Performance enhancement of underwater propulsion motor using differential evolution optimization

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This paper describes the performance enhancement of underwater propulsion motor using differential evolution optimization (DEO). Usually during development stage, an analytical subdomain model (ASM) is often preferred to be used in the design of electric machines since ASM has faster computational time compared to the finite element method. Differential evolution algorithm is deployed to provide the optimization process in searching the optimal motor parameters iteratively and intelligently with specific objective functions. For this purpose, a three-phase, 6-slot/4-pole permanent magnet synchronous motor (PMSM) intended for the underwater propulsion system is first designed by using ASM and then later optimized by differential evolution algorithm. Five main motor parameters, i.e., magnet pole arc, magnet thickness, air gap length, slot opening, and stator inner radius are varied and optimized to achieve the design objective functions, i.e., high motor efficiency, high output torque, low total harmonic distortion (THDv) in back-emf, and low cogging torque. Results from differential evolution optimization show an improved performance of the proposed PMSM where the efficiency of the motor is increased to 96.1% from its initial value of 94.2%, 13% increase in the output torque, and 4.1% reduction for total harmonic distortion in its back-emf. Therefore, DEO can be highly considered during initial design stage to optimize the motor parameters in developing a good underwater propulsion motor.

[Keywords: Underwater propulsion motor; Analytical subdomain; Differential evolution]

Introduction

The use of electrical motor and power electronic converter for the electric propulsion systems in the underwater robotics and underwater vehicles is gaining popularity due to their compactness, light weight and control simplicity. Induction motor, DC motor, switched reluctance motor, and permanent magnet synchronous motor are several types of electrical motors that can be used for the underwater propulsion systems. For instance, a three-phase induction motor for underwater propulsion systems operated using indirect vector control was earlier reported¹. Not only that, separately excited DC motor can also be used by varying its duty cycle using closed-loop control of chopper fed DC drive². Switched reluctance motor with new buck-boost converter able to have high demagnetization voltage using hysteresis current controller was tested for underwater propulsion motor³. A model identification and control analysis for brushless DC motor using four-type system identifications was applied for underwater thruster system⁴. A DC brushed electric thruster was developed using statistical design of experiment by applying two factorial designs, i.e., armature voltage and thruster condition⁵. Performance comparison of electric underwater thruster was conducted using computational fluid dynamic model and experimental measurement⁶. There is a linear relationship between speed, thrust and power of the thruster. Increasing the thruster speed will increase the thrust and power of the thruster and vice versa. A small-scale electrically actuated thruster was developed which shows a good performance for the autonomous underwater vehicle application⁷. However, permanent magnet synchronous machines (PMSMs) are most suitable for the underwater propulsion motor due to their high efficiency, high torque density and good dynamic performance⁸. Rotor magnetic flux is readily available and continuously generated without consumption of input energy by placing permanent magnet materials in the rotor core. Hence, rotor loss is significantly reduced because the rotor does not carry the field winding and magnetizing current. PMSM can be classified by the manner the permanent magnet materials are placed in the rotor core, such as surface-mounted magnet, surface-inset magnet, bread loaf magnet, interior magnet, and spoke magnet⁹. Surface-mounted type of
PMSM can utilize the most magnetic flux compared with other types since the magnet materials are placed next to the air gap, and hence magnetic leakage is almost negligible. The structure of the stator can be either slotted or slotless. Slotless structure has advantages over slotted structure as the slotless structures eliminate cogging torque, exhibit low armature reaction and low inductance due to higher effective air-gap length. There are possibly five different magnetization patterns that can be applied for surface-mounted PMSM: Radial magnetization, parallel magnetization, sinusoidal amplitude magnetization, ideal Halbach, and multi-segmented Halbach. Each of these magnetization patterns can be represented in 2D polar coordinate system in the radial and tangential directions as reported in.

In an earlier study, the authors only studied the motor performance using radial magnetization of permanent magnet and the motor dimensions were not fully optimized. There are many optimization models that can be used to identify the optimal motor parameters namely, genetic algorithm, particle swarm optimization, or differential evolution. In this paper, the performance of a three-phase, 6-slot/4-pole PMSM is investigated before and after optimization using analytical sub-domain model integrated with differential evolution algorithm. This motor employs fractional slot concentrated windings, slotted stator and surface-mounted permanent magnet rotor. The computed results from the optimization exercise are further analysed and compared with 2D finite element method (FEM).

**Motor Design Parameters**

The dimensions of the three-phase, 6-slot/4-pole PMSM are shown in Table 1. The permanent magnet mounted on the rotor surface is initially fixed to have 3 mm thickness. The stator outside diameter is 50 mm, while the axial length is 100 mm. The phase windings and magnet arrangement in the 6-slot/4-pole motor are shown in Figure 1. The stator coils and coil emf vectors in the 6-slot/4-pole are shown in Figure 2. It has symmetric windings since phase A windings are wound on stator teeth number 1 and 4, resulting in balanced magnetic pulls. The magnitude of the coil back-emf is influenced by the pitch-factor \(K_{pn}\). The derivation of \(K_{pn}\) given in Eq. (1), where \(N_s\) is the number of stator slots, \(p\) is the number of pole pairs, and \(n\) is the harmonics numbers. The distribution factor \(K_{dn}\) is given by Eq. (2) which is unity for the case of this 6-slot/4-pole PMSM. Hence, the winding factor \(K_{dpn}\) is shown in Eq. (3). The open-circuit flux-linkage per coil, \(\psi_{coil}\) of the motor can be estimated by Eq. (4), where \(R_s\), \(I_s\), \(N_c\), \(B_n\) and \(\omega_r\) are the stator inner radius, motor active axial length, number of turns per coil, magnitude of flux density, and rotor angular speed in rad/s.

\[
K_{pn} = \cos\left(\frac{np\pi}{N_s}\right) \quad \ldots (1)
\]
\[
K_{dn} = 1 \quad \ldots (2)
\]
\[
K_{dpn} = \cos\left(\frac{np\pi}{N_s}\right) \quad \ldots (3)
\]
\[
\psi_{coil} = 2R_sI_sN_c\sum_{n=1,3,5}^{\infty} K_{pn}B_n(R_s) \cos(np\omega_r t) \quad \ldots (4)
\]

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Dimensions of three-phase, 6-slot/4-pole PMSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Value</td>
</tr>
<tr>
<td>Stator outer radius, mm</td>
<td>25.0</td>
</tr>
<tr>
<td>Stator yoke thickness, mm</td>
<td>3.4</td>
</tr>
<tr>
<td>Tooth body, mm</td>
<td>6.8</td>
</tr>
<tr>
<td>Tooth tip height, mm</td>
<td>2.3</td>
</tr>
<tr>
<td>Tooth end, mm</td>
<td>1.5</td>
</tr>
<tr>
<td>Stator slot opening, mm</td>
<td>2.0</td>
</tr>
<tr>
<td>Stator inner radius, mm</td>
<td>15.0</td>
</tr>
<tr>
<td>Magnet outer radius, mm</td>
<td>14.0</td>
</tr>
<tr>
<td>Rotor outer radius, mm</td>
<td>11.0</td>
</tr>
<tr>
<td>Radial rotor yoke, mm</td>
<td>5.0</td>
</tr>
<tr>
<td>Active axial length, mm</td>
<td>100.0</td>
</tr>
<tr>
<td>Magnet remanence, T</td>
<td>1.26</td>
</tr>
<tr>
<td>Winding turns per phase</td>
<td>30</td>
</tr>
<tr>
<td>Rated speed, rpm</td>
<td>1500</td>
</tr>
<tr>
<td>Rated torque, Nm</td>
<td>0.9</td>
</tr>
<tr>
<td>Magnet pole arc</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Fig. 1 — Allocation of phase windings and magnets arrangement for 6-slot/4-pole PMSM
often, the dominant factor that affects motor efficiency is the rms phase voltage, power to the input power as shown in Eq. (9), where \( B_{2} \) is the rotor angular position in electrical degree, while \( B_{r,j} \) and \( B_{t,j} \) are the radial and tangential components for slotted air-gap flux density. The efficiency of the PMSM is based on ratio of output power to the input power as shown in Eq. (9), where \( E_{K} \) is the rms phase voltage, \( I_{k} \) is the rms phase current, and \( R_{ph} \) is the phase resistance. For simplicity, the motor core loss and windage loss are first assumed to be negligible in estimating the motor efficiency. Most often, the dominant factor that affects motor efficiency is the copper loss.

\[
B_{r}(r, \theta) = \sum_{n=1,3,5...}^{\infty} \frac{\mu_{0}M_{n}}{2n_{p}} \left(\frac{2}{\mu_{r}^{\text{np}} + \frac{1}{\mu_{r}^{\text{np+1}}} - \frac{1}{\mu_{r}^{\text{np+2}}}}\right)\left(\frac{r_{s}^{\text{np+1}}}{r_{s}^{\text{np}}} - \frac{r_{s}^{\text{np+2}}}{r_{s}^{\text{np}}}ight) + \frac{r_{s}^{\text{np+1}}}{r_{s}^{\text{np}}} + \frac{r_{s}^{\text{np+2}}}{r_{s}^{\text{np}}} \cos n\theta \]

\( rR_{sn}p - 1R_{m}R_{sn}p + 1 + R_{mr}n + 1 \cos n\theta \) … (5)

\[
B_{t}(r, \theta) = \sum_{n=1,3,5...}^{\infty} \frac{\mu_{0}M_{n}}{2n_{p}} \left(\frac{2}{\mu_{r}^{\text{np}} + \frac{1}{\mu_{r}^{\text{np+1}}} - \frac{1}{\mu_{r}^{\text{np+2}}}}\right)\left(\frac{r_{s}^{\text{np+1}}}{r_{s}^{\text{np}}} - \frac{r_{s}^{\text{np+2}}}{r_{s}^{\text{np}}}ight) + \frac{r_{s}^{\text{np+1}}}{r_{s}^{\text{np}}} + \frac{r_{s}^{\text{np+2}}}{r_{s}^{\text{np}}} \sin n\theta \]

\( -rR_{sn}p - 1R_{m}R_{sn}p + 1 + R_{mr}n + 1 \sin n\theta \) … (6)

\[
E_{0} = 2R_{e}N_{p}I_{d}\omega_{r} \sum_{n=1,3,5...}^{\infty} K_{d}(\omega_{r}) \sin n\omega_{i}t \]

\( T_{cap}(r, \theta) = \frac{i_{c}}{\rho_{e}} \cdot r^{2} \int_{0}^{2\pi} B_{2r}(r, \theta) \cdot B_{s2}(r, \theta) \, d\theta \)

\[
\eta = \frac{\sum_{n=1}^{N_{p}} E_{n}I_{n}}{\sum_{n=1}^{N_{p}} E_{n}I_{n} + 100}\%
\]

**Optimization Technique**

Differential evolution (DE) is one of the artificial intelligent algorithms that has originated from the genetic algorithm family. DE has four design processes, namely, population, mutation, crossover, and selection. Therefore, DE is a population-based optimization method. A random population of \( N \) D-dimensions with real-valued parameter vectors is generated. A candidate solution to the multi-dimensional optimization problem is formed from each vector, also known as genome/chromosome. The population at the current generation with each parameter of the \( i^{th} \) vector has minimum and maximum bounds which can be represented in Eq. (10). A donor vector \( W_{ij} \) corresponding to each population member \( Y_{ij} \) in the current generation through mutation is generated. A mutation strategy as shown in Eq. (11) is applied, where \( F \) is a constant parameter called mutation scale factor. A crossover operation is run after generating the donor vector through mutation to enhance the potential diversity of the population. The common binomial crossover is applied on each D variable whenever a randomly generated number between 0 and 1 is less than or equal to the crossover constant \( C_{r} \) value as shown in Eq. (12). To determine whether the target or the trial vector survives to the next generation, the selection step is applied. The selection operation is shown in Eq. (13).

\[
\vec{Y}_{ij} = [y_{1,j}, y_{2,j}, y_{3,j}, ..., y_{b,j}], \vec{y} \in R^{b} \]

\[
\vec{W}_{ij} = \vec{Y}_{r,o,j} + F \cdot (\vec{Y}_{r+1,j} - \vec{Y}_{r+2,j}) \]

\[
\vec{u}_{ij} = u_{k,i,j} = \begin{cases} \frac{w_{k,i,j} \cdot f(r_{k}) \leq C_{r} \lor k = k_{rand}}{k = 1...n} \end{cases} \]

\[
\vec{y}_{i,j+1} = \begin{cases} \vec{u}_{ij} \text{ if } f(\vec{u}_{ij}) \leq f(\vec{y}_{ij}) \end{cases} \]

\[
\vec{y}_{i,j+1} = \begin{cases} \vec{u}_{ij} \text{ if } f(\vec{u}_{ij}) > f(\vec{y}_{ij}) \end{cases} \]

**Objective Functions**

In this paper, four objective functions are selected, i.e., to have the lowest cogging torque, \( F_{1} \); to have the lowest phase back-emf total harmonics distortion, \( F_{2} \); to have the highest electromagnetic torque, \( F_{3} \); and to
have the highest efficiency, $F_4$. The optimization results will be in vector form for each objective function and can be simplified as indicated in Eq. (14). The Pareto-chart is applied to identify the best motor parameters that give the best motor performances.

$$\mathcal{F}_{obj} = [F_1, F_2, F_3, F_4]_{min} \quad \ldots \quad (14)$$

**Optimized Parameters**

Since the magnetic flux in the air gap region plays an important role in the PMSM performance, then five parameters near the air gap region will be optimized, i.e., magnet pole arc, $\alpha$; magnet thickness, $h_m$; air gap length, $l_g$; slot opening, $b_o$; and stator inner radius, $R_{si}$, with certain constraints as listed in Table 2.

**Results and Discussion**

**Pareto chart**

To identify the best motor parameters, two Pareto charts are constructed to tabulate the four objective functions as shown in Figs 3 and 4. ASDEO is the acronym for analytical subdomain model integrated with differential evolution optimization. Output torque-initial means the motor output torque from the initial motor parameters as given in Table 1. As can be observed, the best motor performances are available in the square dotted line. After the best motor performance is selected, then the best motor parameters are applied for the optimized design of 6-slot/4-pole PMSM. Then, it is further verified using FEM to validate its performances. Finally, the selected motor parameters that give the best motor performance is selected as given in Table 3.

As given in Table 3, the output torque has increased from 0.822 Nm to 0.928 Nm. The efficiency has improved by 1.9%, and THDv of phase back-emf has reduced by 4.1%. Whereas, the cogging torque remains unchanged. The magnet pole arc slightly increases from 0.8 to 0.9, but the air gap length is reduced by 10%. The slot opening is now 5% smaller, and stator inner radius has increased by 1 mm. Even though the magnet arc has increased which may affect the material cost, the motor efficiency and THDv of phase back-emf have been improved. The cogging torque is nearly 0.1 Nm which is as expected for this type of motor, but it can be further minimized by applying the cogging torque reduction techniques.

**Finite element modeling**

In this section, 2D FEM is used to compute the open-circuit air gap flux density distributions, the induced phase back-emf, cogging torque, and output torque for 6-slot/4-pole PMSM. The motor model with mechanical dimensions from Table 1 has been built in

**Table 3 — Optimized 6-slot/4-pole motor dimensions and performances**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Initial</th>
<th>ASDEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet pole arc</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Magnet thickness, mm</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Air gap length, mm</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Slot opening, mm</td>
<td>2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Stator inner radius, mm</td>
<td>15.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Output torque, Nm</td>
<td>0.822</td>
<td>0.928</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>94.2</td>
<td>96.3</td>
</tr>
<tr>
<td>Phase back-emf THDv, %</td>
<td>8.32</td>
<td>4.2</td>
</tr>
<tr>
<td>Cogging torque, Nm</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Fig. 3 — THDv of phase back-emf versus output torque and efficiency

Fig. 4 — Cogging torque versus output torque and efficiency
2D finite element commercial software, i.e., OPERA2D. The stator and rotor core use silicon steel lamination. The magnet materials used are neodymium iron boron (NdFeB). The open-circuit magnetic flux density contour across motor sectional area can be plotted by applying static analysis in 2D FEM as shown in Figure 5. The motors are modelled with parallel magnetization patterns (PaM) in the rotor magnets. The open-circuit magnetic fields are balanced and equally distributed in the stator core of 6-slot/4-pole PMSM as indicated in Figure 5, yielding zero unbalanced magnetic force acting on the rotor. After being optimized, the maximum magnetic flux density that enters the motor core is reduced to 1.52 T, and this can prevent the core from extreme saturation during load conditions. The winding slot becomes smaller due to increase in stator yoke and tooth body of the motor. This is not a big problem since the total number of winding turns per phase is only 50 using 17 AWG copper wires. By using 2D FEM, the flux density distributions in the middle of the motor air gap can also be predicted as shown in Figure 6. There is not much difference in air gap magnetic flux density before and after optimization.

Phase back-emf waveform

The phase back-emf, electromagnetic torque and cogging torque for 6-slot/4-pole motor with PaM are evaluated by using 2D FEM. The peak voltage of phase back-emf increases to 20 V after it has been optimized.
as shown in Figure 7. Table 4 shows the magnitudes of each harmonic component in the phase back-emf waveform. The total harmonic distortion is reduced to 4.2% after the motor has been optimized.

**Cogging torque**

Generally, the cogging torque exists due to the interaction between the stator slots and magnetic pole edges resulting in unwanted torque ripples, noise and vibration. Therefore, it is always desirable to design PMSM with negligible cogging torque. The motor models in 2D FEM have been used to compute the cogging torque waveform in 6-slot/4-pole motor, and their results are shown in Figure 8. The smallest common multiple $N_{scm}$ for 6-slot/4-pole motor is 12\textsuperscript{15,16}. Usually higher $N_{scm}$ will result in smaller cogging torque\textsuperscript{15}. The cogging torque waveform is repeating every 60° electrical. Its peak is about 0.1 Nm.

**Output Torque**

The output torque during on-load condition is simulated in 2D FEM rotating machine analysis by subjecting the motor to sinusoidal current excitation of 5 A peak. The average output torque has increased to 0.928 Nm but it has nearly similar torque ripple before and after optimization as shown in Figure 9 and Table 5. This is due to the effects of cogging torque and also THDv contents in back-emf waveform. However, this output torque ripple can be further minimized by applying the cogging torque reduction technique\textsuperscript{23,25}.

**Conclusion**

The performance of three-phase, 6-slot/4-pole permanent magnet synchronous motor (PMSM) has been enhanced by using analytical sub-domain model integrated with differential evolution optimization (ASDEO). Five motor parameters were optimized, i.e., magnet pole arc, magnet thickness, air gap length, slot opening, and stator inner radius. Four objective functions were selected, i.e., to have high efficiency, high output torque, low cogging torque, and low total harmonic distortion in phase back-emf. The Pareto chart is used to tabulate the potential motor performance for certain optimized motor parameters, providing the freedom to choose the suitable motor performance value. The optimized 6-slot/4-pole motor has high efficiency and high fundamental phase.
back-emf. Consequently, the average output torque of the motor has been improved. The results from 2D FEM confirms the motor performance accuracy from ASDEO in designing the three-phase PMSM for underwater propulsion system.

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