

Development of Dynamic Simulation Modeling of Power Converters for OWC Wave Power Generation System

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Abstract: The Oscillating Water Column (OWC) wave power generation system consists of an OWC chamber, a turbine, a generator and a power converter. The power converter controls the generator to convert the kinetic energy of an irregularly varying wave to electric energy. The power converter comprises a rectifier that converts the three-phase AC voltage which is the output of the generator, into DC and an inverter that converts the three-phase AC voltage into an AC voltage of a frequency and magnitude required by the grid. In this study, we present a topology of a power converter for an OWC wave power generation system and simulate the mathematical modeling of a permanent magnet synchronous generator and power converter for a wave power generation system to the operation characteristics of the power converter.

Key words: Oscillating Water Column (OWC), power converters, Power Conversion System (PCS), Permanent Magnet Synchronous Generator (PMSG), wave power generation, chamber

INTRODUCTION

Recently, in response to the environmental problems and depletion of fossil energy, a variety of future energy sources have been developed to solve environmental problems and various natural energy utilization technologies have been actively developed for securing pollution-free energy sources. Among the various energy resources, marine energy, given the vast coastline around the Korean Peninsula is a very attractive source of energy to generate electricity. Wave-power generation is not a widely-employed commercial technology, although there have been attempts to use it, since, at least 1890 (M'Zoughi *et al.*, 2017). Moreover, OWC systems exhibit a potential benefit in terms of reliability due to the moving mechanical parts that are not submerged into the seawater (Drew *et al.*, 2009). Although, OWCs have been under development since the end of the 19th century, to build whistling buoys for navigation aid (Fig. 1 and 2), the idea to use this technique in order to produce electricity has been applied starting from 1947 to supply onboard autonomous lights of navigation buoys (Delmonte *et al.*, 2016; Heath, 2012; Jung and Myung, 2016; Febryanti and Gunawan, 2017). Tests to produce electricity with more powerful generators which can be conveniently connected to the grid have been started in 1970's but the high costs of production and maintenance, together with lifetime problems have limited their diffusion.

Wave energy converters have struggled for decades to break through to commercial implementations

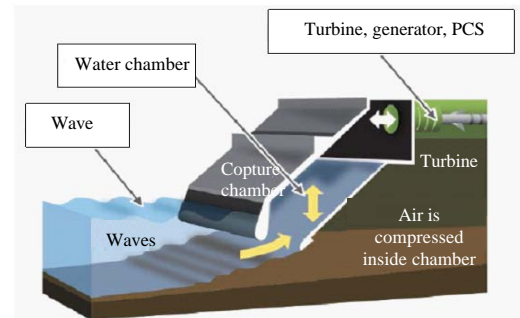


Fig. 1: OWC wave power generation system mounted on a breakwater

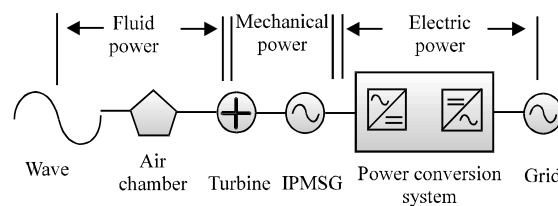


Fig. 2: Block diagram of energy change in an OWC wave power generation system

(M'Zoughi *et al.*, 2017; Adda *et al.*, 2017; Morab and Pandey, 2017; Erfanian and Akrami, 2017). But recent years have begun to see a maturing of some technologies with several commercial companies now conducting in sea trials. Among the several wave energy conversion, the OWC installed in the breakwater is the most reputed.

This study deals with the modeling, simulation and control of an OWC power we present the topology of a power converter for wave power generation system and a mathematical modeling of a Permanent Magnet Synchronous Generator (PMSG). Control algorithm of both generator and grid side controllers are presented. The model is validated by simulation using PSM program.

**OWC WAVE POWER
GENERATION BREAKWATER-MOUNTED
POWER GENERATION SYSTEM**

An OWC wave power generation system mounted on a breakwater is shown in Fig. 1. The up-and-down vibrating water in the OWC chamber performs the same function as the piston and the air is converted into the left and right reciprocating air energy in the turbine by discharging the air to the outside or by sucking it into the inside. The left and right reciprocating air through the turbine can be converted into mechanical energy, so that, the mechanical energy can be converted into electric energy through the generator. The electric energy thus obtained has a primary electrical energy form having a variable frequency variable voltage form. The power converter deals with the control of the generator rotor speed for maximum power tracking of the turbine, stable dc link voltage and active and reactive power into the grid.

Figure 2 shows the block diagram of energy conversion of the OWC wave power generation system from the OWC chamber to the grid.

Power conversion system for owc wave power generation:

Figure 3 shows the schematic of the overall Power Conversion System (PCS) for OWC wave power generation. The first conversion stage is the OWC chamber and wells turbine converting the oscillating wave energy into mechanical energy in the form of torque and speed. The second stage is the generator and the power converter that convert mechanical energy into electric energy. A Permanent Magnet Synchronous Generator (PMSG) has been chosen instead of a doubly fed induction generator. As for the power converter, a

back-to-back topology has been deployed with a three-phase PWM rectifier as a generator side controller and a three-phase inverter as a grid side controller. Between the converter and the grid, a differential mode LCL filter and a delta-wye transformer are connected for reducing harmonics of the currents flowing into the grid and for isolation.

Modeling of machine side converter: Figure 4 shows the block diagram for generator side converter and its control. The outer loop is a speed controller for generator rotor speed control and the inner loop is a current controller for generator current and hence the torque and input power. This resembles the conventional field oriented control of PMSM. Reference transformation from abc to rotor reference dq coordinate system is required to implement this control.

The purpose of the generator side converter is to control the rotor speed of the PMSG in order to achieve maximum power point tracking according to the optimal rotor speed for flow rate of the turbine.

Assuming the sinusoidal wave form of the back EMF of the PMSG and neglecting the magnetic saturation, the leakage current and the hysteresis loss, the mathematical model of the PMSG can be obtained as follows:

$$v_{as} = R_s i_{as} + L_g \frac{d\lambda_{as}}{dt} \tag{1}$$

$$v_{bs} = R_s i_{bs} + \frac{d\lambda_{bs}}{dt} \tag{2}$$

$$v_{cs} = R_s i_{cs} + \frac{d\lambda_{cs}}{dt} \tag{3}$$

Where:

- v_{as}, v_{bs} and v_{cs} = The stator phase voltages
- $\lambda_{as}, \lambda_{bs}$ and λ_{cs} = Stator flux linkages
- i_{as}, i_{bs} and i_{cs} = The phase currents
- R_s = The phase resistance

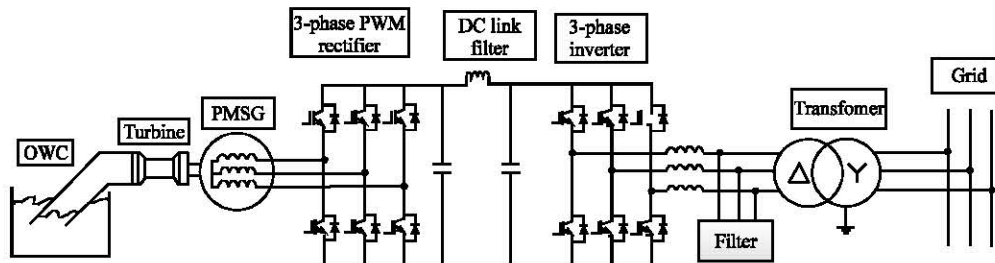


Fig. 3: Power conversion system

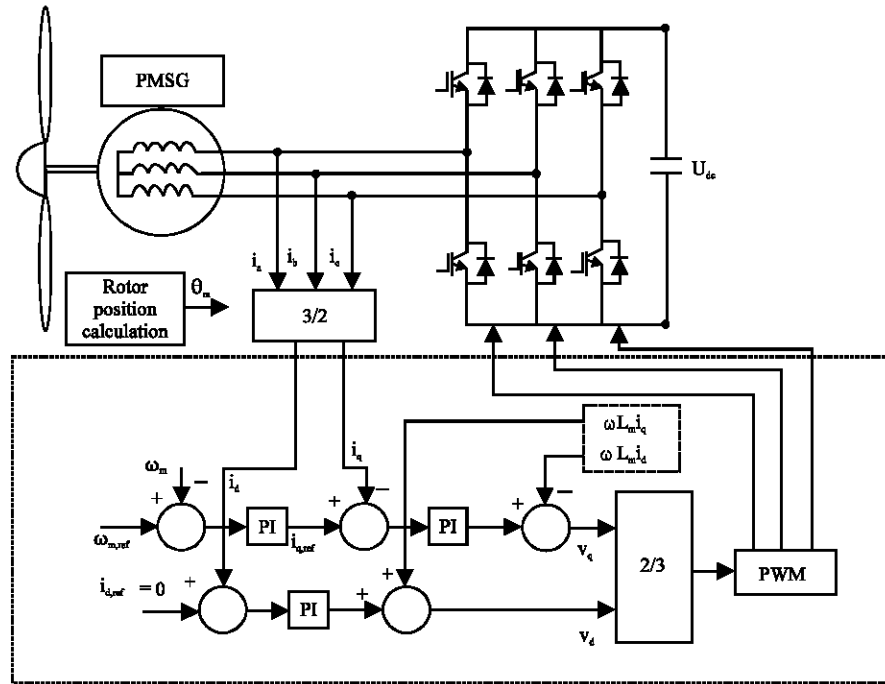


Fig. 4: Generator side control back diagram

The stator voltage equations of can be dq coordinate:

$$v_{ds}^r = R_s i_{ds}^r + \frac{d\lambda_{ds}^r}{dt} - \omega_r \lambda_{qs}^r \quad (4)$$

$$v_{qs}^r = R_s i_{qs}^r + \frac{d\lambda_{qs}^r}{dt} - \omega_r \lambda_{ds}^r \quad (5)$$

Where:

$$\lambda_{ds}^r = L_s i_{ds}^r + \phi_f \quad (6)$$

$$\lambda_{qs}^r = L_s i_{qs}^r \quad (7)$$

Where:

- v_{ds}^r and v_{qs}^r = The d- and q-axis stator voltages
- i_{ds}^r and i_{qs}^r = The d- and q-axis stator currents
- λ_{ds}^r and λ_{qs}^r = The d- and q-axis stator flux linkages
- ω_r = The rotor angular speed
- ϕ_f = The flux linkage of the rotor permanent magnet to the stator winding

The electromagnetic torque of the PMSG is defined as:

$$T_e = \frac{P}{2} \phi_f i_{qs}^r \quad (8)$$

where, P is the number of the stator poles.

Modeling of grid side converter: The goal of the grid-side control is to control the DC-link voltage and

control the active and reactive power hence to meet the power quality standards. Based on the schematic of (Fig. 5) the following mathematical model that describes the dynamics of the grid side inverter neglecting the filter and transformer is obtained as:

$$v_{ag} = R_g i_{ag} + L_g \frac{di_{ag}}{dt} + e_{ag} \quad (9)$$

$$v_{bg} = R_g i_{bg} + L_g \frac{di_{bg}}{dt} + e_{bg} \quad (10)$$

$$v_{cg} = R_g i_{cg} + L_g \frac{di_{cg}}{dt} + e_{cg} \quad (11)$$

Where:

- R_g = The grid side line resistance
- L_g = The grid side line inductance
- v_{ag}, v_{bg} and v_{cg} = The inverter output voltages with respect to the grid neutral point
- e_{ag}, e_{bg} and e_{cg} = The grid phase voltages
- i_{ag}, i_{bg} and i_{cg} = The grid side line currents

The d-q coordinate transformation for the above equations are:

$$v_{dg}^e = R_g i_{dg}^e + L_g \frac{di_{dg}^e}{dt} - \omega_e L_g i_{qg}^e - e_{dg}^e \quad (12)$$

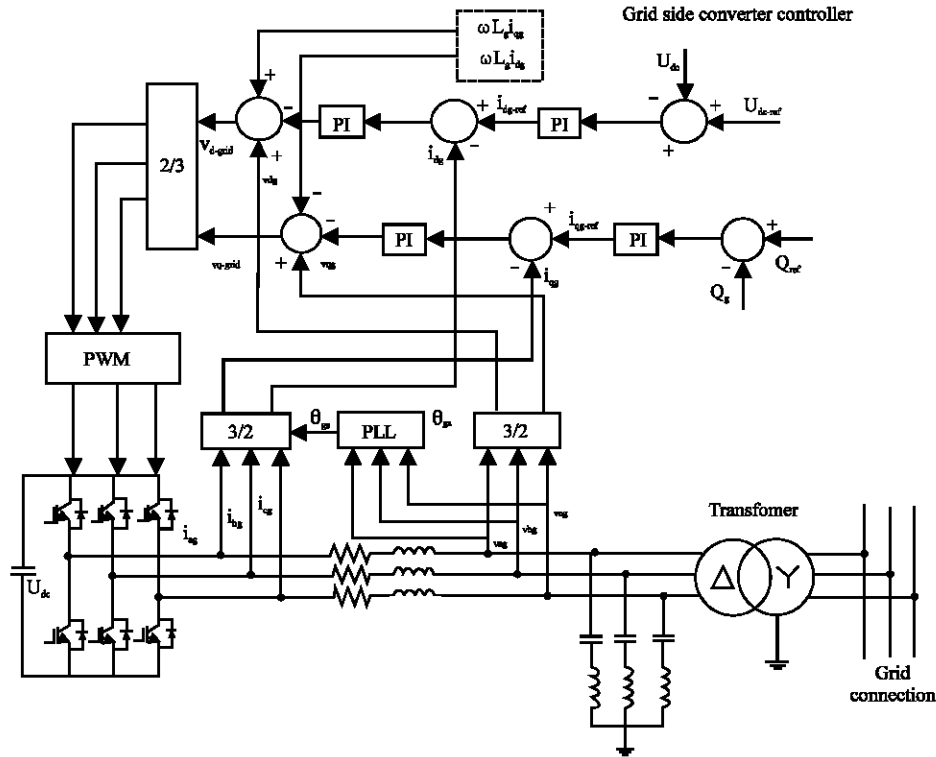


Fig. 5: Generator side control system

$$v_{qg}^e = R_g i_{qg}^e + L_g \frac{di_{qg}^e}{dt} + \omega_e L_g i_{dg}^e - e_{qg}^e \quad (13)$$

The active and reactive power are defined in the dq coordinate as:

$$P_A = \frac{3}{2} (v_{dg}^e i_{dg}^e + v_{qg}^e i_{qg}^e) \quad (14)$$

$$Q_R = \frac{3}{2} (v_{qg}^e i_{dg}^e - v_{dg}^e i_{qg}^e) \quad (15)$$

The main objective is the tracking of a desired reference for the active and reactive power hence resulting in high power factor and high efficiency.

SIMILATIONS

Table 1 shows specification of the simulation of the power conversion system for the OWC wave power generation in this study.

Figure 6 is a circuit diagram of PSIM simulation model of the overall power conversion system for OWC wave power generation. The simulation model is comprised of an OWC turbine, a PMSG, a generator side converter, a grid and a control block for each converter. The wind

Table 1: Specification of power conversion system

Parameter	Values	Unit
Input power	30,000	W
Phase voltage (generator side)	50~400	V (rmsec)
line-line voltage (generator side)	70~692	V (rmsec)
DC-link voltage	122~1100	V
output range	25.5	kW
Rated phase voltage (grid)	220	V
Rated line-line voltage (Grid side)	380	V

turbine block without the pitch angle can be used OWC turbine, since, the OWC turbine model requires only flow rate and rotation speed.

Figure 7 shows the simulation results during the total time 1 sec. The rotor speed of the PMSG changes in response to the turbine rotation when the turbine rotates at 5 m/sec from 0.1-0.3 sec, at 12 m/sec from 0.5-0.7 sec and at 10 m/sec from 0.8-1 sec, respectively.

Figure 8 shows the transient wave forms of the three-phase output voltages of the PMSG in response to change of the rotor speed of the PMSG.

Figure 9 and 10 shows wave forms in which the DC-link voltage is controlled to 800 V when the peak values of the phase voltages of the PMSG are 155 and 250 V, respectively.

Figure 11 shows the waveform of the DC link voltage and the three phase grid voltages when the DC-link voltage is controlled at 800 V.

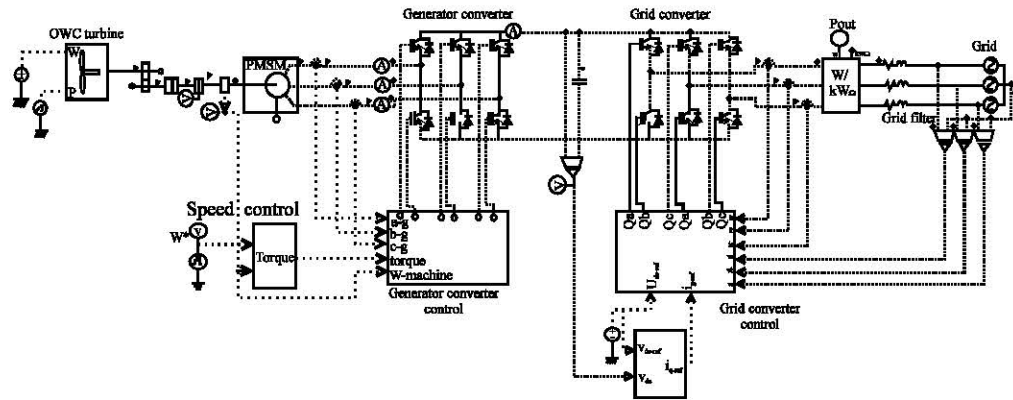


Fig. 6: Wave power generation system control schematic

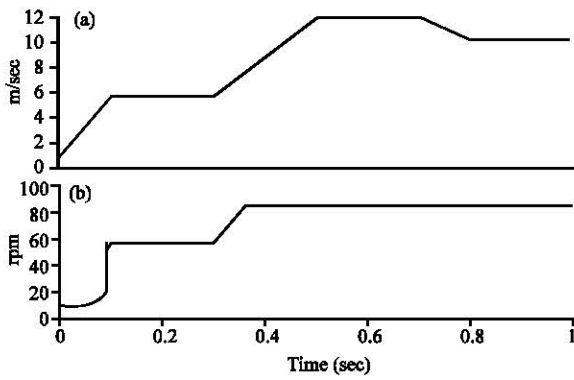


Fig. 7: Input speed and rotation speed; a) Speed and b)W-machine

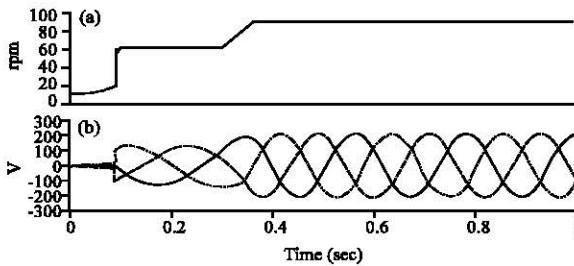


Fig. 8: Generator rotor speed and generator output voltages; a) W-machine and b) v_a, v_b, v_c

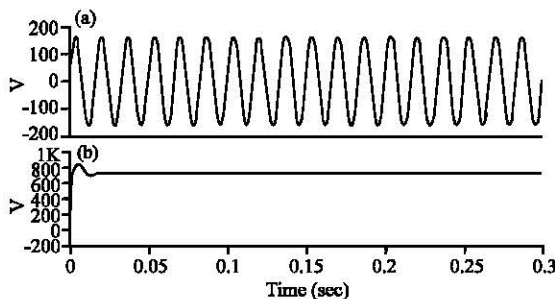


Fig. 9: Wave forms of the PMSG phase voltage with the peak value of 150V (top) and dc-link voltage (bottom); a) V_{an} and b) V_{dc}

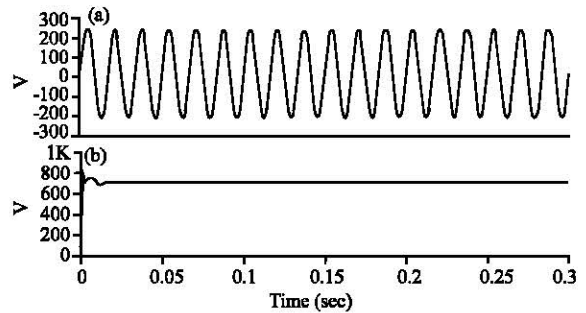


Fig. 10: Waveforms of the PMSG phase voltage with the peak value of 250 V (top) and DC-link voltage (bottom); a) V_{an} and b) V_{dc}

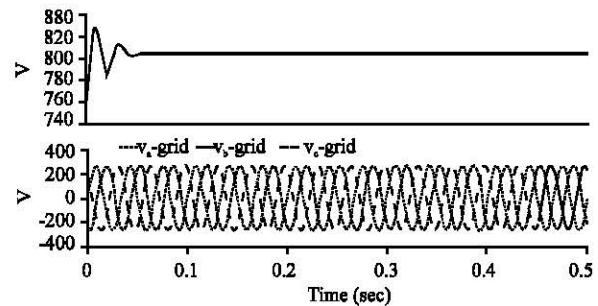


Fig. 11: DC-link voltage (top) and three phase grid voltage (bottom)

From the above simulation results, it is confirmed that DC-link voltage is controlled constantly and hence stable three-phase voltage under different rotor speed change.

CONCLUSION

In this study, a back-to-back power converter for the OWC wave power generation mounted on a break water is modeled and simulated. As for the generator side, a three phase PWM rectifier is employed. Since, the

volumetric flow rate and flow velocity of the turbine change continuously, a rotor speed in response to the flow rate should be controlled for maximum turbine efficiency. As for the grid side, a three phase PWM inverter is employed. A mathematical modeling of a PMSG in conjunction with grid-connected inverter is presented. DC link voltage and active/reactive power control is required for stable power transmission into the grid. Based on the developed modeling and control algorithm, simulation model using PSIM simulation is to validate the power conversion system for OWC wave power generation. A prototype development of the power converter is ongoing and experiment in connection with the generator will be carried out to compare with the simulation results.

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