Wound-rotor induction generator system for random wave input power

Moon-Hwan Kim, *Member, KIMICS*

Abstract—In this paper, the two-axis theory is adopted to analyze the secondary excited induction generator applied to random wave input generation system. The analysis by the two-axis theory helps to know the transmitted power of the induction machine. The electric variables, like as primary and secondary currents, voltages, and electric output power, were able to express as equations. These equations are help to simulate the generation system numerical model and to know the transient state of the system. As it is preferred to stabilize the output voltage and frequency in the constant level, microcomputer controlled VSI connected to the secondary windings supplies the secondary current with slip frequency. For testing the appropriateness of this method, the input torque simulator in the laboratory to drive the secondary excited results show the advantage of secondary excited induction generator system for the random input wave generation system.

Index Terms—Random wave input generation system, wound type induction generator, two-axis theory, VSI, sea wave.

I. INTRODUCTION

In the countries which have little fossil fuel, the efforts of new energy sources, including wave or wind generation are concentrated. However, since this type of natural energy varies randomly. It is difficult to supply this energy effectively according to the general load demands. This is because that the output power from the natural energy source always fluctuates statistically. Therefore stabilizable controller is indispensable.

One superior method to get the CVCF(constant voltage and constant frequency) output power from the natural energy source is the employment of the secondary excited induction generator. There are two main merits to adopt the secondary excited induction generator system. One is the output voltage and current waveform is able to be nearly equal to a sinusoidal waveform. therefore the harmonic components can be suppressed. The other is that this method is considered to be better than the conventional alternator-rectifier-inverter set from the view point of saving the KVA capacity of the power converter.

For confirming the above features in the laboratory, the simulator of the random wave power is required. For the purpose, the data of the random wave power experimental results using impulse type of air turbine. done by JAMSTEC at the sea, is analyzed. This analysis is based on power spectrum density(PSD). According to this analysis, the power flow is clarified and the random wave input can be reproduced by the simulator in the laboratory. In this paper the followings are more analyzed than the reference (11). The one is that the two-axis theory is adopted to analyze the secondary excited induction generator applied to random wave input generation system. The analysis by the two-axis theory helps to know the transmitted power of the induction machine. The electric variables, like as primary and secondary currents, voltages, and electric output power, were able to express as equations. These equations are help to simulate the generation system numerical model and to know the transient state of the system. The other is that one of the applications of this result is the simulation in the case of employment of Wells turbine induction generator set. Besides this example, this simulation system will assist to find out the control method to get CVCF not by the real experiment but by the laboratory sized simulation.

Manuscript received received December 3, 2008; revised March 5, 2009.

Moonhwan Kim is with the Department of Automotive engineering, Silla University, Busan, 617-736, Korea (Tel: +82-51-999-5701, Fax: +82-51-999-5652, Email: mhkim@silla.ac.kr)

II. AN ANALYSIS AND SIMULATION OF THE RANDOM WAVE GENERATION SYSTEM

As it is well known, the energy of nature can be considered as random one, so there is still much left to be studied hereafter for the improvement of system efficiency and the general utility.

For that purpose, the model should reflect the determination of the rating and electromechanical elements. To overview the total system generally, the basic strategy for the random input generation system should be constructed. The method is based on the power spectrum analysis from the input to output waveform. By the total analysis using above method, all the variables, including the inaccessible or the unseen variables in the total power flow, can be reproduced in the computer simulation. This method can become the strong tool to find out the control method because the real sized experiment can be omitted. If the relation between one energy conversion stage (#i) and the following stage (#j) is treated to be linear, the following equation is satisfied.

$$S_{\#j}(\omega) = H(\omega)\cdot H^{*}(\omega)\cdot S_{\#j}(\omega) = |H(\omega)|^{2}\cdot S_{\#i}(\omega) \qquad (1)$$

where, $S(\omega)$ represents the power spectrum density and $H(\omega)$ represents the transfer function in the frequency domain. Here the sea wave generation is analyzed as one example of the random power generation system. Fig. 1 shows the system structure, which consists of air chamber, impulse type air turbine and generator. In this system, air chamber transforms the up-down motion of sea wave level to the air flow. Finally the kinematic energy of the air flow which is controlled by action of valves is transformed to the electrical energy through the air turbine connected to generator.

In each stage, the approximated transfer function is defined from the measured PSD. Fig.2 shows the measured waveform of the sea and the computer simulated waveform. These figures show the validity of the linearized method based on PSD analysis.

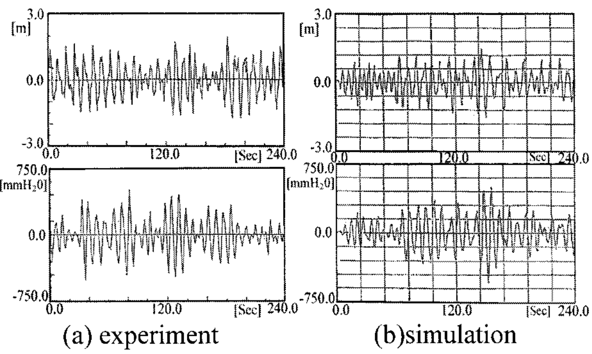


Fig. 2 Waveform of sea wave (upper) and air pressure (down) by experimental (a) and simulation(b)

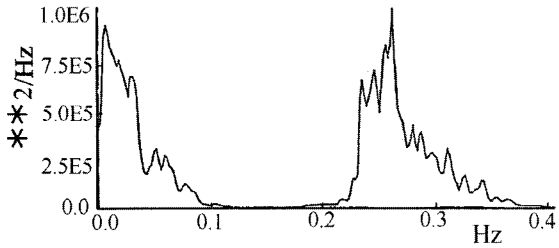


Fig. 3 The power spectrum density of the sea wave generation system(torque into the air turbine)

In Fig.3, the PSD of air turbine torque, which drives the generator is shown. This PSD which is difficult to be measured directly, can be reproduced by the computer simulation.

As well as these results, the waveform in any stage can be reproduced and utilized for the random input generation system. From the results of the analysis, for testing the utility, Wells turbine which is considered suitable for random input generation is taken up. The difference of between Wells turbine and impulse type is that the former always rotates to the same direction in spite of the variation of the air flow direction, and the latter needs a certain device for keeping direction constant.

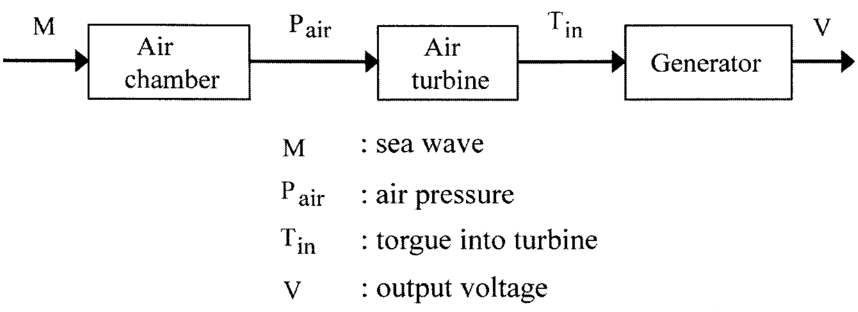


Fig. 1 Power flow diagram of the generation system from sea wave

By these steps, the torque simulator of two type air turbines can be directly realized in the laboratory. In the later examples of the experiments, the obtained results are considered and compared.

III. THE SECONDARY EXCITED INDUCTION GENERATOR SYSTEM

These analysis can help the control design of secondary excited induction generator system for the CVCF generation. When the rotor speed fluctuates according to the wave torque, the constant frequency is attained by exciting of the secondary winding with slip frequency. Similarly, the output voltage is kept constant by the feedback control of the rms value of the output voltage. Fig.4 shows a schematic sectional view of induction generator.

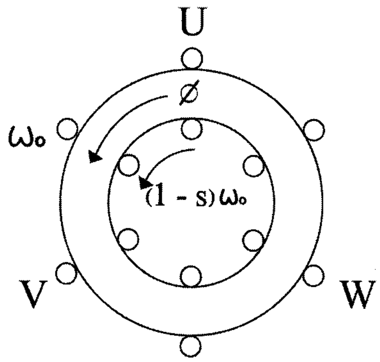


Fig. 4 A schematic sectional view of induction generator

When the speed of rotor is $(1-s)\omega_0$ (rad/see) and the secondary winding is excited at $s\omega_0$ (rad/sec), the speed of the main flux becomes ω_0, which is the sum of the both speed, in spite of the variation of the rotor speed. This relation can be explained like eq. (2).

$$s\omega_0 + (1-s)\omega_0 = \omega_0 \qquad (2)$$

In general, the two-axis theory is convenient to analyze the transient state of induction machine.

Here, the two-axis equation of the induction machine is shown (3), in which the α,β-axis rotating synchronously with magnetic field.

$$\begin{bmatrix} V_{1\alpha} \\ V_{1\beta} \\ V_{2\alpha} \\ V_{2\beta} \end{bmatrix} = \begin{bmatrix} R_1 & -\omega_0 L_1 & 0 & -\omega_0 M \\ \omega_0 L_1 & R_1 & \omega_0 M & 0 \\ 0 & -s\omega_0 M & R_2 & -s\omega_0 L_2 \\ s\omega_0 & 0 & s\omega_0 L_2 & R_2 \end{bmatrix} \begin{bmatrix} -i_{1\alpha} \\ -i_{1\beta} \\ i_{2\alpha} \\ i_{2\beta} \end{bmatrix} \qquad (3)$$

where the subscription 1 and 2 are indicated the primary and secondary, respectively. And ω_0, s, V, I, R, L, M are main flux speed, slip, voltage, current, resistance, self- and mutual inductance. ($L_1 = l_1 + M$, $L_2 = l_2 + M$) From the equation (3), the I_2 and V_2 become,

$$\dot{I}_2 = \frac{R_L + R_1 + j\omega_0 L_1}{j\omega_0 M}\dot{I}_1 \qquad (4)$$

$$\dot{V}_2 = \frac{s\omega_0^2(M^2 - L_1L_2) + R_2(R_1 + R_L) + j\omega_0\{L_1R_2 + sL_2(R_1 + R_L)\}}{j\omega_0 M}\dot{I}_1 \qquad (5)$$

And the output power of stator P_s, the input power of rotor P_r and the mechanical input power P_m are as equation (6) - (8).

$$P_s = -R_1 I_1 + \omega_0 M(i_{2\beta}i_{1\alpha} - i_{2\alpha}i_{1\beta}) \qquad (6)$$

$$P_r = R_2 I_2^2 + s\omega_0 M(i_{2\beta}i_{1\alpha} - i_{2\alpha}i_{1\beta}) \qquad (7)$$

$$P_m = (1-s)\omega_0 M(i_{2\beta}i_{1\alpha} - i_{2\alpha}i_{1\beta}) \qquad (8)$$

According to these equations (6)-(8), the power flow at the supersynchronous and subsynchronous speed can be represented in Fig. 5.

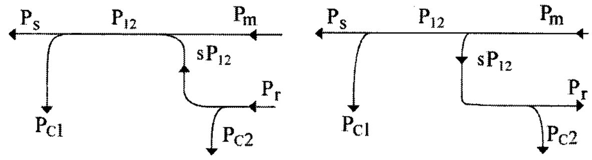


Fig. 5 The power flow at sub- and supersynchronous speed of the rotor

When the driving power from the air turbine to the generator is defined as P_m, then the transmitted power $P_{12} (= P_m/(1-s))$ is accordingly greater than the input power at subsynchronous speed. The secondary power source provides the power $P_r (= sP_{12})$, and the output power becomes, $P_1 (= P_{12})$. On the contrary, in supersynchronous condition the secondary power is regenerated in the secondary side. At that time, in both state, the secondary excited induction generator system control the power P_r. This means that the capacity of power converter is expected smaller than the conventional alternator- rectifier-inverter set method. In spite of fluctuation of input power P_m by the control of P_r, the output power P_1 can be regulated in the level of demanded value.

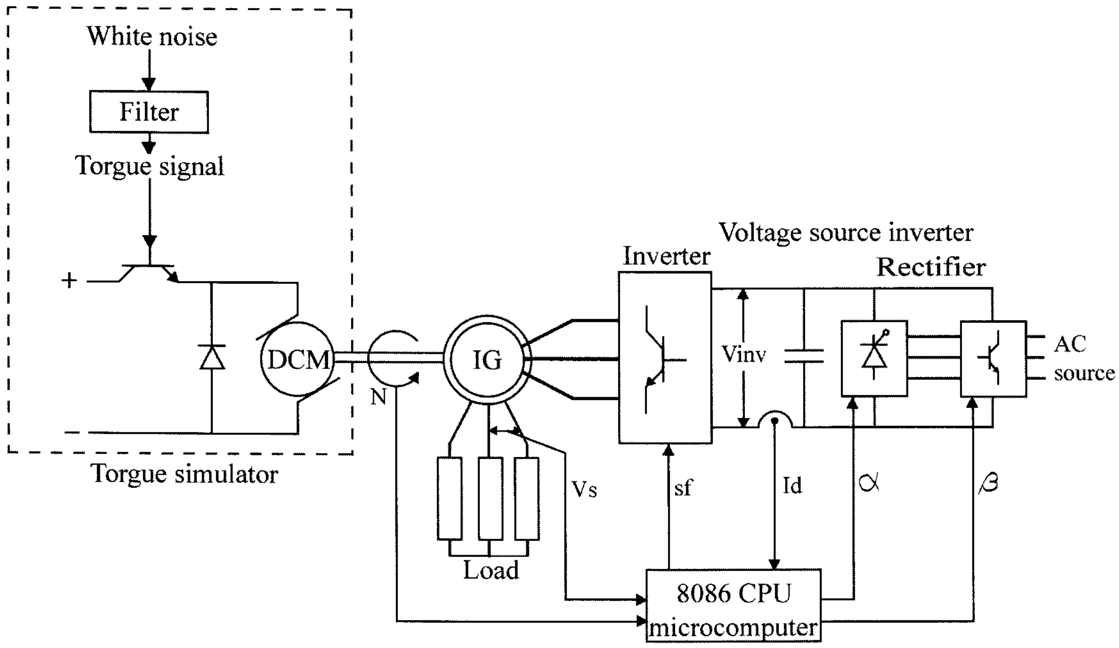


Fig.6 The schematic total generation system

IV. CVCF OUTPUT POWER CONTROL REALIZATION

The secondary excited induction generator system for random wave input can be simulated as shown in Fig. 6. The torque simulator consists of the torque signal generator, the PWM transistorized chopper and dc motor. The torque signal is made from white noise through the shaping filter so that the PSD in each stage coincide with the measured one. The PWM transistorized chopper controls the armature current of the dc motor according to the torque signal to simulate the air turbine torque in the wave power generation. For constant frequency generation, the slip frequency should be determined after equation (2). For that purpose, one unit of increment or decrement of the slip frequency command is added to the last slip frequency command according to the difference of the reference slip frequency drawn from equation (2) and the commanded slip frequency of last stage. The control of slip frequency also determines the power flow as shown in Fig. 5.

The output voltage of the generator is determined by the secondary current and slip. For control secondary current, the three phase full bridge thyristor rectifier is adopted. The firing angle is determined according to difference between the reference voltage and the output voltage. The command of the incremental or decremental action is determined by delta modulation technique. By this voltage feedback loop, the output voltage can be kept constant in spite of the variation of electrical load.

The 8086 microcomputer system controls both the inverter frequency and the firing angle of the rectifier. In this experimental system, the sampling period of the rotational speed and the output voltage is 5msec which is sufficiently small in comparison with the time period of the sea wave.

V. EXPERIMENTAL RESULTS

In the experiment, 6-poles, 2.2(KVA) wound induction generator and 2-poles, 2(KW) dc motor are used in the laboratory. Here, in the laboratory experiments, two types of air turbin was examined. One is based on the ordinary impulse type of air turbine. The other is Wells turbine which is also simulated and connected induction generator.

Fig.7, 8, and 10 show the experimental examples which is driven by the impulse type air turbine.

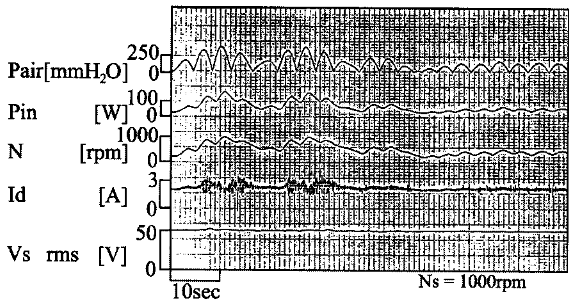


Fig.7 Experimental example of time response (impulse type turbine, with constant load)

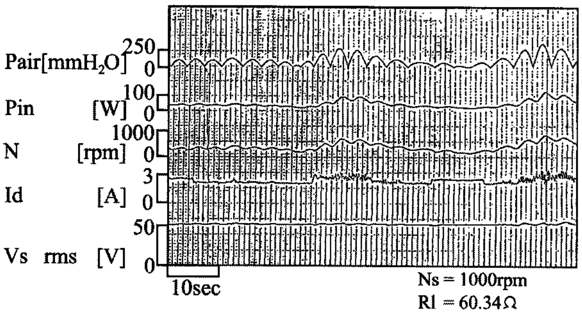


Fig.8 Experimental example of time response (impulse type turbine, with varying load)

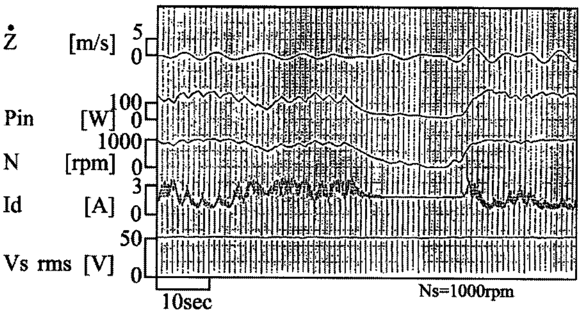
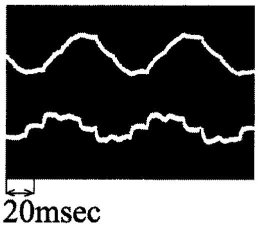


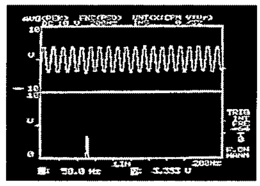
Fig.9 Experimental example of time response (Wells turbine, with constant load)

Fig. 9 shows one example of experimental results of Wells turbine. Fig.7 and 9 show the one example of the system in the case of constant resistance load.

And Fig.8 shows the dynamic response to the change of load. According to these figures, the output waveforms of the simulation system are well realized in laboratory, and the rms value of output voltage can be kept nearly constant.



(a) waveform



(b)PSD

Fig. 10 (a) The waveform of secondary current (upper) and voltage(lower)
(b) The power spectrum density of output voltage

Fig. 10 shows the waveform and its PSD of the output voltage.

By adopting VSI (voltage source inverter), PSD of output frequency is strongly concentrated around the reference frequency, and the output waveform is nearly similar to sinusoidal wave. These results by the laboratory sized simulation system show the validity of the secondary excited induction generator system for CVCF output.

In the experiment, 6-poles, 2.2[KVA], wound induction generator and 2-poles, 2[kw] dc motor are used in the laboratory. The nameplate parameters of both machines are shown in Table 1.

Table 1. The ratings of wound induction generator and dc motor which are used in the experiments

1) Separately excited dc motor

ratings		constants of circuit	
output power	2 kw	Ra	3.36 Ω
poles	2 poles	Ke	0.622 Vs/rad
armature current	20 A		
field current	0.62 Amp		

2) Wound induction generator

ratings		constants of circuit	
output power	2.2 kw	R_1	0.776 Ω
poles	6 poles	R_2	1.030 Ω
primary current	13 Amp	L_1	3.11 mH
primary voltage	200 V	L_2	3.11 mH
secondary current	9.7 A	M	33.69 mH
secondary voltage	137 V	a	1.38

VI. CONCLUSIONS

The torque simulator for the random input wave generation system using the secondary excited induction generator can be constructed based on PSD method. The control method of the inverter connected to the rotor of the secondary excited induction generator is established and tested by the laboratory sized simulation system for random input power generation. The obtained results show the effectiveness of the system for CVCF generation from the random input power. This system is expected to have the merits from the view point of saving the power converter capacity and improving the waveform to the random wave generation system. According to the same manner, CVCF power generation can be easily realized for other random wave input generation system such as wind input power generation system or tidal power generations.

REFERENCES

[1] Yokomizo, "Analysis of sea wave generation system of 'Kaimei' type", Jamstec Experimental report No.10, 1983, pp.97-127

[2] Hotta, "The generation performances of sea wave generation system 'Kaimei'", JSCE symposium, Tokyo, 1987

[3] Nagata, "Construction of Offshore Floating Wave Power Device 'Mighty Whale'", IHI Engineering Review Vol.33, 2000 , No.1 24-29

[4] Washio, "Full-scale performance tests on Tandom Wells turbine", 1st Symposium on wave energy utilization in Japan, Tokyo, 1984, pp.191-199,

[5] Ohgata, "The present and the future of the sea wave generation", Energy and resources, No.132, 3. 2002, pp.50-54

[6] B.S. Hyun et al., "A Study on the Performance of the Ring-type Impulse Turbine for Wave Energy Conversion", The Korea Committee for Ocean Resources and Engineering, Journal of Ocean Engineering and Technology, 1225-0767, Vol.20, No.1, 2006, pp.20-25

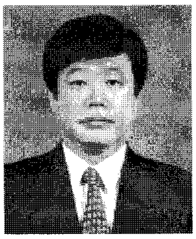
[7] Jin Ha Kim et al., "A Study on Motion and Wave Drift Force of a BBDB Type OWC Wave Energy Device", The Korea Committee for Ocean Resources and Engineering, Journal of Ocean Engineering and Technology,1225-0767, Vol. 20, No. 2, 2006, pp.22-28

[8] B.S. Hyun, et al., "Analysis of Impulse Turbine for Wave Energy Conversion Using CFD Method", The Korea Committee for Ocean Resources and Engineering, Journal of Ocean Engineering and Technology,1225-0767, Vol. 18, No. 5, 2004, pp.1-6

[9] J.G. Hwang, "A study on Structure Design of Speed increaser Mechanism for Wave-Force Generator", Korean Society of Precision Engineering, Proceedings of the Korean Society of Precision Engineering Conference, 2004, pp.1266-1269

[10] J.H. Gyeong, "Numerical Analysis on Wave Energy Absorption of OWC-type Wave Power Generation", The Korea Committee for Ocean Resources and Engineering, Journal of Ocean Engineering and Technology,1225-0767, Vol. 20, No. 4, 2006, pp.64-69

[11] M. Kim, "A control of wound-rotor induction generator for random wave input generation s ystem", International Journal of Kimics, Vol. 5, No.3, 2007, p223-228



Moon-Hwan Kim
received the Ph. D degree in Electrical Engineering from the Keio University, Japan in 1988. He has been with the Division of Automotive Electronic Engineering at Silla University, where he is presently an associate professor. His research interests are system control and energy conversion system.