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RIPPLE REDUCED CONTROL OF SWITCHED RELUCTANCE MOTOR DRIVES

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Abstract. Nowadays switched reluctance motor (SRM) drives have been widely used in the field of controlled electric motor drives. The paper proposes a simple control method for SRM drives. The main goal of the drive control is to improve dynamical performance by compensating for the motor nonlinearities. The ripple free operation can be realize only with an current waveform depending on the angle, speed and torque. The proposed ripple reduced method changes only the turn-on and the turn-off angle in function of the speed and current reference. One off the advantages of using the ripple –reduced method that it does not need the real-time calculation or measuring the motor torque. So it can be implemented on a cheap microcontroller. The test of this control method was performed in an experimental drive system. A SRM of 6/8 pole and 4 kW rated power was used. Simulation and experimental results are presented.

Keywords: SRM Drives, Speed Control, Hardware, Software, Microcontrollers, Simulation

1. INTRODUCTION

Nowadays switched reluctance motor (SRM) drives have been widely used in the field of controlled electric motor drives. Switched reluctance motors are double-salient, single excited motors. This means that the motor has salient poles an both the rotor and the stator, but only the stator carries windings. The motor does not require special material, e.g. magnet, it is simply built up from a stack of salient pole laminations.

2. DRIVE SYSTEM

The block scheme of the examined drive system is shown in Fig.1.

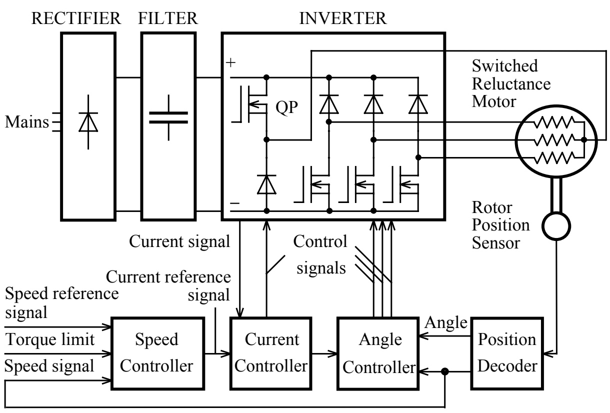

Fig. 1. Block scheme of drive system

The supply unit consists of three main blocks, namely the RECTIFIER, the FILTER and the INVERTER. The inverter is a pulsed width modulated (PWM) one, marked with QP in the figure and it contains one-one switching transistor per phase and a brake chopper, not shown in the figure. The common point of phase windings is supplied by the PWM inverter. It is of autonomous operation and has an inner current control loop. The other ends of phase windings are connected to the phase switching transistors.

It follows from the operational principle of SRM that its phase windings are to be excited at a well determined angle of the rotor position in an appropriate order. This is why a Rotor Position Sensor is to be mounted on the shaft of the motor. In our case the position sensor is a resolver. It can be calculated from the pole numbers that the phase switchings have to follow each other by 15 degree. The resolver is supplied by an oscillator circuit, their signals are evaluated by a Position Decoder.

The Position Decoder has two outputs: the Angle and Speed signals. Based on the two signals, the Angle Controller composes the Control signals for the phase switching transistors.

Fundamentally, SRM drives have two control loops, the outer one is the speed loop, Speed Controller and the inner one is the current loop, Current Controller. The output signal of the Speed Controller serves for a Current reference signal of the Current Controller. The hardware and software tools together fulfil the two-loop control. The Current Controller produces the control signal for the PWM inverter, and receives the Current signal from the PWM inverter at the same time.

At testing and fault detection there is a possibility to connect an intelligent terminal or an computer via RS 232 series data line to the dives. The fundamental part of the control unit is a single-chip microcontroller. It contains a clock generator with 12 MHz, an 256x8 on-chip RAM, four 16 bit timer/counters, a fast 32 bit division unit and a 16 bit multiplication unit, 12 multiplexed input 8-bit A/D converter with programmable reference voltage, two full duplex serial interfaces, a compare/capture unit.

3. OPERATION

The simplified operation principle of the SRM is as follows: When current is passed through the phase (stator) windings the rotor tends to align with the stator poles, that is it produces a torque that tends to move the rotor to a minimum-reluctance position. When a rotor pole is approaching the aligned position of the excited stator pole, positive (motoring) torque is produced, regardless of the direction of the current.

If the phase windings of the stator are supplied by a current of constant peak-value and square-waveform (power semiconductors are excellent for this purpose) with a frequency according to the required speed, then the task seems to be solved, as the SRM is a synchronous motor. But in this case, a significant torque pulsation occurs depending on the load at high currents which results in an additional overheating, while at small currents the motor can fall out of the synchronism and stops. This is why the task is dissolved for two parts. Partly a speed controller is applied, partly the switching on and off of motor phase windings is controlled by a position sensor on the motor shaft. For example at the increasement of speed reference signal originating from the error signal, the controller enlarges the current and the motor will accelerate. At the same time, the shaft position sensor controls the commutations among the phases by ensuring the accelerating torque continuously, otherwise the improper commutations will cause decelerating torque within one period. In the steady-state condition the torque produced by the controller is in balance with the loading torque.

The terminal voltage v on the phase winding can be expressed with the following equation:

$$v = iR + L\frac{di}{dt} + i\omega\frac{dL}{d\Theta} \qquad (1)$$

where:

i is the phase current,
R is the resistance of phase
L is the incremental inductivity of phase winding,
Θ is the rotor angle,
ω is the speed of the motor.

The last member of Eq.1. is the inner voltage of the motor which depends on the speed, the phase current and the slope of inductivity curve [1].

From [1] the torque τ of SRM:

$$\tau = \frac{1}{2}i^2\frac{dL}{d\Theta} \qquad (2)$$

Though Eq.2. is only valid for the linear case, two features follow from it. One of them is that the torque is independent of the sign of current. The other one is that the sign of torque is determined by the slope of inductivity curve.

In Fig.2. the upper curve signed L is the so-called inductivity profile which shows the inductivity of phase A in an idealized form as a function of the rotor shaft angle. (The airgap varies with the rotation of laminated rotor with salient poles.) The inductivity profile is determined fundamentally by the motor construction.

The equivalent circuit of SRM can change from being mainly an inductance to mainly an emf (inner voltage) depending on the rotor angle and the current waveform. Because of the above, and the saturation furthermore the non-linearities, it is not possible to use an equivalent circuit for SRM, usual for other electric motors.

The operation of SRM is illustrated in Fig.2. Phases currents A, B, C are represented by the continuous curves marked by A, B, C respectively in the motoring operation mode. In the generating operation mode the dotted section of curve A is valid.

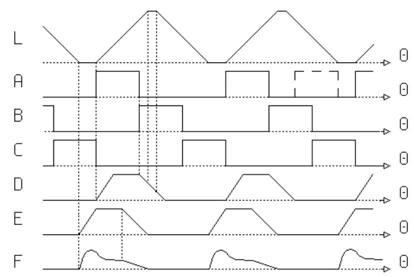

Fig. 2. The inductivity profile and the three-phase currents as a function of the rotor angle position

At high speed phase current A e.g. varies according to curve D in Fig.2., due to the fact that the period of the current pulse can be compared with the magnetizing, resp. demagnetizing period of the inductance (after switching off the IGBT transistor the current is conducted by the diode). This results in a torque pulsation, because the current is not constant, on the one hand, and the current pulse spans to the negative section of the inductance profile of curve L in Fig.2., on the other hand. On this section of curve L the positive torque turns negative. The effect of this detrimental phenomenon can be decreased by advancing the turn-on angle, as shown by curve E in Fig.2. At higher speed the current varies according to curve F in Fig.2. because of the increased role of inner voltage (self-emf).

4. CONTROL OF SRM DRIVE

Current control

The Current Controller is totally based on its hardware solution. Based on the current reference signal, it controls the PWM inverter of fix frequency by installing an analog controller. The current feedback also comes from the PWM inverter.

For the control of the sum of phase currents (Fig.1.) it is suitable a simpler four-transistor inverter and is not necessary a six-transistor one as in the case of control of phase currents independently from each other. But the detriment of the previous solution is that the torque pulsation can be decreased in a smaller degree by changing the turn-on and turn-off angles.

Namely, in the case of the constant current reference signal the current increase is limited by the switched-off, but conducting phase current as the regulator controls the sum of two phase currents. The increase of the phase current at starting the conducting state can be forced by the modification of the current reference signal:

$$i_r = u\sum_{j=1}^{3} C_j + \sum_{j=1}^{3}(1 - C_j)\cdot i_j \qquad (3)$$

where:

i_r is the current reference signal,

i_j is the current signal of phase j ,

u is the output of the speed controller,

C_j is the control signal of phase j (0 or 1).

The supplement of the first member of Eq. 3 makes the overlap of the phase conduction possible, while the effect of second member is to increase the reference signal with the current of the switched-off, but not current-free phase.

Speed control

Based on the Speed reference signal, the Speed Controller produces the Current reference signal taking the Speed signal and the Torque signal into account. The digital output signal determined by the software is converted by a D/A converter to an analog reference signal The software defines the connection between the current and torque.

The control tasks are fulfilled at every 12th sampling period. The speed feedback signal is determined by calculating the difference between the actual position value and the previous one of the resolver to digital converter. The measuring period ensures an accuracy of ± 5 rpm. The controller is of PDF-type (an integral element with Proportional and Derivative Feedback).

The control algorithm is as follows:

$$U(nT) = U(nT-T) + K_i E(nT) + K_p[N(nT-T) - N(nT)] + K_d[2N(nT-T) - N(nT) - N(nT-2T)] \qquad (4)$$

where:

T is the sampling period of speed loop,

$U(nT)$ is the output of speed controller at the n-th sampling period,

$E(nT)$ is the error signal,

$N(nT)$) is the speed feedback signal,

$(nT-T)$) is the previous sampling period,

K_p, K_i, K_d is the proportional, the integral and the derivative constant.

The above PDF algorithm can be applied to control the speed of electrical drives, as it makes an optimal adjustment possible for a step change in both the reference signal and the load [2].

The output signal of speed controller can be used preferably for torque command signal to ensure fast dynamics. One solution for the above task is to insert a torque control loop between the speed control loop and the current one. The formation of an actual torque signal makes the torque control complicated and expensive. Knowing the intermediate dc voltage and dc current, the speed and the efficiency, the approximate calculation of the torque is possible [3]. Because of the above difficulties, other, simpler and more effective methods have been analysed. Their common characteristics are that fast dynamics are ensured by applying a constant gain in the speed control loop.

Neglecting the saturation, the motor torque is proportional to the square of current. This means that the current reference signal can be composed from the torque reference signal, produced by the speed controller by the help of a square-root function after composing its absolute value. The motoring and generating operation modes of the drive can be determined from the sign of torque reference signal and the momentary direction of rotation. The change of operation mode is fulfilled by the Angle Controller, illustrated by the arrow between the Current Controller and Angle Controller in Fig.1.

The saturation of motor, depending greatly on the motor construction, complicates the transient analysis of the system further. In consequence of the saturation, the square relation between the current and the torque will be valid approximately only.

Furthermore, the inner voltage of motor at high speed causes an additional problem, since the current control of PWM cannot produce constant current, given by the command signal. The decrease of torque can be partitionally compensated by angle control, namely by advancing the turn-on angle, resp. by changing the turn-off angle. Due to the above, the starting time of drive increases, on the one hand, and the gain of speed control loop decreases, on the other hand. As at high speed the constant value of maximum torque cannot be reached because of physical limitations, the only purpose for the controller is to maintain the constant gain of loop. This goal can be achieved at least in two ways.

One solution for solving the task is the compensation in the function of speed and torque, using calculated values from a look-up table, stored in the memory.

The other solution is the application of an adaptive control. The up-to-date control theory and the computer hardwares make the application of adaptive control possible, taking the actual parameters of control circuit changing during the operation into account. For controlling electric drives, algorithms ensuring fast adaptation and having simultaneously a fairly few calculation requirement can be applied effectively [4].

Angle control

The Position Decoder in Fig.1. contains the resolver to digital converter, the oscillator circuit and two latches. The resolver to digital converter is set to a 12-bit resolution, which corresponds to a disc with 4096 marks. The microcontroller reads the code at every sampling period in and calculates the speed at every 12^{th} sampling period. In such a way the Angle signal of rotor and the Speed signal are calculated by the software.

The smallest digit bit of the digital output of the resolver to digital converter gets to the input of one port of the microcontroller. The Timer 2 circuit of the microcontroller counts the change of this signal. By the counting the angle resolution is divided into halves, which corresponds to a disc with 2048 marks. At matching the contents of Timer 2 and compare register, the output signal of compare register changes to a level, determined earlier. All three motor phases have one-one compare register and one-one output belonging to them. Three outputs control one-one phase switching IGBT via the Buffer circuit.

The user program calculates the firing angle at every 15 degree, it sets the contents of compare register and prepares the output to start the firing at matching the compare events. The output signal change, induced by the hardware of microcontroller starts an interrupt request at the same time, based on which the interupt routine loads the compare register with a value corresponding to the turn-off angle and prepares the output for switching-off the transistor.

As Timer 2 can count in one direction only, it is unable to follow the reverse of speed through the hardware. For this reason and because of starting problems, the user program controls the outputs directly taking the position angle of Resolver to digital converter into account below a predetermined speed. At small speeds the time-lag caused by sampling and the calculation result in a small angle-error. This additional error is smaller than 2% related to the 15 degree range below 150 rpm. The frequent shift between control modes can be avoided by applying a suitable hysteresis band.

At high speeds the application of the firing in-advance is necessary, which the software completes by using the Speed signal. As a result of calculations, the contents of compare register will change.

It is worth remarking that a minimal turn-on time is necessary for the safe operation of PWM inverter of fixed frequency. The minimal turn-on time results in a minimal voltage at the star-point of motor phase windings. Because of the minimal voltage at no- and a small load, either small or zero speed reference signal will result in a high speed of the motor. To prevent this detrimental effect the Current controller reads the Current signal in by the help of an inner analog-digital converter of the microcontroller and will intervene in the process if it seems necessary.

There are two ways for solving the above problem: either we inhibit the PWM inverter for some strokes or we switch off the phase transistors accomplishing a secondary choppering. The latter solution has been chosen, represented by the arrow between the Current Controller and the Angle Controller in Fig.1.

Ripple reduced control method

The ripple free operation can be realize only with an current waveform depending on the angle, speed and torque [5]. The proposed ripple reduced method changes only the turn-on and the turn-off angle in function of the speed and current reference. The optimum turn-on and turn-off angles of the SRM drive has been determined by computer simulation based on the measured results of the analysed drive. The optimum solution has been fulfilled by four cycles embedded into each other. Two outer cycles give the current and speed reference signals, while two inner ones provide the turn-on and turn-off angles. By this one-one optimum angle pair can be determined to all operating points.

It can be considered an interesting result that the criteria of the minimum torque pulsation does not provide an optimum solution in all cases. The torque pulsation will be minimum in the speed-current plane only in that case if the torque of the motor is relatively small. For this reason a good result can be achieved in such a way if the relative, i.e. compared to the torque of motor, torque pulsation is minimised.

The angle control of the drive determines the actual turn-on and turn-off angles with a two-variable interpolation from the results stored in a look-up table and calculated by the above method.

In Fig. 3 and Fig.4 two of many executed simulations are shown. Fig. 3 shows the run-up with constant turn-on and turn-off angles without current reference compensation, while Fig. 4 with turn-on and turn-off angles depending on the speed and current reference and with current reference compensation (Eq. 3).

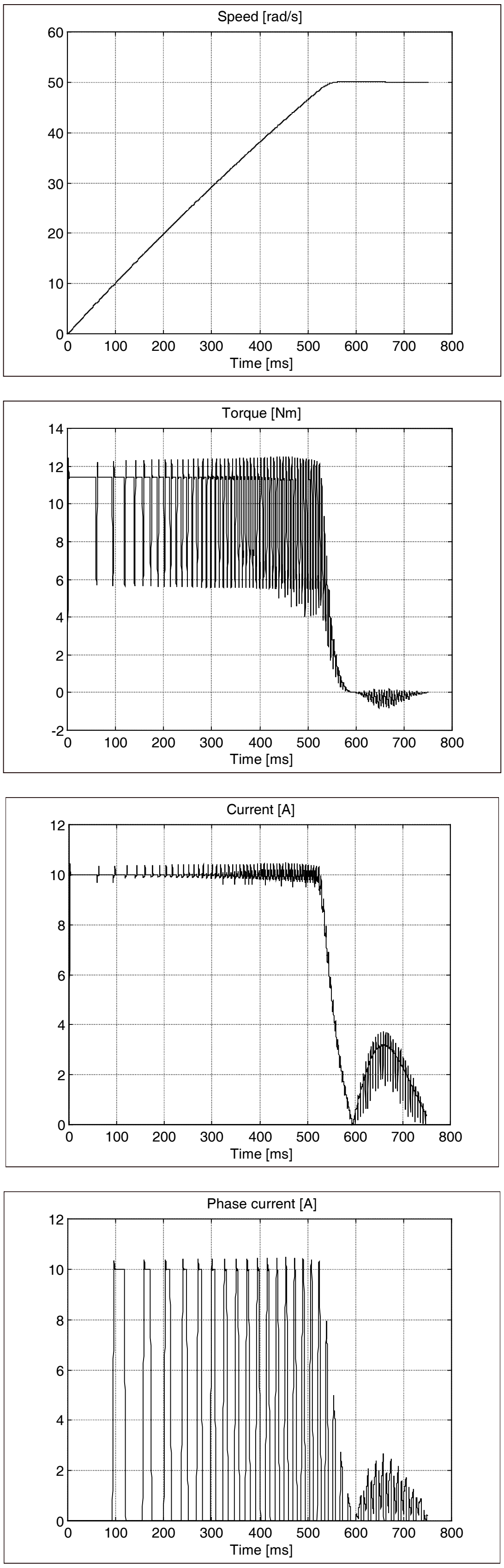

Fig. 3. Simulation results with constant turn-on and turn-off angles

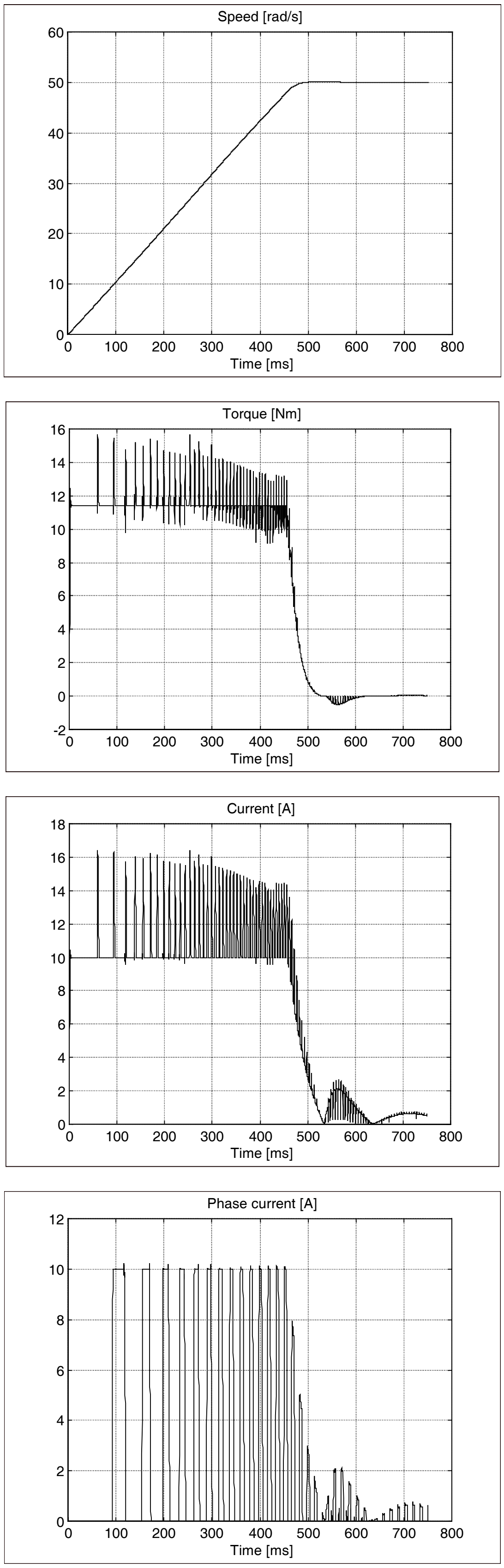

Fig. 4. Simulation results with turn-on and turn-off angles depending on speed and current ref

5. TEST RESULTS

The tests were completed by the described drive system. The test results have supported our theoretical investigations. The oscillograms in the following figures illustrate some typical starting curves and wave forms. The loading machine was a DC motor. Its inertia is about a triple of that of SRM.

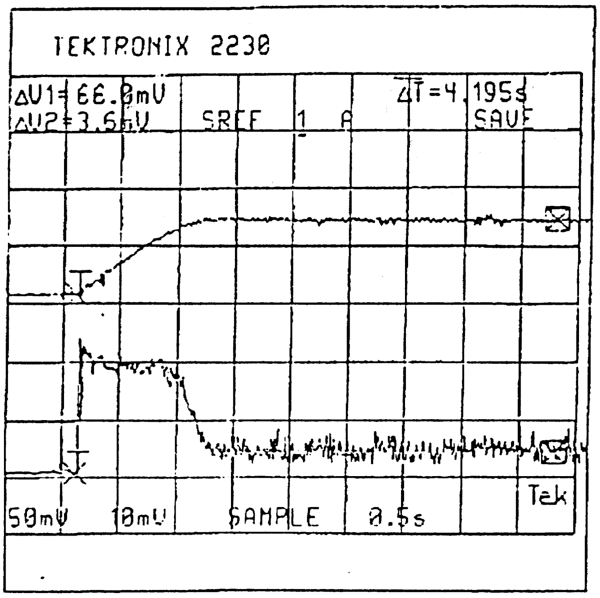

Fig. 5. Oscillograms of the speed and current, PDF-type control

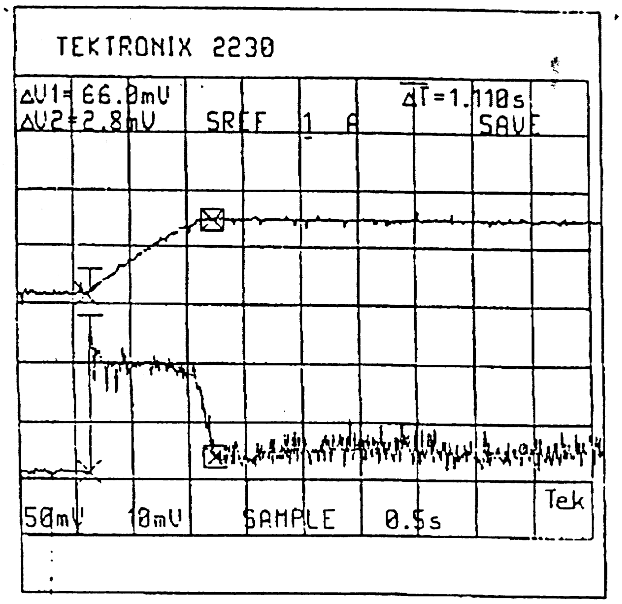

Fig. 6. Oscillograms of the speed and current, modified PDF-type control

Figs. 5. and 6. show the speed and current curves in the course of starting without current reference compensation. In all figures the upper curve is the speed (1000 rpm), the lower one is the current flowing in the common point of stator windings (10 A/div). Figs. 5. and 6. are related to the no-load operation mode. A PDF-type control is applied in the case of Fig 5., while a PDF-type control modified by a square-root function is used in the case of Fig. 6.

6. CONCLUSIONS

The paper proposes a simple control method for SRM drives. The proposed ripple reduced control method changes only the turn-on and the turn-off angles depending on the speed and current reference. The modification of the current reference is suggested for a simpler four-transistor inverter. The simulations and experimental results demonstrate that the proposed method is a promising tool to control the SRM drives.

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8. THE AUTHOR

László Számel was born in Budapest, in 1964. He received the M.S. and dr. univ degrees in electrical engineering from the Technical University of Budapest in 1988 and 1995, respectively. Until 1997 he worked for Computer and Automation Research Institute of Hungarian Academy of Science, since then is with the Budapest University of Technology and Economics. His educational and research fields are electrical drive control, servo and robot drives, digital systems, switched reluctance motor drives, high-accuracy position and speed measurements of electrical drives.

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