Switching Hall Effect Sensor Design Example

Application: commutation sensor – precision motor timing device to control electronic commutation.

Requirements:

- 15 firing positions – no bounce
- Minimal hysteresis – 0 degrees ideal (which is not possible)
- Speed functionality – min speed 50 RPM when operating, otherwise 0
- Poor axial stack-up conditions – alignment ±0.035” axially from nominal position
- Good radial stack-up conditions – radial position of sensor held to ±0.005”
- Gap to be large as possible to allow for maximum air flow for cooling of motor (this counters the minimal hysteresis statement)
- Radial gap of motor is centered on a 2” diameter
- Radial gap of motor is held to 0.010” nominal to allow for an concentricity issues as well as thermal expansion
- Lowest cost possible (also counters the minimal hysteresis statement)
- Due to electronics packaging, the magnet with sensor must be less than 1.5” diameter.
- Temperature range of –40 to 125 °C, with storage temp of 150 °C

Starting the “generic” design

1. Determine the types of Hall sensors that could work.
    a. Switch – will work as it provides the on-off digital output electronics will work with
    b. Latch – this will also work but will require alternating poles
    c. Linear sensor – this will not work without additional electronics
    d. Power – this latching device will work, but the power capacity will be more expensive
    e. Programmable – switching device will work, but will have to program each chip…more expensive than conventional switch or latch.
2. Analyze the options and select a sensor type.
    a. Switches and latches are both valid and similar in cost
    b. Power is not needed so no reason to use.
    c. Programmable will work and allows options should they be needed considering the cost increase.
    d. Based on the firing count of 15, a latching sensor with “reasonable” flux density switching points (Bop and Brp) would work well. Typically, the latching sensors will allow slightly lower to very reduced levels of required flux density and will help to minimize the hysteresis of the system.
3. Select a specific sensor to start the preliminary analysis.
    a. Utilizing a Hall effect summary sheet from the manufacturer, select a sensor that meets the “reasonable” flux density level desired. Typically, this should be as low as possible to meet the hysteresis requirements, but not too low as there is a price vs. performance trade-off.

   b. In this case, selecting the 3281 L-UA from Allegro will allow the “middle” ground to be analyzed on a preliminary basis. Once the preliminary analysis is completed, the selection of the Hall sensor may be reviewed and adjusted as necessary.

4. Determine preliminary magnetic requirements.
   a. Because this is a latch, the Hall sensor must see alternating North and South poles. The South poles will turn the sensor on and North will turn it off. This requires 15 pole pairs to receive 15 firing positions assuming that the system will only recognize leading edges of the electrical signal (when the signal turns on, not when it turns off). Pole pairs x 2 = total number of poles = 30 poles for this example.
   b. Since air gap will be critical in minimizing performance variations in production, it is best to try and maintain this as consistently as possible. Because stack up tolerances are less in the radial direction (±0.005) then in the axial direction (±0.035”), the sensor system will be the most consistent if the sensor is used in a radial fashion.
   c. Because the sensor has an overall maximum thickness of 0.062” and a maximum width of 0.164”, the outside diameter of the air gap can be calculated. The flat of the sensor must fit inside of the allowable diameter, so the radial position must first be calculated. This may be done with the following equation:

$$RadialPosition = \sqrt{\left(\frac{OD_{Package}}{2}\right)^2 - \left(\frac{Width_{Sensor}}{2}\right)^2} = 0.7455''$$

   The gap OR may then be determined by subtracting the sensor thickness from the radial position. This results in 0.6835” for a gap OR.
   d. Applying the radial positional tolerance variation of 0.010” (±0.005”) to the gap OR of 0.6835” yields 0.6735” as a minimum gap OR. Assuming that the motor clearance (radial gap) of 0.010” is on the tight side, adjust the physical air gap to a minimum of 0.015” for a safety factor. This results in a maximum magnet OR of 0.6735” - 0.015” = 0.6585” or a 1.317” diameter.
   e. Using the magnet OD of 1.317” and applying a common tolerance rule which is the greater of ±0.3% or ±0.002”, a tolerance of ±0.004” may be assumed. This results in a nominal magnet diameter of 1.313” and 1.309” as a minimum diameter. The nominal arc length of a single pole may then be calculated as $\frac{\pi D}{N}$ where N is the total number of poles and D is the magnet OD. In this case, the arc length of a single pole is 0.1375”.
   f. The Total Effective Air Gap (TEAG) is a key element in the design of Hall sensor applications. The TEAG is the distance from the surface of the magnet to the location of the Hall element located inside the Hall sensor. In this particular case, the minimum, nominal and maximum TEAG’s should be determined for nominal operating conditions as well as worst case analysis. For the Allegro 3281 L-UA package the Hall element is recessed inside the IC package 0.0195” and applying a typical tolerance of ±0.003” results in a range of 0.0165” to 0.0225” recess.
   g. The nominal TEAG may be calculated by the following equation:

$$TEAG_{nom} = {}_{nom}OR_{gap} - {}_{nom}OR_{magnet} + {}_{nom}Recess_{Hall} = 0.6785 - \left(\frac{1.313}{2}\right) + 0.0195 = 0.0415''$$

h. Calculate the maximum TEAG as follows:

$$TEAG_{\max} = {}_{\max}OR_{gap} - {}_{\min}OR_{magnet} + {}_{\max}Recess_{Hall} = 0.6835 - \left(\frac{1.309}{2}\right) + 0.0225 = 0.0515''$$

i. Continuing on to calculate the minimum TEAG:

$$TEAG_{\min} = {}_{\min}OR_{gap} - {}_{\max}OR_{magnet} + {}_{\min}Recess_{Hall} = 0.6735 - \left(\frac{1.317}{2}\right) + 0.0165 = 0.0315''$$

j. Comparing TEAG to the basic gap equation of: $TEAG \le W_P / 2$ where Wp is the arc length of a single pole. Wp is established in section <e> to be 0.1375”. This means that the TEAG ≤ 0.1375 / 2 = 0.06875” and the TEAG calculated in section <h> meets this criteria.

k. Determine the required axial length of the magnet based on the equation: $AL = 2 \times TEAG + T_{ap}$ where T_{ap} is the tolerance of axial position alignment. T_{ap} must include the positional tolerance of the IC and the positional tolerance of the Hall element internal to the IC. In this example, AL = 2 x 0.0515” + 0.070” + 0.010” = 0.183” for the preliminary analysis.

l. The only dimension of the magnet not identified at this point is the ID of the magnet. In order to provide a starting point for the ID of the magnet, some generic assumptions must be made. Assuming that an operating PC ≥ 1 is acceptable, one may estimate the ID of the magnet per the following equations: $ID = OD - \frac{2}{5} \times \left(\frac{W_p \times \pi \times AL}{(W_p + AL)}\right)$ and $(OD - ID) \le 1.5 \times W_p$ where W_p is the arc length of a single pole, OD and ID refer to the outer and inner diameters of the magnet and AL refers to the axial length of the magnet. The first equation is only useful for obtaining a starting point when experience does not provide a guideline.

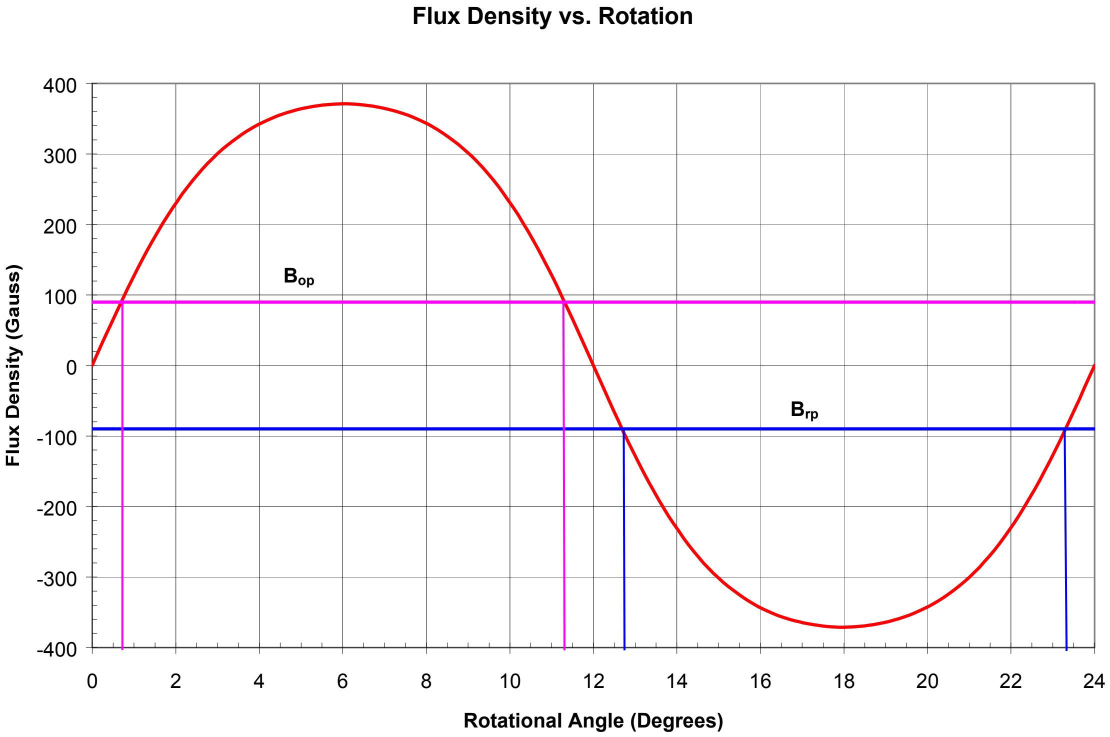
The second equation should usually be a constraint that the magnet must adhere to because it carries a relationship involving successful magnetization as well as a point of diminishing returns to the volume of the magnet. While segments may be pre-magnetized and glued together to obtain parts outside of this spectrum, it is not necessarily the best way to solve many designs. If molding a magnet to size, it is necessary to model with this limitation in place as magnetization will not significantly penetrate beyond this condition. Any additional gains will just provide additional safety factor to the design.

Based on the first equation, the ID may be estimated as 1.214” and the second equation validated by 0.099 < 1.5 x W_p = 0.206”. Adjustments during the refining of the design may occur, but should still fit the second equation.

5. Analyze the preliminary design.

a. Analysis of the design requires selecting a material to use in the application. Based on the temperature and the multi-pole on the OD design, either sintered ceramic 1 or a radially oriented bonded ferrite magnet is likely to provide the most cost effective solution. Due to the tolerance used of ±0.3% the ceramic would require final grinding or a bonded magnet molded to size. In this example, the design will be based around a bonded ferrite magnet that is radially oriented. For this part's temperature requirements and no stress condition, Plastiform 2060 will make an excellent low cost option.

Using an FEA/BEA or other custom package, analyze the flux density condition around the magnet based on nominal dimensions and tolerances. The best way to look at this initial information is a flux density vs. rotation plot as shown below. Note there are only two poles shown as the remaining poles will theoretically have the same performance.



b. Plot out the max Bop and min Brp values to determine the rotational hysteresis from the system. The graph shows that the rotational hysteresis will be about 1.5 degrees.

c. Determine if this design is in the acceptable range. If lower hysteresis is desired, then either convert to a material which will provide a higher peak flux density which in turn will create a faster transition rate and lower rotational hysteresis, or identify another sensor that will switch at lower levels.

   If the hysteresis is tighter than required, consider a chip with higher switching levels or a weaker material. In this case, a non-oriented (isotropic) material might be acceptable.

   For this example, an acceptable level of 3° hysteresis will be assumed which maintains a little safety factor in this design to cover the temperature and tolerance aspects.

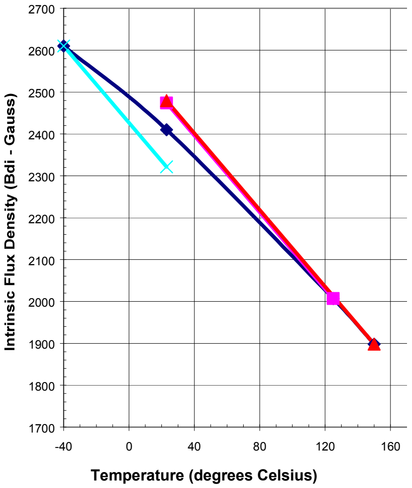
6. Begin worst case analysis of design.

   a. Using worst case Pc conditions, analyze the magnet for the operating load line. Worst case Pc for a ring magnet magnetized on the OD occurs with the following magnet dimensions:

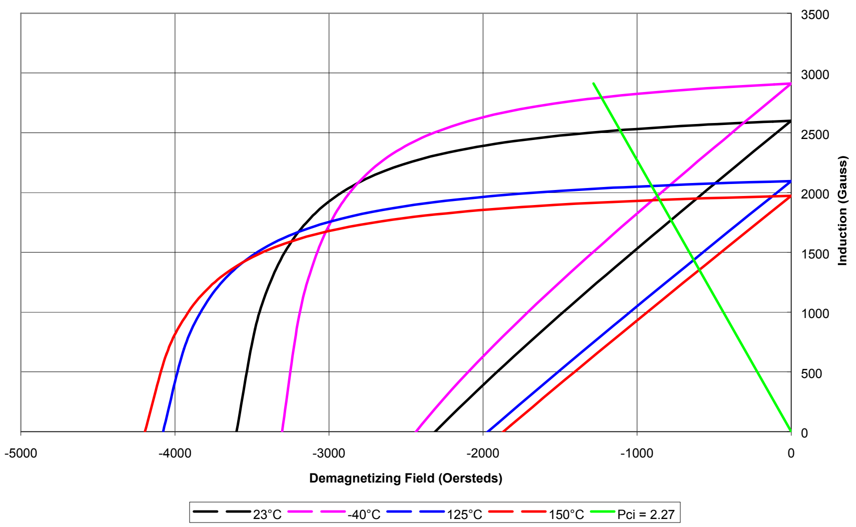
- OD_{min} = 0.654”
- ID_{max} = 0.609”
- AL_{max} = 0.186”

By using a 3D FEA / BEA system or other custom software, the load line of the magnet may be found by determining the Bd_{ave} and Hd_{ave} at the neutral zone. The formula (Pc=Bd/Hd) may then be applied with these average values. This results in a Pc = -1.27 for this ring magnet condition.

b. Using the Pc value calculated, as well as the demag curve for this material, calculate the expected irreversible losses to this system. This requires use of the intrinsic permeance coefficient or $Pc_i = Pc + 1$ when using the absolute values for Pc_i and Pc. In this case, Pc_i = 2.27 and is the slope plotted on the demagnetization curve.



Anisotropic 2060 Typical Demagnetization Curve



Analyzing the intrinsic demagnetization curve and finding the intersections of each temperature curve with the intrinsic permeance coefficient will yield the at temperature intrinsic induction (Bdi) values. Plotting these values vs. temperature will show the performance as the temperature changes. Applying the reversible temperature coefficient to these temperature Bdi values will result in calculation of the short term irreversible loss associated with this permeance condition. In this case, the STILT irreversible loss for –40 °C will be 3.7% and you will note that the positive temperatures result in an increase in Br. This is not something that will happen as it will actually follow the original curve in this case. Using the value of 3.7% and doubling to simulate the long term irreversible losses (LTILT) results in an expected decay of 7.4%.

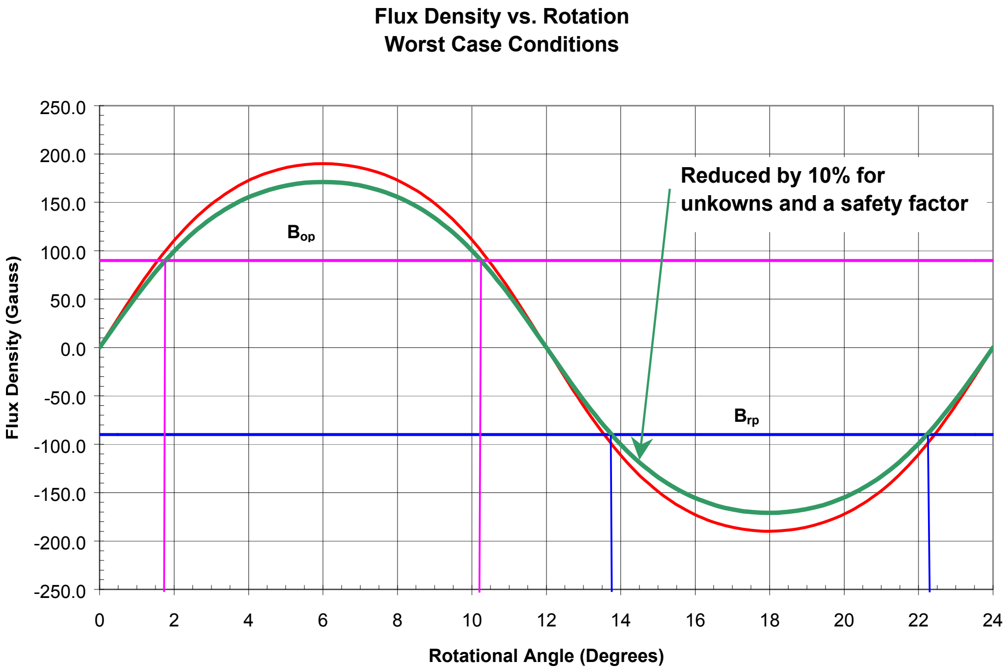
c. Identify conditions that create the worst case scenario for the design.

- $TEAG_{max}$ condition.
- Maximum offset of Hall sensor alignment.

- Maximum operating temperature.
- Thermal demag due to TcHci (occurs at coldest temperature in ferrite).
- Least material condition of magnet (LMC), both physically and magnetically.

d. Re-analyze system using these worst case conditions:

- $TEAG_{max}$ = 0.0515”
- OD_{min} = 0.654”
- ID_{max} = 0.609”
- AL_{min} = 0.180”
- Gap Radius = 0.0515 + 0.654 = 0.7055”
- Axial offset of sensor = 0.040”
- Br_{min} at 125 °C = 2,090 – 7.4% irreversible loss = 1935 Gauss



- Hc_{min} at 125 °C = 1,845 adjusted by 1845/2090 *1935 = 1708 Oe

Applying a 10% reduction to the rotational curve helps to serve as a safety factor in the design and for the potential of having missed some additional criteria. Once the flux density vs. rotation curves are generated, the B_{op} and B_{rp} values should be analyzed to determine the worst case rotational hysteresis. In this case, the rotational hysteresis has increased to 3.5 degrees and is outside the assumed acceptable limit of 3 degrees. At this point, the design needs to be reviewed and determine if 3.5 degrees is acceptable or if the design needs to be modified to reduce the hysteresis to less than 3 degrees. If a design modification is required then reviewing stronger magnetic materials and Hall sensors with lower B_{op} and B_{rp} would two common approaches to resolve this issue as well as adjusting the TEAG (less common as not always controllable). The assumption that the rotational hysteresis may now be up to 4 degrees will be used in this example.

7. Determine the critical evaluation factors for the design. They are usually contradictory in nature so they will have to be weighted appropriately. Some example factors are:
    - System cost.
        - Solved by reducing AL and increasing ID to meet specifications and minimize magnet volume.
    - Minimize irreversible losses.
        - Solved by reducing AL and decreasing ID to maximize length to area ratio and / or changing materials.
    - Minimize variation in magnetic performance vs. positional tolerances.
        - Solved by increasing AL of magnet to improve axial offset results. This may also result in the need to decrease the ID to maintain an acceptable Pc condition and irreversible loss value.

The potential solutions to these various factors demonstrate the contradictory nature in optimization. Balancing these factors to an acceptable solution is often a difficult and time-consuming process.

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