Influence of AC-DC-DC Converter on Radial/Axial Flux Permanent Magnet Wind Power Generators with Mechanical Energy Storage System

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***Abstract*—This paper deals with the influence of AC-DC-DC converter on permanent magnet (PM) wind power generators. Differently from AC load conditions, since the phase current in PM generators with the converter contains harmonic components, their influence on generators' performance is investigated. In particular, in this paper, two PM generator types, radial flux PM generator and axial flux PM generator, are considered for the comparative investigation. The generators are connected to a mechanical energy storage system consisted of a permanent magnet synchronous motor with a heavy wheel, and the generator performance characteristics are dealt with while the mechanical energy storage system is being operated.**

***Index Terms* — AC-DC-DC converter, mechanical energy storage system, PM wind power generator.**

I. Introduction

As the demand on the effective use of wind power is being highly increased, the researches on wind power generators have been actively performed. The types of wind power generators can be various [1][2], and one of the previous studies effectively reported those generator system types [2]. As reported in the study, the system types have largely three categories. They are respectively a squirrel-cage induction generator system, a doubly fed induction generator system and a permanent magnet synchronous generator (PMSG) system. Although each system has various advantages, the interests on the PMSG have been highly increased due to its powerful performance with high energy density and efficiency.

Since PM was introduced in 1983, it has been actively applied to various electrical machines, and it is considered as a very essential material in PMSG application as well [3]. In previous studies, to predict PM machine performance, the machine design optimization and electromagnetic field characteristic analysis methods were presented [4][5], and they can be also employed to the PM wind power generator design. In particular, for the cogging torque reduction of PM machines, the authors in [4] presented the bread type PM shape, and it was very useful method since the cogging torque is directly related to the noise and vibration of wind power generator systems. In our previous study [5], the bread shape PM was analytically modeled for analysis time reduction showing high reliability. With the analytical method, it can be possible to design and analyze the PM machines much faster. For the application of PMSG to the wind power generation system, there are various types of machine topology [6][7], and [6] sufficiently compared the performance of seven machine types including radial flux PM generator (RFPMG) and axial flux PM generator (AFPMG). Besides, in [7], among those generator types, RFPMG and AFPMG showed similar performance in lower power range while AFPMG presented superior performance than RFPMG in higher power range. With their comparative results, machine type determination became much easier.

On the other hand, to store the generated electrical energy, various methods can be applied, and the mechanical energy storage system can be one of the attractive solutions. In general, the system has a heavy wheel to use its moment of inertia, and it is operated as a motor to store the energy or a generator to use the energy from wind power. The mechanical energy storage system is called as a flywheel system with magnetic bearings in many cases, and various topologies have been presented. In [8], the energy storage system with an induction machine was suggested while a PM synchronous motor (PMSM) was applied to the system with a heavy wheel in [9].

When the PM wind power generator and the mechanical energy storage system are integrated, the generated AC power from PMSG should be firstly converted to DC power. In this procedure, the phase current in PM generators contains harmonic components, and they can affect the generators' performance. Therefore, their influence is highly required to be investigated. In [10], the authors showed the phase current shape with three phase diode rectifiers connected to AFPMG presenting various rectifying solutions. Furthermore, in [11], we presented the phase current according to AC and DC load conditions, and our results, in particular, showed that the 5^{th} harmonic component in the phase current resulted from the diode rectifier causes relatively higher eddy current loss on PM surface.

In this paper, we construct experimental set with the PM generators and the mechanical energy storage system with a PMSM, and comparative investigation for the influence of AC-DC-DC converter on the RFPMG and AFPMG is dealt with. In particular, those generators have very similar machine parameters for reasonable comparison.

II. Influence of AC-DC-DC converter on Permanent Magnet Wind Power Generators

A. Mechanical Energy Storage with Wind Power Generator

Fig.1 shows the mechanical energy storage system with a PM wind power generator considered in this paper. In this system, the wind turbine is directly connected to PM generator, and the generated AC power is converted to DC power through the AC-DC-DC converter. In our system, the rated power of PM generators is 300(W) with its rotational speed 150(rpm), and the rectified DC voltage is 200(V) in the speed condition. Here, the voltage can be controlled to be constant regardless of wind speed (rotational speed of generator) variation by the converter. In addition, the DC bus is connected to a SVPWM inverter to control mechanical energy storage system, which is a PMSM with a heavy wheel. The output power of PMSM is 300(W) in 4000(rpm) of its rotational speed, and the 5(A) current control is performed for its acceleration. Since the range of our study is limited to the influence of the AC-DC-DC converter on the generator performance, the mechanical energy storage system is only operated as a motoring mode from 0(rpm) to 4000(rpm).

B. Wind Power Generators according to Machine Topology

The machine topology of the PM wind power generators can be various, and this paper considers its flux direction from PM to stator coil winding. In other words, Fig.2 shows the RFPMG and AFPMG, respectively, and, as shown in the figure, the PM flux direction of RFPMG has 90 degree difference with rotational axis while that of AFPMG is parallel with the axis. The AFPMG dealt with in this paper is presented in our previous study [12], and its electromagnetic characteristic in AC load condition (power factor=1) were predicted and validated by experiment. In this paper, mostly focusing on similar equivalent circuit parameters such as resistance and inductance, RFPMG is newly designed for their comparative study, and the design procedure of AFPMG was presented in [12]. As shown in the Fig.1 of [12], the rated generator input power from the wind turbine is 329(W) with generator speed 150(rpm). The machine parameters and design specifications for both models are presented in Table I. Besides, in Fig.3 and 4, the manufactured models are presented, and both models are slotless type to reduce cogging torque, which is the main cause of the mechanical vibration and the noise of the PM wind power generators. To confirm the validity of similar machine performance, the experimental verification for both models is performed. At first, in Fig.5, no-load voltage of both models at 150(rpm) is presented, and they show very similar values. Besides, as shown in Fig.6, it can be noticed that both machines show well corresponded maximum voltage and rectified DC voltage according to their rotational speed.

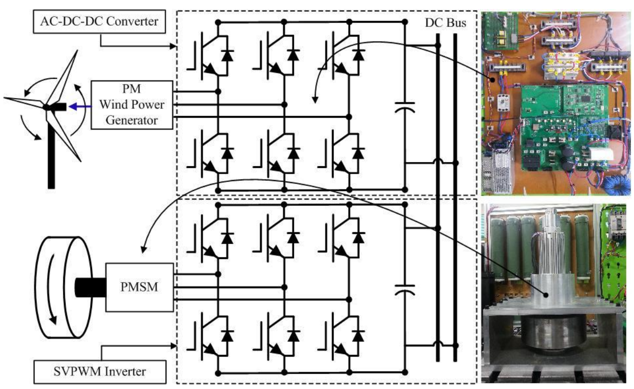

Fig. 1. Mechanical energy storage system with PM wind power generator

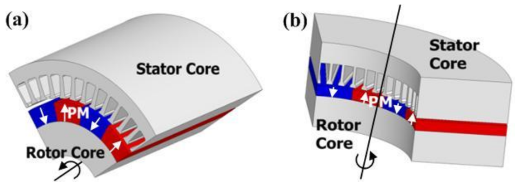

Fig. 2. PM wind power generator according to PM flux direction : (a) radial flux PM generator, (b) axial flux PM generator.

TABLE I. Design Specification of PM Wind Power Generators

Specification	Generator Types	
	RFPMG	**AFPMG**
Number of Poles	40	40
Rated Speed (rpm)	150	150
Output Power (kW)	0.3	0.3
Machine Outer Diameter (mm)	286	314
Stator Outer Diameter (mm)	286	308
Stator Inner Diameter (mm)	277	180
Stator Thickness(mm)	4.5	12
Rotor Outer Diameter (mm)	254	308
Rotor Inner Diameter (mm)	238	180
Rotor Thickness(mm)	8	8
Stack Length (mm)	85	56
Mechanical Air-gap (mm)	1	1
PM Pole Arc Ratio	0.7	1
PM thickness (mm)	5.3	7
Br of PM (T)	1.27	1.27
Number of Turns	760	1200
Resistance (Ω)	12.1	13.0
Inductance (mH)	3.7	4.6

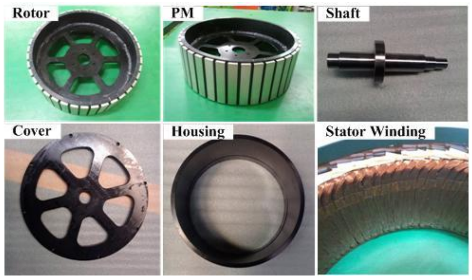

Fig. 3. Manufactured Radial Flux PM Generator.

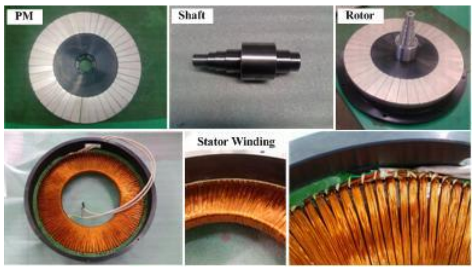

Fig. 4. Manufactured Axial Flux PM Generator.

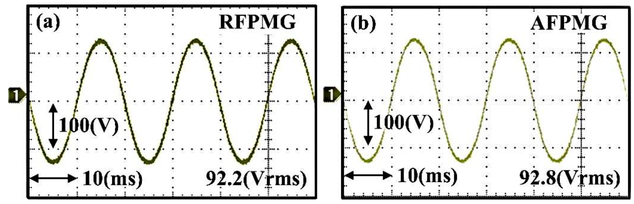

Fig. 5. No-load voltage of RFPMG and AFPMG at 150(rpm).

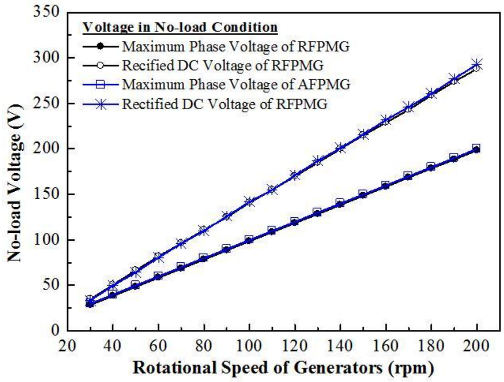

Fig. 6. No-load voltage according to rotational speed of generators.

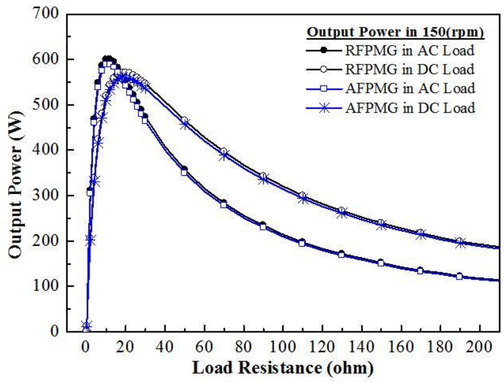

Fig. 7. Output power curve in 150(rpm) according to load Condition.

In addition, Fig.7 presents the power curve according to load conditions in their rotational speed 150(rpm). In the figure, AFPMG shows a bit less values since it has a bit higher value of equivalent circuit parameters, such as resistance and inductance as presented in Table I.

C. Generator Current Characteristics with Energy Storage

In Fig.8, the constructed whole system is presented. The generators are connected to an induction motor for the artificial wind scenario based on turbine characteristics presented in [12]. With the system, identical experiment is performed for both RFPMG and AFPMG, and their phase current characteristics and its influence on the generators are investigated.

To begin with, in Fig.9, the systemic characteristics of AFPMG are presented. Here, the constant DC voltage control is not performed yet, and the generator speed is 150(rpm) in noload condition. In the experiment, during 10(s), the PMSM for the mechanical energy storage system is not operated. In other words, the range is no-load condition in systemic view

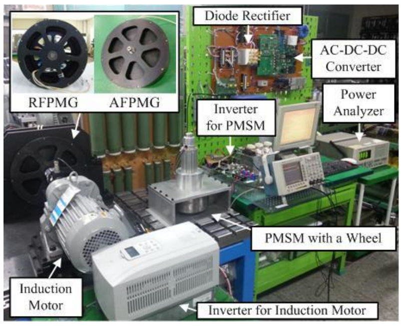

Fig. 8. Constructed experimental set with PM wind power generators.

point with PMSM speed 0(rpm). The q-axis current of PMSM in the mechanical energy storage system is then controlled by 5(A) while d-axis current is controlled by 0(A) for the constant acceleration to 4000(rpm) in 90(s). As shown in the figure, since the current is controlled to be constant, the output power of the AFPMG is increased while the PMSM acclerates. This causes more phase current in AFPMG resulting higher input torque and decreased generator speed with lower generating voltage. In particular, the phase current of AFPMG contains different harmonic components according to the PMSM speed. The identical experiment is also performed with RFPMG, and our comparative investigation is based on the current characteristics in both machines.

In Fig. 10. the Fast Fourier Transform (FFT) results of phase current for both models are presented. In the figure, the 1st harmonic component and the 5th harmonic component are

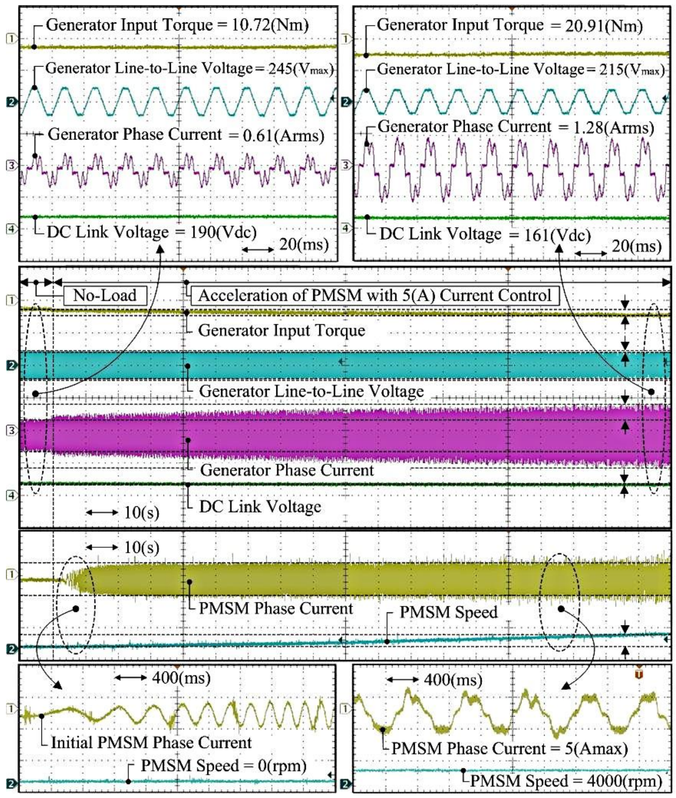

Fig. 9. Systemic characteristics with AFPMG with mechanical energy storage system for acceleration of PMSM to 4000(rpm).

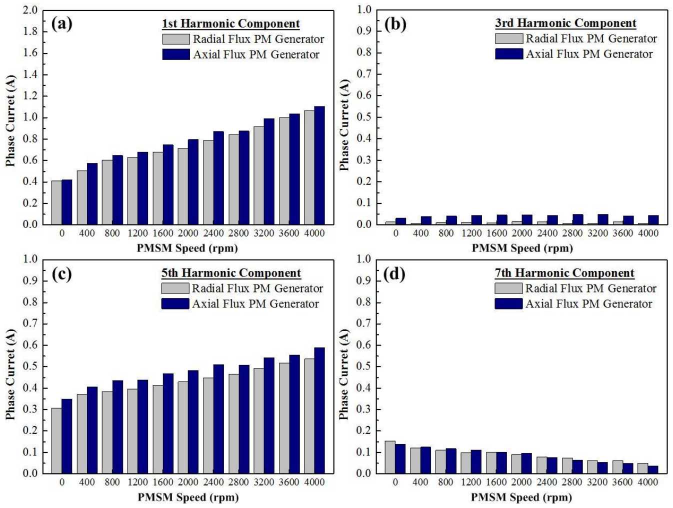

Fig. 10. FFT results of PM wind power generator current according to PMSM speed : (a) 1st harmonic component, (b) 3rd harmonic component, (c) 5th harmonic component, (d) 7th harmonic component.

increased with PMSM speed increment while the 3rd harmonic component is remained constant. On the other hand, the 7th component is decreased. In particular, since the 5th harmonic component is the main reason to cause the rotor loss on PM surface as presented in [11], it can be noticed that the rotor loss is being increased while the speed of PMSM with a heavy wheel becomes higher.

D. Generator Current Characteristics with Constant Voltage

Since the PM wind power generator is directly connected to wind turbine without a gearbox, the generated voltage is dependent on the wind speed and the generator speed. However, the voltage can be controlled to be constant by the duty ratio of AC-DC-DC converter, but this causes the variation of the phase current in the generators with different harmonic components. Furthermore, it can be easily anticipated that they have different influence on those generators.

In Fig.11 and Fig.12, the generator current characteristics are presented, and the DC voltage is controlled to be 200(V). The considered generator speed is 80(rpm),100(rpm), 120(rpm) and 150(rpm) resulted from the wind speed 2.7(m/s), 3.2(m/s), 3.9(m/s) and 5.0(m/s), respectively. As shown in the figure, varied phase current characteristics are confirmed with different values and harmonic components. Those measured current characteristics are also analyzed, and their FFT results are presented in Fig.13. Based on the measured current presented in Fig.10 and Fig.13, electromagnetic field analysis is performed to confirm the electromagnetic losses, such as copper loss, core loss and rotor loss (eddy current loss on PM surface), and their comparative investigation is performed.

E. Electromagnetic Losses in PM Wind Power Generators

The power losses of the PM generators are winding copper loss, stator core loss, mechanical losses such as friction loss, windage loss, eddy current loss on PM surface and so on. In Fig.14, the power flow is presented, and the electromagnetic losses are considered in this paper in that they are only related to the phase current affected by the AC-DC-DC converter. In

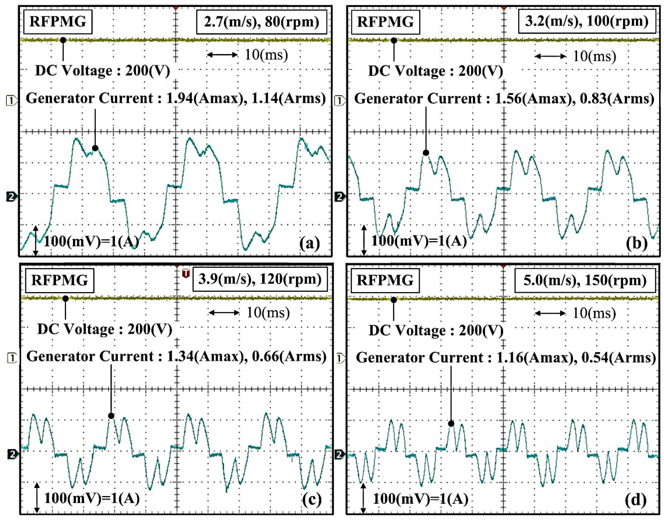

Fig. 11. Experimental generator current of radial flux PM type according to generator speed : (a) 80(rpm), (b) 100(rpm), (c) 120(rpm), (d) 150(rpm).

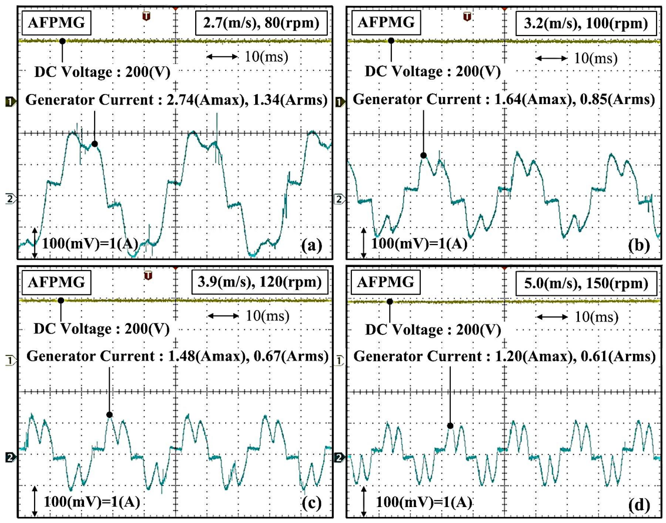

Fig. 12. Experimental generator current of axial flux PM type according to generator speed : (a) 80(rpm), (b) 100(rpm), (c) 120(rpm), (d) 150(rpm).

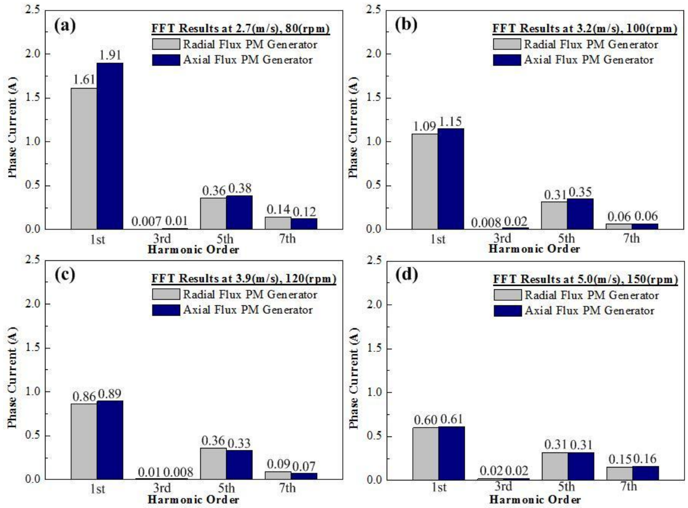

Fig. 13. FFT results of phase current according to generator types and generator speed : (a) 80(rpm), (b) 100(rpm), (c) 120(rpm), (d) 150(rpm).

particular, the values of harminic components in the phase current have high relationship with those losses, so its calculation should consider them.

At first, the copper loss is the dominent loss in PM machines, and it can be calculated by (1). Here, R_s is the resistance of the generator, and i is the *RMS* value of the phase current. The resistance can be classified into DC resistance and AC resistance. In high speed machines with high operating frequency, AC resistance should be considered with somewhat complicated equations. However, in PM wind power generators, its operating frequency is very low, so DC resistance can be employed.

$$P_{copper} = 3R_s i^2 \tag{1}$$

In the second place, the core loss is generally expressed by (2) considering hysteresis and eddy current loss. However, in addition to those losses, the excess loss should be considered for more accurate core loss prediction as shown in (3) [13]. Besides, the core loss is directly related to the harmonic components of flux density in stator core and their behavior, and the flux density behavior can be divided to alternating field and rotating field [14][15]. As a results, the core loss considering the harmonic components of flux density and its behavior can be calculated by (4). Here, Q is the magnetic behavior constant, and *1* indicates alternating magnetic field while *2* indicates rotating filed. In addition, l presents the harmonic component order of these fields. Besides, h, e and ex represent the coefficients of hysteresis, eddy current and excess loss, respectively.

$$P_{core} = P_h + P_e = k_h f B^{n_s} + k_e f^2 B^2 \tag{2}$$

$$P_{core} = P_h + P_e + P_{ex} = k_h f B^{n_s} + k_e f^2 B^2 + k_{ex} f^{1.5} B^{1.5} \tag{3}$$

$$P_{core} = \sum_{l=1,odd}^{\infty} Q_l (k_h f_l B_l^n + k_e f_l^2 B_l^2 + k_{ex} f_l^{1.5} B_l^{1.5}) \tag{4}$$

Although the rotational speed of our analysis model is relatively lower than other PM machines, the harmonic components still cause rotor loss on PM surface. In Fig.15 and Fig.16, the current density on PM surface of both generators are presented, and it can be confirmed that their values are different according to wind speed. These results are obtained by finite element method based on the measured current shown in Fig.10 and Fig.13. As shown in those figures, the higher speed causes higher current density, and this is directly related to rotor loss resulting heat problem.

In Fig.17 and Table II, the electromagnetic losses are compared. At fitst, without the constant output voltage control in Fig.17, the losses are increased as the speed of PMSM becomes higher, and the difference in copper loss can be found in only higher speed region. On the other hand, as shown in Table II, the voltage control with the duty ratio causes more electromagnetic losses while the speed of generators are decreased, which means lower wind speed.

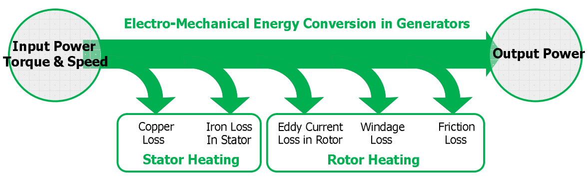

Fig. 14. Power flow of PM wind power generators.

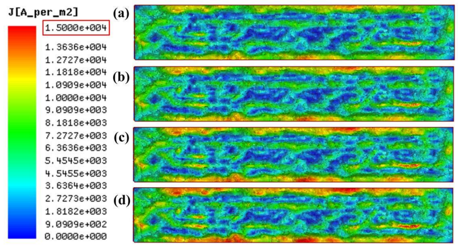

Fig. 15. Current density on PM surface of RFPMG according to generator speed : (a) 80(rpm), (b) 100(rpm), (c) 120(rpm), (d) 150(rpm).

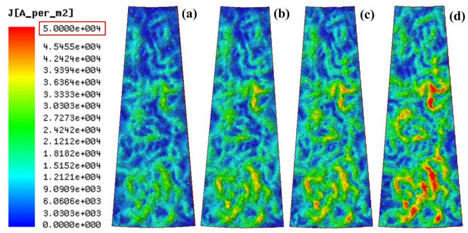

Fig. 16. Current density on PM surface of AFPMG according to generator speed : (a) 80(rpm), (b) 100(rpm), (c) 120(rpm), (d) 150(rpm).

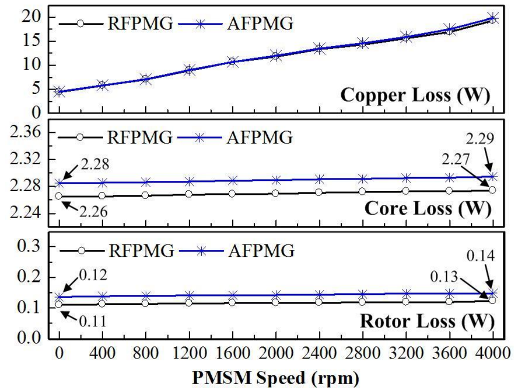

Fig. 17. Electromagnetic loss comparison according to PMSM speed.

TABLE II. ELECTROMAGNETIC LOSS ACCORDING TO GENERATOR SPEED

Wind Speed and Generator Speed	Copper Loss(W)		Core Loss(W)		Rotor Loss(W)	
	R	A	R	A	R	A
2.7(m/s), 80(rpm)	15.33	21.7	2.29	2.30	0.123	0.165
3.2(m/s), 100(rpm)	8.12	8.74	2.28	2.30	0.119	0.159
3.9(m/s), 120(rpm)	5.14	5.43	2.27	2.29	0.113	0.145
5.0(m/s), 150(rpm)	3.44	4.50	2.26	2.28	0.109	0.132

R : Radial Flux PM Generator, A : Axial Flux PM Generator

F. Generator Performance Comparison

For the generator performance comparison during the mechanical energy storage, the output power of both RFPMG and AFPMG is measured. In this experiment, the induction motors connected to those generators are operated to generate identical input torque and rotational speed. In Fig.18, since the dominent electromangtic loss is copper loss in those generators,

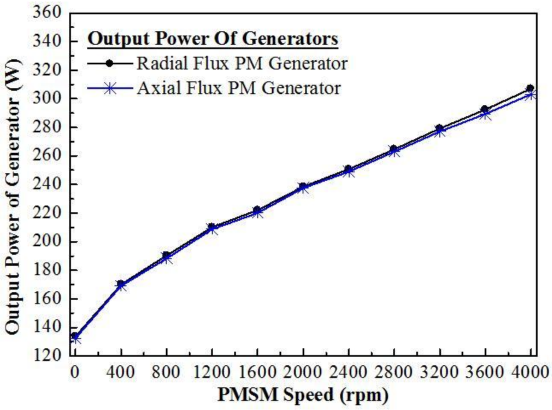

Fig. 18. Measured output power of RFPMG and AFPMG according to the rotational speed of PMSM in mechanical energy storage system.

TABLE III. MEASURED GENERATOR EFFICIENCY COMPARISON

Wind Speed and Generator Speed	Efficiency (%)	
	RFPMG	AFPMG
2.7(m/s), 80(rpm)	73.2	70.2
3.2(m/s), 100(rpm)	86.1	84.2
3.9(m/s), 120(rpm)	90.5	88.3
5.0(m/s), 150(rpm)	94.1	92.5

the trend of output power follows the copper loss in Fig.17 showing the relatively visible difference in higher speed region. Furthermore, in the constant voltage control, as measured generator eiffciency in Table III shows, the lower efficiency is confirmed in the lower speed of the generators. This is also corresponded to the electromagnetic loss characteristics in Table II.

III. CONCLUSION

In this paper, we presented the comparative performance charactersitcs of RFPMG and AFPMG with AC-DC-DC converter and mechanical energy storage system. Differently from AC load conditions, the DC load condition causes various harmonic components in the phase current of those generators, and their influence on the machines were dealt with based on the experimentally measured current and its electromagneitc loss analysis. From the results shown in this paper, it could be concluded that the RFPMG showed a bit better performance when the electrical parameters of the machines are in very similar condition and in ralatively small power applications.

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