VOL. 10, NO. 5, MARCH 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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# PERFORMANCE OF FOUR PHASE SWITCHED RELUCTANCE MOTOR DRIVE USING SINGLE PULSE WIDTH MODULATION TECHNIQUE UNDER CONSTANT TURN OFF ANGLE AND RANDOM TURN OFF ANGLE

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**ABSTRACT**

This paper describes a comparative analysis of electronics switching control schemes to minimize the torque ripples and speed oscillation for 8/6 Sensorless Switched Reluctance Motor (SSRM) drive and development of Fuzzy supervisory control scheme to control the speed of the drive. The Fuzzy logic was used to adjust the classical PI controller parameter in on-line. The electronic control schemes include single pulse width modulation at both level switches and random turn-off angle generation. The switching methods and speed controller have been developed and tested using Matlab/Simulink. To demonstrate the effectiveness, the switching methods have been implemented in PI based speed control system drive and its performance was evaluated. The performance of PI-Fuzzy speed controller was compared with conventional PI controller.

**Keywords:** SRM drive, PI controller, pulse width modulation, random turn-off angle, fuzzy controller.

## 1. INTRODUCTION

SRM drives becomes the commercial adjustable speed motor drives due to simple construction, low weight, potentially low production cost, excellent torque speed characteristics, high operating efficiency. Is an emerging drives for Electric vehicle applications, aerospace and home appliances. From the past three decades, many researchers [1-2] taken steps to design the robust SRM drives in sensorless scheme. Some Studies relative to Electric Vehicle applications have been reported. Fahimi *et al*. [3].To reduce the speed error and settling time under operating condition by Paramasivam *et al* [4] with the help of discrete PI,PID and microcontroller. The minimal NN trained with no hidden layer and preprocessor with single output is realized with inexpensive DSP microcontroller in Hudson *et al* [5].Inderka *et al*. [6] demands on control accuracy of SRM traction drives and the traction controller sampling frequency which are necessary to take the advantage of the dynamic capabilities. An approach of sensorless rotor position estimation using ANN and ANFIS for a 6/4 pole SRM by Paramasivam *et al* [7]. Bahadly [8] examines the theoretical stability of the measurement and shows the measurement errors are not compounded and act as a variable disturbance to the system. The rotor position estimator presented by Echenique *et al* [9] can be applied to a wind energy conversion system where the SRG is used as a variable speed generator. Xue *et al* [10] proposed Torque Sharing Function dependent on the turn on angle, overlap angle and the expected torque provides a valuable method to improve the performance of SRM drives operating under Torque Ripple Minimization control. The development and control of a DSP based SRM drive with its dc link voltage being established by a three- phase single- switch switch-mode rectifier in Chai *et al*. [11] a random based hysteresis current controlled pulse width modulation (CCPWM) scheme .Bateman *et al*. [12] looks at a 100,000 r/min, 1600 ultra high speed SRM drive using the current gradient sensorless (CGS) scheme and analyses parameters that affect the stability of the sytem. Fahimi *et al* [13] for four quadrant operation of the SRM drives to industrial and domestic applications has raised in a sensorless format. Jyoti Koujalagi, B. Umamaheswari [14-16] explores the behavior of SRM in flux weakening mode. The aim of this study is to find an optimal control method to implement the best motoring operation of SRM drives in electric vehicle applications and investigates the dynamic behavior of Switched Reluctance generator under the influence of advance switching angle to gain control over the output voltage. The control objectives were selected to maximize average torque, to maximize torque per rms current, to maximize efficiency, to minimize loss.

## 2. BASIC STRUCTURE OF SWITCHED RELUCTANCE MACHINE

### a) Evolution of switched reluctance motor drives

The name switched reluctance has now become the popular term for this class of electric machine. The first reference to the term switched-reluctance was made by Nasar in a paper in the IEE Proceedings in 1969. The term became popular from the 1980s onwards, through the efforts of the first commercial exploiters of the technology, Switched Reluctance Drives Ltd. The machines are alternatively known as variable reluctance motors, reflecting the origins of the technology being derived from VR stepper motors. Even so the first recognizable reluctance machines were built over 150 years ago, most famously by Davidson as a traction drive for an electric locomotive in 1838.

VOL. 10, NO. 5, MARCH 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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**b) Principle of switched reluctance (SR) machine**

A Switched Reluctance Machine is a rotating electric machine where both stator and rotor have salient poles. The stator winding is comprised of a set of coils, each of which is wound on one pole. The rotor is created from lamination in order to minimize the eddy-current losses. SR machine differ in the number of phases wound on the stator. Each of them has a certain number of suitable combinations of stator and rotor poles. The Figure-1 illustrates a typical 3-Phase SR machine with a six stator / four rotor pole configuration.

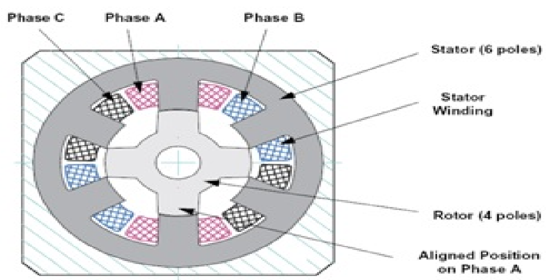


**Figure-1.** A Typical 3-Phase SR machine.

The motor is excited by a sequence of current pulses applied at each phase. The individual phases are consequently excited, forcing the motor to rotate. The current pulses must be applied to the respective phase at the exact rotor position relative to the excited phase. When any pair of rotor poles is exactly in line with the stator poles of the selected phase, the phase is said to be in an aligned position; i.e., the rotor is in the position of maximum stator inductance (see Figure-1). If the interpolar axis of the rotor is in line with the stator poles of the selected phase, the phase is said to be in an unaligned position; i.e., the rotor is in a position of minimal stator inductance. The inductance profile of SR motors is triangular, with maximum inductance when it is in an aligned position and minimum inductance when unaligned.

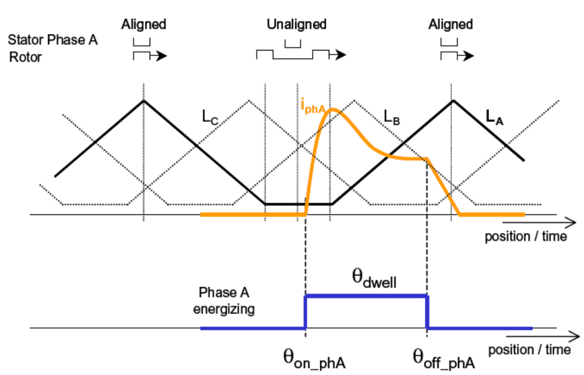


**Figure-2.** Phase Energising.

Figure-2 illustrate the idealized triangular inductance profile of all three phases of an SR motor, with Phase A highlighted. The individual phases A, B and C are shifted electrically by 120° relative to each other. When the respective phase is powered with the interval is called the dwell angle, ($\theta_{dwell}$). It is defined by the turn-on ($\theta_{on}$) and the turn-off ($\theta_{off}$) angle.

## 3. SRM MODELING

A Switched Reluctance Motors does not contain any permanent magnets. The stator is similar to a brushless dc motor. However, the rotor consists only of iron laminates. The iron rotor is attracted to the energized stator pole. The polarity of the stator pole does not matter. Torque is produced as a result of the attraction between the electromagnet and the iron rotor. Figure-3 shows the cross section of typical 4 phase (8/6) SRM.

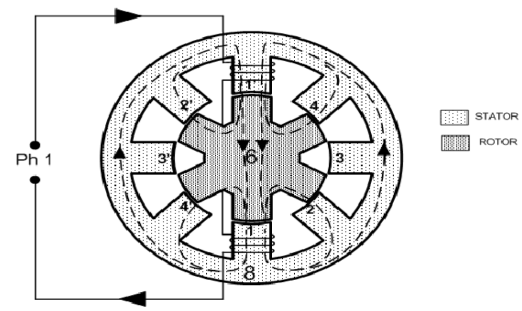


**Figure-3.** Cross-sectional view of 4 Phase SRM.

The mathematical model of SR motor can be modelled as follows:

$$v_k = R_k i_k + \frac{d\psi_k(\theta_r, i_k)}{dt} \qquad k = 1,2,3,4 \qquad (1)$$

Where $v_k$ is the stator phase voltage, $R_k$ is the stator phase resistance; $i_k$ is the stator current, $\psi_k$ is the stator phase flux linkage and $\theta_r$ is the rotor positon.

The stator flux linkage can be expressed without mutual phase to phase inductance as

$$\psi_k(\theta_r, i_k) = L_{kk}(\theta_r, i_k) \times i_k \qquad k = 1,2,3,4 \qquad (2)$$

Where $L_{kk}(\theta_r, i_k)$ is the per phase self-inductance.

The electromagnetic torque can be represented as

$$T_e = \frac{1}{2}\frac{dL_k}{d\theta} i_k^{\ 2} \qquad (3)$$

The mechanical equation of the SRM is

$$T_e = J_m \omega_r + B_m \omega_r + T_L \qquad (4)$$

Where $J_m$ the moment of inertia is, $B_m$ is the viscous frictional coefficient, $\omega_r$ is the rotor speed and $T_L$ is the load torque.

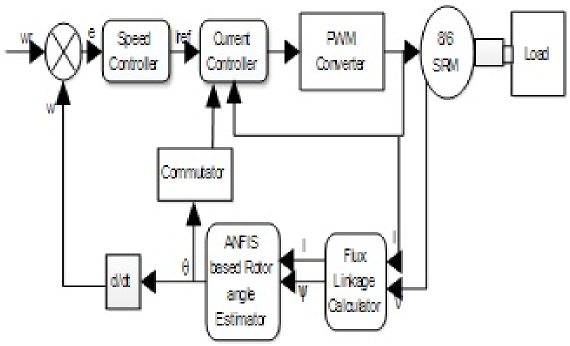


**Figure-4.** Control configuration of an SRM drive.

Figure-4 shows the control system of an SRM drive. The control system consists of SRM with eddy current load, a current regulator device, a commutator, a speed controller, flux linkage calculator, ANFIS based rotor angle estimator, and voltage and current sensors. The current reference is processed by the current controller based on the duty cycle signals to be given to PWM convertors. The flux linkage is calculated using mathematical equations and the rotor angle is estimated by ANFIS based on input current and calculated flux linkage values. Commutator process and generates the switching angle based on the estimated rotor position. The speed error is processed by speed controller to generate the reference current signals to current controller.

## 4. ELECTRONIC SWITCHING CONTROL

The Switching control algorithm or methods is playing very important role in the control of electrical drives system. In particularly the switching control methods can reduce the torque ripples, noise and vibration of the switched reluctance motor drive [15]. In SRM, there are three key tunable parameters exists, namely the turn-on angle, turn-off angle and the current shape in the convertor control methods. In this work, the electronic control schemes include single pulse modulation (hysteresis) and random turn-off angle generation methods are implemented in 4 phase SSRM drive.

### a) Randomized turn-off angle

The randomized turn-on and turn-off angles to reduce the torque ripples, noise and speed oscillations have been reported in [15]. Though the turn off angle is the important variable relating to the operation of the drive, only the randomized values are considered.

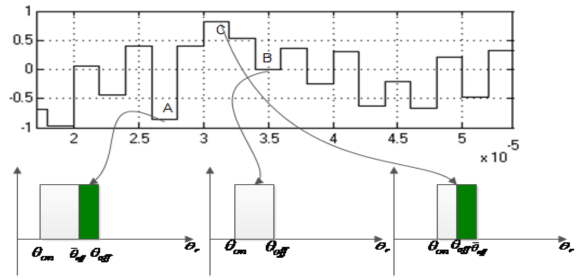


**Figure-5.** Random turn-off angle generation.

The random turn-off angle tuning is shown in Figure-5. The turn- on angle is fixed and turn-off angle is randomly varied around the average value based on:

$$\overline{\theta}_{off} = \theta_{off} + y(t)\Delta\theta \quad (5)$$

Where $\theta_{off}$ is the original turn off angle, $\overline{\theta}_{off}$ is the varied turn-off angle , $\Delta\theta$ is the magnitude of turn-off angle variation and $y(t)$ is the uniformly distributed random numbers between [-1 to +1]. The equivalent overlap angle is reduced as the results of randomizing turn-off angle. It will minimize the torque ripples considerably.

## 5. INTELLIGENT PI FUZZY CONTROLLER

Design and analysis of the Intelligent PI-Fuzzy controller (IPIFC) are discussed in this section. The structure of the proposed IPIFC is shown in Figure-6. The control structure consists of a simple upper-level rule-base (supervisory) controller and a lower PI controller. A standard Mam-dani type FLC has been applied in upper level of this control structure. The supervisory fuzzy system determines the Kp and Ki values for the PI controller at each sampling time by evaluating the inputs $e(k)$ and Iref($k$).

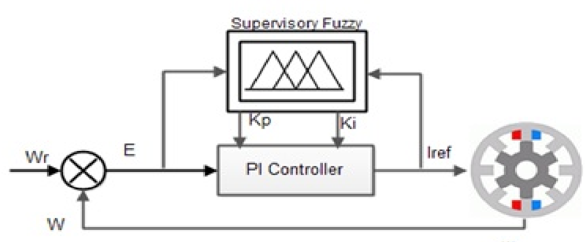


**Figure-6.** PI-Fuzzy controller structure.

The fuzzy supervisor is normally modifying the PI controller gain. The PI controller can be define as:

$$u_{PI} = K_P e(t) + TK_I \sum_{n=0}^{t} e(t) \quad (6)$$

$$e(t) = w(t) - w_r(t)$$

VOL. 10, NO. 5, MARCH 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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The Proportional (Kp) and integral (Ki) gain values are tuned by the rule base fuzzy controller. In fuzzy controller the five, three and five triangular membership function is used for error, current reference and Kp and Ki parameters respectively. The rules are framed based on the conventional drive operating knowledge about the controller parameter settings. The error(e) and the current reference(Iref) are the premise and proportional gain(Kp) and integral gain (Ki) are consequent of the IF-THEN rules. The structure of the supervisory fuzzy rules is given below. Figure-7 shows the rule base of the supervisory controller.

IF e is NB and Iref is L THEN Kp is NB and Ki is NB

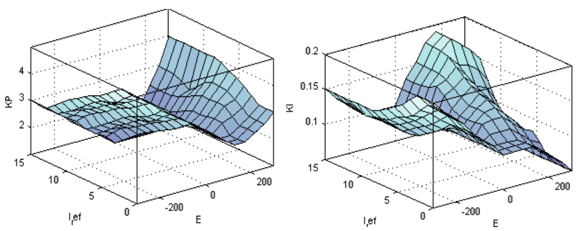


**Figure-7.** Surface view of the rule base of supervisory fuzzy controller.

## 6. NUMERICAL SIMULATION

SRM drive was simulated in MATLAB/Simulink software. The developed IPIFC was implemented to be the speed controller of the SRM drive in Figure-4. The PWM controller was used to be the current controller for inner-loop control in this work. The self- inductance profile of the SRM model was obtained by making off line measurement of a practical 4 phase 8/6 motor at current from 1 to 10 A. the flux linkage of the measure inductance profiles is shown in Figure-8. Table-1 lists detail specifications of SRM used in this simulation work. The Matlab/Simulink implementation block is shown in Figure-9

**Table-1.** Specification of SRM.

| | |
|---|---|
| Phase | 4 |
| Stator pole number | 8 |
| Rotor pole number | 6 |
| Rated voltage | 230V |
| Rated current | 10A |
| Rated speed | 4000 rpm |
| Rated load | 0.75 kw |
| Moment of inertia(Jm) | 0.005 kg-m$^3$ |
| Viscous friction coefficient(Bm) | 0.005 Nm/(rad/s) |
| Stator resistance ($R_k$) | 50 m-ohm |

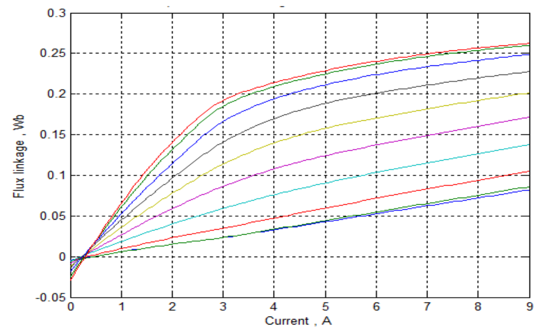


**Figure-8.** Flux linkage characteristics of 4 phase SRM.

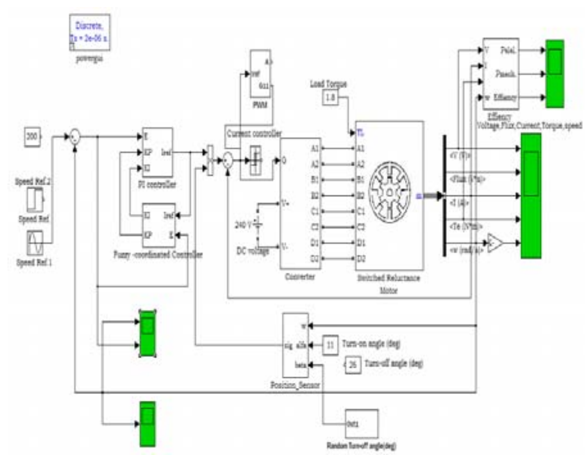

**Figure-9.** Matlab/Simulink implementation block.

## 7. NUMERICAL RESULTS AND DISCUSSION

To check the feasibility, tracking capability of the proposed IPFFC are tested by Numerical simulations in a 4 phase SRM drive system using different switching control algorithms and the results are compared to demonstrate the performance of the proposed IPFF. The following simulation studies were carried out. Fist the drive was operated at 2000 rpm and 1500 rpm with external load $T_L$=1.8 Nm to find out the optimal switching control algorithm with reduction of torque ripples and speed oscillation under steady state condition. Second, the developed IPIFC was tested by constant speed (200 rad/sec) and variable speed (-200 rad/sec to 200 rad/sec) at different times for testing the dynamic tracking capability. The controller parameters of the conventional PI controller were obtained with Cohen and Coon (CC) controller tuning method.

The voltage and current profile and torque and speed curve of SRM drive under single pulse width modulation with constant turn-off angle and random turn-off angle is shown in Figure-10. The torque ripple and speed oscillation is measured. The randomized turn-off angle is reducing the torque ripples and speed oscillations considerably compare than constant turn-off angle. In constant turn-off angle torque ripple is varied from -1 to 3 Nm but in randomized turn-off angle the torque ripples is varied from 1 to 2 Nm. Due to the reduction of ripples the

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speed oscillation also reduce 10 rpm from 30 rpm of the constant angle operation.

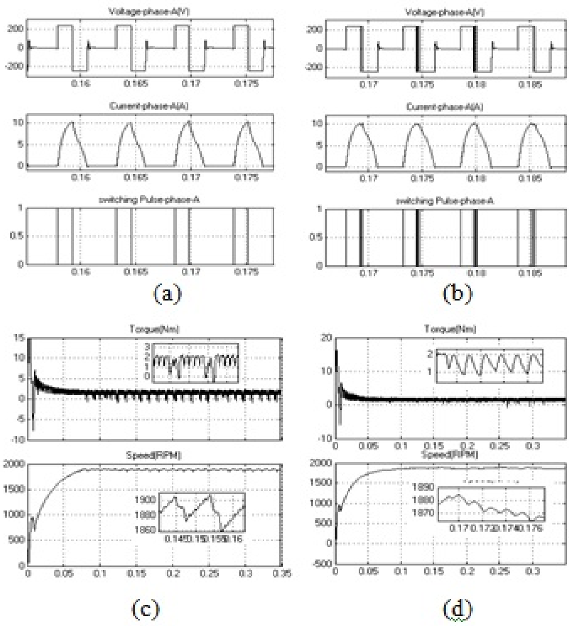


**Figure-10.** Performance of single pulse width modulation (a) voltage and current profile at constant turn-off angle (b) voltage and current profile at random turn-off angle (c) torque and speed curve at constant turn-off angle (d) torque and speed curve at random turn-off angle (3°).

However, the turn-on angle is fixed and the turn-off angle is advanced, the conduction period of the winding current is reduced and it leads the reduction of torque generating power. If the turn-off angle is reduced tragically, the negative torque produced. The current profile and voltage profile also varied based on pulse width and turn-off angle values.

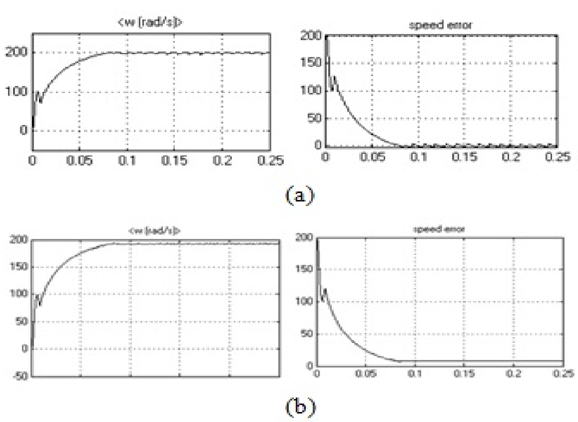


**Figure-11.** Steady state response of SRM drive (a) PI controller (b) IPIF controller.

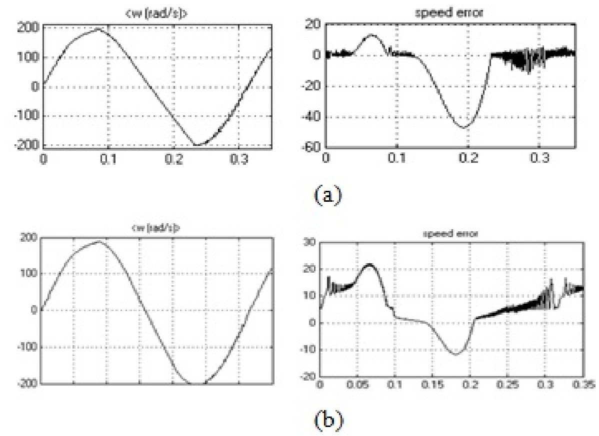


**Figure-12.** Speed tracking response of SRM drive (a) PI controller (b) IPIF controller.

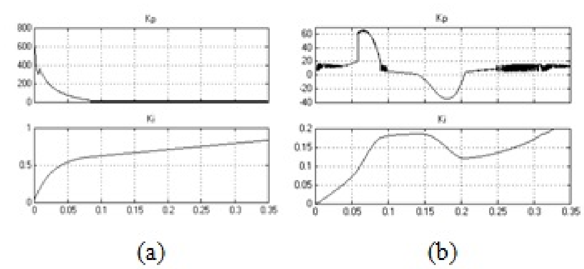


**Figure-13.** Propotional and integral gain variation (a) statey state conditon (b) tracking conditon.

The optimum switching control a method was implanted in IPIF controlled 4 phase SRM drive. Initially the controller performance was studied in steady state. Second the controller tacking performance was studied by varying speed commends in four quadrant. The speed and speed error curve at constant speed 200 rad/sec are shown in Figure-11. The IPIF controller gives better result than PI controller with 5 rad/sec steady error. The tracking speed curve and its tracking speed error are shown in Figure-12. The speed error at braking and reverse running period is significantly reduced than PI controller. The proportional and integral gain values variation at constant speed and variable speed are shown in Figure-13. It reflects the tracking capability of the IPIF controller.

## 8. CONCLUSIONS

This paper proposed an Intelligent PI- fuzzy controller for the speed control of SSRM drive. The torque ripples and speed oscillation reduction capability of different switching control methods have been studied by numerical simulation for 8/6 SRM drive. The single pulse width modulation with randomized turn-off control method is the optimal switching control method for 4 phase drive. The optimal switching control method was implanted in IPIF controller based SRM drive. The simulation results proved that the proposed IPIF control

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scheme maintains the motor speed at set speed with very minimum steady state error. From the results of the tracking speed changes in four quadrants, understand that the dynamic response of the proposed controller was good with minimum transient speed error. In future by using multiple pulse width modulation with randomized turn-off control gives the excellent optimal output with fast tracking speed.

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