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# Analysis of Airgap Flux Densities of BLDC Motor by Expert Systems

**M. V. Ramana Rao[1], G.Mallesham[2]**

Assoc. Professor and Research Scholar, Dept. of EE, College of Engineering, Osmania University, Hyderabad, India[1]

Professor, Dept. of EE, College of Engineering, Osmania University, Hyderabad, India[2]

**ABSTRACT**: The design of BLDC motors is a comprehensive process based on several factors, including economic factors, material limitations, specifications and special application-dependent factors. At the same time, it is a multi-physics task comprising of electric design, magnetic design, insulation design, thermal design and mechanical design. The designer has to consider all aspects and then decide the best possible combination of parameters to suit the application requirements viz. Commercial, Industrial, or Military. This work focus on the development of an Expert System for design of BLDC motor as influenced by the mechanical loads, thermal effects, and the available material options that have a bearing on the design of BLDC Motor. The involved software (MATLAB R2015a) iteratively calculates the basic dimensions, magnetic circuit calculations, stator slot design and analysis of airgap flux densities, suggestions for optimization, and acceptance of the design.

**KEYWORDS:** BLDC Motor, Expert System, flux density Analysis, Graphical User Interface

## I.INTRODUCTION

With the growth of civilization, men started living in increasingly larger families and groups. This led to the formation of societies where there was exchange of material and information. Initially, this exchange was done on a limited scale on a barter system. This phase was followed by a rapid development in transport and communication facilities. Soon, trading took place even across the high seas. Concurrently, writing paper and the printing press were invented. Currency notes made their appearance to facilitate trade. Algebra and geometry were required for trade and construction and there was a need for a fast-accounting system. This need was partially fulfilled by the development of a calculator. There was healthy competition in this field and the main focus was on developing faster calculators with more and more facilities.

During this entire epoch, all calculations were done on the decimal system, probably because counting was initially done using the ten fingers of the hand. But there was a revolutionary change in this philosophy when George Boole demonstrated how just two digits 0 and 1 could be used to make computations. This system was not only used to make arithmetic calculations but also served to write logical statements e.g. a zero (0) represented a falsehood and one (1) a truth. The two states in Boolean algebra could easily be replicated using electrical switches. Rapid advances in the electronics and semiconductor industry gave a major boost to Boolean algebra. The development of logic gates and logic circuitry was a natural consequence. This gave birth to the first Digital Computer, which was a forerunner to the highly advanced computing systems that we see today. The modern Personal Computer is a miniaturized version of the same but it has very high memory storage capacity, faster computing speed, innumerable accessories and peripherals and very user-friendly software. So far, the accent in computer development was on speed and versatility.
Very little effort was directed in making computers ***think***. Thinking computers or robots were considered unrealistic and impractical and could only be imagined or written about in science fiction or movies. But software engineers at IBM thought otherwise. They developed a main frame computer called ***Deep Blue***, which could play a game of chess. IBM revised the PC repeatedly until it could defeat the then World Champion Gary Kasparov. This was a landmark achievement for software engineers and led to a spurt in the development of Artificial Intelligence and Expert systems.

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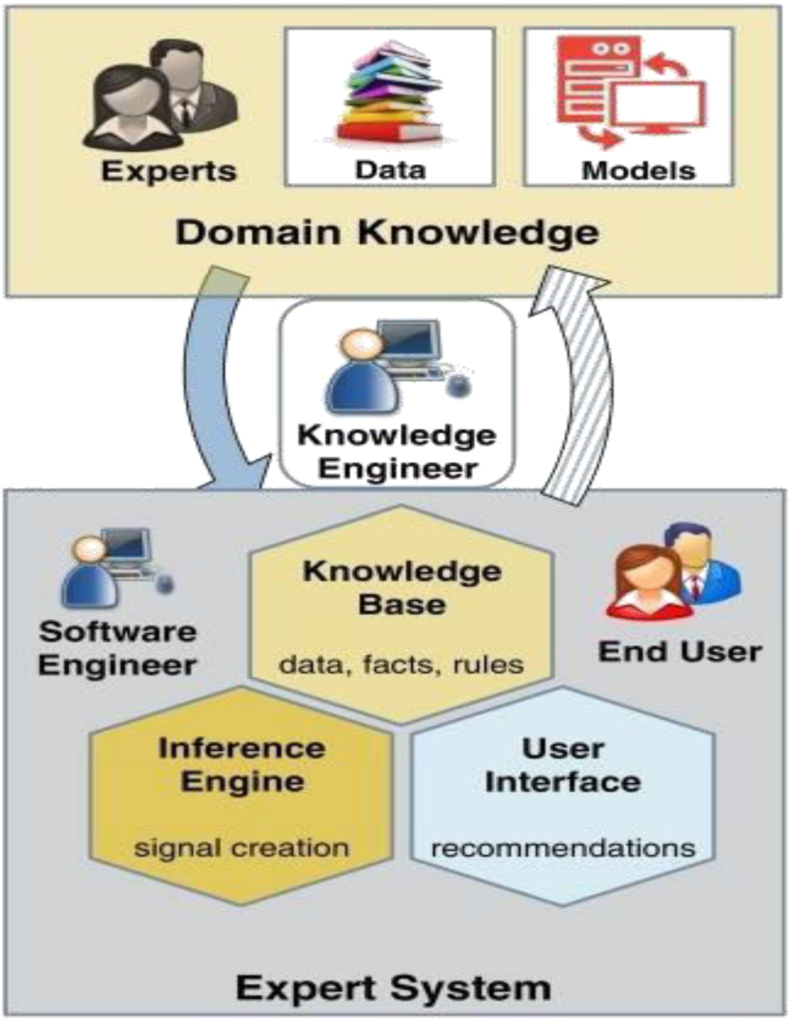


**Fig 1: Expert System Model**

## II.CONSCEPTS OF EXPERT SYSTEM

Expert Systems (ES) are a subset of *Artificial Intelligence*. They are used to solve very complicated problems using Artificial Intelligence. These types of problems are difficult to solve without using human brains. So, human expert knowledge is converted into data and rules and put inside computer programs. In this way because of high memory capacity, computers can store large knowledge of books and apply rules to solve complex problems at high speed.

**Knowledge Base (KB).** Computers can store great amount of knowledge and data from different experts in many different topics and different countries. This knowledge is also called ***Domain knowledge***. It is used with the rules, called ***heuristics***, which are programmed.

**Inference Engine (IE).**An Inference Engine is a software system that produces results by analysing the problems using the knowledge base. Generally, the analysis is logical. But sometimes inference engines also use a probability factor. Such results are indirect hints in the data. They are not purely facts.

**User Interface (UI).** This is the part that allows the operator to input questions and get answers for his problems. The ***user interface*** is a very important part of any program. If the user interface is designed nicely, the program can be used very conveniently. If the design is bad, it can create many difficulties during running

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## III.BRUSHLESS DC MOTORS

Nowadays, Brushless Direct Current (BLDC) motors are one of the motor types, rapidly gaining popularity with machine manufacturers in the industrial, commercial, military and aerospace sectors. BLDC motors are recommended for many low and medium power drives applications. BLDC motors have many advantages over Brushed DC motors and induction motors which have better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation and higher speed ranges. In addition, the ratio of torque delivered to the size of the motor is higher, thus making it useful in applications where space and weight are critical factors. Due to these advantages, they find applications in numerous areas such as in hard disks for computers, wheelchairs for the handicapped, portable life support systems in space, household application, transportation (hybrid vehicle), aerospace, heating, ventilation and air conditioning, motion control and robotics, renewable energy applications, in medical, automotive and commercial Instruments. These motors have all the advantages of conventional DC motors; over and above are much more rugged and reliable. The BLDC motor is a three-phase synchronous motor consisting of a stator having three phase concentrated windings and a rotor having permanent magnets. It does not have mechanical brushes and commutator assembly. Hence, wear and tear of the brushes and sparking issues as in case of conventional DC machines are eliminated in BLDC motor and thus has low EMI problems. The input DC supply is converted to 3 phase variable frequency supply with a specially designed Inverter Drive. This motor is also referred as an electronically commutated motor since an electronic commutation based on the Hall-effect rotor position signals is used instead of a mechanical commutator and the construction is to some extent simpler than a DC motor. But the design of BLDC motors as well as the associated drive electronics is quite complex because of the interplay of many parameters, which affect the final motor performance. Quite often, some of these parameters adversely affect one another, which make their selection even more difficult. Over and above, the available design equations cannot always account for all the factors such as weight, cost, losses, etc.

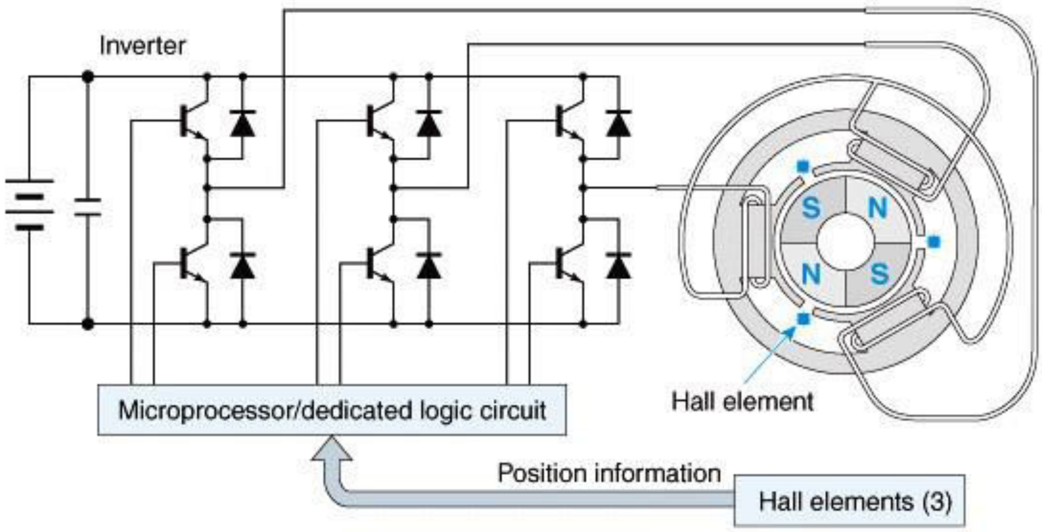


Fig2: BLDC Motor Schematic diagram

## IV.DESIGN CALCULATIONS OF FLUX DENSITIES

The flux density distribution in the magnetic components at Table 6-1 need to be reiterated for the laminated Silicon Steel with $B_{max} = 1.9\ Tesla$. Thus, the flux density in the following magnetic components is limited to Stator back iron flux density, $B_{sy}$

$$B_{sy} = \frac{1.2}{2.3} \times B_{max} = \frac{round\left(\frac{1.2}{2.3} \times 1.9 \times 10\right)}{10} = 1.0\ Tesla \quad (1)$$

Stator tooth flux density, $B_t$

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$$B_t = \frac{1.8}{2.3} \times B_{max} = \frac{round\left(\frac{1.8}{2.3} \times 1.9 \times 10\right)}{10} = 1.5\,Tesla \tag{2}$$

Rotor back iron flux density, $B_{ry}$

$$B_{ry} = \frac{1.4}{2.3} \times B_{max} = \frac{round\left(\frac{1.4}{2.3} \times 1.9 \times 10\right)}{10} = 1.2\,Tesla \tag{3}$$

**Optimum ratio of pole-arc to pole-pitch**

The optimum ratio of pole-arc to pole-pitch, $\alpha_p$ for minimizing the fundamental component of cogging torque, for any combination of slot and pole number, is given by eqn. (6-9) which is calculated as

$$\alpha_p = \left(\frac{N - k_1}{N}\right) + k_2 = \left(\frac{\frac{lcm\,(N_{slot}, N_{poles})}{N_{poles}} - k_1}{\frac{lcm\,(N_{slot}, N_{poles})}{N_{poles}}}\right) + k_2$$
$$= \left(\frac{\frac{lcm\,(24,8)}{8} - 1}{\frac{lcm\,(24,8)}{8}}\right) + 0.2 = \left(\frac{3-1}{3}\right) + 0.2 = 0.8667 \tag{4}$$

where, $k_1 = 1$ and $k_2 = 0.2$.
Since the 6 N-m example BLDC motor is designed to have $N_{poles} = 8$; hence the pole pitch angle, $\beta_p$ is

$$\beta_p = \frac{2\pi}{N_{poles}} = \frac{2\pi}{8} = 0.7854\,radM \tag{5}$$

where, $radM$ is angle radians in mechanical measure.

The angular magnet width, $\theta_m$ is

$$\theta_m = \alpha_p \times \beta_p = 0.8667 \times 0.7854 = 0.6807\,radM \tag{6}$$

The outer radius of rotor, $R_{ro}$ is calculated as

$$R_{ro} = \sqrt{\frac{1}{\pi L_{stk}} \times \frac{T_R}{2BA}} = \sqrt{\frac{1}{\pi \times \left(\frac{144.75}{1000}\right)} \times \frac{1.8}{2 \times 0.3144 \times 8000}}$$
$$= \frac{round(0.0281 \times 1000)}{1000} = 0.0280\,mtr \tag{7}$$

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The outer diameter of the rotor, $D_{ro}$ is

$$D_{ro} = 2 \times R_{ro} = 2 \times 0.0280 = 0.0560\, mtr \tag{8}$$

The stator bore diameter, $D_{si}$ is calculated using eqn. (9) as

$$D_{si} = D_{ro} + 2g = 0.0560 + 2 \times 0.0005 = 0.0570\, mtr \tag{9}$$

Tthe pole area of the air-gap is

$$\begin{aligned} A_g &= \theta_m \left(R_{ro} + \frac{g}{2}\right) \times L_{stk} \\ &= 0.6807 \times \left(0.0280 + \frac{0.0005}{2}\right) \times (144.75 \times 10^{-3}) \\ &= 2.7835 \times 10^{-3}\, m^2 \end{aligned} \tag{10}$$

The $g^{'}$ used in the eqn. (11) is not necessarily the air-gap length$g$, but an effective value determined by the use of Carter‘s coefficient $K_c$to allow for slotting. The initial value of $K_c$ is assumed as 1.05.
The air-gap reluctance, $R_g$given by

$$\begin{aligned} R_g &= \frac{g^{'}}{\mu_o A_g} = \frac{g \times K_c}{\mu_o A_g} = \frac{0.0005 \times 1.05}{(4\pi \times 10^{-7}) \times (2.7835 \times 10^{-3})} \\ &= 1.5009 \times 10^5\ \frac{At}{Wb} \end{aligned} \tag{11}$$

The air-gap permeance, $P_g$is

$$P_g = \frac{1}{R_g} = \frac{1}{1.5009 \times 10^5} = 6.6627 \times 10^{-6}\ \frac{Wb}{At} \tag{12}$$

The magnet area $A_m$ is usually considered one-third way through the magnet, measured from the inside radius of the magnet. However, a safer approach is to use the actual inner radius of the magnet for calculation of $A_m$ as

$$\begin{aligned} A_m &= \theta_m (R_{ro} - l_m) \times L_r \\ &= 0.6807 \times (0.0280\ \ 5.25 \times 10^{-3}) \times (150 \times 10^{-3}) \\ &= 2.3229 \times 10^{-3}\, m \end{aligned}$$

The magnet permeance, $P_m$ given by

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$$P_m = \mu_R \mu_o \left(\frac{A_m}{l_m}\right) = 1.05 \times 4\pi \times 10^{-7} \times \left(\frac{2.3229 \times 10^{-3}}{5.25 \times 10^{-3}}\right)$$
$$= 5.8381 \times 10^{-7} \frac{Wb}{At} \tag{13}$$

The rotor leakage permeance, $P_l$ is calculated using eqn. (14) as

$$P_l = 10\% \times P_m = 10\% \times 5.8381 \times 10^{-7} = 5.8381 \times 10^{-8} \frac{Wb}{At} \tag{14}$$

The total permeance, $P$ given

$$P = P_m + P_l = 5.8381 \times 10^{-7} + 5.8381 \times 10^{-8} = 6.4219 \times 10^{-7} \frac{Wb}{At} \tag{15}$$

It is assumed that the temperature of the machine parts is at $T_{amb} = 45°\text{C}$. Hence the temperature vector, $\boldsymbol{T} = [45]_{7\times1}°\text{C}$ represented in eqn. is in equilibrium condition.
The initial temperature of coil sides, end winding, magnets are at

$$T_{cs} = T_{ew} = T_{mag} = 45°\text{C} \tag{16}$$

At 45°C, the remanent flux density of magnet is calculated using eqn. (17) as

$$B_{r(45)} = B_{r(20)} \times \left(1 + \alpha_{Br} \frac{T_{mag} - 20}{100}\right)$$
$$= 0.4750 \times \left(1 - 0.18 \times \frac{45 - 20}{100}\right)$$
$$= 0.4536\, Tesla \tag{17}$$

It is observed that the above calculated remanent flux density $B_{r(45)}$value is near to the value if read B/H curve of TDK ferrite magnet material FB13B. The air-gap flux, $\emptyset_g$ using eqn. is

$$\emptyset_g = \frac{B_r A_m}{(1 + P \times R_g)} = \frac{0.4536 \times 2.3229 \times 10^{-3}}{(1 + 6.4219 \times 10^{-7} \times 1.5009 \times 10^5)}$$
$$= 9.6104 \times 10^{-4}\, Wb \tag{18}$$

The air-gap flux density, $B_g$ calculated using eqn. (19) is

$$B_g = \frac{\emptyset_g}{A_g} = \frac{9.6104 \times 10^{-4}}{2.7835 \times 10^{-3}} = 0.3453\, Tesla \tag{19}$$

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The magnet flux density, $B_m$ calculated using eqn. (20) is

$$B_m = \frac{(1 + P_l R_g)}{(1 + P \times R_g)} \times B_r$$
$$= \frac{(1 + 5.8381 \times 10^{-8} \times 1.5009 \times 10^5)}{(1 + 6.4219 \times 10^{-7} \times 1.5009 \times 10^5)} \times 0.4536 \quad (20)$$
$$= 0.4173\ Tesla$$

## V. RESULT AND DISCUSSION

### AIR GAP FLUX DENSITY PLOTS

The numerical methods for field computation, such as finite elements, provide an accurate means of determining the flux density distribution, with due account of saturation etc., they are often time-consuming and do not provide nearly as much insight as analytical solutions into the underlying behaviour. The analytical technique for determining the open-circuit air gap field distribution based on a two-dimensional model in polar coordinates that cater for internal rotor topologies modeling the effect of slotting as detailed in Section 6.9 for the example motors are shown in Figure 3 to Figure 5 below. The variation in the peak air gap flux density is due to the size and power of the permanent magnets in motors.

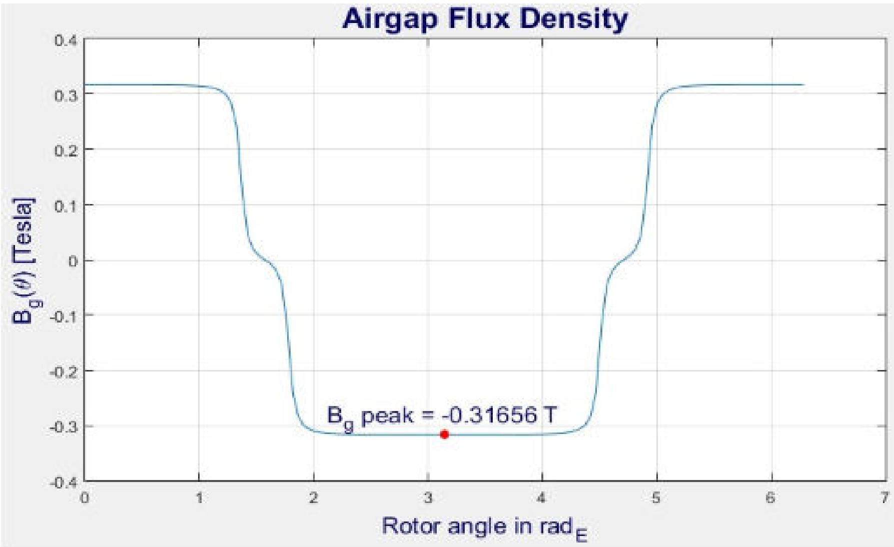


Fig 3: Air Gap Flux Density plot of 6 N-m Commercial Application Motor

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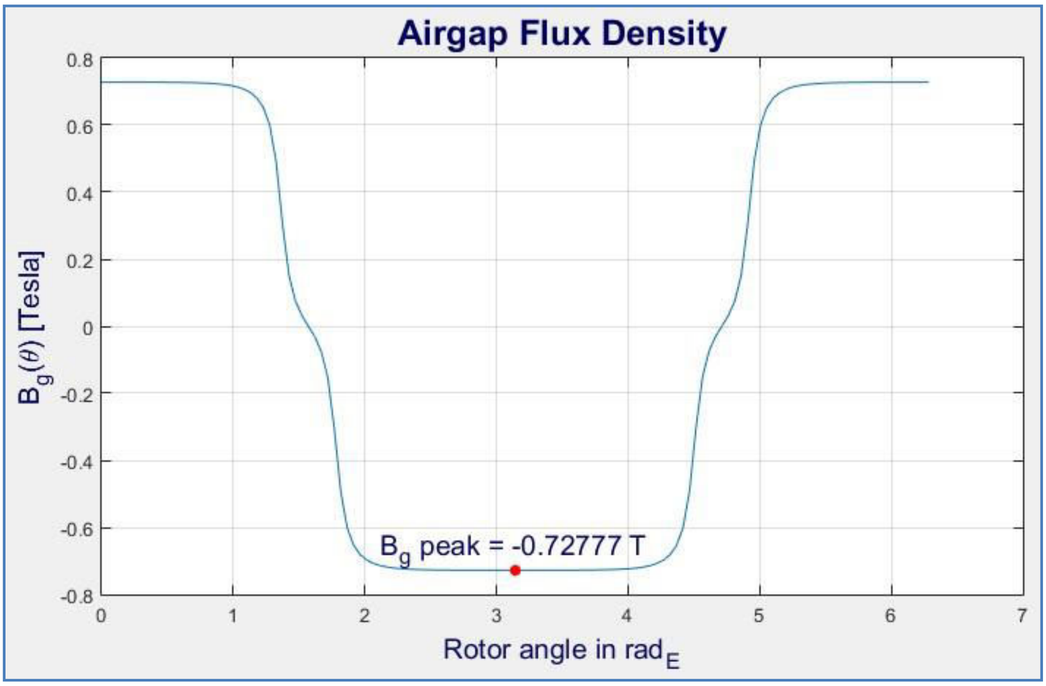


Fig4 Air Gap Flux Density plot of 6 N-m Industrial Application Motor

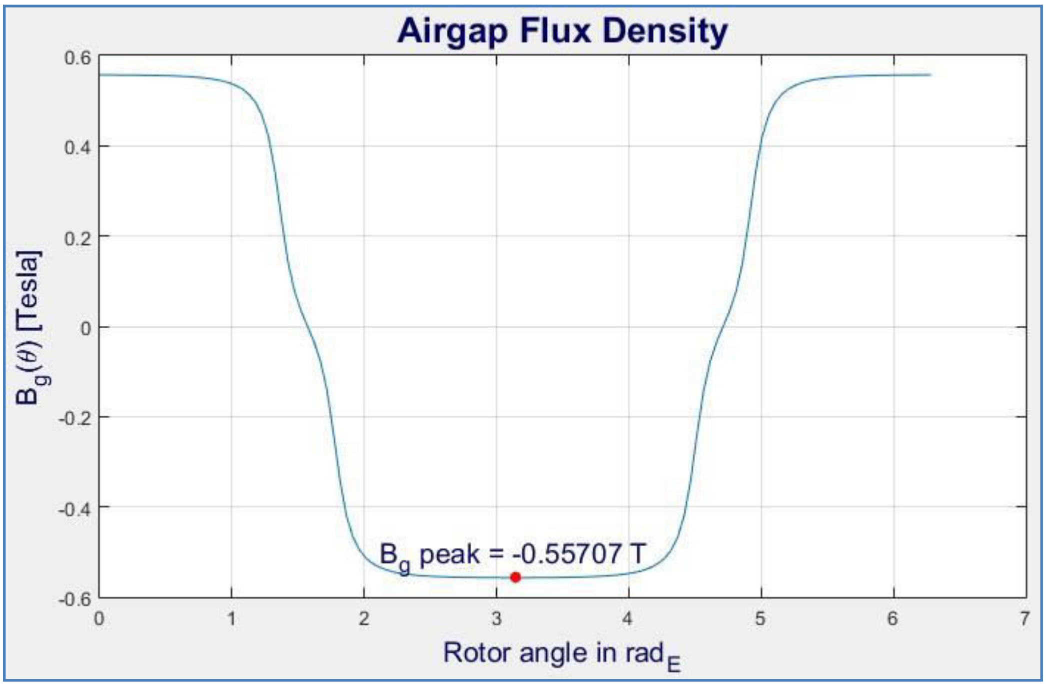


Fig. 5 Air Gap Flux Density plot of 6 N-m Military Application Motor

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## VI.CONCLUSION

The purpose of this thesis is to develop an Expert System (ES) for Design of BLDC Motors for various applications (Commercial, Industrial, and Military / Aero-space). This is to benefit any scientist / engineer who are new to BLDC motor, but still can learn and design as per their requirement. Hence, several choices are given in the ES such that the latest material can be selected at the click of mouse and user friendly. For developing this ES an exhaustive literature study, interaction with experts is carried out. Many references involving complex analytical equations are consolidated, reworked and systematically integrated to thermo electro-magnetic design to utmost accuracy and faster computation. Special attention is given to up-to-date material capabilities, stator winding configuration, motor casing dimensions, effect of demagnetization, cooling capability, and thermal limits.

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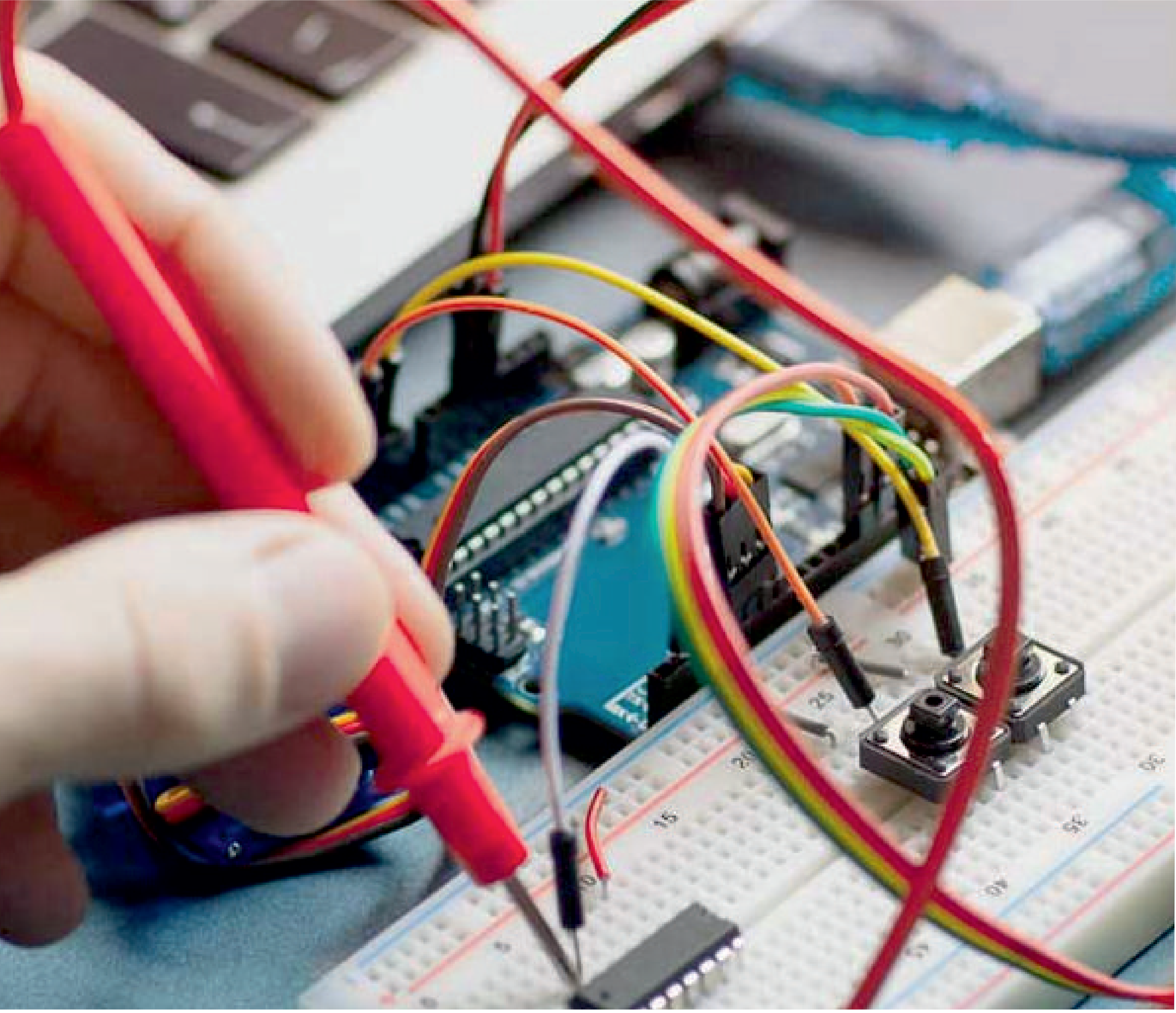


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