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Electromagnetic Analysis and Experimental Study to Optimize Force Characteristics of Permanent Magnet Synchronous Generator for Wave Energy Converter Using Subdomain Method

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Abstract: This paper presents an electromagnetic analysis and experimental verification to optimize the noise, vibration, and harshness (NVH) characteristics of a permanent magnet synchronous generator (PMSG) for wave energy converters (WECs). WECs applicable to breakwater installed in island areas require a wider operating range and a robust design for maintenance compared with wind-turbine systems. Owing to the use of a permanent magnet with a high energy density, the PMSG has a higher power density than other types of generators; however, strong electromagnetic excitation forces that affect the NVH characteristics are generated. Therefore, in this study, the electromagnetic forces are analyzed through an electromagnetic-field analysis using a subdomain analytical method. Based on the analytical solution, electromagnetic forces were determined. Four electromagnetic excitation forces were classified, and the methods for reducing electromagnetic excitation forces are presented here. Finally, a method for evaluating the system resonance through electromechanical analysis is presented. The proposed analysis, optimization, and experimental study are validated through comparison with finite-element analysis and experimental results.

Keywords: electromagnetic force; permanent magnet synchronous generator; subdomain method; wave energy converter

1. Introduction

With the increasing concerns regarding the depletion of fossil fuels and environmental problems, renewable-energy technologies are attracting attention worldwide [1,2]. Compared with other renewable-energy sources, ocean wave energy has several interesting features, such as a high power density, high availability, and abundant resources [3]. Over the years, academia and industry have directed considerable effort toward developing, evaluating, and improving methods of converting electrical energy from various wave sources. The oscillating water column (OWC) wave energy converter (WEC)—an ocean wave energy conversion technology—has a relatively stable structure compared with other types of wave power conversion because mechanical parts are not submerged in seawater [4–7]. Therefore, the OWC WEC, which can be applied to the breakwater, is useful in island areas where the cost of transportation of fossil fuels for power generation and the cost of facilities to supply electricity from land are high.

In OWC WECs applicable to breakwater, electricity is generated by a generator by driving an air turbine through a coupling between a wave and an air chamber. This system consists of a chamber, a turbine, a generator, and power electronics in a fixed structure.

Here, a generator is a secondary energy-conversion system that converts mechanical energy generated by a turbine into electrical energy that can be used in the grid along with power electronics. According to previous studies, a permanent magnet synchronous generator (PMSG) with a simple structure, high efficiency, and high power density is suitable for use in OWC WECs applicable to breakwater [7–9]. Additionally, a robust design for maintenance of PMSGs in OWC WECs applicable to breakwater is important.

To design a robust PMSG for maintenance, it is necessary to improve the noise, vibration, and harshness (NVH) characteristics. In PMSGs, NVH characteristics are caused by aerodynamic, mechanical, and electromagnetic problems [10–12]. Aerodynamic problems—mainly caused by turbines—and mechanical problems caused by bearing and assembly errors can be ignored in the design stage of a PMSG. In contrast, electromagnetic problems directly affect the NVH characteristics and cause failures such as bearing failure and insulation breakdown. Cogging torque [13], torque ripple [14], magnetic pull force (MPF) [15], and unbalanced magnetic force (UMF) [15] are the main electromagnetic sources of NVH characteristics. Studies have been conducted to optimize or improve individual force characteristics, but improvement of the overall force characteristics is required for improving the NVH characteristics.

This paper presents an electromagnetic analysis and experimental study for improving the NVH characteristics by optimizing the force characteristics of the PMSG for OWC WECs. The subdomain technique is useful for gaining insights into the relationships between design parameters and the performance through a simplified analytical model of the PMSG based on electromagnetic-field theory. The governing equations of the PMSG are in the form of second-order differential equations such as Laplace and Poisson equations, and analytical solutions can be derived by applying appropriate boundary conditions. Based on the analytical solutions, the force characteristics of the PMSG can be predicted using the Maxwell stress tensor. The results of the analytical method were validated through comparison with a finite-element (FE) analysis. Because the subdomain method allows faster analysis than the FE method, it is possible to design a model with optimal force characteristics that satisfies the required efficiency and output power through parametric analysis according to the design variables. A prototype with optimal force characteristics that satisfies the required machine performance was analyzed and manufactured using the subdomain method and FE analysis. Evaluation of the system resonance through electromechanical analysis was proposed. An experimental system for vibration measurement was established, and the proposed method was validated using the experimental results.

2. Electromagnetic Field Analysis of PMSGs

The structure of the generator used in OWC WECs is a PMSG with a slotted stator and inner rotor, as shown in Figure 1a. Several assumptions are needed to define a simplified analytical model [16–20]: the end effects in the z -axis direction are neglected in the simplified analytical model, the permeability of the iron core is infinite, the permeability of the permanent magnets (PMs) has linearity, and the width of the slot and the slot opening each have a fixed angle. In the proposed analytical method, the whole geometry is divided into five domains, and the analytical solution for each domain is obtained via Fourier analysis.

As shown in Figure 1b, a simplified analytical model based on the polar coordinate system can be established. r_5 and r_4 represent the outer and inner radii of the stator slot, respectively; r_3 and r_2 represent the outer and inner radii of the airgap, respectively; and r_1 represents the inner radius of the PM. $r_{sm} = [(r_4^2 + r_5^2)/2]^{1/2}$ to make the two parts of each slot have the same area. The number of semi-closed stator slots is Q . The width of the slot-opening angle is β , and the width of the slot angle is δ . θ_i and θ_j represent the angular positions of the i^{th} stator slot opening and the j^{th} stator slot, respectively. Table 1 presents the specifications of the PMSG used in the analysis.

Figure 1. Structure of the PMSG: (a) analytical model; (b) simplified analytical model.

Table 1. Specifications of the designed PMSG.

Parameters	Designations	Value	Unit
p	Number of poles	28	-
Q	Number of slots	60	-
r_1	Inner radius of PMs	82	mm
r_2	Outer radius of PMs	85	mm
r_3	Inner radius of stator	87	mm
r_4	Inner radius of slots	90	mm
r_5	Outer radius of slots	118	mm
r_6	Outer radius of stator	125	mm
l_{stk}	Axial length	90	mm
w_{tooth}	Tooth width	4.5	mm
$P_{elec.}$	Electric power (rated)	3	kW
N_{rpm}	Rotating speed (rated)	800	rpm
$P_{elec.}$	Electric power (rated)	3	kW
h_{pm}	Height of PMs	3	mm
α_p	Pole-arc to pole-pitch ratio	0.85	-
w_{so}	Width of slot opening	3	mm

For each domain, the governing equations are derived from the Maxwell equations in the form of magnetic vector potentials.

$$\begin{aligned} \nabla^2 \mathbf{A}_{zn}^I &= \mu_0 (\nabla \times \mathbf{M}_0^I) & \nabla^2 \mathbf{A}_{zn}^{II} &= 0 & \nabla^2 \mathbf{A}_{zk}^{III,i} &= 0 \\ \nabla^2 \mathbf{A}_{zm}^{IV,j} &= -\mu_0 \mathbf{J}_z^{IV,j} & \nabla^2 \mathbf{A}_{zm}^{V,j} &= -\mu_0 \mathbf{J}_z^{V,j} \end{aligned} \quad (1)$$

Here, μ_0 represents the vacuum permeability.

Figure 2 presents the parallel magnetization distribution of the PM region. $\mathbf{M}_0$ represents the magnitude of magnetization, and θ_0 represents the initial position of the rotor. θ_m represents the width of the PM. In the two-dimensional polar (2D) coordinate system, the magnetizations in the r and θ directions can be expressed as follows:

$$\begin{aligned} \mathbf{M}_0 &= M_r \mathbf{i}_r + M_\theta \mathbf{i}_\theta \\ M_r &= \sum_{n=1}^{\infty} M_{rn} \cos n\theta_0 \cos n\theta + M_{rn} \sin n\theta_0 \sin n\theta \\ M_\theta &= \sum_{n=1}^{\infty} -M_{\theta n} \sin n\theta_0 \cos n\theta + M_{\theta n} \cos n\theta_0 \sin n\theta \end{aligned} \quad (2)$$

where $\mathbf{i}_r$ and $\mathbf{i}_\theta$ represent the radial and circumferential directions of the vector, respectively. M_{rn} and $M_{\theta n}$ represent the n th-order radial and circumferential Fourier components of the parallel magnetization $\mathbf{M}_0$, respectively.

Figure 2. Two-dimensional FE analysis model.

By obtaining the Laplace and Poisson equations using the variable separation method, general solutions can be derived for each domain.

$$\mathbf{A}_{zn}^I = \sum_{n=1}^{\infty} \left[\begin{aligned} &\left(\left(\frac{r}{r_1} \right)^{-n} A_n^I + \left(\frac{r}{r_2} \right)^n B_n^I + \frac{r \mu_0 n}{((n)^2 - 1)} M_n \cos n\theta_0 \right) \sin n\theta \\ &+ \left(\left(\frac{r}{r_1} \right)^{-n} C_n^I + \left(\frac{r}{r_2} \right)^n D_n^I - \frac{r \mu_0 n}{((n)^2 - 1)} M_n \sin n\theta_0 \right) \cos n\theta \end{aligned} \right] \mathbf{i}_z \quad (3)$$

$$\mathbf{A}_{zn}^{II} = \sum_{n=1}^{\infty} \left(\left(\frac{r}{r_2} \right)^{-n} A_n^{II} + \left(\frac{r}{r_3} \right)^n B_n^{II} \right) \sin n\theta + \left(\left(\frac{r}{r_2} \right)^{-n} C_n^{II} + \left(\frac{r}{r_3} \right)^n D_n^{II} \right) \cos n\theta \mathbf{i}_z \quad (4)$$

$$\mathbf{A}_{zk}^{III,i} = A_0^{III,i} + B_0^{III,i} \ln r + \sum_{k=1}^{\infty} \left(\left(\frac{r}{r_3} \right)^{-\frac{k\pi}{\beta}} A_k^{III,i} + \left(\frac{r}{r_4} \right)^{\frac{k\pi}{\beta}} B_k^{III,i} \right) \cos \left(\frac{k\pi}{\beta} (\theta - \theta_i) \right) \mathbf{i}_z \quad (5)$$

$$\begin{aligned} \mathbf{A}_{zm}^{IV,j} &= A_0^{IV,j} + B_0^{IV,j} \ln r - \frac{1}{4} \mu_0 J_0^{IV,j} r^2 \\ &+ \sum_{m=1}^{\infty} \left(\left(\frac{r}{r_4} \right)^{-\frac{m\pi}{\delta}} A_m^{IV,j} + \left(\frac{r}{r_{sm}} \right)^{\frac{m\pi}{\delta}} B_m^{IV,j} + \frac{\mu_0 J_m^{IV,j} r^2}{\left(\frac{m\pi}{\delta} \right)^2 - 4} \right) \cos \left(\frac{m\pi}{\delta} (\theta - \theta_j) \right) \mathbf{i}_z \end{aligned} \quad (6)$$

$$\begin{aligned} \mathbf{A}_{zm}^{V,j} &= A_0^{V,j} + B_0^{V,j} \ln r - \frac{1}{4} \mu_0 J_0^{V,j} r^2 \\ &+ \sum_{m=1}^{\infty} \left(\left(\frac{r}{r_{sm}} \right)^{-\frac{m\pi}{\delta}} A_m^{V,j} + \left(\frac{r}{r_5} \right)^{\frac{m\pi}{\delta}} B_m^{V,j} + \frac{\mu_0 J_m^{V,j} r^2}{\left(\frac{m\pi}{\delta} \right)^2 - 4} \right) \cos \left(\frac{m\pi}{\delta} (\theta - \theta_j) \right) \mathbf{i}_z \end{aligned} \quad (7)$$

where $\mathbf{i}_z$ represents the z-axis direction of the vector. M_n is defined as $M_n = M_{rn} - M_{\theta n}/n$, $J_m^{(IV \text{ or } V),j}$, which are the components of the current density distribution [16]. The unknown coefficients ($A_0^{III,IV,V}$, $B_0^{III,IV,V}$, $A_n^{I,II}$, $B_n^{I,II}$, $C_n^{I,II}$, $D_n^{I,II}$, A_k^{III} , B_k^{III} , $A_m^{VI,V}$, and $B_m^{VI,V}$) can be solved using a set of boundary conditions determined by the geometry of the problem [16–18]. Based on analytical solutions, the force characteristics are derived using the Maxwell stress tensors.

Using the definition of the magnetic vector potential $\nabla \times \mathbf{A} = \mathbf{B}$, the normal ∇ magnetic flux density ($\mathbf{B}_r$) and the circumferential magnetic flux density ($\mathbf{B}_\theta$) can be derived as follows:

$$\mathbf{B}_r = \frac{1}{r} \frac{\partial \mathbf{A}}{\partial \theta} \mathbf{i}_r, \quad \mathbf{B}_\theta = -\frac{\partial \mathbf{A}}{\partial r} \mathbf{i}_\theta \quad (8)$$

According to the specifications in Table 1, the FE analysis model is shown in Figure 3. Figure 4 shows the radial and circumferential magnetic flux densities in the air gap according to the electromagnetic sources. Figure 4a shows the magnetic flux density in the air gap caused by the PM, based on one electrical cycle. Figure 4b shows the magnetic flux density in the air gap caused by the armature coils, mechanically at 90° due to the winding

arrangement. The derived analytical solutions were validated by comparing the magnetic flux density in the air gap with FE analysis result.

Figure 3. Two-dimensional FE analysis model.

Figure 4. Magnetic flux density distributions due to (a) PMs and (b) armature coils.

According to Maxwell stress theory, the total force on a body placed in an electro-magnetic field can be calculated by integrating the magnetic stress on the closed surface around the body. Therefore, the two force components exerted on the cylinder are defined as follows [20,21]:

$$\mathbf{F} = \frac{1}{\mu_0} \left(B_r^2 - \frac{1}{2} |\mathbf{B}|^2 \right) \mathbf{i}_r + \frac{1}{\mu_0} B_r B_\theta \mathbf{i}_\theta \quad (9)$$

The electromagnetic force consists of two components: radial and circumferential. The radial force is used to calculate the radial force density, and the circumferential force is used to calculate the torque. According to the definition of torque, an electromagnetic torque can be derived using the radius of the airgap including the rotor and the stress vector of the circumferential component.

$$\mathbf{T}_z = \mathbf{r} \times \mathbf{F}_\theta = \frac{r}{\mu_0} \int_0^{l_{stk}} \int_0^{2\pi} B_{rg} B_{\theta g} r d\theta dz \mathbf{i}_z \quad (10)$$

Here, r represents the radius of the integration surface, and B_{rg} and $B_{\theta g}$ represent the radial and circumferential components of the flux density at radius r , respectively.

In addition to the electromagnetic torque expressed as mechanical power, the MPF, which is a magnetic force generated between the rotor and the stator, is important for analyzing the electromagnetic excitation source. According to the stator and rotor core with infinite permeability, the radial and circumferential force distributions acting on the stator surface can be obtained from the Maxwell stress tensor.

$$f_r = \frac{1}{2\mu_0} \left(B_{rg}^2 - B_{\theta g}^2 \right) \quad (11)$$

$$f_{\theta} = \frac{1}{\mu_0} B_{rg} B_{\theta g} \quad (12)$$

This can be transformed to Cartesian coordinates:

$$f_x = f_r \cos \theta - f_{\theta} \sin \theta \quad (13)$$

$$f_y = f_r \sin \theta + f_{\theta} \cos \theta \quad (14)$$

The UMF is the resultant global magnetic force that acts on the rotor owing to the asymmetric magnetic-field distribution in the airgap. The force components F_x and F_y , which act on a rotor having axial length l_{stk} , can be computed by evaluating the following expressions along a surface of radius r in the center of the airgap:

$$F_x = \frac{rl_{stk}}{2\mu_0} \int_0^{2\pi} \left[(B_{rg}^2 - B_{\theta g}^2) \cos \theta - 2B_{rg}B_{\theta g} \sin \theta \right] d\theta \quad (15)$$

$$F_y = \frac{rl_{stk}}{2\mu_0} \int_0^{2\pi} \left[(B_{rg}^2 - B_{\theta g}^2) \sin \theta + 2B_{rg}B_{\theta g} \cos \theta \right] d\theta \quad (16)$$

3. Electromagnetic Force Analysis and Optimization with Mechanical Analysis for Improving NVH Characteristics

The NVH sources of the PMSG can be divided into two main categories: (1) mechanical problems, such as rotor eccentricity, shaft misalignment, and bearing defects, and (2) electromagnetic problems caused by electromagnetic excitation forces. In this paper, a method for improving the NVH characteristics by optimizing electromagnetic excitation forces such as the cogging torque, torque ripple, MPF, and UMF generated in the PMSG is presented.

3.1. Cogging Torque

The cogging torque arises from the magnetic field generated by the PMs and the tooth-slot structure of the stator under no-load operating conditions. It affects not only the vibrations generated during starting and stopping but also the torque ripple component during on-load operating conditions. Among the many optimization methods for reducing the cogging torque, one that can be applied in the initial design stage is the selection of an appropriate pole-slot combination. According to previous studies, the magnitude of the cogging torque is significantly reduced in a fractional-slot combination with a large least common multiple of the numbers of poles and slots [22,23]. To select a combination of slot and number of poles, a factor was introduced to indicate the “goodness” of a combination of slot and pole number with regard to the cogging torque [16]. The goodness factor, whose magnitude is proportional to that of the cogging torque, can be expressed as follows [23]:

$$C_t = \frac{P \cdot Q}{LCM(P, Q)} \quad (17)$$

The cogging torque increases as the goodness factor increases [22,23].

The PMSG used in the analysis was designed with a structure of 28 poles and 60 slots, considering the goodness factor, and the analysis result for the cogging torque is shown in Figure 5. The cogging torque of the presented model is $1.87 \times 10^{-8} \text{ N} \cdot \text{m}_{pk-pk}$, and the rated torque is $35.81 \text{ N} \cdot \text{m}$; thus, the cogging-torque ratio is 5.22×10^{-8} . In high-performance electric machines, the cogging torque is less than 1–2% of the rated torque [24].

Figure 5. Cogging torque according to the rotor position.

3.2. Torque Ripple

Torque ripple should be minimized as an excitation-force source because the fluctuation of the electromagnetic torque not only transmits the excitation force to the other structures connected to the shaft in the circumferential direction but also causes fluctuations in the output power. Excluding the cogging torque and the torque generated by electromagnetic losses, the electromagnetic torque can be expressed as [23]

$$T = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_r} \quad (18)$$

where e and i represent the instantaneous values of the induced voltage and current, respectively, over time for each of the three phases, and ω_r represents the mechanical angular velocity of the rotor.

The induced voltage and sinusoidal current of each phase can be expressed as follows:

$$e_{ph} = \omega_r \sum_{n=1,odd}^{\infty} K_n \sin(np\omega_r t) \quad (19)$$

$$i_{ph} = I_{\max} \sin(p\omega_r t) \quad (20)$$

where K_n is the induced-voltage constant, which represents the flux linkage with the pole pair according to spatial harmonics. $I_{\max}$ represents the maximum sinusoidal current.

Assuming that the output current is a sinusoidal waveform, the torque ripple is determined by the harmonics of the induced voltage. From the product of three-phase voltage and current at a constant speed, the rated torque can be expressed as follows [25,26]:

$$T = \frac{3}{2} K_1 I_{\max} + \frac{1}{2} I_{\max} \sum_{n=1,odd}^{\infty} K_n (1 + 2 \cos(\frac{2\pi}{3}(n-1))) \cos((n-1)p\omega_r t) + \frac{1}{2} I_{\max} \sum_{n=1,odd}^{\infty} K_n (1 + 2 \cos(\frac{2\pi}{3}(n+1))) \cos((n+1)p\omega_r t) \quad (21)$$

The first term represents the average electromagnetic torque, and the second and third terms are components that affect torque ripple, respectively. Therefore, improving the total harmonic distortion (THD) of the induced voltage at the design stage can reduce the electromagnetic excitation source. Figure 6a,b show the induced-voltage waveform and the fast Fourier transform (FFT) result. The FFT result of the induced voltage indicates that the THD of the induced voltage is 0.841%. On the basis of the analysis result, the induced voltage of the PMSG was designed with a sinusoidal waveform. As shown in Figure 6c, low torque ripple (0.4305%) in the PMSG with a low THD occurs under the rated operating condition.

Figure 6. Electromagnetic performance: (a) induced-voltage waveform; (b) FFT result for the induced voltage; (c) rated torque.

3.3. MPF

The MPF in the air gap is caused by the interaction of the magnetic field with the PM and the magnetic field with the stator coil. The MPF generated in the magnetic fields of the rotor and stator affects the vibration mode of the PMSG. A symmetric MPF can be obtained by selecting an appropriate pole–slot combination at the design stage. The MPF can be calculated using the radial and circumferential magnetic flux densities in the airgap.

Figure 7 shows the analysis results for the MPFs due to the PM and the stator coil, respectively. In both cases, the MPF is symmetric.

Figure 7. MPFs due to (a) PMs and (b) armature coils.

3.4. UMF

UMFs can occur in fractional-slot PMSGs with an asymmetric winding arrangement and pole–slot combinations, even in the absence of eccentricity and other manufacturing tolerances [20,27]. Because the bearing life is approximately inversely proportional to the third power of the applied load, UMFs can significantly reduce the bearing life. They can also cause significant NVH in the overall system. The UMF is an important parameter for measurement and comparison with other systems. This is because it is based on newton [N], which is the unit of force directly applied to the rotor. According to the pole–slot combination, the optimal design point can be identified by deriving a design model with a uniform MPF distribution and changing the pole-arc ratio [28]. As shown in Figure 8, compared with previous studies, the results of the UMF analysis were lower, even though the machine size and power were increased [20,28]. The analysis results confirm that the force acting on the rotor due to the electromagnetic excitation source is weak.

Figure 8. UMFs due to (a) no-load and (b) rated load conditions.

3.5. Parametric Analysis for Optimizing Electromagnetic Forces

Based on an analytical solution that can be analyzed quickly, optimized electromagnetic force characteristics can be derived through parametric analysis according to design variables. In this study, a parametric analysis was performed according to the pole-arc to pole-pitch ratio and slot-opening width, which are design variables that directly affect the force characteristics. The design parameters are presented in Table 1. Because the volume of the PM changes as the pole-arc to pole-pitch ratio changes, the parametric analysis was performed by changing the thickness of the PM so that its area remained the same.

Figures 9 and 10 show the results for the analysis of the force characteristics based on the pole-arc to pole-pitch ratio and slot opening under no-load and rated-load conditions, respectively. From the pole-slot combination and symmetric winding distribution, the analysis model indicates that the cogging torque and UMF have small values and do not affect the performance when the pole-arc to pole-pitch ratio is 0.77–0.85.

Figure 9. Parametric analysis under the no-load condition: (a) cogging torque; (b) UMF.

Figure 10. Parametric analysis under the rated-load condition: (a) torque ripple; (b) UMF.

However, the torque ripple of the design model is significantly affected by the slot opening and pole-arc to pole-pitch ratio. Therefore, according to the analysis results, the

force characteristics of the PMSG are optimized when the pole-arc to pole-pitch ratio is 0.85 and the slot opening is 3 mm.

3.6. Modal Analysis

The resonance of the OWC WEC system, which is one of the main causes of NVH characteristics, can be confirmed through analysis of the natural frequency of the PMSG combined with the housing and shaft, as shown in Figure 11. Modal analyses of the stator combined with the housing and the rotor combined with the shaft were performed using Ansys Workbench, and the analysis results are shown in Figures 12 and 13, respectively. The analysis results show the mode shape results of the 1st, 2nd, and 3rd orders, and the natural frequencies of each order are presented in Table 2. It is suggested that the operating frequency and harmonic characteristics of the PMSG can avoid resonance with the system.

Figure 11. Schematic of the prototype combined with the housing and shaft: (a) cross-sectional view; (b) side view.

Figure 12. Modal analysis for the stator with the housing: (a) first, (b) second, and (c) third modes.

Figure 13. Modal analysis for the rotor with the shaft: (a) first, (b) second, and (c) third modes.

Table 2. Natural frequency analysis results for the stator and rotor considering assembly.

	Harmonic Order		
	1st	2nd	3rd
Stator	2671 Hz	3076 Hz	3281 Hz
Rotor	1067 Hz	3155 Hz	4379 Hz

The OWC WEC system of this study operates at 100–1200 rpm, and the PMSG has 28 poles. The operating frequency can be calculated as follows:

$$f = \frac{n_m P}{120} \quad (22)$$

where n_m represents the mechanical speed (rpm) of the rotor.

Table 3 presents the operating frequency according to the operating speed and harmonic order. According to the results, the designed PMSG does not have NVH characteristics due to resonance caused by the operating frequency.

Table 3. Operating frequency of the PMSG.

RPM	Harmonic Order				
	1st	2nd	3rd	4th	5th
200	46.67 Hz	93.33 Hz	140.00 Hz	186.67 Hz	233.33 Hz
400	93.33 Hz	186.67 Hz	280.00 Hz	373.33 Hz	466.67 Hz
600	140.00 Hz	280.00 Hz	420.00 Hz	560.00 Hz	700.00 Hz
800	186.67 Hz	373.33 Hz	560.00 Hz	746.67 Hz	933.33 Hz
1000	233.33 Hz	466.67 Hz	700.00 Hz	933.33 Hz	1166.67 Hz
1200	280.00 Hz	560.00 Hz	840.00 Hz	1120.00 Hz	1400.00 Hz

4. Results and Discussion

Figure 14 shows a motor-generator (MG) set for the performance evaluation system with a torque sensor. The evaluation system consists of a driving motor, a PMSG, an inverter with a controller for the driving motor, equipment to measure torque and speed, and a vibration sensor.

Figure 14. MG set for experimental evaluation: (a) schematic; (b) actual system.

For the driving motor (MPP1426P6S-KPSN), a servomotor was selected to perform accurate speed control. The experiment was performed up to a limit speed of 800 rpm owing to the limitations of the motor torque and speed. A torque sensor manufactured by DACELL was used to measure the input power from the driving motor. It can measure the input speed and torque from the driving motor. To measure the terminal voltage and current, an oscilloscope (DL850, Yokogawa) was used. To measure the output power,

e.g., the voltage, current, power factor, and efficiency, a power analyzer (PPA5530, N4L) was used. Figure 15 shows a schematic of a system for measuring rotor vibrations in a PMSG. The position of the gap sensor at 90° intervals in the x and y directions allows the measurement of the displacement of the rotor.

Figure 15. Conceptual view of a rotor vibration measurement system.

Figure 16 shows the voltage and current measurement results, the loci graph, and the FFT analysis results for the rotor displacement when the alternating-current (AC) load operation is performed under the rated operating conditions. Under AC load conditions [29], the output current has a sinusoidal waveform when the resistor is connected to the Y connection. The 13th order based on one period mechanically at 800 rpm was measured as the major harmonic.

Figure 16. Experimental results for the AC load condition: (a) measurement of voltage and current; (b) rotor displacement; (c) FFT analysis results for the rotor displacement.

According to KS B 0411, the shaft diameter of the PMSG is 35 mm, and the machining error of the rotor shaft is 0.3 mm. From the measurement results, it was confirmed that the vibration of the PMSG was smaller than the machining error, and the PMSG hardly vibrated under the AC load operating condition.

Even under the DC load operating condition [30], the rotor displacement was measured similarly to the measurement result of the AC load operating conditions, as shown in Figure 17. In particular, the magnitude of the rotor displacement hardly changed even though the output current contained many harmonics due to the rectifier. From the measurements, the main vibration components were the first and second components, and the vibration components of the PMSG were mostly generated by the mechanical imbalance and mechanical looseness [31]. From the analysis and experimental results, the PMSG, which minimized the electromagnetic excitation source component, hardly generated vibration due to the electromagnetic excitation source.

Figure 17. Experimental results for the DC load condition: (a) measurement of voltage and current; (b) rotor displacement; (c) FFT analysis results for the rotor displacement.

5. Conclusions

This paper presented an electromagnetic analysis and experimental verification to improve the NVH characteristics through electromagnetic excitation source analysis of a PMSG applied to an OWC WEC system using the subdomain method. An analytical solution for each domain was derived using an analytical method, and an electromagnetic excitation source was derived according to the Maxwell stress tensor. The excitation-source components were classified as the cogging torque, torque ripple, MPF, and UMF, and methods for minimizing the excitation forces based on electromagnetic analysis were presented. In the final design stage, a resonance analysis was performed by comparing the natural frequency and electromagnetic operating frequency through a modal analysis considering mechanical coupling. The analysis results confirmed that the PMSG with the optimized electromagnetic excitation source has excellent NVH characteristics generated by the electromagnetic excitation source through experimental verification. The analysis method and experimental verification of electromagnetic excitation sources presented in this paper can be widely used for electric machines applied to various systems.

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