ACCIONAMIENTOS DE RELUCTANCIA AUTOCONMUTADOS CON CONTROL DE PAR PARA DIRECCIÓN ASISTIDA ELÉCTRICA

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TORQUE CONTROL OF SWITCHED RELUCTANCE MOTOR DRIVES FOR ELECTRIC POWER STEERING

ABSTRACT:
Power steering is a standard device in modern commercial vehicles. Electric power steering is becoming an alternative to traditional hydraulic power steering. The electric drive commonly used today in this application is the brushed DC motor drive. Several electric drives are seen as a future option but the best candidate seems to be the permanent magnet synchronous motor drive. On the other hand, the constructive simplicity, absence of permanent magnets and fault tolerance of the switched reluctance motor drive make this option worth considering. In this article, a switched reluctance motor drive is presented for a rack-type electric power steering for midsize cars with a rack force 10 kN. The drive consists of a four-phase switched reluctance motor with 8 stator poles and 6 rotor poles fed through an electronic power converter with Power MOSFET switches, an incremental encoder and digital torque control to minimise torque ripple and to mitigate disturbances that appear when clearing a fault and the drive works with one or two open phases. The drive was built and tested in the laboratory and experimental results confirmed its suitability as a drive for electric power steering.

Key Words: electric power steering, switched reluctance motor drives, torque control

RESUMEN:
La dirección asistida es ya un dispositivo de serie en los automóviles comerciales. La dirección asistida eléctrica se está convirtiendo en una alternativa a la tradicional dirección asistida hidráulica. En estos momentos el accionamiento eléctrico comúnmente utilizado para esta aplicación utiliza el motor de corriente continua con escobillas. Hoy por hoy, diferentes accionamientos eléctricos se ven como una opción de futuro, aunque el mejor candidato es el accionamiento con motor síncrono con imanes permanentes. No obstante, debido a su sencillez constructiva, ausencia de imanes permanentes y tolerancia a faltas, el accionamiento con motor de reluctancia autoconmutado es una alternativa que no debe ignorarse. En este artículo se presenta un accionamiento con un motor de reluctancia autoconmutado para dirección asistida eléctrica para automóviles de tamaño medio con una fuerza en el eje de la cremallera (Rack Axis Force) de 10 kN. El accionamiento está constituido por un motor de reluctancia autoconmutado de cuatro fases con 8 polos en el estator y 6 polos en el rotor, alimentado a través de un convertidor electrónico de potencia con interruptores Power Mosfets, encoder incremental y control digital para minimizar el rizado de par y mitigar las perturbaciones que aparecen al despejar una falta, trabajando el accionamiento con una o dos fases abiertas. El accionamiento se ha construido y se ha probado en el laboratorio, confirmando los resultados experimentales su idoneidad como accionamiento para dirección asistida eléctrica.

Keywords: electric power steering, switched reluctance motor drives, torque control.

1.- INTRODUCTION. ELECTRIC POWER STEERING (EPS)

Early vehicles were already equipped with mechanical power steering systems to assist steering, especially in slow-speed and parking maneuvering [1]. In 1926, Francis W. Davis invented the first hydraulic power steering [2]. Chrysler introduced the first commercial hydraulic power steering system in the 1951 Chrysler Imperial under the name *Hydraguide*. Since then, hydraulic power steering has been gradually introduced in passenger cars until becoming standard. In 1988, the electric power steering (EPS) column was first introduced by Koyo [3] and Mitsubishi Electric Corp. [4] in microcars in Japan. From that moment on, EPS started being used in many vehicles, particularly in compact

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vehicles where it was difficult to fit hydraulic power steering because of lack of space. Apart from volume and weight reduction, advantages of EPS over traditional hydraulic power steering include lower fuel consumption since power is supplied only when necessary rather than by the continuous action of a pump activated by the internal combustion engine; reduced gas emissions into the atmosphere, no use of hydraulic fluid; and possibility to integrate functions such as sensitivity to speed and drift control for improved driving safety [5]. Most modern vehicles are equipped with EPS. However, this system requires higher capacity batteries and greater wire gauge, that is, an electrical system capable of supplying the additional power required by EPS [6]. Thus, the decision on the use of EPS must be made in the initial design phase of the vehicle.

Assist torque in EPS depends on steering wheel torque. EPS is a fedback system comprising a torque and position sensor, electric drive, and electronic control and diagnosis unit, i.e. Electronic Control Unit (ECU). An EPS schematic is illustrated in Fig. 1. According to the position of the motor in the system, EPS can be classified as

- Column EPS
- Pinion EPS
- Rack EPS

Fig. 2 is a photo of a pinion EPS for midsize vehicles.

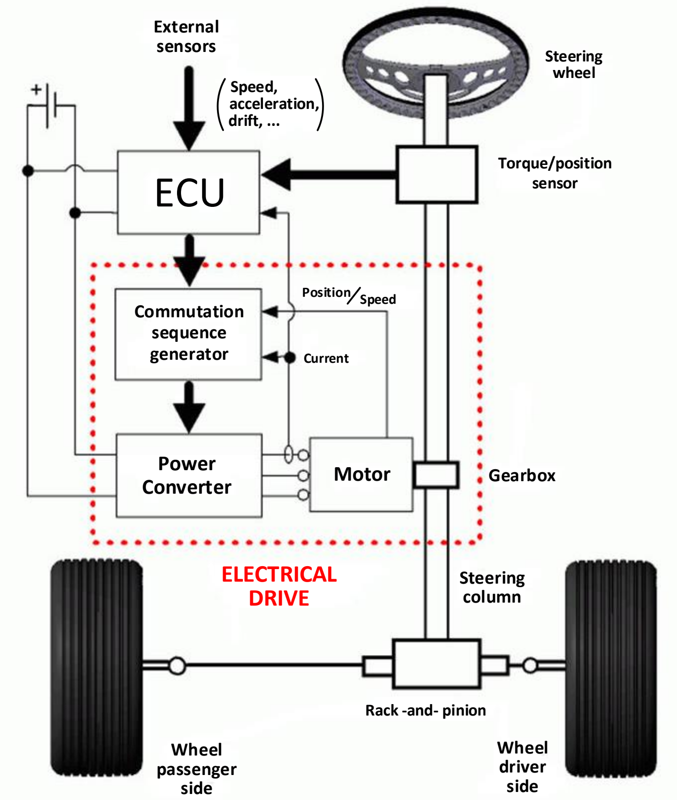

Fig. 1: EPS schematic

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Fig. 2: Pinion EPS

The force exerted on the rack axis is fundamental in the selection of an EPS. Rack axis force is determined by the axial effort required to move the front wheels of the vehicle under all driving conditions, suspension and tyre type, and steering wheel torque. Other aspects to be considered are
- Available space for its location in the vehicle
- Voltage of the vehicle's electrical system
- Pinion rack transmission mechanical effort
- Safety requirements against collision
- Waterproof and thermal dissipation measures

Table 1 shows EPS requirements according to vehicle size.

EPS type	Vehicle size	Rack axis force (kN)	Recommended voltage (V)	Power required by electric drive
Column EPS	Small	6	12	Low
Pinion EPS	Midsize	8	42	Medium
Rack EPS	Large	12	42	High

Table 1: EPS requirements according to vehicle size

The main goal of this work is to present the advantages of switched reluctance motor (SRM) drives over drives traditionally used for EPS. Based on EPS requirements for midsize vehicles, an SRM drive with an electromechanical converter, electronic power converter, position capture devices and digital control was dimensioned. Apart from providing torque ripple reduction under all driving conditions, digital control must be capable of mitigating disturbances due to fault clearing and allowing drive operation with one or two open phases. A prototype was built and tested for suitability as EPS drive.

2. EPS ELECTRIC DRIVES

EPS electric drives are electronically-controlled drives that must meet the following requirements:
- High power/weight ratio
- Low inertia
- Low friction torque
- High quality torque (low torque ripple)
- Fault tolerance

Table 2 shows the suitability of current electric drives for use in EPS. Their level of compliance with specifications is presented.
Brushed DC motor drives have been so far the most common alternative. However, the best candidate is the permanent magnet synchronous motor, as can be seen in Table 2 [7-14]. Against this option, it can be argued that it has a high cost

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because of the use of neodymium magnets, which can increase in the mid-term due to circumstances of the rare earth market [14].

	Brushed DC motors	Brushless DC motors	Permanent magnet synchronous motors
Control	Simple	Trapezoidal	Sinusoidal
Position sensor	Not necessary	Hall sensors; Simple and cheap	Absolute encoder, Resolver; expensive
Power converter	H bridge	Three-phase VSI inverter	Three-phase VSI inverter
Inertia	High	Low	Low
Friction	HIgh	Low	Low
Torque ripple	Low	High	Low

Table 2: Compliance of electric drives with EPS specifications

3. SWITCHED RELUCTANCE MOTOR DRIVES FOR EPS

The switched reluctance motor (SRM) drive is a dc motor drive without brushes and permanent magnets, composed of a salient pole rotor and stator structure. Concentrated coils are wound around each stator pole and, connected in series in opposed pairs, form the motor phases. Phase current commutation is achieved using an electronic power converter in which the commutation sequence of solid state switches is controlled by the rotor position through optical or magnetic sensors according to pre-established control strategies.

Switched reluctance motor (SRM) drives have the following competitive advantages over traditional drives used for EPS:

- Easy-to-build electromagnetic structure, and therefore lower manufacturing costs
- Absence of permanent magnets
- Torque-speed characteristic adaptable to load requirements
- Fault tolerance
- Specific controls, with little effect on the final cost of the drive, which can minimise negative aspects traditionally attributed to SRM, like torque ripple and acoustic noise.

In order to demonstrate the suitability of this type of drives for EPS, a switched reluctance motor drive for midsize vehicles with 10 kN rack axis force was designed. In these conditions, the motor has to provide 475 W rated power and produce 2.52 Nm torque at 1800 rpm. For slow speed manoeuvering, a 5 Nm torque for 5 s over a period of 1 minute is required (S3, 8.3%). Supply voltage is 42 V and ambient temperature ranges between -40 ºC and 125 ºC. The design involved dimensioning of its electromagnetic structure and electronic power converter, selection of position capture devices and implementation of digital control, including controls for torque ripple reduction [15] (for a 4 Nm torque, it is restricted to $\pm$ 0.5 Nm) and to mitigate disturbances due to fault clearing and drive operation with one or two open phases [16].

3.1.- ELECTROMECHANICAL CONVERTER, SWITCHED RELUCTANCE MOTOR

A four-phase, eight-pole stator, six-pole rotor switched reluctance motor was chosen to reduce torque ripple and ensure better performance under fault conditions. Two photos of the prototype's rotor and stator are shown in Fig. 3 and the main motor data are summarised in the annex.

The dimensioning of the motor was optimised by the finite element method. Fig. 4 shows the distribution of the magnetic field lines on the motor for positions of alignment and no-alignment between stator and rotor for 25 A current.

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The following eco-design criteria were also considered in the motor design: reduction in the number of materials, particularly non-recyclable ones, easy assembly and disassembly of the motor and easy winding stripping [17].

Fig. 3: Prototype: rotor (left), stator (right)

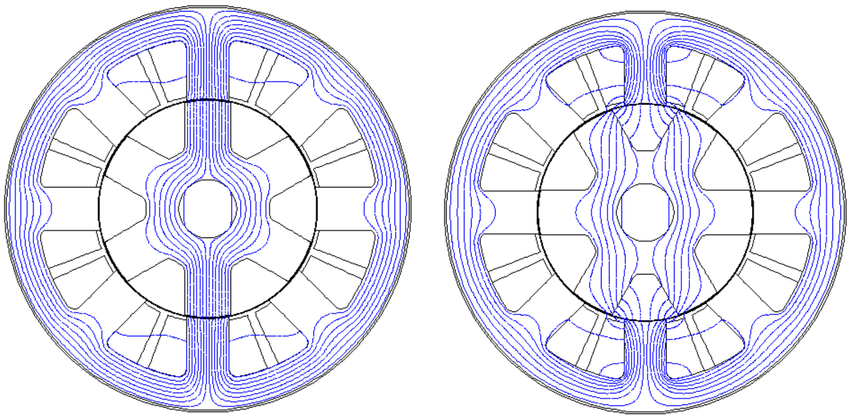

Fig. 4: Finite element analysis of the prototype, with distribution of magnetic field lines in aligned (left) and non-aligned (right) position for 25A current

3.2.- ELECTRONIC POWER CONVERTER

In order to ensure independent operation of motor phases under fault conditions, a four-phase asymmetrical power (classic) converter with two Power MOSFET switches (IXFN180N20) and two diodes (DSGI2x61) per phase was selected, Fig. 5. A photo of the power converter including drivers, current sensors, snubbers, condensers, fan and heat sinks is shown in Fig. 6.

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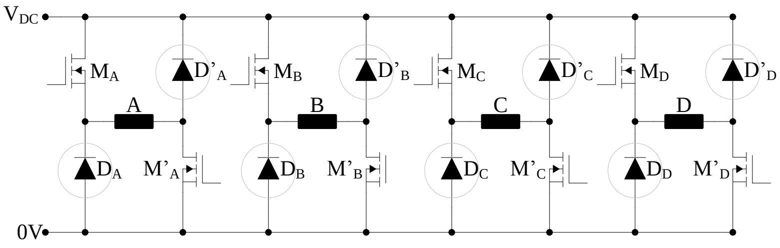

Fig. 5: Asymmetric bridge power converter schematic with phases A, B, C and D of the motor

Fig. 6: Three-phase electronic power converter

3.3.- POSITION CAPTURE DEVICES

Although a position sensorless system would be desirable, it was ruled because of its greater complexity and lower reliability. Instead, a more conventional alternative was preferred, i.e. 0530 172 Hengstler incremental rotary encoder since the DSP chosen for control implementation has integrated encoder function.

3.4.- DIGITAL CONTROL

The drive must be able to rapidly produce reduced ripple torque according to the driving conditions at all instants. It must also plan controls to mitigate torque waveform disturbances occurring during fault clearing and be able to operate with one or two open phases. To these ends, alternatives based on instantaneous torque direct control by hysteresis controllers [18 -19] which provided improvements over those proposed by Inderka *et al*. were initially considered [20].

Finally, a PI torque controller and PWM controllers operating at 16 kHz switching frequency where only the upper switch of one branch of the electronic power converter is chopped (softchopping operation) were selected. This alternative was also useful in reducing audible noise, which is one of the main drawbacks of switched reluctance motors.

A block diagram of the torque control is illustrated in Fig. 7. The torque reference, T_{ref}, is compared with the average torque, T_{med}, calculated from the instantaneous position and current values using a torque-position-current table obtained by finite element analysis of the motor's electromagnetic structure and experimentally validated, Fig. 8. The torque error signal, e_t, is fed into a PI regulator. Its output produces a current reference, i_{ref}, which is compared with the phase current signal. The current error, e_i, is fed into a P regulator that generates the duty cycle. At the same time, the turn Θ_{ON} and turn off Θ_{OFF} angles required to reduce torque ripple are computed in function of the drive's speed of rotation in the switching controller. To do this, the real position of the rotor and the average torque of each phase, T_{fase},

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as well as the total average torque, $T_{med,}$ obtained in the torque calculation block are used. Finally, the trigger signals of the eight solid-state switches of the electronic power converter are generated in the PWM block from the duty cycle and turn on and turn off angles. In this way, the motor provides the assist torque according to the reference required at each instant with a torque ripple within the set limits. The control system monitors the phase current and torque in all operation modes. Thus, in the event of fault, the fault detection and clearing system disables the affected phase and computes the new turn on and turn off angles for each active phase. These angles, which are stored in the switching controller, are previously determined experimentally for all operation speeds in such a way that they compensate for the absence of torque in the disabled phase, thus modifying steering time in healthy phases.

In order to implement the control system, a TMS320F28335, which is a high-performance 32-bit floating-point DSP capable of running at a clock frequency up to150 MHz, was used. Optimisation techniques were employed for faster operation. Fig. 9 shows the control board implemented using TMS320F28335 and all its peripherals.

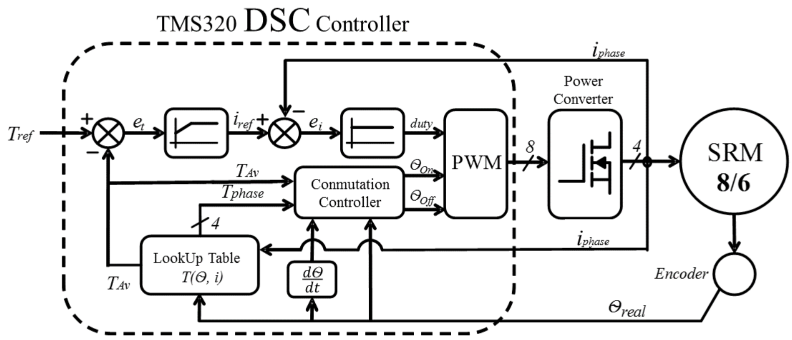

Fig. 7: Block diagram of the torque control. Dashed-line rectangle shows TMS320F28335tasks.

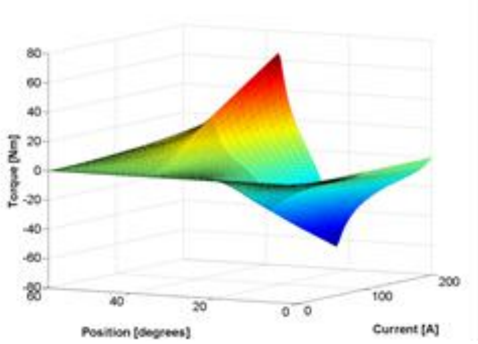

Fig. 8: Three-dimensional graph of the torque-position-current table T(Θ, i) for the SRM obtained by finite element analysis

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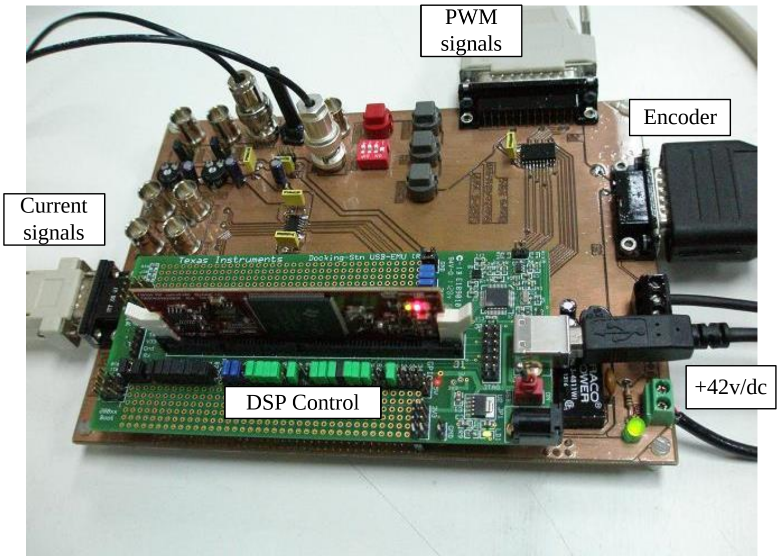

Fig. 9: Control board implemented using TMS320F28335

4. EXPERIMENTAL RESULTS

In order to evaluate the drive operation, a test bench was set up with the drive loaded with a permanent magnet synchronous brushless motor, Fig. 10.

Torque-speed curves were obtained from the experimental results, Fig. 11.The torque-speed curve, CR-DAE, required by EPS is represented by a dashed line (most significant values given in Section 3). Pot 500 W is the operating characteristic curve at a 500 W constant power with variable turn on and turn off angles. CR-SPC is the torque-speed characteristic curve with constant turn on and turn off angles (-2º, 13º). M2, M3, M4 and M5 are operating characteristic curves at constant torque. The results demonstrate that the drive meets EPS requirements.

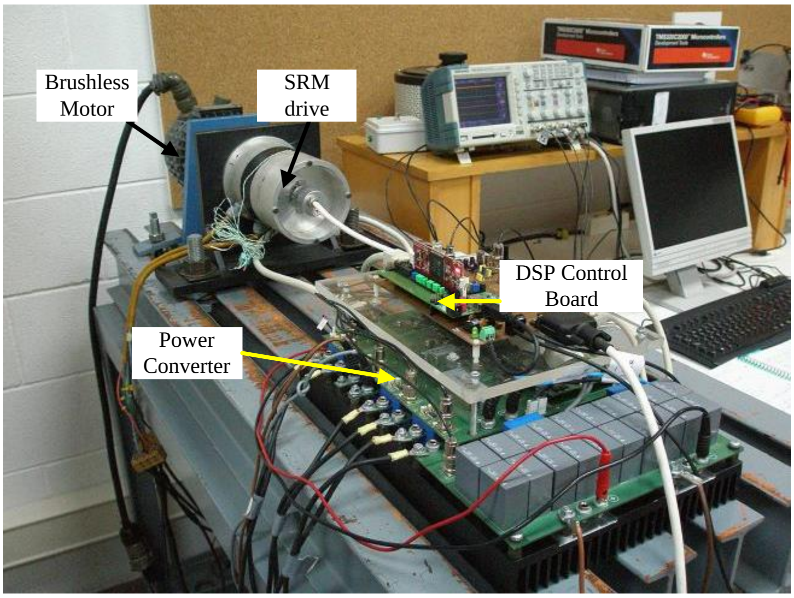

Fig. 10: Test bench

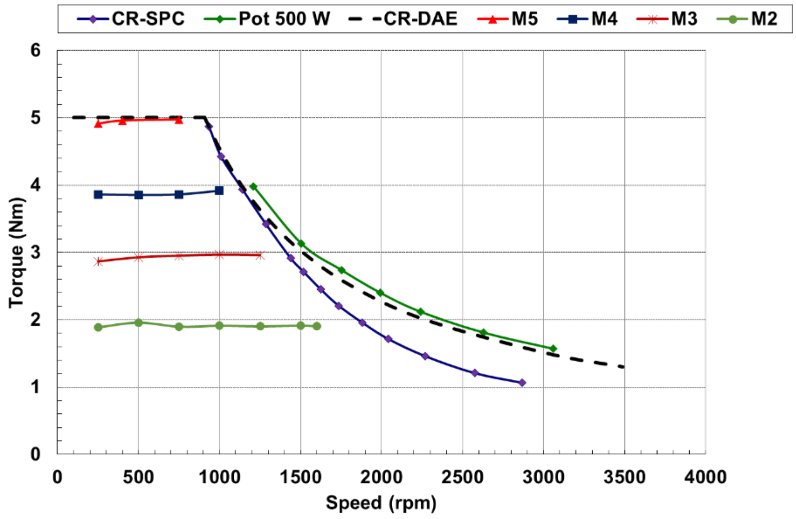

Fig. 11: Experimental results. Torque-speed curves

Oscillograms of the total instantaneous torque and phase A current waveforms, as well as trigger signals of phase A Power MOSFET switches are shown in Fig. 12. The upper chopped switch (soft-chopping operation) is worth noting.

Fig. 13 plots the instantaneous torque and phase current waveforms, except for phase D. For a 4 Nm torque reference, the torque ripple at 1100 rpm remains within a ±0.5 Nm window, in accordance with EPS requirements.

While audible noise reduction is not among EPS requirements, the drive's average acoustic pressure, L_{pA}, and average acoustic power, L_{wA}, values should be evaluated. Table 3 shows experimental results obtained under several test bench conditions. As a reference, according to UNE 203001-17:2000 and UNE-EN 60034-9:2006, for a three-phase, four-pole asynchronous motor of rated power 1.0 $<P_N$ (kW) < 2.2 fed through a converter, the maximum average acoustic power , L_{wA}, in no-load conditions would range between 75 a 85 dB(A). Therefore, the drive's level of acoustic noise is within acceptable limits.

Test conditions	L_{pA}, dB(A)	L_{wA}, dB(A)
800 rpm (no-load)	70.4	81.4
2500 rpm (no-load)	75.5	86.5
1100 rpm (4Nm)	75.1	86.1
1800 rpm (2Nm)	73	84

Table 3. Experimental values. Average acoustic pressure, L_{pA}, and average acoustic power, L_{wA}.

The ability of torque control to mitigate the effects of phase disabling caused by a fault is plotted in Fig. 14. The upper and lower oscillograms show instantaneous torque and healthy phase current waveforms at faulty phase disabling instant and upon modification of operation of phases adjacent to the disabled phase by the control, respectively.

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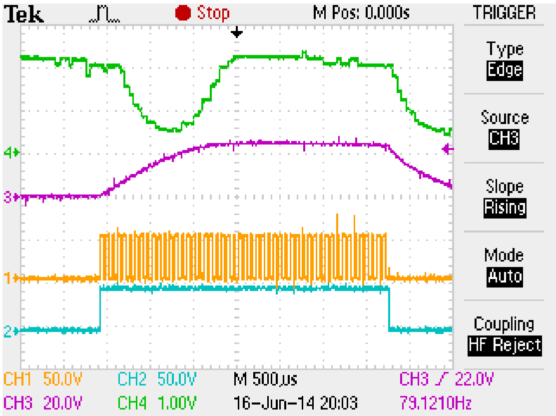


Fig. 12: Waveforms of instantaneous torque, current and trigger signals sent to Power MOSFET switch gates of the corresponding phase: Channel 3 (magenta) phase A current; Channel 1 (orange) trigger signals of upper Power MOSFET switch of phase A branch; Channel 2 (blue) trigger signals of lower Power MOSFET switch of phase A branch; Channel 4 (green) total instantaneous torque

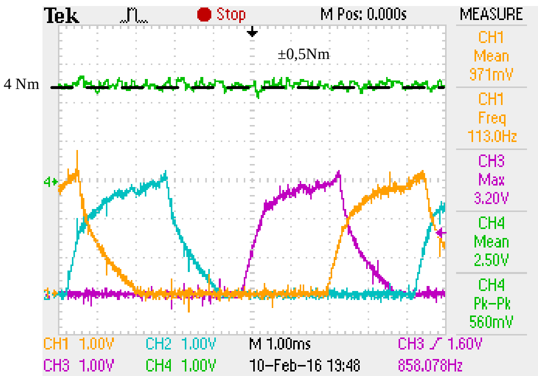
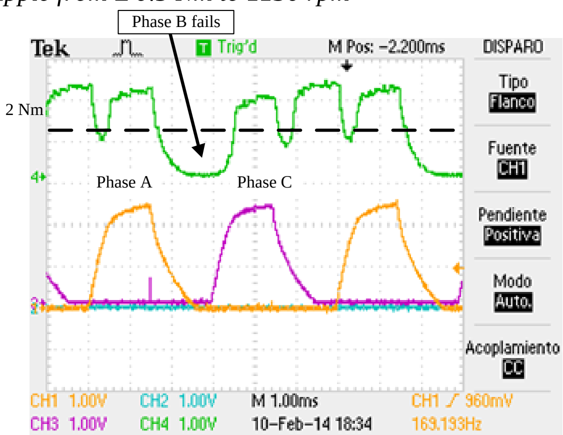


Fig. 13: Torque ripple control. Channels 1(magenta), 2(orange) and 3(blue) show phase A, B and C currents; phase D current not shown. Channel 4 (green) shows 4 Nm total instantaneous torque with torque ripple from ± 0.5 Nm to 1130 rpm



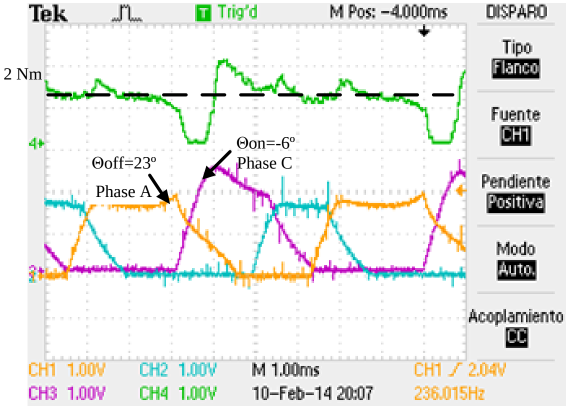


Fig. 14: Upper screen shows the instantaneous torque waveform after disabling of phase B because of a fault; angles are kept constant for all phases (control does not act). Lower screen shows how fault mitigation control acts by prolonging operation of phase A (orange) and anticipating the trigger of phase C (magenta); steering angles are also increased for phase D (blue), compensating for the torque contribution of the disabled phase.

5. CONCLUSIONS

After a description of EPS, this article showed that SRM drives have competitive advantages over other electric drives, such as construction simplicity, absence of permanent magnets, adaptability of torque-speed characteristic to load requirements and fault tolerance. A drive was designed and built for midsize vehicle EPS. It is composed of a three-phase SRM comprising eight stator poles and six rotor poles fed through an electronic power converter with Power MOSFET switches and controls. Apart from providing the assist torque required at all instants, the controls reduce the main drawbacks of SRM drives, particularly torque ripple, and take advantage of their fault tolerance. Laboratory tests showed that the drive can provide the torque-speed characteristic and instantaneous torque waveform with torque ripple according to EPS requirements. It was also demonstrated that the control can mitigate torque disturbances due to fault clearing and that the driver can operate with one or two open phases. Suitability of SRM drives for EPS was thus proved. In the future, the prototype will be installed in a vehicle for evaluation under real operating conditions.

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ANNEX: 8/6 SRM DATA

Parameter	Symbol	Value
Number of stator poles	N_S	8
Number of rotor poles	N_R	6
Stator outer diameter	D_0	104 mm
Length	L	80 mm
Stator inner diameter	D_i	88 mm
Airgap stator diameter	D_s	56.7 mm
Airgap rotor diameter	D	56 mm
Airgap	g	0.35 mm
Stator pole angle	β_s	22.37º
Rotor pole angle	β_r	24.12º
Stator pole width	b_s	11 mm
Rotor pole width	b_r	11.7 mm
Stator yoke thickness	h_y	8 mm
Rotor yoke thickness	h_n	8.5 mm
Stator slot depth	h_s	15.65 mm
Rotor slot depth	h_r	12 mm
Axis diameter	D_e	15 mm
Axis diameter (drive end)	D_{out}	12 mm
Magnetic material		FeV 270-50 HA
Number of turns per pole	N_p	28
Wire diameter	d_c	1.4 mm
Class of isolation		180ºC

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