Magnetic Circuit Design for Correct Direction Detection of TLE4966

Application Note

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1 Introduction

For many applications the information of speed and rotation direction of a motor is necessary to know. This can be done very convenient with a Hall switch and a magnetized pole wheel mounted on the axle of the motor. To determine the rotation direction, two sensors in a certain distance are used (**Figure 1**). The direction information is then obtained from the phase difference of the two output signals of the Hall elements S1 and S2. The TLE4966 consists of two Hall elements with a distance of d = 1.45mm and calculates this information internally. A dedicated output pin provides the direction of rotation (HI /LO) corresponding to “right” or “left” whereas the speed is provided on a second output pin.

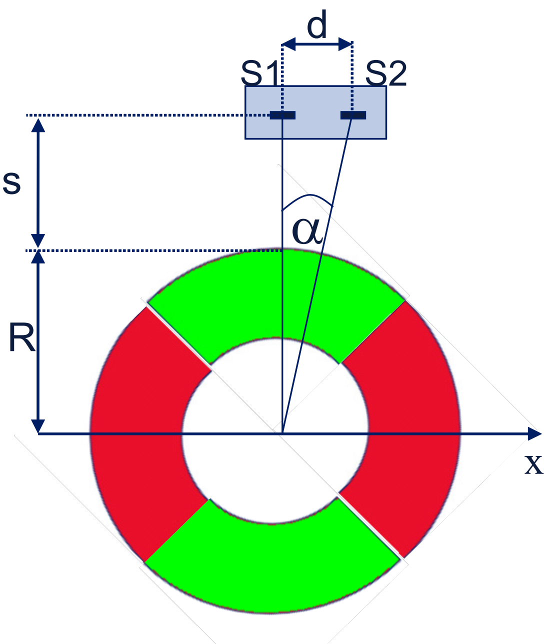

Figure 1 Configuration with pole wheel and TLE4966 double Hall sensor

However, the reliability of the provided direction information depends on various parameters as well as the design of the magnetic circuit. This application note gives a guideline of the magnetic circuit design and explains the influence of the parameters (e.g. magnetic field strength, geometry of the pole wheel, distance to the sensor)

2 Direction Detection Mechanism

The basic principle of the direction detection algorithm implemented in the TLE4966 is based on the fact that two internal signals are generated (from Hall elements S1 and S2 respectively), which have a certain phase shift. The direction of rotation corresponds to the sign of this phase shift (“which sensor switches first”). **Figure 2** shows the block diagram of the TLE4966.

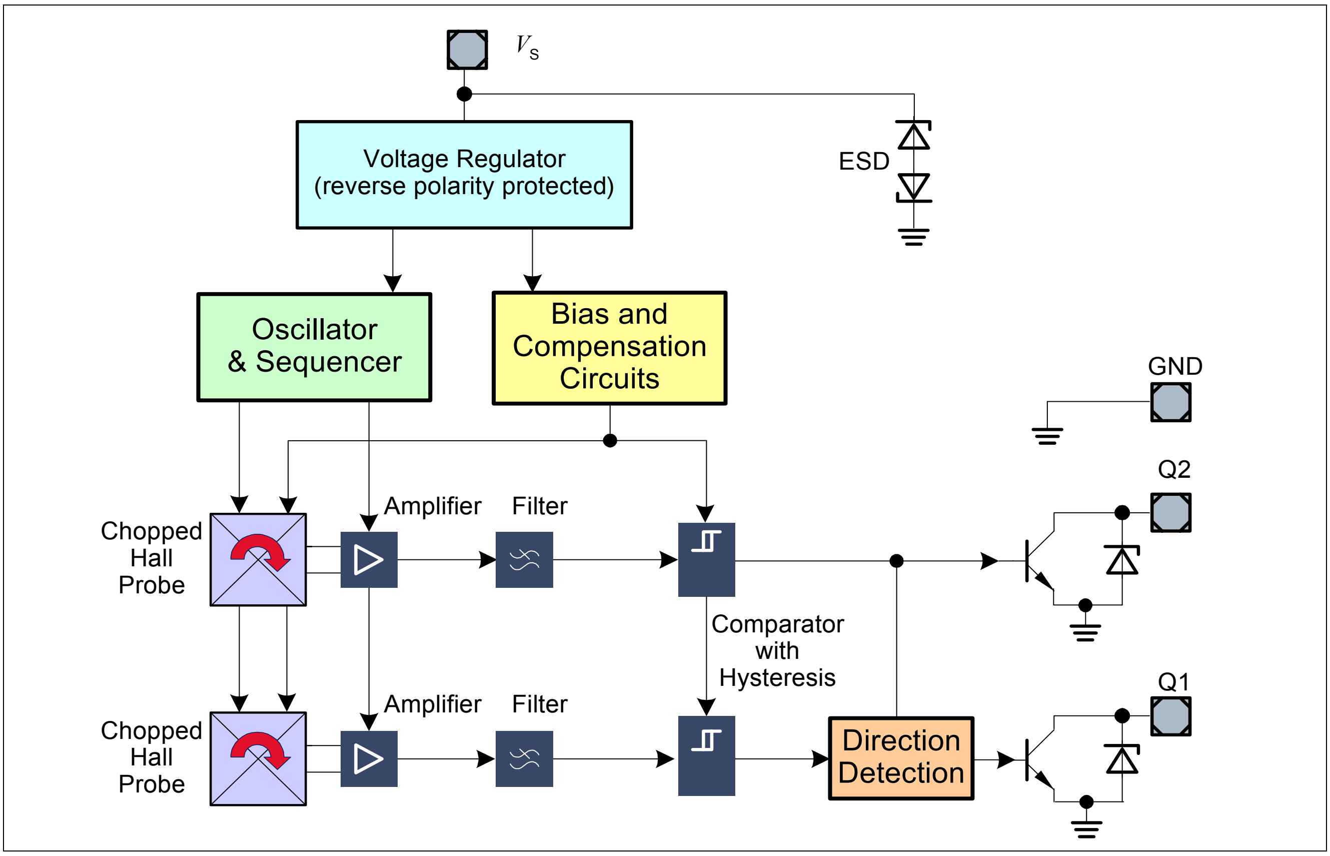

Figure 2 Block diagram of the TLE4966

The chopped Double Hall Switch comprises two Hall probes S1 and S2, bias generator, compensation circuits, oscillator, and output transistors.

The bias generator provides currents for the Hall probes and the active circuits. Compensation circuits stabilize the temperature behavior and reduce technology variations.

The Active Error Compensation rejects offsets in signal stages and the influence of mechanical stress to the Hall probes caused by molding and soldering processes and other thermal stresses in the package. This chopper technique together with the threshold generator and the comparator ensures high accurate magnetic switching points.

The direction detection algorithm considers the two comparator switching of the two sensing elements S1 and S2 and determines the direction of rotation.

In **Figure 3** the two internal phase shifted signals from S1 and S2 are shown.

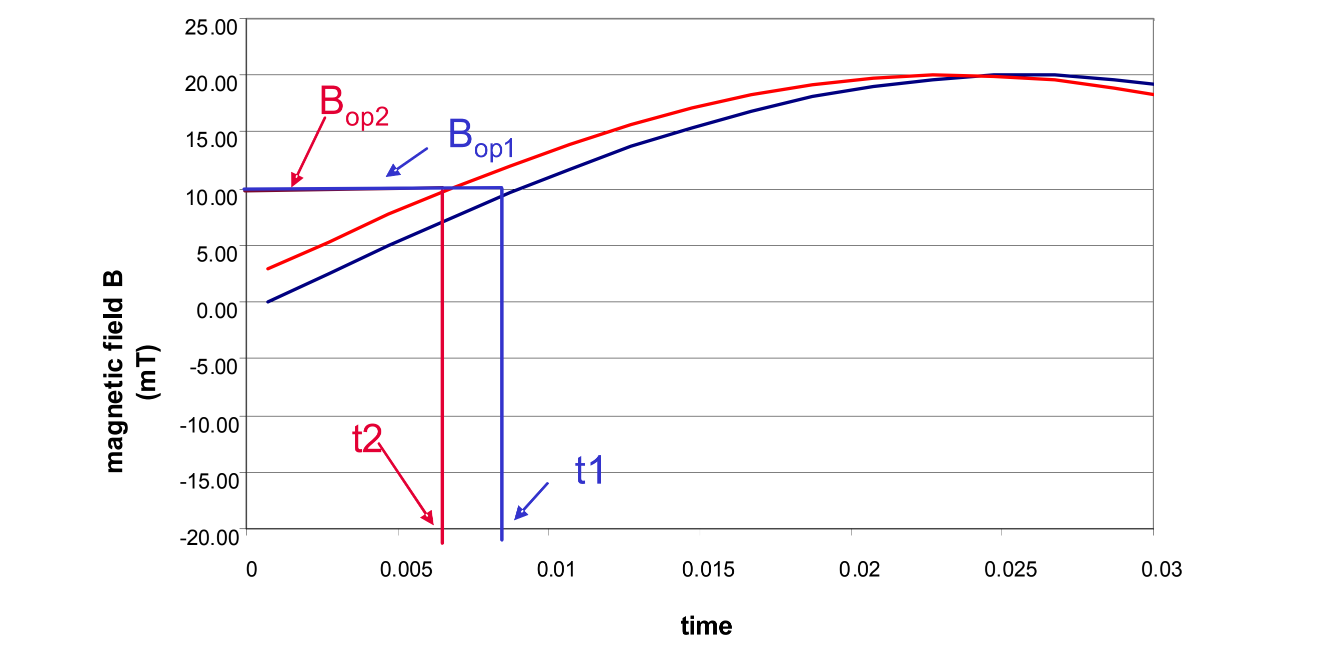

Figure 3 Internal phase shifted signals of S1 and S2

In the ideal case the magnetic parameters (B_{op}, B_{rp}) of the two Hall elements S1 and S2 are identical. Due to the phase difference of the signals, in the given example of **Figure 3**, S2 reaches the operating point B_{op2} before Hall sensor S1. This determines the calculated direction information

However, in reality, there is always a mismatch of the magnetic parameters of S1 and S2 due to process and manufacturing tolerances. The matching of the magnetic properties is called magnetic matching $B_{Match.}$ (B_{Match} = B_{op1} - B_{op2}). For the TLE4966 the magnetic matching B_{Match} is below +/-2mT at room temperature (see corresponding data sheet).

Under certain conditions it can happen, that the provided direction information is wrong. This depends on the magnetic field strength, the geometry and the value of B_{Match}. Such an example is shown in **Figure 4** where sensor S1 reaches the threshold B_{op1} before sensor S2 reaches B_{op2}. This leads to a wrong calculation of rotation direction compared to the correct value (**Figure 3**, S2 before S1).

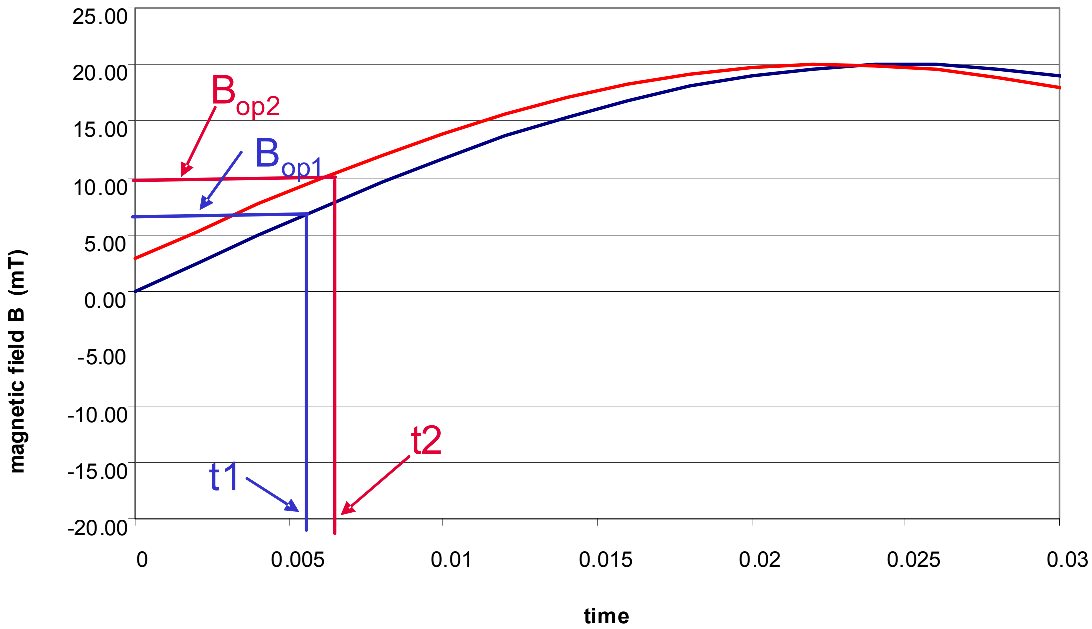

Figure 4 Wrong direction information (compare to ideal case in Figure 3)

In the following chapter a mathematical description of this effect is given. With the provided equations an estimation is possible whether the magnetic circuit is robust enough to provide always the correct rotating direction information.

3 Mathematical Description

The starting point is **Figure 1** where the geometry of the setup is displayed. R describes the radius of the pole wheel, s is the distance from the pole wheel to the sensing element and d is the distance of the sensing elements S1 and S2. For the TLE4966 d = 1.45mm. Due to this spatial distance of S1 and S2 a phase difference of the magnetic signal at the sensing elements S1 and S2 occurs. This phase difference Φ can be calculated with the following **Equation (1)**, where N describes the number of pole pairs of the pole wheel:

$$\Phi = N \cdot \alpha = N \cdot \operatorname{atan}\left(\frac{d}{s+R}\right) \tag{1}$$

It is obvious that the larger the phase difference Φ the easier is the detection of the correct rotation direction.

The magnetic field $B_1(t)$ and $B_2(t)$ at the location of the sensing elements S1 and S2 can be expressed with the following equation (**Equation (2)**). A sinusoidal magnetic field is assumed.

$$B_2(t) = B_0 \cdot \sin(\omega \cdot t + \Phi),\ B_1(t) = B_0 \cdot \sin(\omega \cdot t) \tag{2}$$

A sensor switching occurs at the time t_1 and t_2 as soon as $B_1(t_1) = B_{op1}$ and $B_2(t_2) = B_{op2}$.

With the help of **Equation (2)** the time t_1 and t_2 can be expressed:

$$t_1 = \frac{1}{\omega} \cdot \operatorname{asin}\left(\frac{B_{op1}}{B_0}\right) \tag{3}$$

$$t_2 = \frac{1}{\omega} \cdot \left[\operatorname{asin}\left(\frac{B_{op2}}{B_0}\right) - \Phi \right]$$

Introducing now the magnetic matching B_{Match} as $B_{Match} = B_{op1} - B_{op2}$ leads to **Equation (4)**:

(4)

$$t_2 = \frac{1}{\omega} \cdot \left[\operatorname{asin}\left(\frac{B_{op1} - B_{Match}}{B_0}\right) - \Phi \right]$$

As long as $t_2 - t_1$ does not change the sign, the calculated direction is correct. A change from correct to not-correct happens when $t_2 = t_1$. This gives the worst case condition which must be met in order not to have an error in rotation direction calculation. Substituting Φ from **Equation (1)** gives the final **Equation (5)**:

(5)

$$\operatorname{asin}\left(\frac{B_{op1}}{B_0}\right) = \operatorname{asin}\left(\frac{B_{op1} - B_{Match}}{B_0}\right) - \left(N \cdot \operatorname{atan}\left(\frac{d}{s + R}\right)\right)$$

For d << s+R the approximation atan(x) = x is valid. This leads to the **Equation (6)**

(6)

$$\operatorname{asin}\left(\frac{B_{op1}}{B_0}\right) = \operatorname{asin}\left(\frac{B_{op1} - B_{Match}}{B_0}\right) - \frac{N \cdot d}{s + R}$$

In this equation B_{op1} is the operating point of the sensor, B_0 is the amplitude of the magnetic field at the sensing element, B_{Match} describes the magnetic matching, N and R stand for the number of pole pairs and radius of the pole wheel and d = 1.45mm is the distance of the sensing elements in the TLE4966. This equation can be solved numerically and the minimum magnetic field amplitude B_0 can be determined which is necessary to provide a correct rotation direction information for a given pole wheel and geometry of the magnetic circuit.

Due to the assumptions made and the simplifications in the model, the obtained value of B_0 is only an approximation. However, it gives a good indication whether the magnetic circuit is robust enough to provide a correct rotation direction information. When designing such a magnetic circuit, a safety margin should be included to account for the simplifications made. In addition, the temperature behavior of the magnetic material has to be considered. There is generally a decrease of magnetic flux density with the temperature which can be up to -2000ppm/K for ferite magnets.This degradation has to be taken into account when designing the magnetic circuit which should work within the full temperature range of the application.

4 Example

In this chapter an example is shown how the reliability of calculated direction information depends on the geometry and pole wheel. The minimum magnetic field amplitude B_0 is estimated which is necessary to obtain a correct value of the rotation direction. The following parameters are used:

- B_{op} = 10mT (worst case value from data sheet TLE4966
- B_m = +/-3mT: magnetic matching (assumed worst case value, typical value +/-2mT according to data sheet)
- R = 7.5mm, radius of the pole wheel
- s = 2.5mm, distance between pole wheel and sensing element
- d = 1.45mm, distance of sensing elements on the TLE4966

Three different numbers of pole pairs are considered (N = 1, 2, 3). The **Equation (5)** is solved and the zero crossing ($t_1 = t_2$) is determined. This point of zero-crossing gives the necessary magnetic field strength B_0 to provide correct direction information (**Figure 5**, **Figure 6**, **Figure 7**). For each pole wheel three curves for B_{Match} = +3mT, 0mT and -3mT are calculated.

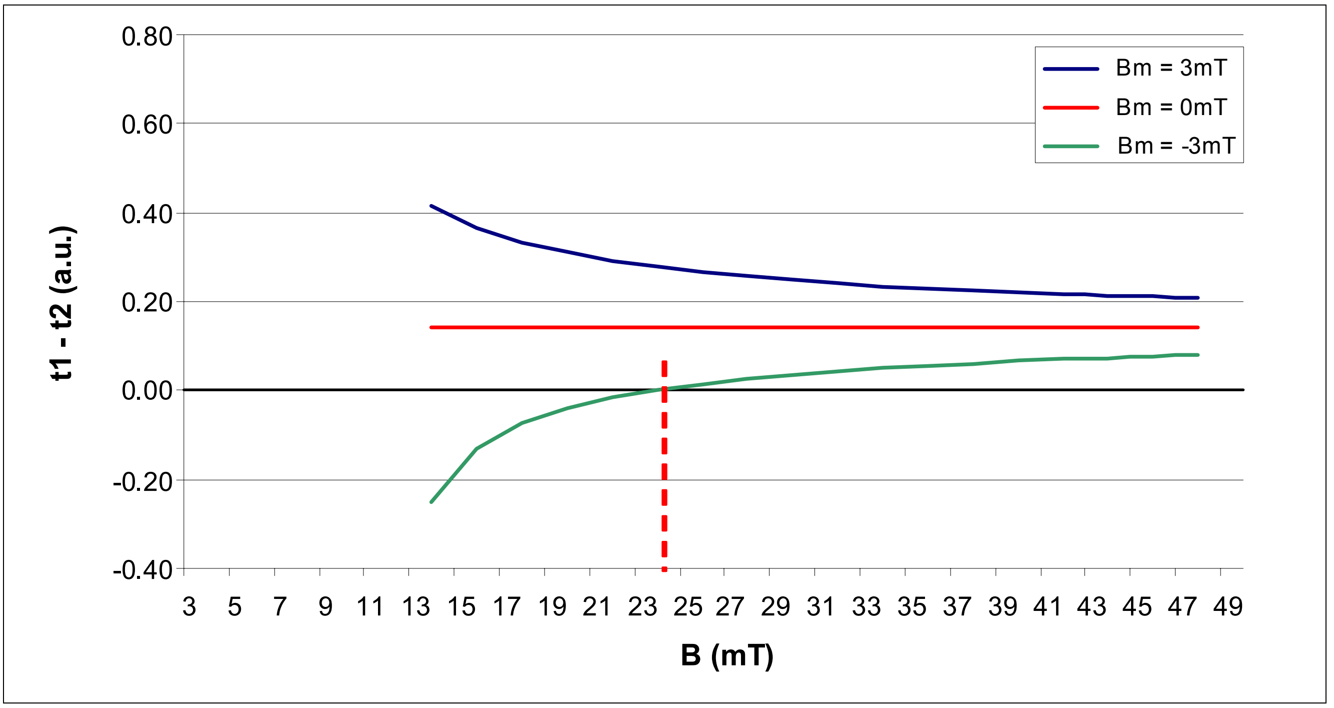

Figure 5 Pole wheel with N =1, B_0 = 24mT

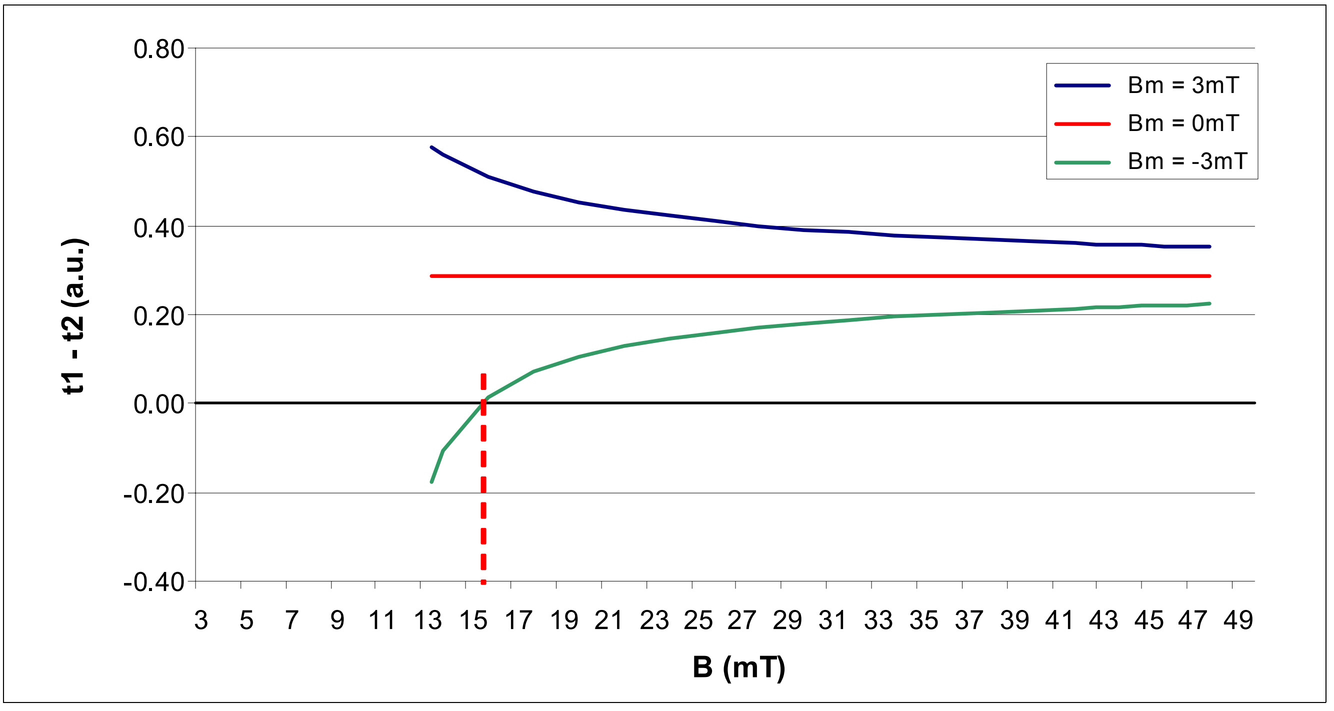

Figure 6 Pole wheel with N = 2, B_0 = 16mT

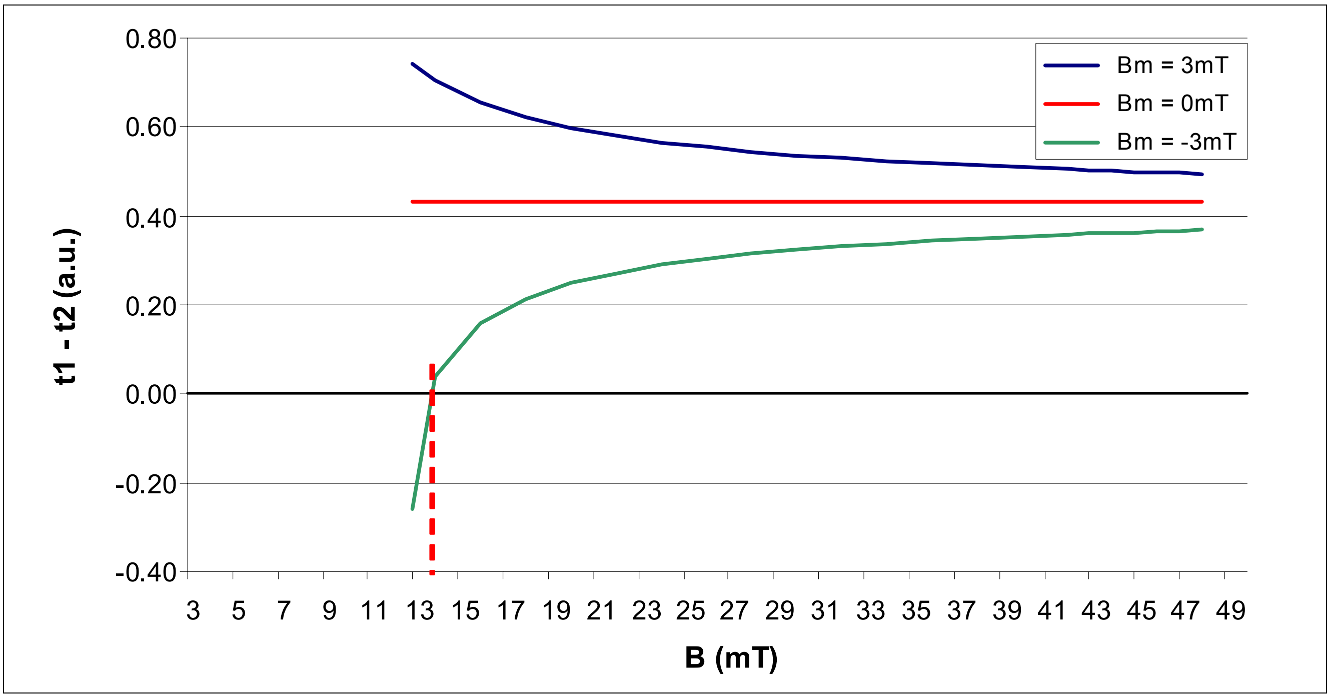

Figure 7 Pole wheel with N = 3, B_0 = 14mT

For a perfect magnetic matching (Bm = 0mT) the switching (t_2-t_1) is independent of magnetic field strength B_0. In any case the provided direction information is correct. The same is true for a positive magnetic matching ($B_m > 0$). Only for the case of a negative magnetic matching a wrong direction information can happen. This is visible in the zero crossing of the curves in above figures. The magnetic field value at the zero crossing corresponds to the minimum required magnetic field. For values below this the calculated direction information is wrong. It can be seen that with increasing numbers of pole pairs N the necessary magnetic field strength B_0 to obtain correct rotation direction information is decreasing. For a pole wheel with three pairs (N = 3, Figure 7) it is reduced to B_0 = 14mT whereas for N = 1 a magnetic field of approx. 24mT is necessary.

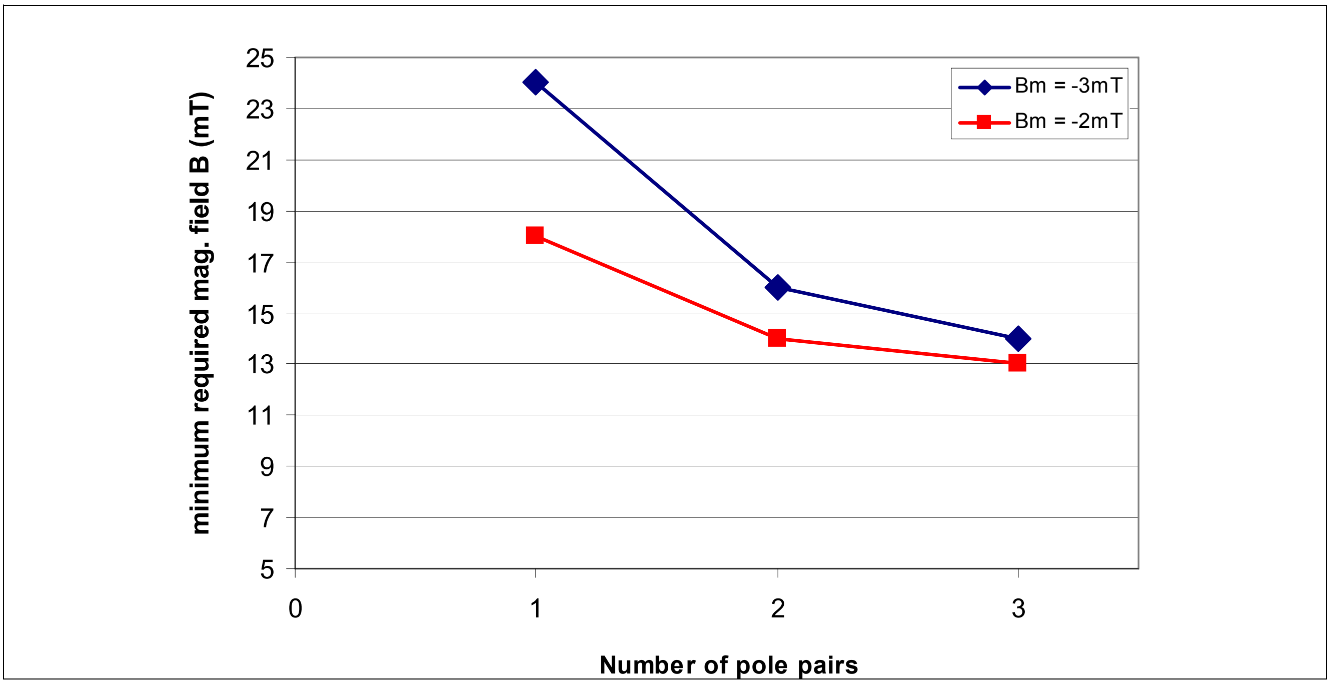

Figure 8 Minimum magnetic field B_0 for different numbers of pole pairs and magnetic matching B_m

5 Summary

The provided **Equation (5)** and **Equation (6)** can be used to estimate whether the used magnetic circuit is robust enough to prove always a correct rotation direction information. With the known geometry of the pole wheel and setup (N, R, s), along with worst case values from the data sheet (B_{op}, B_{Match}) the minimum required magnetic field strength B_0 at the location of the sensing elements can be calculated. If this value is below the magnetic field strength of the used pole wheel, a wrong direction information can occur. In such a case it is recommended that the magnetic circuit is changed so that more robustness is achieved. Due to the approximations used for calculation of the equations, a safety margin has to be included to ensure correct functionality in any condition.

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