Simulation of Wave Generation System with Linear Generator

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Abstract

This study analyses power generation system from ocean waves by using linear generator. A buoy is placed on the ocean surface and connected to the linear generator. Due to the movement of the buoy, the mover of the linear generator is reciprocated. The power is generated by movement of the mover. A converter system is needed for the power generation between the linear generator and the grid. For the study of the power generation system, a simulation model was made in MATLAB-Simulink. This paper aims at studying the converter system of wave generator and using when the converter system is designed.

Keywords: linear generator, Converter system, Wave generation.

1. Introduction

Over the last decade, there has been a growing concern in renewable energy. For the power generation, new attempts are being conducted actively. Among various energy sources, offshore energy technology is still progressing slowly compared to other renewable energy technologies. Ocean wave energy of offshore energy can be easily seen and utilized widely. The ocean wave power generation system is utilized with offshore wind power generation system because the place for the development of ocean wave generation is usually consistent with the location of offshore wind power system.

There exist lots of different technical solution on how to convert the energy in the ocean waves into electric energy [1]-[3]. Some examples of conversion systems presented in [3], [4]. The generator studied in this paper is a

linear synchronous generator for the wave power generation. The wave energy is carried out from the movement of a floating buoy. The buoy is connected to the mover of the linear generator. When the buoy is reciprocated, the permanent magnetized translator gets a linear motion in the generator and a voltage is induced in the stator winding. Because the reciprocating motion is correlated with wave motion, the voltage produced by the converter has an irregular amplitude and frequency. It has to be converted before it connected to the grid. For an analysis of the power system, the simulation modeling of the wave generation system was proceeded. This paper is analyzed in the electrical point of view and the simulation is performed. The model has been constructed in MATLAB-Simulink, which is a commonly used simulation program for electrical systems.

2. Configuration

2.1 Dynamic Model of Wave Generator

Fig. 1. Wave generator model.

Fig. 1 shows the wave generation model. In the Fig. 1, the floating body is the structure above the sea and the stator of a linear generator in this structure is mounted. The mover of the linear generator is connected to the buoy and reciprocates by the movement of the ocean waves. The forces acting on the wave generation system were analyzed in [5] and [6], and detail motion equation of the wave generation system was also derived. Based on the motion equation, a simplified motion equation was given in [7], which is suitable for the power system analysis. The simplified motion equation is given by

$$F_{wave} = (M + m_a) \frac{d^2 y(t)}{dt^2} + (b + c) \frac{dy(t)}{dt} + Ky(t) \quad (1)$$

where $y(t)$ is the displacement of the translator, M is the mass of the translator, m_a is the added mass, b is the radiation damping coefficient, K is the spring constant, $cdy(t)/dt$ is the generator electromagnetic force, and F_{wave} is the sum of the forces.

2.2 Power Generation

Fig. 2. Transformation from abc to dq frame.

Fig. 2 shows the transformation between abc frame and dq frame [11],[12]. The transformation from variables in the abc frame to the variables in the dq reference frame is chosen as follows

$$f_{dq} = T f_{abc}$$

$$T = \frac{2}{3} \begin{bmatrix} \cos(\alpha) & \cos(\alpha - \frac{2\pi}{3}) & \cos(\alpha + \frac{2\pi}{3}) \\ -\sin(\alpha) & -\sin(\alpha - \frac{2\pi}{3}) & -\sin(\alpha + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (2)$$

where $\alpha = (\pi/\tau_p)x$, x is the translator position of the linear generator. The dq reference frame is fixed in the translator and reciprocates with the translator. The amplitude of speed varies and the direction of the motion of the dq reference frame changes along with the reciprocating motion of the translator. However, in the modeling of the rotating synchronous motor, as the dq reference frame is fixed in the rotor, rotating speed of the dq reference frame is equal to the rotating speed of the rotor. Due to the difference motion of the rotor, the dq transformation should be changed to equation (2).

The stator voltage equation of a permanent magnet synchronous generator in the synchronous reference frame is described by [8]

$$\begin{aligned} v_d &= -Ri_d - \frac{d\psi_d}{dt} + \omega\psi_q \\ v_q &= -Ri_q - \frac{d\psi_q}{dt} - \omega\psi_d \\ \psi_d &= L_d i_d - \psi_{PM} \\ \psi_q &= L_q i_q \\ P &= \frac{3}{2} \omega \psi_{PM} i_q \end{aligned} \quad (3)$$

where v_d and v_q are the d and q axis stator voltage, respectively, i_d and i_q are the d axis and q axis stator current, ω is the angular speed of the stator variables, ψ_{PM} is the flux from permanent magnet, P is the active power.

The voltage equation shown in equation (3) is appropriate for a rotating permanent machine, not a linear generator. The rotor of the rotating permanent magnet generator rotates in the generator, while the rotor, called translator, of the linear generator reciprocates. Because of difference of the motion, the speed term should be considered. When the rotor of the linear generator moves in one direction, ω can be given by

$$\omega = v_t \frac{\pi}{\tau_p} \quad (4)$$

where v_t is the linear speed of the linear generator, τ_p is the pole pitch. Using equation (4), the voltage equation of the linear generator in the reference frame is derived [9], [10]

$$\begin{aligned}
v_d &= -Ri_d - \frac{d\psi_d}{dt} + v_t \frac{\pi}{\tau_p} \psi_q \\
v_q &= -Ri_q - \frac{d\psi_q}{dt} - v_t \frac{\pi}{\tau_p} \psi_d \\
\psi_d &= L_d i_d - \psi_{PM} \\
\psi_q &= L_q i_q \\
F &= \frac{3}{2} \frac{\pi}{\tau_p} [i_d i_q (L_d - L_q) - \psi_{PM} i_q]
\end{aligned} \tag{5}$$

where F is the force from generator.

The linear generator is a surface permanent magnet generator. In case of a surface magnet type, the d axis inductance is the same as the q axis inductance. Therefore, the reluctance torque is not used in this type of generator. The reluctance torque term is canceled. The generating force in equation (5) can be written as

$$F = -\frac{3}{2} \frac{\pi}{\tau_p} \psi_{PM} i_q. \tag{6}$$

In equation (6), the force is related to q axis current. Because the generating force is proportional to the q axis current, the command value of the d and q axis current can be derived as

$$\begin{aligned}
i_d^* &= 0 \\
i_q^* &= -\frac{F}{\frac{3}{2} \frac{\pi}{\tau_p} \psi_{PM}}
\end{aligned} \tag{7}$$

where $*$ represents the command value of the current controller.

2.3 Converter Control

Fig. 3 shows the control block diagram for the converter controller. Due to the force of ocean wave, a floating buoy moves and the translator of generator reciprocates. The speed of translator can be calculated from measured position sensor value and the position of translator can be obtained through the integration of the speed. And then, the generating force command is estimated from the obtained position value. The current command is determined by force command and the current controller generates the voltage reference. The PWM duties are determined normally by the space vector PWM (SVM)

method from the voltage references v_d^* and v_q^* in the dq reference frame. The gate driver controls switches of IGBTs by gating signals from PWM duties.

Fig. 3. Converter control block diagram.

Fig. 4. Current controller.

Fig. 4 shows current controller of the converter. Commonly, two proportional-integral (PI) controllers are used to control the currents. The outputs of current controller are voltage references, which are removed decoupling term. Currents are measured by phase current sensor and transformed to dq reference frame using the position of translators. The d axis current command i_d^* and the q axis current command i_q^* are obtained as shown in equation (7). By controlling the d and q axis current in reference frame, the proper power generation from wave can be performed.

3. Simulation Results

Fig. 5 shows the configuration for a single operation of the linear generator. The buoy is reciprocated and the power is generated by operation of the linear generator. To extract maximum power from the ocean wave, the movement of the ocean wave should be predicted. However it is difficult to predict the movement of the wave. Therefore the algorithm tracking the maximum output power was applied. Fig. 6 shows the flowchart of maximum power searching algorithm. The operating point is searched by the algorithm which can obtain maximum power by comparing current output power and output power before adjusting.

Fig. 5. Configuration of single operation.

Fig. 6. Flowchart of maximum power searching algorithm.

Table I shows the specification of linear generator which is used in the simulation. We configured the linear generator and the converter, as shown in Fig. 7 using MATLAB-Simulink. Fig. 8 shows the simulation results. The first figure illustrates the buoy position of linear generator and the second figure shows the output force of linear generator. The third figure represents a filtered output power and shows that the controller is changing the operating point to find the maximum power point. The maximum power was approximately 250kW.

Table I - Specification of linear generator

Parameter	Unit	Specification
Phase resistance	Ω	4.5
Phase inductance	mH	5.3
PM core length	m	11.5
Mover length	m	2.5
Pole pitch	mm	125

Fig. 7. Wave generator simulation block-diagram.

Fig. 8. Simulation results.

4. Conclusions

In this paper, we described the power generation from ocean wave by using the linear generator. For the analysis, the wave generation modeling and the simulation were performed. The simulation was performed by irregular buoy speed. The maximum power was 250kW. The converter controller is well changing the operating point to find the maximum power point. The simulation results will be used when the converter is designed.

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