Design optimization for torque density in brushless DC motor with IPM V-type using PSO Method

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Abstract. The analysis model is the first stage used to determine the design parameters of the motor. It is coupled with an optimization method to find a combination of design parameters. The purpose of this paper is optimizing the torque density of the Brushless DC (BLDC) Motor with Interior Permanent Magnet (IPM) V-type. The reference design is 3-phase and 12/8 pole BLDC motor with a concentrated winding. To obtain this optimal design, this is done by eliminating the rotor area that is not covered by magnetic flux without reducing the main performance of the motor. Elimination area prediction refers to initial motor design simulation which is operated on rating condition. Mathematical modeling is based on the 2-D finite element analysis (FEA) using software Ansys Maxwell. Particle Swarm Optimization (PSO) algorithm with multi-objective function has been applied to determine the area of the rotor structure to be eliminated, resulting in an optimal torque-density design. Matlab code is also included to execute the optimization algorithm. Excitation uses the ideal sinusoidal signal by ignoring harmonic distortion. This paper features a new optimal design for IPM by considering torque density, cogging torque, harmonic distortion in back-electromagnetic force (back-EMF), and material demagnetization constraints using PSO. Quality of PSO optimization can be proven by increasing the torque density without compromising the main performance of the motor compared with FEA. With this method also provide disadvantage, such as the cost of production is more expensive because it should add a profile of the rotor mold.

1. Background

Brushless DC (BLDC) motor has the advantages of efficiency, torque, and ease of control. But the geometry of the motor needs to be considered more serious so that it is more efficient. One of them is the torque density value, which is the ratio between torque and the overall mass of the motor. Modifying certain parts of the motor needs to be done but the performance of the motor does not decrease significantly. BLDC motor has the main construction of stator, rotor, magnet and coil. Stator is a fixed motor part, while the rotor is a rotating motor part. A permanent magnet is placed on the rotor. To increase the torque density of the motor, one of them is by modifying the rotor shape as has been done by [1]–[4]. Multi Objective can use a variety of algorithms such as Bat-Inspired Algorithm [5], Genetic Algorithm and Particle Swarm Optimization [6].
In this paper the motor that will be used is a type of radial BLDC motor with a configuration of 12 stator slots and 8 magnetic poles. The combination of slots and stator affects the magnitude of the winding factor. The 12 slot combination and 8 pole magnet have a winding factor of 0.866 [7] which has the advantage of easy winding and high efficiency.

Table 1. Mass of each part

| Part               | Material       | Volume (cm³) | Mass Density (g/cm³) | Mass (g) |
|--------------------|----------------|--------------|----------------------|----------|
| Stator             | Electrical Steel | 812.27       | 7                    | 5697.96  |
| Enamled Wire       | Copper         | -            | 8.96                 | 1477.05  |
| Shaft              | Stainless Steel | 201.48       | 8                    | 1611.88  |
| Magnet             | NdFeB          | -            | -                    | 800.00   |
| Casing             | Aluminium      | -            | 2.7                  | 8566.44  |
| Bearing            | -              | -            | -                    | 200.00   |
| Rotor (existing)   | Electrical Steel | 520.59       | 7                    | 3644.16  |
| Total              |                |              |                      | 21997.52 |

2. Modelling of Motor Torque
To get a calculation of the motor torque value is done by using the concept of conservation of energy. This concept is carried out by modeling the energy flow from electrical energy to magnetic energy and
mechanical energy. Rules that must be fulfilled can be formulated into $dW_e = dW + dW_m$, where $dW_e$ is a differential value of electrical energy, $dW$ is a differential value of magnetic energy, and $dW_m$ is a differential value of magnetic energy[8]. The Torque can be influenced by differential of Inductance $L$, Reluctance $R$, magnetic flux $\Phi$ to the rotational angel of rotor $\theta$. Mathematically it can be formulated into[8]:

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} - \frac{1}{2} \Phi^2 \frac{dR}{d\theta} + Ni \frac{d\Phi}{d\theta}$$ (1)

Finite Element Method is used for modeling. In this study the software used was 2-D Ansys Maxwell simulation. Simulation using 2-D reduces time rather than 3-D simulation. There are three basic topologies that use on hybrid energy storage. Series, parallel and series-parallel configurations [3]. These topologies developed on energy storage for electric vehicle based on the capacity of electric vehicle’s drive train. And also, all of the topologies can be connected as a passive or active configuration. Advantage of active configuration is can be a potentially smaller dimension that passive configuration as the same load.

In existing conditions, the rotor has an area that is not aligned by magnetic fluxes. This zero area of magnetic flux must be eliminated but must still have a sturdy structure. The elimination is extended towards an area that has a larger flux, but the expected final result is that the torque does not decrease significantly. The average torque produced is 34.41 Nm with a total mass of 21.977 kg. That means the existing motor has a torque density of 1.56 Nm / kg.

3. Optimization Strategy and Methodology

Particle swarm optimization (PSO) is an algorithm used to determine the optimal parameters that adopt the habits of birds in foraging. PSO was first initiated by Kennedy and Eberhart [9]. Some particles are scattered randomly in a certain range. Each particle is calculated the solution value. The best solution of all particles is called the global best (gbest). The other particle moves to gbest with a certain speed. The position of the new particle is also a potential solution. The best value of each solution in each particle is called particle best (pbest). The value of the partilce transfer speed depends on the value of the gbest and pbest. These steps are repeated to get the steady state gbest value.

To find particle speed at any time can be calculated by formula [9].

$$v_i(t) = Wv_i(t - 1) + C_1 r_1 (x_{pbest i} - x_i(t)) + C_2 r_2 (x_{gbest} - x_i(t))$$ (2)
where $v_i$ is particle speed, $W$ is inertia weight, $C_1, C_2$ are cognitive and social parameter, $x_{p,i}^{best}$ is position that has best solution for each particle, $x_{gbest}$ is particle position that has best solution for all particle, and $r_1, r_2$ are a random value between 0 and 1.

![Figure 3. Cross section of ¼ purpose model](image)

### Table 2. PSO Parameter

| Parameter          | Symbol | Value  | Unit |
|--------------------|--------|--------|------|
| -                  | a      | [3.23] | mm   |
| -                  | b      | [2.15] | mm   |
| Weight Inertia     | W      | 1.2    | -    |
| Cognitive and Social Parameter | $C_1$ | 1.2    | -    |
|                    | $C_2$  | 0.8    | -    |
| Number of Particle | -      | 100    | -    |
| Number of Iteration| -      | 20     | -    |

### 4. Optimization result

The first step in carrying out optimization is to determine the particle with dimensions $a$ and $b$ randomly with a range according to Table II. Each particle was evaluated for the value of torque density using Ansys Maxwell software. The largest density of all random particles is called gbest. Determine the next position of each particle using equation (2). Matlab software is used to speed up calculations. The particle that initially spreads in a large range, then moves closer to the position that has the best solution value (See Fig. 4 and Fig. 5).
Figure 4. Particle position for 0, 5, 10, and 20 iteration.

Figure 5. Torque vs mass of all particle.

Figure 6. Value of best torque density each iteration.
The final result of 20 iterations is a design with a value of $a = 4.096$ mm and $b = 15.481$ mm. With this design, the average torque value $= 34.34$ Nm and the overall mass is $20.89$ kg. So that the torque density value of the desired design $= 1.6438$ Nm / kg.

Examined from the distribution of magnetic flux, the rotor and stator parts have an average value of $1.5$ T. Meanwhile, there are only small areas that exceed the saturation limit of electrical steel material, which is $1.8$ T. That design is still possible to do prototyping.

The peak-to-peak induced voltage generated by the initial design is $88$ V. The peak-to-peak induced voltage produced by the purposed design is $87.2$ V. Both the initial design and purposed design have a voltage drop from the source voltage with a value $100$ V. This is due to the armature reaction. Initializing the speed in the simulation software is equal to $3000$ rpm. The torque produced in the purposed design is $34.34$ Nm. $0.2\%$ lower than the initial design which has a value of $34.41$ Nm. However, the torque ripple produced by the initial design is higher at $4.36\%$ compared to the purposed design of $3.89\%$. Greater torque ripple results in increased vibration and acoustic noise on the motor. The maximum cogging torque value for both initial design and purposed design is $572.425$ mNm. There is no difference between the two designs because there is no change in shape between the surface of the rotor or the adjacent stator surface.
Table 3. Comparison of initial design and purposed design

| Parameter                  | Initial Design | Purposed Design | Improvement |
|----------------------------|----------------|-----------------|-------------|
| Average Torque             | 34.41 Nm       | 34.34 Nm        | -0.2 %      |
| Total Mass                 | 21.977 kg      | 20.89 kg        | -4.9 %      |
| Torque density             | 1.56 Nm/kg     | 1.6438 Nm/kg    | 5.37 %      |
| Maximum flux density       | 2.44 T         | 2.46 T          | 0.8 %       |
| Ripple Torque factor       | 4.36 %         | 3.89 %          | 12 %        |
| Peak to peak Induced voltage| 88 V          | 87.2 V          | 0.9 %       |
| Maximum cogging torque    | 572.425 mNm    | 572.425 mNm     | 0 %         |

5. Conclusion

In this paper, increasing the value of torque density is done by eliminating certain areas of the rotor. The algorithm used is PSO with 100 particles and 20 iterations. The purpose of the design with the PSO algorithm is the dimensions of $a = 4,096$ mm and $b = 15,481$ mm.

The maximum torque of the purposed design is lower than the initial design, but the purposed design has a lower torque ripple. The induced purposed design voltage is lower than the initial design when rotated at 3000 rpm. Meanwhile the maximum value of cogging torque does not change because the focus of the research is not to change the stator and rotor surface.
6. References

[1] K. Y. Hwang, S. B. Rhee, B. Y. Yang, and B. Il Kwon, “Rotor pole design in spoke-type brushless DC motor by response surface method,” *IEEE Trans. Magn.*, vol. 43, no. 4, pp. 1833–1836, 2007.

[2] A. Fatemi, D. M. Ionel, M. Popescu, Y. C. Chong, and N. A. O. Demerdash, “Design Optimization of a High Torque Density Spoke-Type PM Motor for a Formula e Race Drive Cycle,” *IEEE Trans. Ind. Appl.*, vol. 54, no. 5, pp. 4343–4354, 2018.

[3] S. Nikam, R. Vandana, and B. G. Fernandes, “A high torque density permanent magnet free motor for in-wheel electric vehicle application,” no. c, 2011.

[4] M. H. Mohammadi, “Rotor Design Optimization of Permanent Magnet – Assisted Synchronous Reluctance Machines for Traction Applications,” no. November, pp. 4–8, 2015.

[5] T. C. Bora, L. D. S. Coelho, and L. Lebensztajn, “Bat-inspired optimization approach for the brushless DC wheel motor problem,” *IEEE Trans. Magn.*, vol. 48, no. 2, pp. 947–950, 2012.

[6] A. Sarikhani and O. A. Mohammed, “Multiobjective design optimization of coupled PM synchronous motor-drive using physics-based modeling approach,” *IEEE Trans. Magn.*, vol. 47, no. 5, pp. 1266–1269, 2011.

[7] S. E. Skaar, O. Krovel, and R. Nilssen, “Distribution, coil-span and winding factors for PM machines with concentrated windings,” *XVII Int. Conf. Electr. Mach. ICEM 2006*, p. 346, 2006.

[8] H. Duane C, Brushless permanent magnet motor design. 2006.

[9] J. Kennedy and R. Eberhart, “Particle swarm optimization,” in *Proceedings of ICNN’95 - International Conference on Neural Networks*, 1995, vol. 4, pp. 1942–1948 vol.4.