ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 25(1), 56-63 (2020) https://doi.org/10.4283/JMAG.2020.25.1.056

Power Consumption Analysis and Miniaturization Design of Permanent Magnet Synchronous Motor for Washing Machine with respect to Gear Use

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(Received 8 October 2019, Received in final form 8 January 2020, Accepted 30 January 2020)

In this paper, the energy consumption of PMSM was compared simultaneously in direct and indirect drive systems, considering the efficiency of the operating point in the washing and dehydration modes. DD (Direct Drive) washing machines have the disadvantage of high-power consumption due to the difference in driving point efficiency of washing and dehydration. Therefore, in this paper, a method of changing the washing operation point using a gear is proposed. Two types of miniaturization models that satisfies the output level under two gear conditions are designed, and energy consumption with respect to the operating mode of the washing machine is analyzed and compared. From the viewpoint of power consumption, optimal stacking and gear combination model is selected. In conclusion, the energy consumption of the optimum gear model is decreased about 97 Wh and material cost of the motor down by 57.3 % compared with base DD motor.

Keywords : washing machine, energy consumption, gear

1. Introduction

Due to the recent enforcement of global regulations in energy rating, the improvement of efficiency has been rigorously studied in various fields relating to an electric motor and generator. Significant advancements in consumer electronics with 5G and IoT (Internet on Things) require less energy consumption, and this technological collaboration enables consumers to check the performance of home appliances by a cell phone or other ways in real time. In this paper, the energy consumption of a permanent magnet synchronous motor (PMSM) in washing machines is analyzed, and a better way to enhance energy savings is proposed.

How to spin a drum in a washing machine is either a direct or an indirect method in terms of physical connection of a motor with the drum. In a direct drive, since a motor is directly assembled to a washing drum, the structure of power transmission is relatively simple. On the other hand, an indirect-type drum requires a belt or a gear between a motor and the drum, and hence, there are pros and cons in terms of cost and performance. Most of previous studies on a washing machine driven by a PMSM focused on the operation of the system mainly around its rated point [1, 2]. However, since the actual washing mechanism of a drum is the repetition of forward and backward rotations, it is not sufficient to calculate the energy consumption of a motor at the rated condition.

In this paper, the energy consumption of a PMSM has been compared in direct and indirect drive systems at the same time considering the plot of variable torque versus speed based on washing and dehydration modes, and a helical gear is used in the indirect set-up. In order to analyze energy consumption in a wide speed range, the efficiency of a PMSM is plotted as a map on the x-y plane of speed and torque to track the entire washing and drying operations [3, 4]. During the washing mode, a drum starts spinning at first, and it experiences acceleration and constant speed in a consecutive way. In this paper, the ratio of acceleration to constant speed is considered in terms of energy waste, and a drum with and without a gear is compared to investigate the feasibility of volume decrease in a PMSM.

2. Analysis of Washing Machine Operation Characteristics by Driving Method

Figure 1 shows a PMSM by which a direct-driven washing drum is rotated, and the motor as a base model has a 36/48 structure in terms of stator/rotor pole com-

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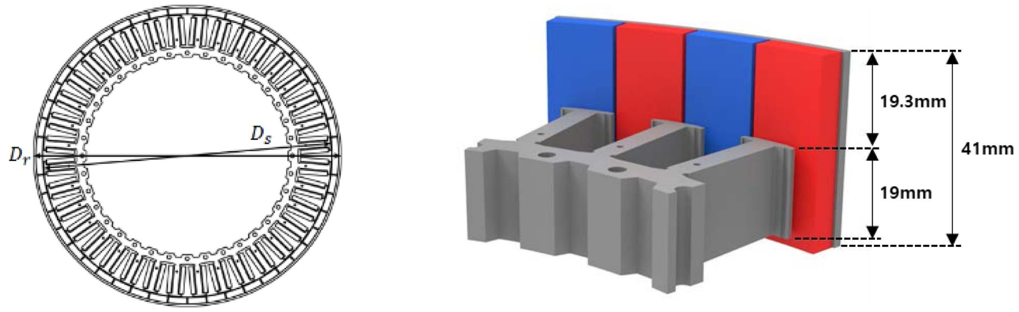


(a) (b)

Fig. 1. (Color online) PMSM base model, (a) 36/48 structure, (b) the three-dimensional view of its stator and rotor.

Table 1. Specification of base model and its limitations.

	Unit	Value
Phase (m)	ea	3
Residual magnetic flux density (B_g)	Tesla	0.42
Magnet thickness (l_m)	mm	6
Number of slots/poles (N_s/N_r)	ea	36/48
No. of turns per pole (N_p)	turns	100
Outer diameter of stator (D_s)	mm	265
Axial length of stator (L_{stks})	mm	19
Outer diameter of rotor (D_r)	mm	283
Axial length of rotor (L_{stkr})	mm	41
Air-gap length (g)	mm	1
Coil diameter	mm	0.9
Phase resistance	ohm	4.317
DC bus voltage	V	310
Maximum current	A	11
Material of PM	-	7B Ferrite
Material of iron core	-	50JN1300
Winding type	-	concentrated
Material of winding	-	aluminum
Fill factor	%	~60

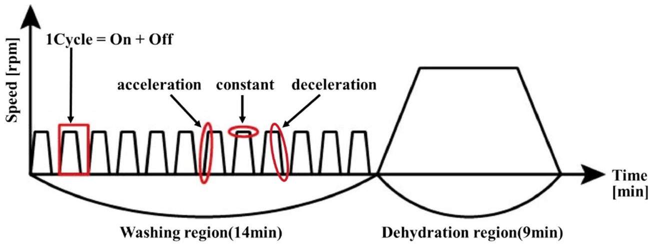


Fig. 2. (Color online) Operation profile of the washing machine motor.

bination along with the three-dimensional view of its assembly in Fig. 1(b). The specification of the base model is detailed in Table 1, and the low-cost material of permanent magnets and coils is applied to this base model. Due to the utilization of aluminum in coils, segmented pieces of silicon steel are fabricated just after the concentric winding process of coils to guarantee enough slot space with fill factor of approximately 60 %. As shown in Fig. 1(b), the rotor assembly is asymmetrically placed with respect to the center of stator stacked core, and the limit of speed and current are 1,400 revolutions/min and 11 amperes, respectively.

2.1. Analysis of power consumption according to the washing machine operation profile

The washing system has various washing modes which the user can perform an appropriate washing according to the amount and type of laundry. Among the various operation modes, in this paper, focus on the profile of Fig. 2 to analyze energy consumption of the washing machine. The operating process of the washing machine consists of a washing mode in which 17 cycles of forward and reverse rotation are repeated, and dehydration mode, which rotates in a constant direction. In the wash mode, the drum rotates back and forth with water and laundry to wash out the dirt. Therefore, the rotational inertia becomes very large, and in this process, the motor needs high torque in order to overcome the rotational inertia of water and laundry and to perform the washing while changing the direction of rotation. On the other hand, the dewatering operation is intended to remove moisture inside the laundry through the centrifugal force by the high-speed rotation of the drum. Therefore, unlike washing operation, it rotates in one direction at high speed and low torque point.

In order to analyze energy consumption according to the washing machine operation mode, Finite Element Method (FEM) is implemented with commercial software Maxwell. The efficiency of a PMSM according to the 150 operating points are calculated in the motor speed and torque operation range, and the calculated efficiency map is shown in Fig. 3. The star point on the upper left corner, which requires 150 rpm, 34 Nm of performance, represents

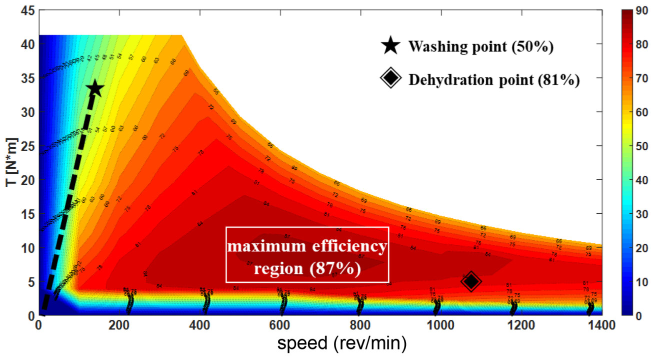


Fig. 3. (Color online) Efficiency map of the machine for washing drum.

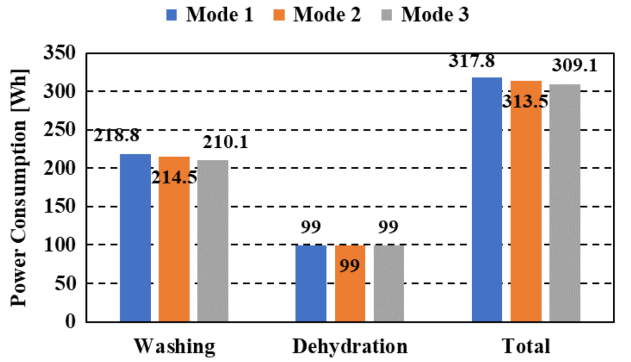


Fig. 5. (Color online) Energy consumption of the base DD washing machine.

a constant operating point during washing. And the diamond mark on the lower right, which is the performance point of 1,100 rpm and 4.7 Nm, represents the constant speed operation point during dehydration. The broken line drawn from the zero point toward the constant speed operating point during washing mode shows the acceleration period.

In order to calculate the accurate energy consumption, the ratio of constant speed to acceleration must be considered. Since dehydration is mostly operated at a high speed rotation in a constant direction, the dehydration power consumption is calculated as the power consumption of the constant speed section, excluding the acceleration/deceleration section. On the other hand, the washing operation must accurately distinguish between the acceleration/deceleration section and the constant speed section due to the frequent change of the rotational direction. Therefore, in this paper, the ratio of acceleration/deceleration to constant speed is considered as three modes as shown in Fig. 4.

Washing machine power consumption is calculated using the washing machine operating profile shown in Fig. 2 and the efficiency map shown in Fig. 3. The energy consumption of the constant speed operation and the acceleration operation in the washing mode, and the dehydration mode is calculated as follows.

$$P_w = (P_{wa} \cdot 2 + P_{wc}) \cdot t \cdot cycle/3600 \quad \text{[Wh]} \tag{1}$$

$$P_{wa} = \Sigma_{n=1}^{k}\left(P_{an} \cdot \frac{100}{E_{an}}\right)/k \quad \text{[W]} \tag{2}$$

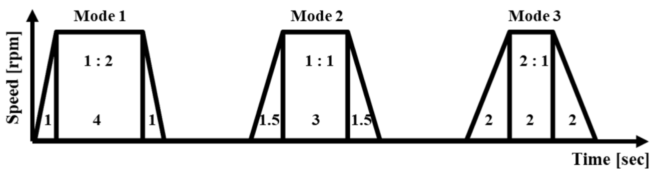


Fig. 4. Three washing modes according to the acceleration time.

$$P_d = P_{dc} \cdot t/3600 \quad \text{[Wh]} \tag{3}$$

where, P_w, P_{wa}, P_{wc}, P_d, P_{dc}, P_{an} and E_{an} are energy consumption of the washing mode, acceleration region of washing, constant region of washing, dehydration mode, constant region of dehydration, power of the each point, and efficiency of the each point, respectively. The power consumption of the acceleration area is obtained by dividing the acceleration section by k points, calculating the power consumption of each point and averaging it, as shown in equation 2. At this time, since the acceleration section is short in the washing operation, it is calculated by dividing into 10 points. The energy consumption for the operation profile in Fig. 2 is calculated by the three acceleration conditions of Fig. 4, and the energy consumption for each mode is given in Fig. 5.

Efficiencies of the washing and dehydrating sections are 50.6 % and 81.8 %, respectively, and the washing operation takes up about 65 % of the entire washing machine operation time. As a result, about 2.2 times more energy is consumed compared to the dewatering operation. And, in case of washing, the energy consumption differs with respect to the ratio between constant speed mode and acceleration mode, and the condition of mode 3 is most advantageous.

2.2. Energy consumption of washing machine according to gear use

In this chapter, possibility of improvement of energy consumption when using the gears is analyzed. The gear box is coupled to the shafts only during washing operation without for dehydration operation. For this operation, a helical gear with the same gear axis as the axial direction is applied, and a gear ratio of 3.8 are used to move the washing point to the highest efficiency point. Fig. 6 shows the movement of the washing point according to gear usage on the efficiency map and efficiency of the washing operation point rises from 50 % to 87 %. The

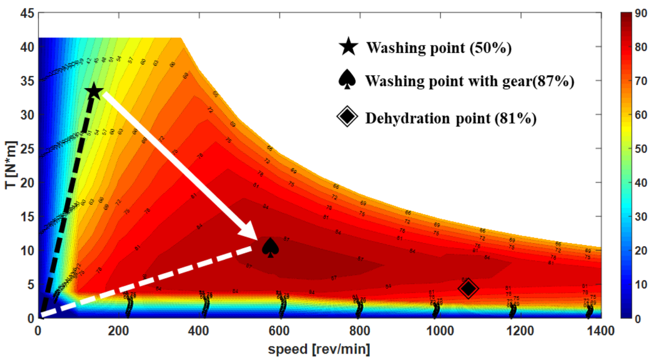


Fig. 6. (Color online) Variation of washing point according to use of gear on the efficiency map.

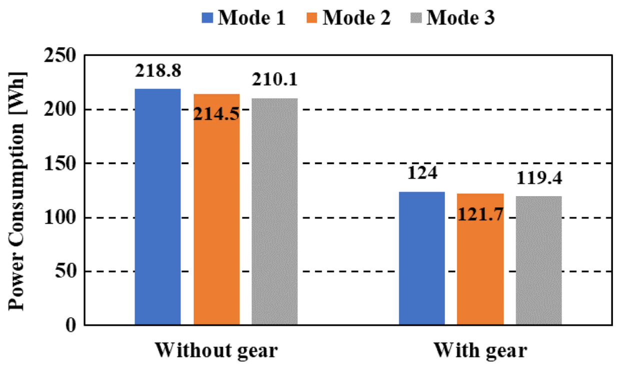


Fig. 7. (Color online) Energy consumption comparison in washing mode according to use of gear.

energy consumption is calculated in the same way as the previous method, and the energy consumption is reduced about 90Wh in the washing mode according to the gear use as shown in Fig. 7.

3. Analysis of Washing Machine Operation Characteristics according to Gear Use

Based on the previous research, the transition from the direct drive system to the indirect drive system using gears is analyzed. When gears are used, required torque for washing is reduced from 34 Nm to 8.94 Nm as shown in Fig. 6. Therefore, it is possible to appropriately change the design parameters within the range satisfying the output torque. The torque of the motor is as follows [7].

$$e = 2N_c B_g D_g L_{stk} \omega_m \tag{4}$$

$$T = \frac{ei}{\omega_m} = 2N_c B_g D_g L_{stk} i \tag{5}$$

Where, N_c, B_g, D_g, and L_{stk} are number of turns per phase, airgap flux density, airgap diameter, and stack length, respectively.

Among the various variables in equation (5), the optimum design performed for gear use is selected by selecting the stack length as the design factor.

3.1. Performance comparison by overhang structure

Prior to stack length selection, the performance with respect to the overhang structure is compared. Fig. 8(a) and Fig. 8(b) show asymmetric overhang structure and symmetric overhang structure, respectively. The magnitude of back EMF according to the overhang structure is shown in Fig. 9, and the symmetrical overhang structure is advantageous to increase the output at the same overhang height. Therefore, the symmetrical overhang is applied and considering the mechanical limitations, the total overhang is determined to be 6 mm.

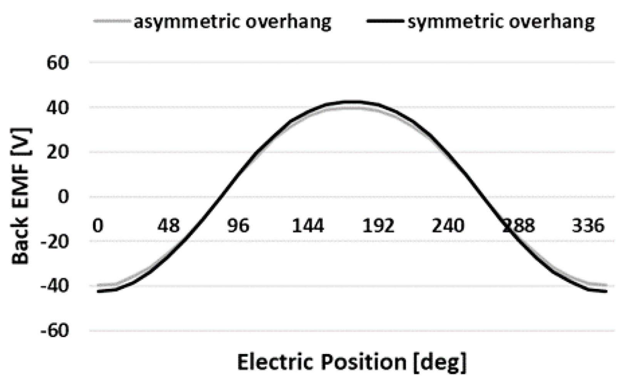


Fig. 9. Back EMF comparison by overhang structure.

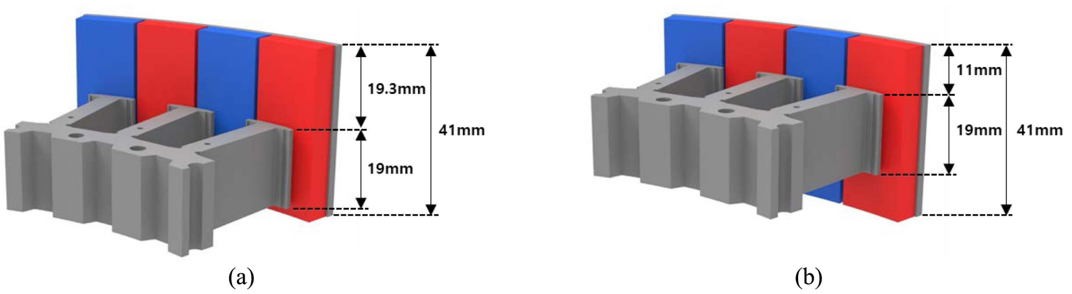


Fig. 8. (Color online) Three-dimensional view according to overhang structure. (a) asymmetric overhang, (b) symmetric overhang.

Table 2. Motor operation point according to gear ratio.

Gear ratio	1:1	4:1	8:1
Motor speed, rpm	150	600	1,200
Average torque, Nm	34	9.0	4.5
Maximum torque, Nm	40.8	10.7	5.4
Maximum current, A	11	5	5

3.2. Miniaturization design of electric motor according to gear use

In this paper, 4:1, and 8:1 gear ratio is selected based on even ratio gear. The 4:1 gear ratio, which is the most similar to the 3.8:1 discussed in Chapter 2, is selected, and 8:1 gear ratio is selected in consideration of the mechanical speed limit of 1,400 [rpm]. Efficiency of the gear is considered as 95 % [6]. Table 2 shows the required motor performance for washing operation according to the gear ratio. The maximum torque is set to 120 % of the average torque in consideration of acceleration and deceleration during washing, and the maximum current is limited to 5 [A] in consideration of torque reduction. The 10 mm stator and 16 mm rotor model is selected as the minimum stack length model that satisfies the maximum torque of 10.7 [Nm] by comparing the torque according to stator stack length under 5 [A] current condition. As a comparative model, stator stacking 14 mm and rotor stacking 20 mm with a larger maximum torque is selected. Fig. 10 illustrates two miniaturization models satisfying the condition of Table 2, and main parameter of the two models are given in Table 3.

3.3. Loss characteristics of miniaturized design model

This section attempts to predict losses through the performance characteristics of two miniaturized models at the same operating point. The loss of the motor is divided into winding loss and iron loss. The winding loss can be calculated through equations (6) to (8), [7] and a model having a large torque constant and a small resistance is advantageous. In Model 1, the torque constant is relatively high, but the resistance is also large. However, the torque constant acts as the square term in equation (8), so it is more influential than the resistance, and as a result, Model 1 is advantageous for winding loss.

Table 3. Geared model specifications.

	Model 1	Model 2
Back EMF @ 800 rpm, V	154.12	119.24
No. of turns per poles, turns	100	100
Torque constant, $K_{T[pk]}$	2.75	2.13
Phase resistance, ohm	3.78	3.36

$$P = T\omega_m = E_{rms}I_{rms} = \frac{1}{2}e_{pk}i_{pk} \quad (6)$$

$$T = \frac{1}{2}\frac{e_{pk}}{\omega_m}i_{pk} = \frac{1}{2}K_{E[pk]}i_{pk} = \frac{1}{2}K_{T[pk]}i_{pk} \quad (7)$$

$$\text{Winding loss} = \left(\frac{T_e}{K_{T[pk]}}\right)^2 \cdot R \cdot 3 \quad (8)$$

where K_T, K_E, and R are torque constant, back EMF constant, and phase resistance, respectively.

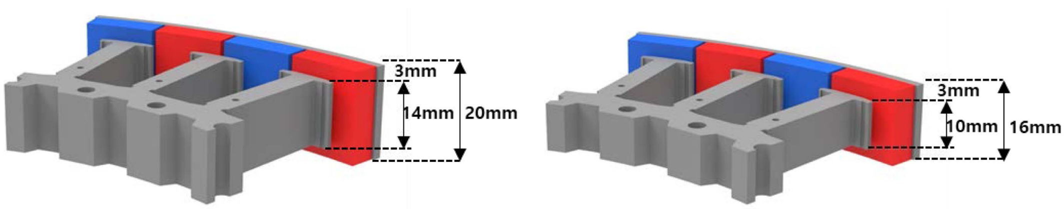
Iron loss is expressed as the sum of the hysteresis loss and the eddy current loss as follows [7].

$$\text{Core loss} = (K_h B_{max}^m f + K_e B_{max}^2 f^2) \cdot m \quad (9)$$

where f, K_h, K_e, B_{max}, and m are the frequency, hysteresis loss coefficient, eddy current loss coefficient, maximum flux density, and volume of core, respectively. The eddy current loss coefficient and hysteresis loss coefficient are determined by the material of the iron core, and the loss coefficients are the same because the iron core of the two models are the same. Fig. 11 shows the airgap flux density and iron loss of the two models at three operating points. Model 2 has higher airgap flux density but less iron loss. Therefore, iron loss is greatly influenced by the amount of iron core (m), and Model 2 having a small stack length is advantageous for iron loss.

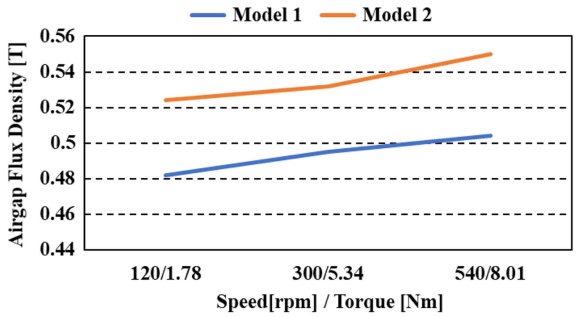
3.4. Operation point of washing machine according to gear ratio and stack length of motor

Figure 12 gives the efficiency map of Model 1 and Model 2 with operation points of washing and dehydration

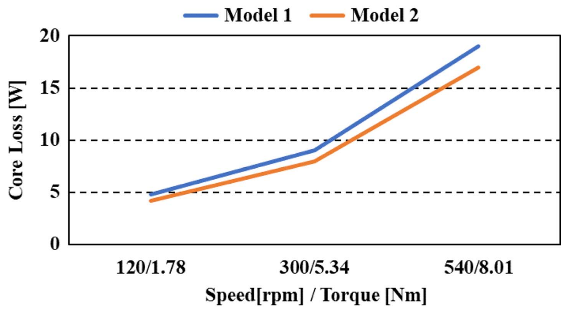


(a) (b)

Fig. 10. (Color online) Downsizing model according to use of gear. (a) Model 1, (b) Model 2.

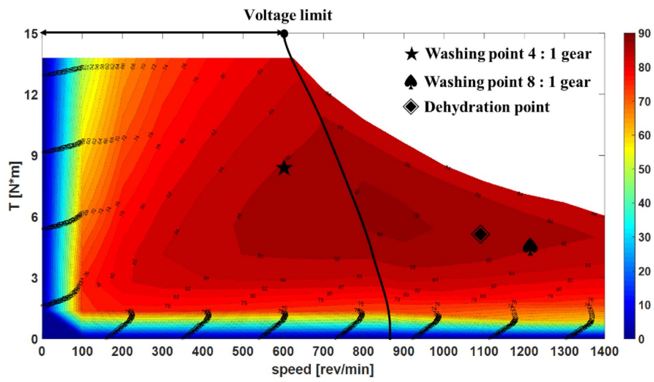


(a)

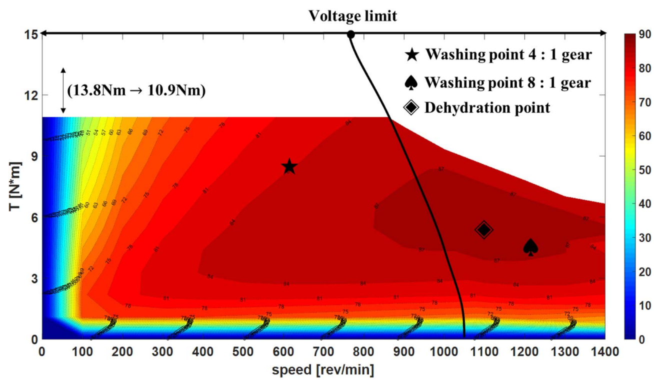


(b)

Fig. 11. (Color online) Comparison of core loss with respect to stack length. (a) airgap flux density, (b) core loss.



(a)



(b)

Fig. 12. (Color online) Comparison of washing point on the efficiency map with respect to gear ratio. (a) Model 1, (b) Model 2.

according to gear ratio. It is evident that the maximum torque decreases as the stacking decreases and the maximum efficiency point moves to the high-speed region. And, when the 4:1 gear is applied, the washing point is located in the constant torque region, and the washing point is located in the flux weakening region when the 8:1 gear is applied.

4. Energy Consumption of Compact Model according to Operation Mode of the Washing Machine

In this chapter, two types of gear are applied to two miniaturized models and the efficiency characteristics with respect to the constant speed mode, the acceleration mode, and the dehydration mode, respectively are analyzed, and the most favorable model for the energy consumption of the washing machine system is selected.

4.1. Comparison of power consumption in washing

Table 4 shows the washing points of the motor according to the gear ratios and Fig. 13 illustrates the average efficiency of the constant speed range of the two motor models according to the gear ratios. In the case of 4:1 having a relatively low gear ratio, large current is required to rotate drum since it operates at low speed and high torque points. Therefore, it is seen that the efficiency of Model 1, which is advantageous to winding loss, is 2.8 % higher. In the case of a gear ratio of 8:1, the efficiency of Model 2, which is advantageous in iron loss characteristics,

Table 4. Washing point according to gear ratio.

	4:1 gear	8:1 gear
Speed, rpm	600	1,200
Torque, Nm	9.0	4.5
Output, W	565	565

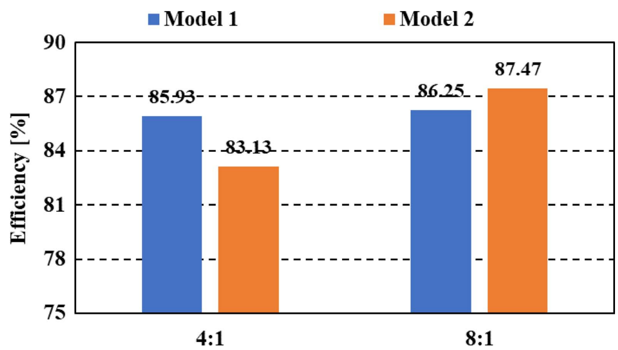


Fig. 13. (Color online) Efficiency of constant speed region in washing mode according to gear ratio and axial length of motor.

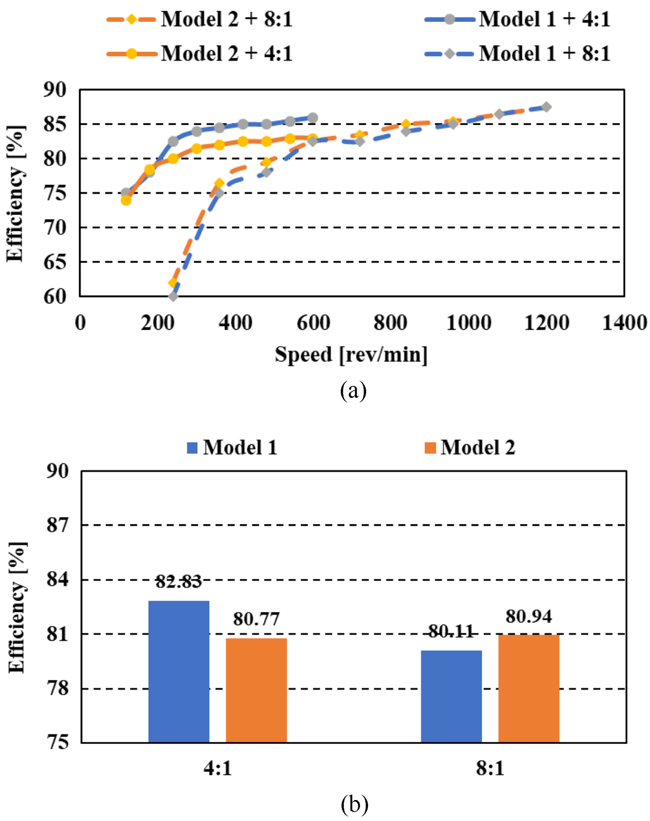


Fig. 14. (Color online) Efficiency in washing mode according to gear ratio and axial length of motor, (a) acceleration point, (b) average.

is 1.2 % higher because washing is performed in the flux weakening region. In conclusion, Model 2 with 8:1 gear is most advantageous in terms of constant speed operation during washing mode.

The efficiencies of acceleration and deceleration are obtained by dividing the shortest distance reaching the washing point into 10 sections, and the efficiency of each point was averaged. Fig. 14(a) demonstrate the efficiency locus of the two models in terms of gear and Fig. 14(b) shows the average efficiency. Unlike the constant speed region, the average efficiency of the acceleration/deceleration region is most advantageous when 4:1 gear is applied to the Model 1 structure.

4.2. Comparison of power consumption in dehydration

Dehydration is performed without gear, unlike washing, and both models operate in the flux weakening region. In the case of high-speed and low-torque region, Model 2 with low stack length is expected to be advantageous, and as shown in Fig. 15, the efficiency of Model 2 is 0.1 % higher than that of Model 1.

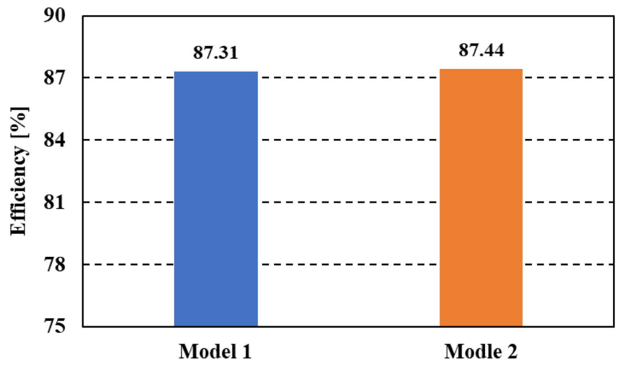


Fig. 15. (Color online) Efficiency comparison in dehydration mode according to axial length of motor.

4.3. Comparison of overall washing machine power consumption

In the combination of two stacking models and two gear ratios, each energy consumption according to washing machine operating mode was analyzed. The ratios of the constant speed to the accelerating area is the mode 3, and Fig. 16 shows the energy consumption of the washing machine according to four combination of gear ratio and stack length. As a result of analysis of the energy con-

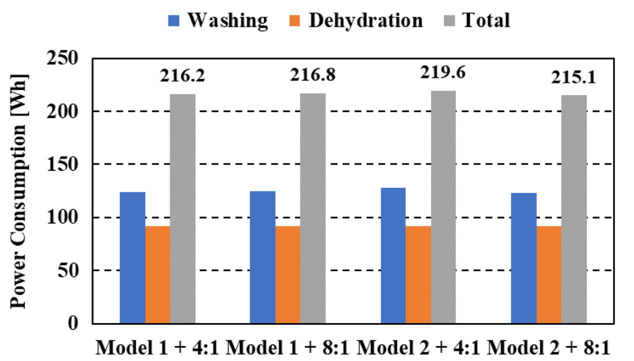


Fig. 16. (Color online) Energy consumption of the washing machine according to four combination of gear ratio and stack length.

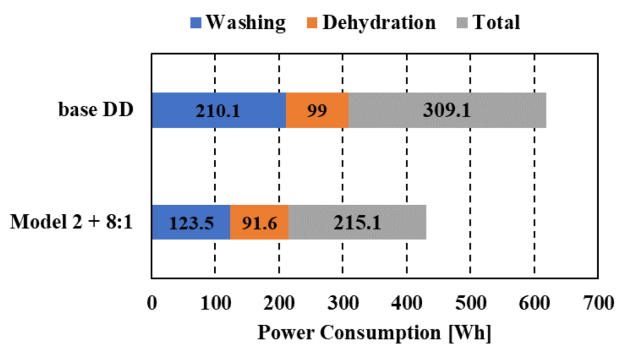


Fig. 17. (Color online) Comparison of energy consumption between geared model and base DD.

Table 5. The cost coefficient according to use of gear.

	Base DD	Model 2+8:1 gear
Volume of core, Kg	1.74	0.91
Volume of magnet, Kg	0.99	0.39
Gear, EA	0	1
Max current, A	11	5

Table 6. The core and magnet cost according to use of gear.

	Base DD	Model 2+8:1 gear
Core, won	1,696	887
Magnet, won	4,950	1,950
Total, won	6,646	2,837

sumption according to the washing profile, there is no big difference, but it is confirmed that the gear ratio 8:1 with Model 2 is optimal.

In order to analyze the effect of gear use on the energy consumption in the washing machine system, base model system without gear and Model 2 with 8:1 gear is compared, and it is shown in Fig. 17. The Model 2 with 8:1 gear improves energy consumption by 86.6 Wh in washing and 7.4 Wh in dehydration compared with base direct drive system. Finally, it is confirmed that the total energy consumption of 94 Wh for one operation of washing machine was improved. The main cost factors are summarized in order to analyze the cost change due to the addition of gear and are shown in Table 5. As gears are used, additional maintenance costs are incurred, but motor stacks and currents are reduced. Table 6 gives the core and magnet cost of the gear ratio optimal model and the base DD model. According to gear use, 57.3 % reduction in the material cost of motor compared to the base DD has been confirmed, and therefore, it is expected that there will be no significant increase in cost according to gear use.

5. Conclusion

In this paper, energy consumption of a PMSM has been compared in direct and indirect drive systems at the same time considering the plot of variable torque versus speed based on washing and dehydration modes, and a helical gear is used in the indirect set-up. It has been confirmed that the energy consumption of the direct drive system is large due to the characteristic of the washing machine system having a wide range of speed-torque operation, and a method of changing the washing operation point by using the gear is proposed. Two types of miniaturization models that satisfies the output level under two gear conditions are designed, and energy consumption with respect to the operating mode of the washing machine is analyzed and compared. Model 2 with 8:1 gear is excellent in terms of efficiency in the constant speed section during washing and the dehydration section, and Model 1 with 4:1 gear is advantageous in the acceleration section. In conclusion, Model 2 with 8:1 gear is the most advantageous in terms of energy consumption of the washing machine, and 97 Wh of energy consumption is improved compared with base direct drive system which does not use gears. In addition, 57.3 % reduction in the material cost of motor compared to base DD motor was confirmed, and therefore, it is expected that there will be no significant increase in cost according to gear use.

Acknowledgements

This work was supported by BK21PLUS, Creative Human Resource Development Program for IT Convergence and In part by the National Research Foundation of Korea (NRF) funded by the Ministry of Education through the Basic Science Research Program under Grant NRF-2018R1D1A1B07049717.

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