**Magnetic Resolver for Angular Position Sensing of Electric Drives Based on Hall-Effect Sensors**

**Abstract\_** Control of AC electric drives operating with sinusoidal current and sinusoidal airgap flux waveforms require an accurate rotor position feedback for a stable performance. Among all existing sensors for angular position measurement, encoders and resolver, are the most used in industry. Variable reluctance resolvers are the preferable option when operating in harsh environments due to its robustness, but this is a costly solution. This paper presents a magnetic resolver for angular position sensing of electric drives based on Hall effect sensors and a magnetic rotor. The proposed sensor presents the same mechanical advantages of the VR resolver with a simpler mechanical design, without wounded parts and fully compatible, in terms of signal levels, with available resolver to digital converters or commercial drives.

1. INTRODUCTION

AC electric drives operate with sinusoidal current and airgap flux waveforms so that they need an accurate rotor position feedback for a stable performance under closed loop control. Rotor position can be detected in most machine types by applying self-sensing strategies, but due to complexity, angular position is typically measured using an angular position sensor [1]. Despite the large number of types of angular position measurement systems that can be found in literature based on different operation principles: magnetic [2], capacitive [3],[4], inductive [5]; optical encoders and resolver, are the most used sensors in industry [1].In addition, most commercial inverters for electric drives applications provide compatibility with encoders and/or resolvers.

Optical incremental encoders are widely used as position feedback of AC drives because of their easily processed digital output signals, precise incremental position measurement and high resolution. However, some applications, e.g. using vector control algorithms, require absolute position measurement [1] to perform a torque, motion or position control. Optical absolute encoders provide absolute position information but at a higher cost and larger size. In general, optical encoders are characterized for a limited mechanical robustness due to a reduced range of temperature of operation and limited shock and vibration withstand capability compared to resolvers[6].

Compared to encoders, most electromagnetic resolvers have the capability to provide absolute position signals with high precision. In addition, the brushless resolver [8] and the variable reluctance resolvers [9],[10], inherently add high vibration withstand capability, wide range of temperature of operation and can be easily made frameless mounted, integrated into the motor without the need of a coupling device and without adding friction to the system [7].

As variable reluctance resolvers are made of a thin structure and does not add windings in the rotor, this is frequently the choice for robots and electric vehicles and hybrid electric vehicles applications[7]. However, variable reluctance resolvers are an expensive option due current patent protection and constructive aspects: complicated winding, unsuitability for mass-production and unsatisfactory performance [6]. In addition, both stator and rotor need to be laminated to minimize power losses due to eddy current in the stator and rotor cores.

This paper proposes a magnetic resolver for angular position sensing of electric drives based on Hall-effect sensors and a magnetic rotor to overcome the mechanical limitations of optical encoders, and with a full compatibility with traditional resolvers (i.e wound field and variable reluctance). The proposed sensor presents the same mechanical advantages of the VR resolver with a simpler mechanical design: lamination is not needed and neither rotor nor stator are wounded, it is slim with reduced thickness and requires low power to operate. Its design allows it to be installed in-shaft (like VR resolvers) or through flexible couplings. FEA results are provided to demonstrate the viability of the proposed system and its accuracy. Experimental results will be included in the final paper, Different versions of the sensor prototype detailed in this digests are un being constructed.

1. DESIGN OF THE MAGNETIC RESOLVER.
2. Principle of Operation of a magnetic resolver

Resolvers can be classified into wound field (WF), brushless WF and variable reluctance (VR). These devices are generally made of two parts, one rotating (i.e. the rotor), magnetically coupled with two identical windings having a 90º electrical phase shift place in the stationary part (i.e. the stator). In VR resolvers, excitation windings are also placed in the stator (see Fig. 1a), the excitation signal in WF resolvers being transferred to its wounded rotor (see Fig. 1b) through slip rings (i.e. brush WF) or through a magnetic coupling (i.e brushless WF). A sinusoidal high frequency voltage or current signal is applied from the stator terminals. The resulting voltages in the two stator windings are a *sine* and *cosine* signals whose angle is modulated by the rotor angle. WF resolvers have a wide temperature range of operation and with a simple and robust construction; in addition they are highly insensitive to noise and tolerate long transmission cables length [7] ,[8]. On the other hand, VR resolvers have both the output and the exciting windings in the stator, avoiding the use of brushes or slip rings and the inherent mechanical disadvantages. VR resolvers are lighter and can be installed in-shaft.

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| a) | Macintosh HD:Users:daviddiazreigosa:Documents:OneDrive - Universidad de Oviedo:Congresos:ECCE2019:Resolver_to_encoder:Paper:Figuras:Fig1b.tiff |
| b) | Macintosh HD:Users:daviddiazreigosa:Documents:OneDrive - Universidad de Oviedo:Congresos:ECCE2019:Resolver_to_encoder:Paper:Figuras:Fig1c.tiff |
| b) | Macintosh HD:Users:daviddiazreigosa:Documents:OneDrive - Universidad de Oviedo:Congresos:ECCE2019:Resolver_to_encoder:Paper:Figuras:Fig1d.tiff |
|  | Fig. 2. Resolver signals, a) *excitation*, *ve(t)*, b) *Output 1* of the resolver, *vc(t)* (i.e. *cosine*), c) *Output 2* of the resolver, *vs(t)* (i.e. *sine*). *ωs* = 2*· π ·* 500 rad/s, *ω*r = 2*· π ·* 50 rad/s |

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| a) |  | b) |  |
|  | Fig. 1. Variable reluctance resolver | | |

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|  | (1) | |  | | (2) |  | (3) |
|  | | (4) | |  | (5) |  |  |

Both WF and VR resolvers are a special type of rotary transformer that couples a primary winding (*Input*, see Fig. 1) with two secondary windings (*Output 1* & *2*) that are 90 electrical degrees phase shifted. Excitation signal, i.e. *vE(t)* in Fig. 1, is generally a sine wave (1) (see Fig. 2a ), where *E0* and *ωs* are the magnitude and frequency of the excitation signal respectively. The output signals of the resolver are *vS(t)* (2) and *vC(t)* (3) (see Figs. 2a and 2b.), where *k* is the equivalent turn ratio of the magnetic coupling, *θr* is the rotor position, *X* is a multiplication factor for the angle [6].

*vS(t)* and *vC(t)* signals are the input of a resolver-to-digital (R/D) converter, which typically includes a demodulation stage to subtract the carrier signal; *vS(t)* and *vC(t)* after the demodulation being expressed by (4) and (5); A large variety of methods have been proposed to obtain the rotor position, *θr*, from (4) and (5).

1. **Proposed Magnetic Resolver**

The proposed magnetic resolver schematically shown in Fig. 3. It is made of two parts, one rotating (i.e. the rotor) made of a ferromagnetic core and permanent magnets (*PMs* in Fig. 3) and one stationary (i.e. the stator) containing mainly two Hall-effect sensors (*HallC* and *Halls* in Fig. 3) 90 electrical degrees phase shifted. As the angular position of the rotor changes, the rotor flux seen form the stator will vary from positive and negative field due to the PMs arrangement. For a proper rotor design, a sinusoidal flux distribution on the rotor surface can be achieved.

Hall-effect sensors are usually fed using DC voltage or current (6), see Fig. 4a. Under these conditions and for a constant rotor speed and sinusoidal rotor flux variations, the output signals of the Hall-effect sensors *vHS(t)* and *vHC(t)* are as shown in Fig. 4b (7) and Fig. 4c (8) respectively. Although rotor position can be obtained from (7) and (8), these equations does not represent the same behavior of traditional encoders and may not be compatible with available resolver to digital converters. Full compatibility with signals provided by traditional resolvers, see Fig. 2 are achieved with the proposed magnetic resolvers when the Hall-effect sensors are fed with AC signals, since Hall-voltage, *vHall(t),* in Hall effect sensors is proportional to both current through the Hall element, *i(t)*, and flux density applied, *B(t)*, (9). Fig. 4e and f show the signals *vHS(t)*(11) and *vHC(t)* (12) when the Hall sensors *Hallc* and *Halls* have been supplied with and AC voltage (10), Fig. 4d.

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|  | a) |  | d) |  |
| b) |  | e) |  |
| c) |  | f) |  |
| Fig. 3. Schematic representation of the proposed magnetic resolver and position of the Hall-effect sensors. |  | Fig. 4. Excitation and resulting waveforms of the proposed resolver: a) DC excitation, b) Sin output for DC excitation, c) Cos output for DC excitatation, d) AC excitation, e) sin output for AC excitation and f) cos output for AC excitation. | | |

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|  | | | (6) |  | | | (7) |  | (8) |
|  | (9) |  | | | (10) |  | | | (11) |
|  | | | | | (12) |  | | | (13) |

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| Table I. Parameters of the Multi-objective function | | |
| Symbol | Function | Definition |
| *O1* | THD | Harmonic distortion of flux in % |
| *O2* |  | Fundamental flux amplitude in Tesla with target amplitude of 0.08 |
| *O3* | PM Volume | Magnet volume in mm3 |
| *w1* | 20 | Weighting factor of *O1* |
| *w2* | 20000 | Weighting factor of *O2* |
| *w3* | 10 | Weighting factor of *O3* |
| Penalty | 0 if within boundary  100 if outside boundary | Penalty given when the input variables are outside the minimum and maximum range. |

1. **Optimization of the magnetic resolver**

Magnetic geometry of the proposed sensor needs to be optimized to achieve a sinusoidal flux density waveform with a minimum harmonic distortion (THD), maximum flux density in the airgap (i.e. position of the hall effect sensors) and minimum magnet volume, which is achieved with multi-objective design optimization. The parameters of the multi-objective function (13) are shown in Table. I and is used for calculating the cost of each design. *On* are objective variables, and *wn* are weighting factors. The goal is to minimize the cost of the multi objective function. The penalty is used for eliminating designs that either violate the geometric constraints set for the geometrical parameters shown in Table II. Differential evaluation is used for Hall effect sensor optimization. Differential evaluation optimization technique is used to search the design space by 2D finite element analysis (FEA) evaluation given predefined sensor parameters as shown in Fig. 4 and Table. II. Stack length has been kept fixed to 5 mm thickness, but this parameter can also be optimized. The results will be included in the final paper.

Three different cases have been optimized, the only difference being the permanent magnet materials: ferrite, sintered NdFeB and bonded NdFeB magnets. Table III shows a comparative analysis of the results and Fig. 5 shows FEA results with the flux distribution on the resulting geometry designs. As expected, the maximum peak flux density in the airgap is obtained with the prototype equipped with sintered NdFeB magnets, which is important from the point of view of the sensitivity of the Hall-effect sensor in a practical application. Similar peak flux density values are obtained with the prototype equipped with bonded NdFeB magnets but nearly double the volume of magnetic material. The prototype based on ferrite magnets induces the smallest flux density in the airgap, leading to peak values close to half the results obtained with the NdFeB-type magnets. However, the total cost of the ferrite-based prototype would be the lowest and avoids dependency on rare earth materials.

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| a) |  | b) |  | Table II. Geometric patameters description | |
| *Darc1* | Rotor d-axis outer diameter |
| *Darc2* | Rotor q-axis outer diameter |
| *ϕDhall* | Hall sensor distance from center |
| *ϕDin* | Rotor inner diameter |
| *ϕDring* | Ring outer diameter |
| *Ring\_th* | Ring thickness |
| *Rarc1* | Rotor d-axis outer arc |
| *Rarc2* | Rotor q-axis outer arc |
| *mth* | Magnet thickness |
| *Min1* | Magnet distance from *ϕDarc1* |
| *mgap* | Magnet gap in slot |
| *SW* | Slot width |
| *Bth1* | Outer bridge thickness |
| *Bth2* | Inner bridge thickness |
|  | Fig. 4. Parameters of the magnetic resolver sensor a), general view and b), detailed view. | | |  | |

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| a) | b) | | | c) | |
| Fig. 5. Flux lines distribution for the optimized magnetic resolver design equipping a) Sintered NdFeB magnets, b) Bonden NdFeB magnets and c) Ferrire magnets. | | | | | |
| Table III. Optimization results of the magnetic resolver according to PM material | | | | | |
|  | | Ferrite | Sintered NdFeB | | Bonded NdFeB |
| THD (%) | | 1.55 | 0.27 | | 0.84 |
| Fundamental flux amplitude (mT) | | 36.23 | 95.81 | | 86.68 |
| permanent magnet volume (mm3) | | 97.33 | 37.16 | | 60.65 |

1. FEA RESULTS

This section shows FEA results obtained for the three prototypes optimized for sintered NdFeb, bonded NdFeB and ferrite magnets shown in Fig. 5. Fig. 6a shows the magnetic flux density obtained at the position of the Hall-effect sensor corresponding to the *sine* signals. Figs. 6b, c and d shows the FFT of the signals in Fig.6a, used to calculate the THD shown in Table III.

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| a) | | Bonded Nd  Ferrite  Sintered Nd | b) |  | |
| c) | |  | S |  | |
|  | Fig. 5. a) Sin output of the hall effect sensors for the three types of resolvers, b) FFT of sin output for sintered NdFeB magnets, c) FFT of sin output for bonded NdFeB magnets d) FFT of sin output for ferrite magnets. | | | |

1. CONCLUSIONS

This paper proposes a new sensor for angular position measurement. It can emulate a resolver behavior without the need of any wounded parts, using low cost Hall-effect sensors. The proposed device consists of two Hall-effect sensors mounted of on the stationary part, 90 electrical degrees phase shifted, which measure the magnetic flux leakage of the PM embedded in the moving part. The system provides a signal which is fully compatible with conventional resolver circuitry. The proposed system can be integrated in a machine avoiding the use of coupling devices and bearings, resulting therefore in a simple, compact and robust construction. FEA results have been provided to demonstrate the viability of the proposed system. The final paper will include experimental results of the real sensors, currently under construction.

1. REFERENCES
2. R. M. Kennel, "Why Do Incremental Encoders Do a Reasonably Good Job in Electrical Drives with Digital Control?," Conference Record of the 2006 IEEE Industry Applications Conference Forty-First IAS Annual Meeting, Tampa, FL, 2006, pp. 925-930.doi: 10.1109/IAS.2006.256635
3. F. Jiang, D. Lou, H. Zhang, L. Tang, S. Sun and K. Yang, "Design of a GMR-based magnetic encoder using TLE5012B," 2017 20th International Conference on Electrical Machines and Systems (ICEMS), Sydney, NSW, 2017, pp. 1-4. doi: 10.1109/ICEMS.2017.8056197
4. B. Hou, C. Li, Z. Gao, Q. Wei, B. Zhou and R. Zhang, "Design, Optimization, and Compensation of a High-Precision Single-Excitation Absolute Capacitance Angular Encoder up to ±4’’," in IEEE Transactions on Industrial Electronics, vol. 66, no. 10, pp. 8161-8171, Oct. 2019. doi: 10.1109/TIE.2018.2886762
5. H. Pu, H. Wang, X. Liu, Z. Yu and K. Peng, "A High-Precision Absolute Angular Position Sensor With Vernier Capacitive Arrays Based on Time Grating," in IEEE Sensors Journal, vol. 19, no. 19, pp. 8626-8634, 1 Oct.1, 2019.  
   doi: 10.1109/JSEN.2019.2921479
6. M. Howard, Incremental encoders, absolute encoders & pseudo-absolute encoders, Feb. 2013. Accessed on: Dec. 15, 2019. [Online]. Available: <https://www.zettlex.com/wp-content/uploads/2017/08/incremental-encoders-vs.-absolute-encoders_Rev_3.1.pdf>
7. C. Jin, I. Jang, J. Bae, J. Lee and W. Kim, "Proposal of Improved Winding Method for VR Resolver," in IEEE Transactions on Magnetics, vol. 51, no. 3, pp. 1-4, March 2015, Art no. 8102404. doi: 10.1109/TMAG.2014.2348321
8. L. Sun, "Analysis and Improvement on the Structure of Variable Reluctance Resolvers," in IEEE Transactions on Magnetics, vol. 44, no. 8, pp. 2002-2008, Aug. 2008. doi: 10.1109/TMAG.2008.923315
9. J. Figueiredo, “Resolver models for manufacturing,” IEEE Trans. Ind. Electron., 58(8): 3693–3700, Aug. 2011.
10. L. Z. Sun, J. B. Zou, and Y. P. Lu, “New variable-reluctance resolver for rotor-position sensing,” in Proc. IEEE Region 10th Conf. TENCON, vol. 4. Chiang Mai, Thailand, pp. 5–8, Nov. 2004.
11. “Design-Oriented Modelling of Axial-Flux Variable-Reluctance Resolver Based on Magnetic Equivalent Circuits and Schwarz–Christoffel Mapping,” IEEE Trans on Ind. Appl., 65(5): 4322–4330, May 2018.