Magnetic Resolver Using Hall-Effet Sensors

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*Abstract*— Control of AC electric machines requires, in many cases, accurate knowledge of rotor position. Encoders and resolvers are the most widely used option in the industry. Variable reluctance (VR) resolvers are advantageous in harsh environments due to their robustness; however, they represent a significant portion of the total drive cost. This paper presents a magnetic resolver using low-cost Hall effect sensors. Advantages with conventional encoders include compactness and reduced cost, which are achieved without penalizing the other properties of VR resolvers. The proposed sensor is fully compatible with conventional drives and supports wide carrier frequency and supply voltage variations.

Keywords—Magnetic Resolver, Hall-sensor, angular position measurement.

# Introduction

Electric drives are used in a vast range of applications, including domestic, industrial, traction, aerospace, etc. Precise control of AC electric machines requires accurate knowledge of the rotor position. Optical encoders (optical-based angular position sensors) and resolvers (inductive-based angular position sensors), are the most used sensors in the industry [1]-[5], although many other alternatives have been reported in the literature: capacitive [2]-[3], inductive [4] or magnetic-based angular position sensors are available for specific applications. Capacitive-based angular position sensor in [3] provides high precision output but requires additional circuitry to be compatible with standard encoder or resolver signals. Inductive position sensors are axially planar [4], low weight, with a similar operation principle to a transformer but lack robustness. Magnetic angular positions sensors are mainly based on Hall-effect or Giant Magnetoresistance (GMR) devices. Magnetic sensors are used for automotive applications (e.g., throttle position detection, shaft position…) are also commercially available [16], [17]. The main drawbacks of these devices are the robustness decrease, inertia increase, and extra room. In addition, their accuracy depends on the offset or misalignment of the permanent magnet material that must be attached to the rotating part.

Optical encoders are likely the preferred option in general purpose applications and can provide incremental or, at a higher cost, absolute angular position. However, they often suffer from a limited range of temperature of operation and a reduced capability to withstand shock and vibration compared to resolvers.

Resolvers inherently detect the absolute position and exhibit high vibration and shock withstand capability, a wide range of temperature of operation, and high rotational speed. Resolvers can be brushless [8], brushed (in disuse), or variable reluctance (VR) [9]-[10]. A brushless resolver is a rotatory transformer excited by AC voltage to the rotor winding [8]. An AC voltage is induced in the output winding (stator), which is modulated by the rotor position. VR resolvers do not have rotor windings and bearings and have both the output and the excitation windings in the stator; no brushes or rotating transformer is therefore required. They 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], what makes them appealing in traction applications (i.e., electric vehicles and hybrid electric vehicles), [7], [8]. Their main drawback, however, is the cost [6],[11].

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This paper proposes an alternative design of a magnetic resolver using field sensors (i.e., Hall-effect) and a magnetized moving part made of non-laminated electrical steel and permanent magnets. Compared to VR resolver, the proposed design is simpler, more compact, cheaper, and easier manufacturability: it does not require stator/rotor laminations nor windings. Its power consumption is very low, and it can provide more than one independent output for a redundant mode of operation. It can be easily scalable in size, or the number of poles to meet the requirements of a specific application. Still, it will retain the main properties of VR resolver, and is fully compatible, meaning that no modification in the cabling or electronics of the drive is required.

The paper is organized as follows: principles of operation are discussed in Section II, design optimization is discussed in section III, and the validation of the model using FEA is presented in Section IV. Section V shows an assembly of the proposed prototype, and preliminary experimental results and conclusions are presented in sections VI and VII, respectively.

# Principle Of Operation Of Operation

A brief description of conventional resolvers aimed to establish the basis for the assessment of the proposed concept is presented following.

Resolvers can be classified into brushless wound field (WF) and variable reluctance (VR). Both are a special type of rotary transformer that couples a primary winding (*Excitation* 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), of magnitude and angular frequency *E0* and *ωs,* respectively. The output signals of the resolver are *vS(t)* (2) and *vC(t)* (3) (see Figs. 2b and 2c.), 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].

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

Voltages *vS(t)* and *vC(t)* are the input to a resolver-to-digital (R/D) converter, which typically includes a demodulation stage to subtract the carrier signal; (4) and (5) being obtained after demodulation. A large variety of methods have been reported to obtain the rotor position, *θr*, from (4) and (5) [15].

Rotor winding of WF resolvers is excited by an AC voltage, which can be produced by means of a magnetic coupling (i.e., brushless WF, see Fig. 1a). Voltages in the stator windings are a *sine* and *cosine* signal, which is modulated by the rotor angle . In VR resolvers, excitation winding is also placed in the stator (see Fig. 1b), avoiding the use of brushes or slip rings. In addition, they can be in-shaft installed. An AC voltage/current signal is injected into the excitation winding, the resulting voltages in the two stator windings being a *sine* and *cosine* signals whose angle is modulated by the rotor angle as for the WF case. VR resolvers have a wider temperature range of operation and, with simple and robust construction, are less sensitive to noise and allow longer transmission cables [7] ,[8].

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| a) |  |
| b) |  |
| Fig. 1. Resolvers, a) WF and b) VR. | |

## Principle of Operation of the magnetic resolver

The proposed magnetic resolver is schematically shown in Fig.3. It consists of a rotor and a stator: the rotor is made of a non-laminated ferromagnetic core and permanent magnets (*PMs* in Fig.3); the stator consists of two Hall-effect sensors 90 electrical degrees phase shifted. Linear Hall-effect integrated circuit (IC) sensors must be used for the assembly of the proposed magnetic resolver. These types of ICs allow current control through the Hall element without integrated electronics.

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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 |
| c) | 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 | |

Hall-effect sensors are usually fed using DC voltage (6) or current, see Fig. 4a. The output voltage (Hall voltage) of the Hall-effect sensors *vHS(t)* and *vHC(t)* (see Fig. 3) for the case of a constant rotor speed are (7)-(8), (see Fig. 4b and Fig. 4c). While these signals are modulated by the rotor position, they differ from the signals provided by conventional resolvers, where the position information signals produce an amplitude modulation of a carrier signal (see Fig. 2). Alternatively, the Hall-effect sensors can be fed with and AC voltage (or current). The output voltage when the rotor speed is constant will be in this case (11)-(12) (see Fig. 4d and Fig. 4f), which are equal to the signals provided by conventional resolvers. For every pair of poles (p) in the rotor, four Hall-effect sensors can be installed in the rotor providing duplicated signals for applications where redundancy is required.

It must be remarked that to obtain (11)-(12) implies a sinusoidal flux distribution in the rotor surface. Rotor design to achieve this target is described following.

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

# Design Optimization

Differential evolution optimization technique [13] was used to find the optimum solution in the design space using 2D finite element analysis (FEA). Rotor parameters are shown in Fig. 4 and Table. II.

The desired properties of the hall effect sensor based resolver are included in the objective function variable, *On*, in the multi-objective (MO) in (13): the magnitude of the airgap flux density, *Q2*, Total harmonic distortion (THD) of the flux density, *Q1*, and the volume of the permanent magnet (PM), *Q3*. The fundamental component of the airgap flux density will decide the sensitivity of the proposed resolver, where the level of THD indicates the quality of the signal for the rotor position estimation. The PM volume is included in the objective function to result in a low-cost, high accuracy resolver. The goal for the multi-objective optimization is to find a minimum cost of the MO in (13), where *wn* is the weighting factor of each objective variable. More details about the variable used in the multi-objective optimization is in Table I. The penalty is used for eliminating designs that violate the geometric constraints set for the geometrical parameters shown in Table II.

The resulting optimized resolver design, therefore, will be high sensitivity, low distortion, low-cost resolver given the pre-defined boundary conditions. Three different types of permanent magnet materials have been evaluated: Ferrite, sintered NdFeB, and bonded NdFeB magnets. Table III summarizes the optimization results.

1. Parameters Of The Multy-Objective Function

| Symbol | Function | Definition |
| --- | --- | --- |
| O1 | THD | Harmonic distortion of flux in % |
| O2 |  | Fundamental flux amplitude in Tesla with a 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 the boundary  100 if outside boundary | Penalty is given when the input variables are outside the minimum and maximum range. |

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| a) |  |
| b) |  |
| Fig. 4. Dimensions of the magnetic resolver a), general view and b), detailed view. | |

1. Geometric Parameters Description

| Symbol | Definition |
| --- | --- |
| 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. 5 shows an example of the flux distribution on using the selected geometry for the three permanent magnet materials. As expected, the maximum peak flux density in the airgap is obtained with the prototype equipped with sintered NdFeB magnets. This will allow better use of the measuring range of the Hall-effect sensor, eventually improving the signal to noise ratio. Obtaining a similar peak flux density bonded NdFeB magnets requires almost twice of magnetic material. Ferrite magnets provide, as expected, the smallest flux density, with a peak value in around half of that obtained with NdFeB magnets. The Ferrite vs. NdFeB volume to achieve the same peak flux density is around 2.5. Even in this case, the ferrite-based solution is expected to be cheaper.

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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) Ferrite magnets. Blue (•) and red (•) spots represent the HallC and HallS sensors. | |

1. Optimization Results Of The Magnetic Resolver

|  | PM Material | | |
| --- | --- | --- | --- |
|  | Ferrite | Sintered NdFeB | Bonded NdFeB |
| THD (%) | 1.55 | 0.27 | 0.84 |
| Fundamental flux amplitude (mT) | 36.23 | 95.81 | 86.68 |
| PM volume (mm3) | 97.33 | 37.16 | 60.65 |

1. Results obtained from FEA simulation

# Validation Of The Resolver Using FEA

This section shows FEA results for the three optimized prototypes using sintered NdFeb, bonded NdFeB, and Ferrite, respectively. Fig. 6a shows the magnetic flux density at the position of *Halls* sensor (see Fig. 3) along with a rotor revolution for the three cases. Fig. 6b shows the corresponding FFTs, from which the THD in Table III are obtained. It can be observed that THD in all the cases is small, all harmonics being at least two orders of magnitude smaller than the fundamental component. It is noted that these results might be influenced by the bandwidth of the Hall-Effect sensors, which is typically >250kHz [12]. However, the bandwidth of the Hall-effect sensors will have virtually no influence in standard machines used in traction applications [14]. Fig. 6c shows the measured position for the three different rotor designs compared to FEA results. Fig. 6d shows the error in the measured position, which is due to the harmonics in the flux waveform shown in Fig. 6b and does not account for errors due to assembling tolerances, circuitry, noise, misalignments, etc.

It can be observed in Fig. 6d that the lower error is obtained with the sintered NdFeB magnet, ferrite magnets showing the worst behavior. Measurement errors are ±1.1º (Ferrite based), ±0.35º (bonded NdFeB based), and ±0.09º (sintered NdFeB based). Position error of commercially available resolvers is in the range of ±0.5-1.0º for VR resolvers [11] and around ±0.16º for brushless resolvers, meaning that the accuracy is comparable with commercially available resolvers.

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| a) |  |
| b) |  |
| c) |  |
| d) |  |
| Fig. 6. Performance of the three types of resolvers, a) *sin* output of the hall effect sensors, b) FFT of *sin* output (in a)), c) resulting position angle and d) resulting angle error. | |

# Assembly Of The Proposed Prototype

The proposed prototype can be assembled in two different configurations: in shaft mounting and shaft type for connections through flexible couplings. In any case, the necessary circuitry is the same, both allowing redundant configuration (i.e., provides duplicated signals). Fig. 7a shows the laser cutout of the optimized designs equipping Ferrite magnets and equipping Bonded NdFeB magnets, the PM samples being shown in Fig. 7b. The same laser cutout and magnets can be used for both the in-shaft and the shaft-type resolvers.

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| a) |  |
| b) | Imagenes de imanes |
| Fig. 7. a) Lamination of the optimized geometries for the magnetic resolver design equipping: sintered NdFeB (left) and Ferrite (right). Scale in mm, and b) NdFeB and Ferrite magnets for the designs in Fig. 7a. | |

## Shaft-type assembly

The shaft-type magnetic resolver is shown in Fig. 8. It is equipped with the rotor cutout and PMs shown in Fig 7. It was designed with a Ø8 mm shaft the diameter of the body and axial dimensions being Ø52 mm and 17 mm respectively. This design is suitable to be connected to a rotating shaft through flexible couplings. It can be observed that the PCB integrates four Hall-effect sensors (i.e., two HallC and two HallS), and therefore it can provide redundant output signals. The design includes two bearings, one at each rotating part and the rear cover hosts wiring interconnection.

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| Fig. 8. Disassemble view of the Shaft-type magnetic resolver |

## In-shaft mount assembly

The in-shaft type magnetic resolver is shown in Fig. 9. It is equipped with the rotor cutout and PMs shown in Fig 7. The rotor of the sensor is directly connected to the machine shaft and fixed by a nut. The axial length of the sensor exploding bolts is 5 mm, and the diameter of the sensor is Ø 70 mm. It can be observed that the PCB integrates only two Hall-effect sensors (i.e., HallC and HallS), but this design allows a redundant configuration by increasing the number of Hall-effect sensors. This design requires no bearings. The wiring interconnection is designed for a shielded flat cable.

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| Fig.9 In-shaft type magnetic resolver inserted in an endshield of a machine. |

## Electronic circuitry

A conditioning system is required for the proposed prototype to achieve full compatibility with commercial drives in terms of power supply, power consumption, and output voltage levels. Its objective is twofold: provide supply voltages for the Hall elements and the additional ICs and adapt output voltage levels within the range of commercial drives.

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| Fig. 10. Simplified representation of the electronic circuitry. |

Fig. 8 shows a simplified representation of the electronic circuit needed for the proposed sensors. The excitation signal is rectified to provide symmetrical voltage supply to the circuit, as demanded by the operational amplifiers. Hall elements (i.e., HallC and HallS) are feed using constant voltage what produces a constant current through the hall elements since hall elements are resistors from an electrical point of view. Note that a temperature variation of the hall element will have a direct impact on the current through the hall element. However, this will not affect the position measurement since the rotor position information is in the phase of the current waveforms and not the amplitude (see Fig. 2).

The total power consumption of the proposed system is approximately the power consumption of the Hall-element. The power consumption of the rectification stage can be negligible (i.e., conduction losses of a rectifier diode). The power consumption of the gain stages can also be negligible since ultra-low power differential operational amplifiers are used.

The circuit in Fig. 8 provides differential output signals to enhance noise immunity in the transmission wire.

# Preliminary Experimental Results

An initial prototype of the shaft-type sensor is shown in Fig. 11. In this design, the fixed parts of the sensor (i.e., shaft, stator, and cover) have been 3D printed using polyacid material (PLA). The moving parts (i.e., magnets and rotor) are made of the materials shown in Fig. 7: Bonded NdFeB magnets and the laser-cut silicon steel 50H350. The PCB integrates two Hall-effect sensors (i.e., HallC and HallS), the simplified power and conditioning stages being shown in Fig. 10.

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| 3D printed design |
| Fig.11 Picture of the 3D printed design in a testbench |

The sensor is attached to a Brushless PMS motor in a testbench, see Fig. 11. Fig. 12 shows the output waveforms provided by the magnetic resolver and Fig. 13a) shows a speed variation profile and Fig. 13b) shows the measurement error. It can be observed that the maximum error is XX rad.

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| --- | --- |
| a) | Excitation signal |
| b) | Cosine signal |
| c) | Sine signal |
| Fig. 12. Magnetic 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 · XX rad/s, ωr = 2· π · XX rad/s | |

|  |  |
| --- | --- |
| a) | Speed profile |
| b) | Measurement error |
| Fig. 13. a) Speed profile and b) measurement error. ωs = 2· π · XX rad/s | |

# Conclusions

A magnetic resolver using hall effect sensors is proposed in this paper. While it provides similar accuracy, its construction is simpler and cheaper. FEA results have been provided to demonstrate the viability of the proposed system. Two different designs have been proposed allowing redundant position measurement. Preliminary experimental results shown that the maximum accuracy is.. INCOMPLETE

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