# An Expert System for Design of Output Parameters for BLDC Motor

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***Abstract*: Classical DC motors are no doubt good and simple but inefficient in some ways. Although brushed dc motors possess good control characteristics and ruggedness, however their performance and applications are inhibited due to sparking and commutation problems. Permanent Magnet Brushless DC (BLDC) motors overcomes the limitations, which are now competing with many other types of motors in the world industries application. For low and medium power applications, BLDC motors are often the main option due to its recognized advantage such as having no commutator, more efficient, needless maintenance, smaller in size and can operate at higher speeds than conventional motors. This concept (Expert System) does not have the heuristic selection of design variables and does not need much manual design iterations. The design cycle is significantly reduced which has advantage over the traditional and other existing design method. Graphical User Interface (GUI) adds wide flexibility to user for designing BLDC motors for different application domains.**

***Keywords*: BLDC motor, Expert system.**

## 1. Introduction

Artificial Intelligence (AI) is the study and creation of computer systems that can perceive reason and act. The primary aim of AI is to produce intelligent machines. The intelligence should be exhibited by thinking, making decisions, solving problems and more importantly by learning. AI as shown in Figure 1, is an interdisciplinary field that requires knowledge of computer science as well as the domain of development. The latter can be acquired from another expert or if possible even a team of experts in the particular field e.g. engineering, medicine, linguistics, psychology, biology, philosophy, brain games like chess, and so on.

Artificial Intelligence can also be defined as a branch of science to create intelligent computers. Such computers can be taught learning and reasoning to solve problems. In this way, many difficult commercial and industrial problems can be solved. It deals with creation of real intelligence artificially. Strong AI believes that machines can be made sentient or self-aware. There are two types of strong AI: Human-like AI, in which the computer thinks and reasons to the level of human-being. Non-human-like AI, in which the computer program develops a non-human way of thinking and reasoning. There are many AI applications that we witness: Robotics, Machine translators, *chat bots* short form of chatting robot which can converse with humans, voice recognizers to name a few. AI techniques are used to solve many real-life problems. Some kind of robots are used for detecting dangerous explosives e.g. helping to find land-mines, searching humans trapped in rubbles due to natural calamities. Now-a-days, AI techniques developed with the inspiration from nature is becoming popular. A new area of research known as Computing is emerging. Biological inspired AI approaches such as neural networks and genetic algorithms are already in place. There are several methods by which Computers can learn. The simplest way is by trial and error. The computer can try to solve a problem. If the answer is wrong, it can store the result in memory so that it will not repeat same mistake.

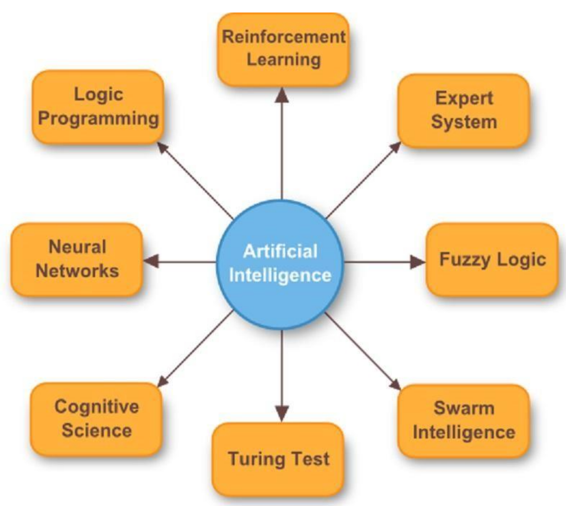


Fig. 1. Artificial intelligence

## 2. Brushless DC Motor

BLDC motors are a type of synchronous motor. This means the magnetic field generated by the stator and the magnetic field generated by the rotor rotates at the same frequency. BLDC motors do not experience the “slip” that is normally seen in induction motors. BLDC motors come in single-phase, 2-phase and 3-phase configurations. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motors are the most popular and widely used. This application note

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focuses on 3-phase motors. The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery (as shown in Figure 2).

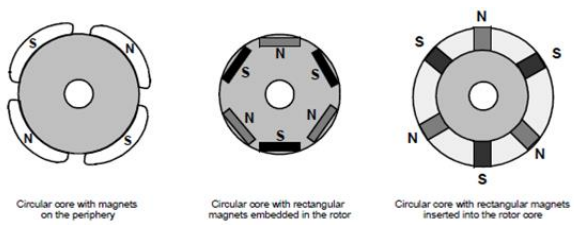


Fig. 2. Rotor magnet with different cross sections

Traditionally, the stator resembles that of an induction motor; however, the windings are distributed in a different manner. Most BLDC motors have three stator windings connected in star fashion. Each of these windings is constructed with numerous coils interconnected to form a winding. One or more coils are placed in the slots and they are interconnected to make a winding. Each of these windings is distributed over the stator periphery to form an even number of poles. There are two types of stator windings variants: trapezoidal and sinusoidal motors. This differentiation is made on the basis of the interconnection of coils in the stator windings to give the different types of back Electromotive Force (EMF). As their names indicate, the trapezoidal motor gives a back EMF in trapezoidal fashion and the sinusoidal motor's back EMF is sinusoidal, in addition to the back EMF, the phase Current also has trapezoidal and sinusoidal variations in the respective types of motor. This makes the torque output by a sinusoidal motor smoother than that of a trapezoidal motor. However, this comes with an extra cost, as the sinusoidal motors take extra winding interconnections because of the coil's distribution on the stator periphery, thereby increasing the copper intake by the stator windings.

The rotor is made of permanent magnet and can vary from two to eight pole pairs with alternate North (N) and South (S) poles. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are traditionally used to make permanent magnets. As the technology advances, rare earth alloy magnets are gaining popularity. The ferrite magnets are less expensive but they have the disadvantage of low flux density for a given volume. In contrast, the alloy material has high magnetic density per volume and enables the rotor to compress further for the same torque. Fig. 3 shows cross sections of different arrangements of magnets in a rotor. Also, these alloy magnets improve the size-to-weight ratio and give higher torque for the same size motor using ferrite magnets. Neodymium (Nd), Samarium Cobalt (SmCo) and the alloy of Neodymium, Ferrite and Boron (NdFeB) are some examples of rare earth alloy magnets. Continuous research is going on to improve the flux density to compress the rotor further.

## 3. Expert Systems

In many of the applications noted above, there can be uncertainty in the result, which can be right or sometimes wrong. But, there is a probability that one answer is more correct than the others in every different situation. Neuro Fuzzy logic can be applied in such cases to get better results.

Most of the present applications use the rule based system. In these cases, the experience and knowledge of a human expert is captured to formulate IF-THEN rules and facts. These are used to solve problems by answering questions typed at a keyboard attached to a computer on many diverse topics.

An Expert System can serve as a standalone advisory system for the specific knowledge domain, and if required even in combination with monitoring by a human expert. It also can provide decision support for a high-level human expert. The BLDC designer electrical expert system also allows a high-level expert to be replaced by a subordinate expert aided by the expert system. The main reason for the high rise of ES is because it acts as a delivery system for the following:

- Extending information.
- Providing management education for decision makers.
- Dissemination of up-to-date scientific information in a readily accessible and easily understandable form to engineering researchers and advisers.

## 4. Electrical Design Calculations

### *A. Calculating the Number of Turns*

If the number of turns in series per phase per path is $N_{ph}$

$$N_{ph} = \hat{e}_{ph} \Big/ B_g \omega_{NL} D_{si} L_{stk} \tag{1}$$

where,

$\hat{e}_{ph} = V_s/2$

$V_s$ is the input DC voltage ($User\ defined\ input\ data$),

$B_g$ is the air-gap flux density from eqn. (6-16)

$\omega_{NL} = 2\pi/60 \times N_{NL}$ $[rad/s]$ given in eqn. (4-1),

$N_{NL}$ is the no-load speed in RPM ($User\ defined\ input\ data$),

$D_{si}$ obtained from eqn. (6-24), and

$L_{stk}$ is the stator core axial length ($User\ defined\ input\ data$),

The $N_{ph}$ is rounded to nearest integer as,

$$N_{phR} = round(N_{ph}) \tag{2}$$

If $\hat{Z}$ is the total number of conductors in the machine, and the number of parallel paths is $a$,

then $N_{phR} = 1/3 \times \hat{Z}/2a$, or

$$\hat{Z} = 6a \times N_{phR} \tag{3}$$

*B. Back EMF, Torque and Motor Constants*

The back EMF constant $k_{E(wye)}$ is defined as,

$$k_{E(wye)} = V_s/\omega_{NL} \quad (4)$$

The Torque constant $k_T$ is determined from,

$$k_T = \frac{2}{3} K_{w1} \frac{\hat{Z}\emptyset_g p}{a \times \pi\alpha_p} \quad (5)$$

where,

$K_{w1} = 1$ is the fundament component of winding factor for 24 slot / 8 pole motor,

$a = 4$ is the number of parallel path per phase.

$p = \frac{Npoles}{2} = 4$ is the number of pole pairs,

$\hat{Z}$ is the total number of conductors in the motor $\emptyset_g$ *is* the air-gap flux.

$\alpha_p$ is the Pole coverage ratio.

In ideal case, the torque produced by one phase is given by,

$$|T| = 2\left(\frac{N_{poles}}{2}\right) N_{phR} B_g L_{stk} R_{ro}\, i \quad (6)$$

As there is one coil side per slot, the resistance per slot is given by

$$R_{slot} = \frac{\rho_c L_{stk} N_{phR}^2}{K_{wb} A_s} \quad (7)$$

Using the ideal torque eqn. (6) and the total slot resistance, and ignoring the resistance of the end turns, the motor constant $K_m$ for one phase of an ideal motor is,

$$K_m = \frac{|T|}{\sqrt{i^2\left(\frac{N_{poles}}{2}\right) R_{slot}}} = B_g R_{ro} \sqrt{2K_{wb} L_{stk} N_{poles} A_s / \rho_c} \quad (8)$$

where,

$B_g$ is the air-gap flux density,
$R_{ro}$ is the rotor diameter,
$K_{wb} = 0.5$ is bare wire slot fill factor,
$L_{stk}$ is the stator core axial length,
$N_{poles} = 8$ is the number of poles ,
$\rho_c = 0.01724 \times 10^{-6}\ [ohm.m]$ is the resistivity of copper.

*C. Conductor Size Calculation*

Available copper area per slot

$$A_{cu} = A_s \times K_{fill} \quad (9)$$

where,

$K_{fill}$ is slot fill factor = 0.6

The wire diameter of bare conductor, $D_w$ using

$$D_w = \sqrt{A_{cu}/Z_s} \quad (10)$$

where,

$Z_s = \hat{Z}/N_{slot}$ , Number of conductors per slot (for Single layer wound motor)

The corresponding bare wire diameter, $d_{wb}$

The actual Cross-sectional area of bare wire $A_{wb}$ is ,

$$A_{wb} = \pi \times \frac{{d_{wb}}^2}{4} \quad (11)$$

*D. Back EMF*

The back EMF of a general coil having *N* turns is,

$$e_t = \frac{d\lambda}{dt} = \frac{d\theta}{dt}\frac{d\lambda}{d\theta} = \omega_e \frac{d\lambda}{d\theta} = N\omega_e \frac{d\emptyset}{d\theta} \quad (15)$$

Where, $\emptyset$ is the sum of the tooth fluxes linked by the coil and $\theta$ and $\omega_e$ are in electrical measure.

If the tooth flux, as modified for skew, gives a Fourier series representation of the back EMF of,

$$e_t(\theta) = \sum_{n=-\infty}^{\infty} E_{tn} e^{jn\theta} \quad (16)$$

where, the Fourier series coefficients are,

$$E_{tn} = jnN\omega_e \emptyset_{tn} \quad (17)$$

The back EMF of a general coil is the superposition or sum of the back EMFs of its single tooth equivalent coils.

The back EMF of the coil is given by

$$e_{coil}(\theta) = e_t(\theta) + e_t(\theta - \theta_s) + e_t(\theta - 2\theta_s) \quad (18)$$

Where $\theta_s$ is the angular slot pitch in electrical measure.

Once the back EMF of a single coil in a phase winding has been found using the above approach, the back EMF of other coils in the winding are found by considering the relative coil offset angles of each coil relative to the first. Under the assumption that all coils have the same number of turns, the back EMF of the other coils have the same amplitude and shape as the first coil but are shifted in phase by their respective coil offset angles.

## 5. Flow Chart of Expert System for BLDC Motor

Main objective of the program is to take inputs from user such as motor application (Commercial, Industrial, Military), motor rating in N-m, physical dimensions, operating time, operating ambient temperature and a few more as per the sequence listed user input data in the Table 1. Once the ES is run, and after answering to certain questionnaire, the user is prompted with option to load input data in either "**File**", "**Console**", or "**Default**" Mode, wherein the design process is initiated. On selection of "File" Mode, the previously stored data if available can be loaded in the 'User In-put Data Table' and the data can be modified as per the requirement. To initiate a new design, a set of new input data can be entered using "Console" Mode. Invalid data entries will not be processed and the User will be prompted to correct the entries. By clicking "**Next**" button, the basic parameters like rated torque, rated speed, rated current, mechanical output power, etc., are calculated and will appear in the ES GUI as shown in Table 2. Upon clicking the "Next" button successively; the electrical property displayed in tabular form as in Table 3. Then upon clicking the "Next" button, the output parameters are displayed as shown in the Table 4 and Table 5. If the output parameters are valid; for example, current density, and motor temperature are within the permissible limits then the winding configuration, magnetic flux density plots of various sections of the motor (air gap, stator back iron, stator tooth), its internal dimension, and drive rating etc., are displayed upon clicking Next button successively. The inputs, the design outputs, and graphics can be saved and printed at user's discretion. The user will be able to visualize the core saturation from the stator tooth flux density plot and iteratively optimize the motor design by varying the corresponding input data, magnet, stator and electrical property values. Upon successful completion of design, the user can save the results and may choose to close the program or continue with a new design process. This is an exhaustive document that contains all commercial and technical data about every component in the system. The IF.....THEN rules in the knowledge base need not act independently. They can have access to a large **DATA BASE.** For such exigencies, a **Data Entry** facility can be provided so that additional or new data can be easily added to the expert system. The Data entry block also allows the existing data to be modified, if required. The user is expected to be fully conversant with the BLDC motor design and development of the ES program.

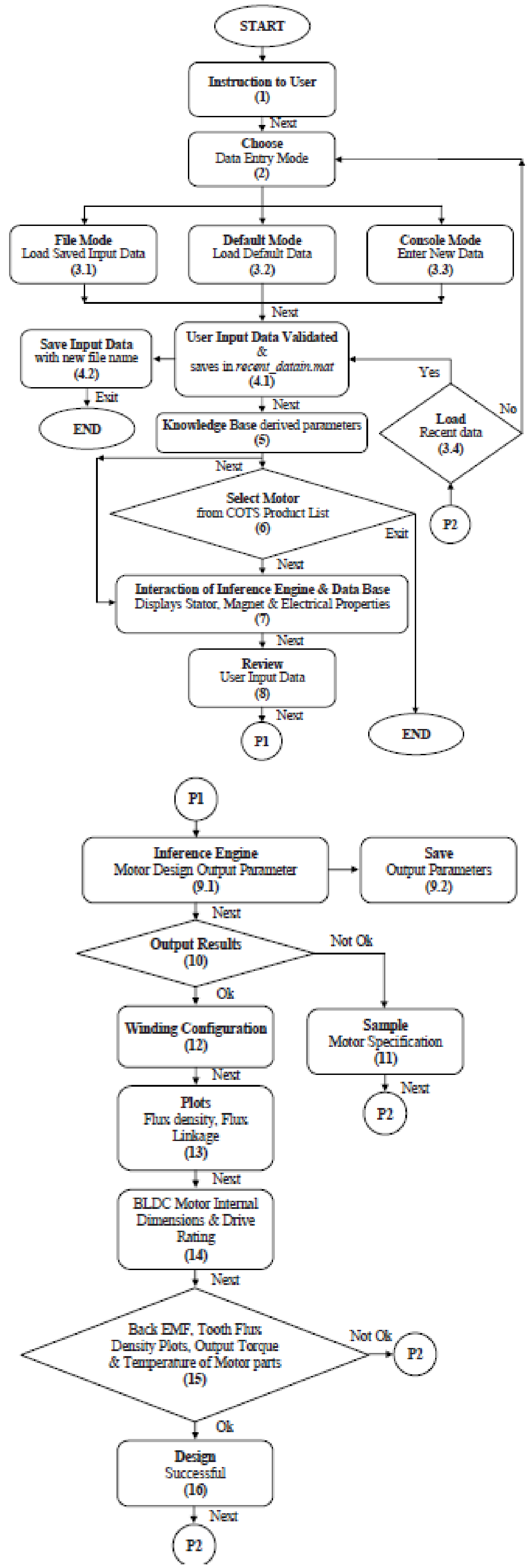


Fig. 3. Main flow chart of expert system

Table 1
User in-put data

| Input Parameter | Unit | User Data | | | |
|---|---|---|---|---|---|
| | | Case – I | Case – II | Case – III | Case – IV |
| Application (*Commercial, Industrial, Military*) | *Military (default)* | Comm. | Indu. | Mil. | Mil. |
| Maximum desirable Torque ($T_{LR}$) | *N-m* | 6 | 6 | 6 | 1.15 |
| Maximum No-load Speed ($N_{NL}$) | *rpm* | 4000 | 4000 | 4000 | 4000 |
| Nominal In-put Supply Voltage ($V_s$) | *Volts* | 48 | 48 | 48 | 48 |
| Maximum permissible diameter of motor ($D_{so}$) | *mm* | 90 | 75 | 40 | 40 |
| Maximum permissible length of motor ($L_r$) | *mm* | 150 | 115 | 70 | 70 |
| Maximum continuous run time of motor ($t_{max}$) | *secs.* | 200 | 200 | 200 | 200 |
| Maximum ambient temperature ($T_{amb}$) | *deg-C* | 45 | 50 | 55 | 55 |

Table 2
Knowledge base derived parameter

| Parameter | Units | Derived Value | | | |
|---|---|---|---|---|---|
| | | Case – I | Case – II | Case – III | Case – IV |
| Rated Torque, $T_R$ | *N-m* | 1.8 | 1.8 | 1.8 | 0.3450 |
| Rated Speed, $N_R$ | *rpm* | 2800 | 2800 | 2800 | 2800 |
| Rated Current, $I_R$ | *Amp* | 15.7080 | 15.7080 | 15.7080 | 3.0107 |
| Peak Current, $I_{pk}$ | *Amp* | 52.3599 | 52.3599 | 52.3599 | 10.0356 |
| Rated Mechanical Power Output, $P_R$ | *Watt* | 527.7876 | 527.7876 | 527.7876 | 101.1593 |
| Rated Electrical Input Power, $P_{in-elec}$ | *Watt* | 753.9822 | 753.9822 | 753.9822 | 144.5133 |
| Peak Electrical Input Power, $P_{pk-elec}$ | *Watt* | 2513.3 | 2513.3 | 2513.3 | 481.7109 |
| Torque Constant, $k_T$ | *N-m/Amp* | 0.1146 | 0.1146 | 0.1146 | 0.1146 |
| Motor Diameter, $D_{so}$ | *cm* | 9 | 7.5 | 4 | 4 |
| Motor Length, $L_r$ | *cm* | 15 | 11.50 | 7 | 7 |
| Power Density, $P_{denc}$ | *Watt/cm$^3$* | 0.5531 | 1.0388 | 6 | 1.15 |
| Torque Density, $T_{denc}$ | *mN-m/cm$^3$* | 1.8863 | 3.5429 | 20.4628 | 3.9220 |

Table 3
Knowledge base inferred electrical property

| Electrical Property | Units | Inferred value | | | |
|---|---|---|---|---|---|
| | | Case – I | Case – II | Case – III | Case – IV |
| Electrical Loading, $A$ | *AT/m* | 8000 | 11700 | 67600 | 13000 |
| Total No. of conductors, $\hat{Z}$ | | 960 | 600 | 2736 | 2736 |
| No. of turns per phase | | 160 | 100 | 456 | 456 |
| No. of turns per coil | | 40 | 25 | 114 | 114 |
| Total No. of coils | | 12 | 12 | 12 | 12 |
| Number of parallel paths per phase, $a$ | | 4 | 4 | 4 | 4 |
| Winding factor, $K_{w1}$ | | 1 | 1 | 1 | 1 |
| Fill Factor, $K_{fill}$ | | 0.6 | 0.6 | 0.6 | 0.6 |
| Skew factor, $K_s$ | *Slot* | 1 | 1 | 1 | 1 |

Table 4
BLDC motor design output parameter

| Parameter | Units | Output values | | | |
|---|---|---|---|---|---|
| | | Case – I | Case – II | Case – III | Case – IV |
| Phase | | | | | |
| Armature Inductance per Phase | *mH* | 0.2112 | 0.1827 | 1.1230 | 1.2924 |
| Peak Armature Current | *Amp* | 16.1726 | 16.0625 | 16.0666 | 3.0822 |
| Current Density | *Amp/sq. mm* | 2.0845 | 2.8094 | 29.5361 | 6.6913 |
| Back EMF Constant | *V-sec/rad* | 0.1146 | 0.1146 | 0.1146 | 0.1146 |
| Torque Constant | *Nm/Amp* | 0.1113 | 0.1121 | 0.1120 | 0.1119 |
| Motor Constant | $K_m$ | 0.6135 | 0.6514 | 0.1234 | 0.1169 |
| Rotor Inertia | *g.cm$^2$* | 10335 | 1196.10 | 91.1983 | 90.6389 |
| Weight to Torque ratio | *kg/Nm* | 3.9801 | 2.1779 | 0.4681 | 1.9641 |
| Machine Temperature | *deg-C* | 115.65 | 134.08 | 1177.60 | 193.72 |
| Efficiency | *%* | 95.27 | 95.92 | 71.62 | 86.40 |

Table 5
BLDC motor design output parameter

| Parameter | Units | Output values | | | |
|---|---|---|---|---|---|
| | | Case – I | Case – II | Case – III | Case – IV |
| Frame Material | *mm* | Mild Steel | Al. alloy | Al. alloy | Al. alloy |
| Machine Casing Length | *mm* | 167 | 130 | 86 | 80 |
| Machine Casing Diameter | *mm* | 92 | 78 | 48 | 42 |
| Machine Net Weight | *kg* | 7.1650 | 3.9210 | 0.8430 | 0.6780 |
| Stator Material | *mm* | Si Steel | CoFe | CoFe | CoFe |
| Stator Axial Length | *mm* | 144.75 | 115 | 70 | 70 |
| Stator Outer Diameter | *mm* | 90 | 75 | 40 | 40 |
| Stator Inner Diameter | *mm* | 57 | 35 | 21 | 21 |
| Rotor Outer Diameter | *mm* | 56 | 34 | 20 | 20 |
| Air Gap Length | *mm* | 0.5 | 0.5 | 0.5 | 0.5 |
| Magnet Material | | FB13B | NdFeB-30 | SmCo-18 | SmCo-18 |
| Magnet Flux Density Operating Point | *Tesla* | 0.3580 | 0.8507 | 0.7579 | 0.7119 |
| Magnet Field Strength Operating Point | *kAT/m* | 26.9836 | 97.8318 | 60.0162 | 58.5177 |
| Permeance Coefficient | *Pc* | 10.5564 | 6.9196 | 10.0489 | 9.6812 |
| Magnet Wire Data | *SWG* | 17 SWG | 18 SWG | 28 SWG | 29 SWG |
| Number of Turns per Phase per Path | | 23 | 21 | 78 | 83 |
| Number of Parallel Paths | *a* | 4 | 4 | 4 | 4 |
| Total No. of Turns | | 276 | 252 | 936 | 996 |
| Armature AC Resistance per | *ohm* | 0.0344 | 0.0353 | 0.6036 | 1.1549 |

## 6. Conclusion

The ES thus incorporates superior design capability compared to traditional design approach. It has the merit of good computational efficiency and provides a significant time reduction of the design cycle such that the output parameters can be readily adopted for preparing of detailed manufacturing drawing for BLDC Motors.

The outputted parameters of ES have been correlated with various types of small and medium rating which showed acceptable correlation with BLDC motors from leading manufacturers like Maxon, Source Engineering Inc (SEI), Indian Military, several Journals and Publications.

In conclusion, it must be mentioned here that no BLDC motor can work without a suitable drive. Various types of drives and controllers are available commercially and development work on these aspects is continuously in progress.

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