an excessive increase in modulation index yields a decrease in power factor but avails a supper synchronous speed and this aids the adjustment of the motor speed under large load torques. Hence the trade-off exist between the super synchronous speed and the unity power factor. This conforms to the literature of [6]. A clearer view of this is shown on the speed response at different modulation indexes in Figure 7, where different speed levels are displayed at different modulation indexes, thus this proves the phenomenon of modulation index control, for any increase in modulation index results in a corresponding increase in drive speed [9]. Also, in Figure 6, the phase ac voltage and current waveforms of modulation index of 0.8 attained unity power factor earlier than other modulation indexes, with the modulation index of one being the least. Thus validating the literature of [11-14]. And this presents the drive overall performance at different modulation indexes. This can be applicable in a dc-link formation of any scheme with an intelligent selection approach, where a modulation index of 0.8 can be initialized through the transient state and one at the steady state. Similarly, this can be applicable in balancing the drive speed at large load torques, where a modulation index of one is applied to expedite the drive from the transient state to steady state.

A. Conclusion

This work demonstrates the effectiveness of the actorcritic reinforcement learning algorithm for selecting the optimal modulation index for the slip energy recovery scheme (SERS) in electric traction systems. Through training and evaluation, the algorithm was able to converge to an optimal modulation index of 0.8823, which maximizes energy recovery while minimizing the impact on overall system performance. The results also showed that the drive speed is highest at a modulation index of 0.1, validating the optimality of the reinforcement learning algorithm. The trade-off between super synchronous speed and unity power factor was also demonstrated, with excessive increases in modulation index resulting in a decrease in power factor but availing a supper synchronous speed. The presented results have practical applications in dc-link formation and balancing drive speed at large load torques, making this approach a promising solution for improving the overall performance of electric traction systems.

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