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Modelling and Control System Design of Modified Zeta Converter with Coupled Inductor - Capacitor for Seawater Battery Application

(Case Study at Indonesian Fishing Boat)

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***Abstract*—Seawater battery is one of renewable energy resources generated by electrochemical process due to different water salinity. The electromotive force is determined by the number of membrane and ratio of water concentration. In fact, the seawater salinity varies in ocean. It leads to the electromotive force changes in every point (latitude and longitude) on the ocean. This research proposes: 1) a model of seawater battery which is applied in fishing boat, 2) a design of modified zeta converter with coupled inductor and capacitor and PI controller to keep output voltage remain constant. The simulation result verifies the proposed system and control strategy.**

Keywords— renewable energy resources, seawater battery, PI controller, zeta converter, coupled inductor, capasitor.

I. Introduction

Global electricity generation has grown rapidly in recent years. Since 2012, the electricity production has reached 22,200 TWh annually. Fossil fuels (including coal/peat, natural gas and oil) contribute around 70% of the annual electricity gross productions [1]–[3]. Those resources are not renewable; and the conversion into electricity produces pollution and emission. The green energy is required to replace conventional power plants to reach energy demand friendly in future.

There are various renewable energy resources in the world, however, particularly in ocean, there is only a little resources to be used and developed. There are so many type of renewable power generation application of ocean energy, some of them are thermal, tidal and wave such as shown in Table 1. However, based on [4] the potential of seawater battery has not been undertaken research previously. Seawater battery generate electricity through electrochemical process

Table 1. Potential of Ocean Energy Resources in Indonesia

No	Energy Types	Resources (MW)
1	Wave Energy	1,995.2
2	Ocean Thermal Energy Conversion	41,012
3	Tide and Tidal Power	4,800

During the chemical process, the seawater battery established electromotive force due to the electrons flown that are affected by the difference salinity.

Seawater battery has been researched and developed since 80's. In 1985, Alcatel-STK, Marintek and the Norwegian Defence Research Establishment (NDRE) joined forces with the Norwegian oil company Statoil to develop a power source for an autonomous deep sea oil well for Statoil [5] In 1989, it was developed a design for aluminum-seawater battery for undersea water vehicle [6]. An unmanned underwater vehicle was estimated to have a battery requirement of about 1 kWh. This research is focused on study case in conventional fishing boat.

Due to the movement of boats, it may get different salinity at each different point (latitude and longitude) on the sea. The research has been undertaken in [7], as depicted in Figure 1. It will establish changes in electromotive force. Theoretical power density from salinity gradients using reverse electrodialysis and seawater model has been presented in detail [8].

To keep electromotive generated by seawater battery remain constant, it is required a boost converter to increase and control the output voltage to match the voltage requirement of the load. Conventional boost converter can be used in applications but the voltage step-up ratio is still small. There is some boost converter topology that has a high voltage step-up ratio, such as SEPIC converters, zeta converters and others [9],[10]. A modified zeta converter with a coupled inductor and capacitors has been studied [11] and was proven to produce a quite high voltage step-up ratio and high efficiency. It is suitable for low voltage power source.

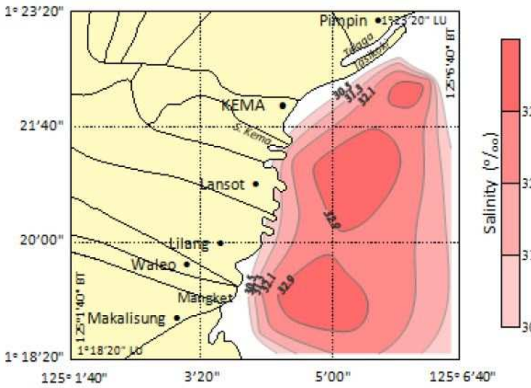

Figure 1. Different salinity (°/oo) in East-Indonesia

This paper presents design and modeling of seawater battery and zeta converter coupled with inductor and capacitor to support renewable energy application on a fishing boat. In addition, this paper also presents a zeta converter control strategy in order to keep the output voltage remain constant due to the fluctuation of electromotive force and different salinity. Section 2 presents seawater battery mode and design. The proposed design of modified zeta converter with coupled inductor and capacitor and seawater battery parameters is discussed in section 3. Simulation results and conclusion are respectively presented in section 4 and 5.

Table 2. Nomenclature

Nomenclature	
E	Electromotive (Volt)
Nm	Number of membranes (-)
α	Apparent permeable selectivity (-)
R	Universal constant (8.31 J/(mol.K))
T	Temperature (K)
z	Valence of ions (-)
F	Faraday constant (96485 C/mol)
γ	Activity coefficient (-)
C	Concentration of feed water (mol/liter)
R_{ohmic}	Ohmic area resistance (Ω. m^2)
β	Mask factor (-)
h	Intermembrane distance (m)
ε	Porosity (-)
κ	Feed water conductivity (S/m)

II. Seawater Battery

A. *Seawater Battery Principle*

Seawater contains various components, such as sodium, chloride, sulfur, etc, as shown in Figure 2. The seawater battery generates electricity from two different salinity of solutions. The principle process involves charge and discharge state.

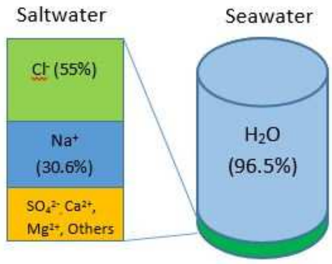

Figure 2. Seawater components

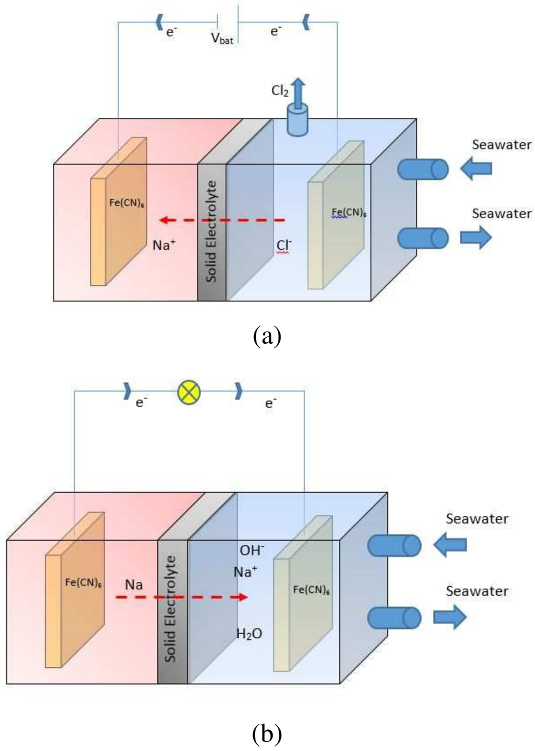

Figure 3. Charge (a) and discharge (b) schematics of seawater battery

During charge and discharge process depicted as schematic diagram in Figures 3.(a) and (b), the ion transport and chemical reaction are occurred. During charging process, Na^+ ions are extracted and transported to negative electrode, then electrons flow from cathode to anode through electrodialysis chemical reaction:

$$Na^{+} + e^{-} \rightarrow Na \quad (1)$$

$$2Cl^{-} \rightarrow Cl_2 + 2e^{-} \quad (2)$$

In case when the load is connected to the seawater battery system, it will be discharged through following chemical reaction:

$$Na \rightarrow Na^{+} + e^{-} \quad (3)$$

The electrons flow towards to the cathode, on the other hand, the current flows from cathode to anode.

B. Seawater Battery Model

The potential difference established by seawater battery is determined by the number of membranes, and the difference between concentrations of seawater and freshwater.

$$E = N_m.\alpha\frac{R.T}{z.F}\ln\left(\frac{\gamma_{sea}c_{sea}}{\gamma_{river}c_{river}}\right) \quad (4)$$

In this Nernst equation, E is electromotive force (volt), R is the universal constant {8.31 K/(mol/K)}, T is absolute temperature (K), z is the valence of the ions, F is Faraday constant (96485 C/mol), γ is activity coefficient, and c_{sea} and c_{River} are sea water and river water concentration respetively.

Electrode has a resistance depending on the number of membranes, called R_{ohmic}. The self-resistance, R_{ohmic}, is also determined by resistance of the material of electrode, $R_{electrode}$. The $R_{electrode}$ values vary from 1 to 100Ω m^2. The relation between number of membranes and resistance area is expressed in equation (5).

$$R_{Ohmic} = \frac{N_m}{2}\left(\frac{R_{AEM}}{1-\beta} + \frac{R_{CEM}}{1-\beta} + \frac{h_{sea}}{\varepsilon^2 \cdot \kappa_{sea}} + \frac{h_{river}}{\varepsilon^2 \cdot \kappa_{river}}\right) + R_{electrodes} \quad (5)$$

The anion R_{AEM} and cation R_{CEM} are resistance area (Ω m^2), h is the distance of inter membrane electrode (m), and κ is the conductivity of electrolyte solution (S/m). The voltage in electrode will be produced when the circuit is connected. The self-resistance (R_{Ohmic}) will decrease the voltage over the electrode. Thus it can be estimated by:

$$V_{bat} = E - R_{Ohmic} \cdot j \quad (6)$$

in which R_{Ohmic} is resistnace area (Ω m^2), and j is current density (A/m^2).

$$j = \frac{I}{A} \quad (7)$$

The area, A (m^2) is electrodes (the anode and cathode) designed by considering its width (m) and length (m). Thus, based on equation (6)-(7), it is determined that:

$$I = \frac{(E - V_{bat})}{R_{Ohmic}}.A \quad (8)$$

the power out based on design can be determined as:

$$P_{out} = I.V_{bat} \quad (9)$$

The methodology to set the membrane values is pointed out in Figure 4.

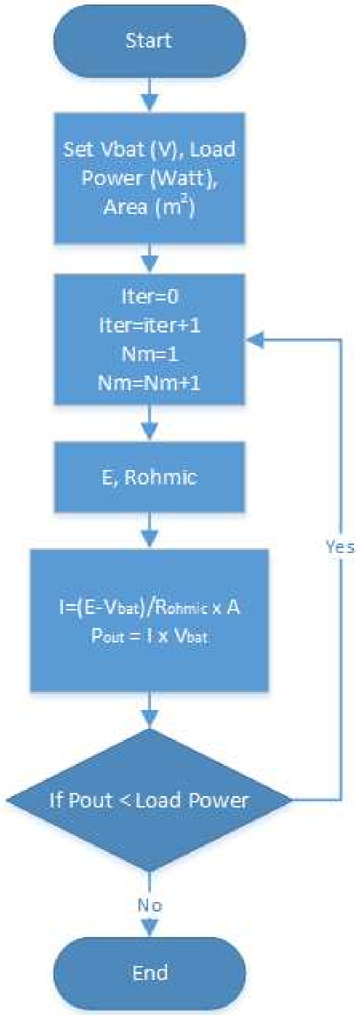

Figure 4. Flowchart to set power output

Thus from the equation (4)-(9), the circuit can be illustrated as:

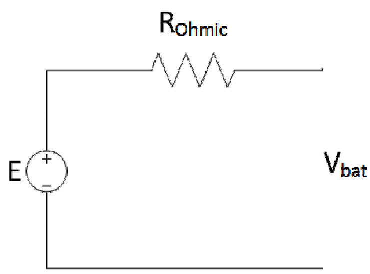

Figure 5. Seawater battery circuit

The electromotive force (E) is generated by the different salinity solution. However, there is a drop voltage during the current flow due to the self-reactance (R_{Ohmic}). As a result, the output voltage designed should consider the R_{ohmic} to satisfy load power. In this section, it is stated that V_{bat} is the same terminology as V_{out}.

Referring to equation (6), the V_{bat} in volt, is the voltage designed. The voltage in the output terminal of the battery is designed 48 volt with rating power P_{batt} = 3 kW. The seawater salinity concentration may be changed during the boat movement. This will effect on terminal potential (V_{bat}). Therefore in subsection 3, it will be discussed the plan to generate electromotive force constantly by utilizing zeta converter.

III. PROPOSED DESIGN AND ANALISYS OF ZETA CONVERTER WITH COUPLED INDUCTOR AND CAPACITOR

The converter proposed for seawater battery application is high step up zeta converter with coupled inductor and capacitor multiplier. Zeta converter is usually designed to provide either step up or step down operation. Two inductors, a series capacitor and a diode are usually used in the conventional zeta converter. By using coupled inductor, it can reduce the dimension of power supply and the capacitor multiplier is to increase the step up ratio the output for further.

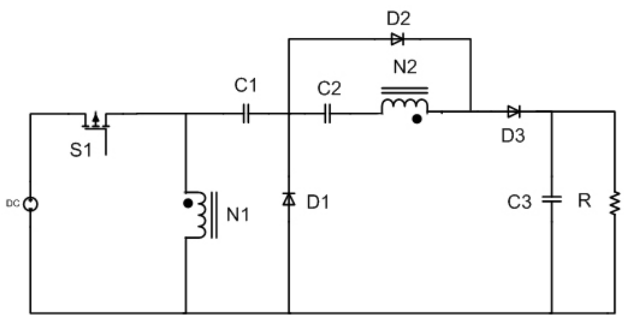

Figure 6 . Zeta converter with coupled inductor and capacitor multiplier.

The zeta converter is configured from a coupled inductor L_1, with primary side N_1 connected to C_1 and D_1 to recycling the leakage energy from inductor N_1. The secondary side of N_2 is connected to C_2 and D_2. To simplify the analysis, the Figure 6 can be shown in Figure 7.

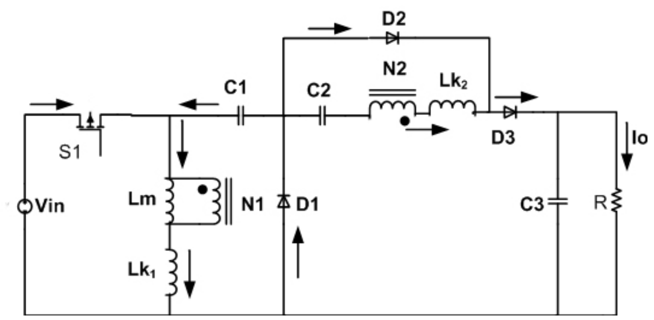

Figure 7. Simplified circuit model of the coupled inductor and capacitor multiplier zeta converter.

The coupled inductor and capacitor multiplier zeta converter has some advantages, those are 1) the leakage energy of the coupled inductor can be recycled, so the efficiency will be increased; 2) to step up the output voltage is used both coupled inductor ration and capacitor multiplier, so it increases the efficiency of voltage ratio conversion; and 3) the DC input from seawater battery can be isolated during the non-operation condition.

A. *Converter Circuit Analisys*

To obtain voltage required to supply some loads from seawater battery in a fishing boat, the zeta converter is operated in CCM (Continuous Conduction Mode). There are five operation scheme modes of the zeta converter, which can be found in [5]. In CCM operation mode, there are only two modes used and the leakage inductances of the primary and secondary inductors are ignored. The modes used in the operation are shown as follows:

1). when switch S_1 is "On", C_1, C_2, secondary winding N_2 and L_{k2} are series connected to the input V_{in}. The energy from N_2 flows and charges C_3 through D_3, while L_m and Lk_1 are energized by the input V_{in}. During this condition, it can be described that:

$$V_{Lm} = V_{in} \quad (10)$$

$$V_{N2} = nV_{in} \quad (11)$$

2). when switch S_1 is "Off", the inductor L_m releases the stored energy to the C_1 simultaneously and C_2 through the inductances of primary and secondary sides. In this mode, only diode D_1 and D_2 are conducting. The stored energy in capacitor C_3 is discharged to the load R. During this condition, it can be formulated that:

$$V_{Lm} = -V_{C1} \quad (12)$$

$$V_{N2} = -V_{C2} \quad (13)$$

The equation of a voltage balance on the inductor L_m can be written as follows:

$$\int_0^{DTs} V_{in} dt + \int_{DTs}^{Ts} -V_{C1} dt = 0 \quad (14)$$

$$\int_0^{DTs} n.V_{in} dt + \int_{DTs}^{Ts} -V_{C2} dt = 0 \quad (15)$$

where the voltages of capacitor C_1 and C_2 are obtained from the following equations:

$$V_{C1} = \frac{D}{1-D} V_{in} \quad (16)$$

$$V_{C2} = \frac{nD}{1-D} V_{in} \quad (17)$$

During the switch S_1 "On", the output voltage can be calculated as follows:

$$V_0 = V_{in} + V_{C1} + V_{N2} + V_{C2} \quad (18)$$

$$V_0 = V_{in} + \frac{D}{1-D} V_{in} + nV_{in} + \frac{nD}{1-D} V_{in} = \frac{1+n}{1-D} V_{in} \quad (19)$$

Therefore, the voltage gain of the zeta converter is:

$$G = \frac{1+n}{1-D} \quad (20)$$

B. Proposed Design of Converter

The Value of power component is depend on the load. In this case $P_{Load} = 2,2kW$ (cold storage and lighting). The parameters of converter are shown in Table 3.
The value of C_1 and C_2 calculated with eq, 21, see [5].

$$C \geq \frac{2.P_{\max}}{V_c^2 . f_{sw}} \quad (21)$$

The value of L_m (magnetizing inductance) has been calculated with eq. 22, see [5].

$$L_m = \frac{(D - 2D^2 + D^3) R_B}{(2 + 2n + n^2)\, \mathrm{F}_{sw}} \quad (22)$$

Table 3. Zeta Converter Design

Zeta Converter Design	
V_{in}	47 – 49 Volt
V_{out}	311 Volt
Fsw	50 kHz
n	4
C_1	1 uF
C_2	100 nF
C_3	50 uF
L_m	359.38 uH
L_{k1}	4.506 uH
L_{k2}	62.07 uH

The value of *D* (duty ratio) calculated at the minimum input voltage of converter, The value of R_B (boundary resistance) calculated when the converter has been operated at BCM (Boundary Conduction Mode) see [5], n is winding ratio of coupled inductor. The value of Lk_1 and Lk_2 are leakage inductances of each winding.

C. Proposed Control Method

In order to obtain constant voltage in the output of the zeta converter since the voltage output of seawater battery is not constant due to the changes of seawater concentration, it is required to apply a controller, in which the controller applied is using PI controller. The output of the controller is used to set the duty cycle of the switch S_1, so that the constant voltage in the output of the zeta converter is obtained. The block diagram of the controller can be shown in Figure 8.

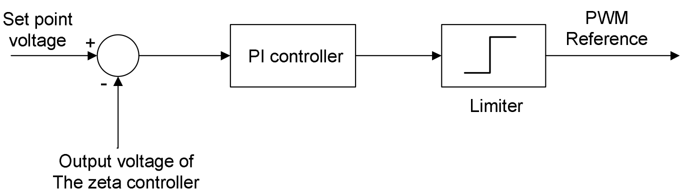

Figure 8. Control system diagram

IV. SIMULATION RESULT

The Simulation using PSIM has been implemented as shown in Figure 10. In this simulation, it was set various values of seawater concentration, since it always changes at each different point (latitude and longitude) on the sea. In this case, the value is various from 30.5 to 32.9. The graphical simulation of the seawater concentration can be seen in Figure 9.

Table 4. Sea water battery parameters

Seawater Battery Parameters	
Nm	464
Alpha	0.97
R	8.3
T	300
Z	1
F	96458
G_{sea}	1
C_{sea}	30.5 – 32.9
G_{riv}	1
C_{riv}	0.5

Table 5. LPF and inverter parameters

Inverter & Low Pass Filter Parameters	
$C_{DC\ Link}$	6800 uF
LF1	2.82 mH
CF1	1 uF
LF2	1.01 mH
CF2	1 uF
SPWM freq	5 kHz

Table 6. Load parameters

Load parameters	
Cold storage	P = 2 kW
Lighting, etc	P = 200 W
Power factor of the total of load	0.85

The simulation parameters are shown in Table 3 - 6.

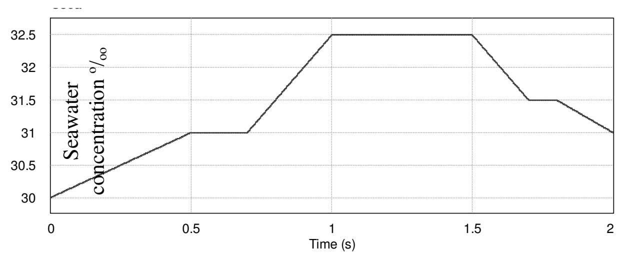

Figure 9. The changes of seawater concentration

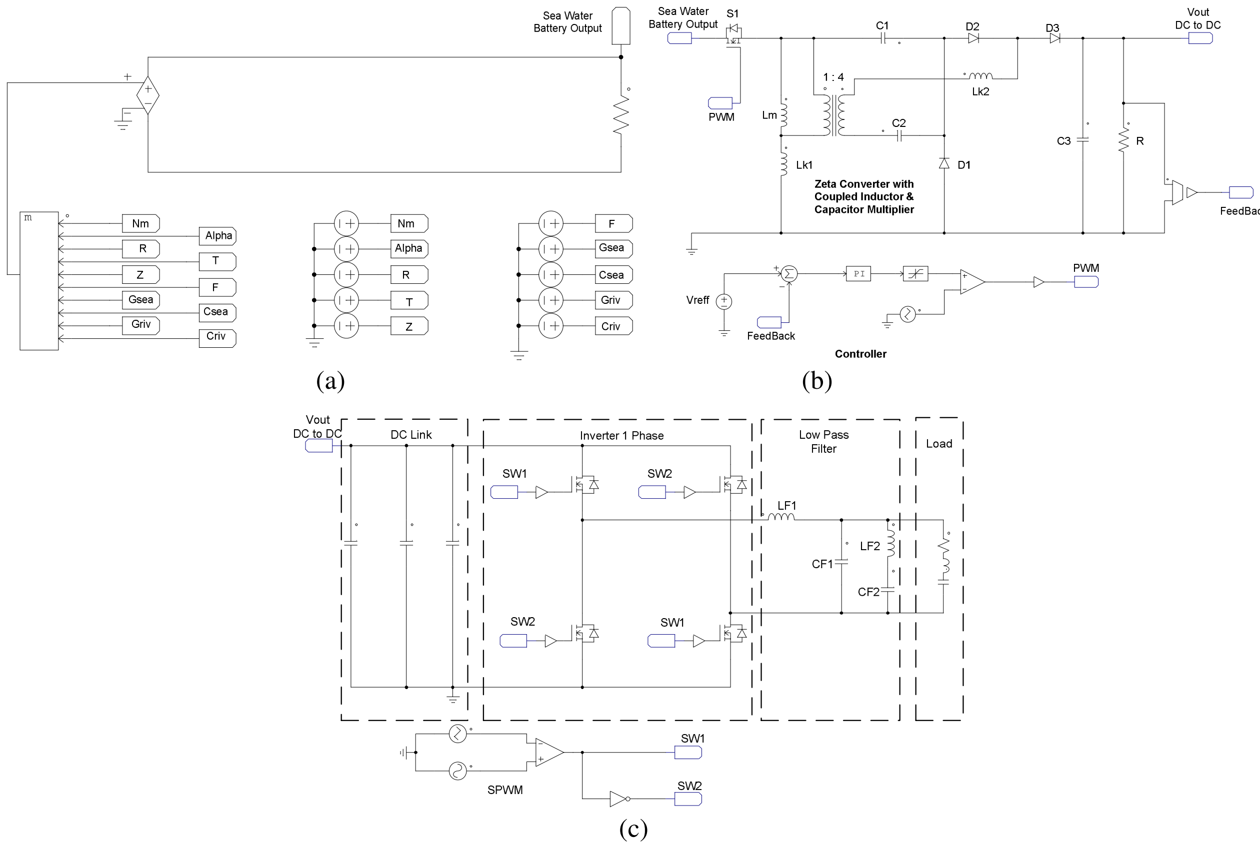

Figure 10. Simulation of the system; (a) Seawater battery simulation model; (b) Zeta converter with inductor coupled and capacitor multiplier; (c) Inverter and low pass filter

Since all the parameters on the seawater battery are made fixed, it is only the seawater concentration that works on the changes of seawater battery voltage. Based on that condition, the changes of the output voltage of the seawater battery are shown in Figure 11. It can be seen that the value varies from 48 – 49 volt.

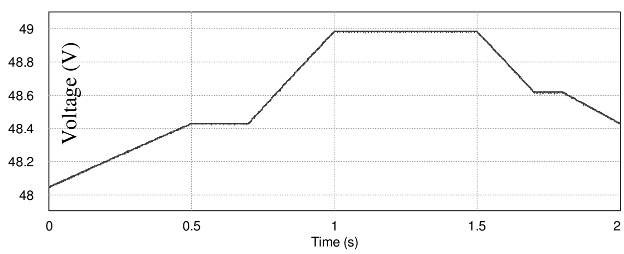

Figure 11. The output voltage of seawater battery according to the changes of seawater concentration

The controller of zeta controller is responsible for maintaining the output voltage, which is set 311 volt before it is used for the inverter. The PI controller is used to control the error value of the output voltage, and it maintains very well to keep the output voltage constant. The result simulation of the output voltage is shown in Figure 12. The average value of the zeta converter output is 310.57 volt. There, however, is a ripple in the output voltage waveform, but it is not such a significant since the error ripple of the output voltage towards the desired value is about 0.5 %.

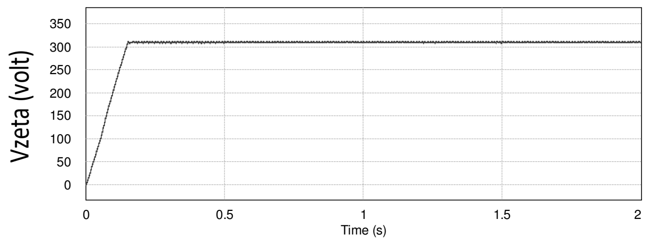

Figure 12. The output voltage of zeta converter

In fact, the output voltage of the inverter is not pure sinusoidal, but it is a modulated square wave. To get the output sinusoidal, it needs to apply filter in the output side of the inverter. There are two kinds of filter implemented to the output of the inverter, which are a low pass filter and a single tune filter. The use of combination between those filters gives a good performance to improve the output signal. The output voltage of the inverter shows as a sine waveform with THD 7.3 % and the RMS output voltage is 214.79 volt. From the simulation, it can be seen that the RMS output voltage is still in the tolerance value, since the tolerance is considered ± 5% (209-231 volt). Furthermore, the RMS current is 11.46 A with THD 0.17 %. The simulation result of the inverter output voltage and current can bee seen in figure 13 and 14 respectively. According to the simulation, the apparent power generated is 2715.85 VA with power factor 0.85, so the real power of the inverter output is 2308.43 watt.

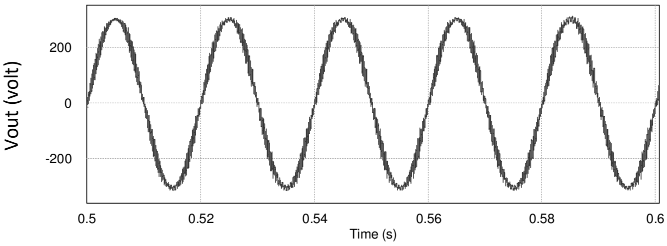

Figure 13. The output voltage of inverter from t = 0.5s to 0.6s

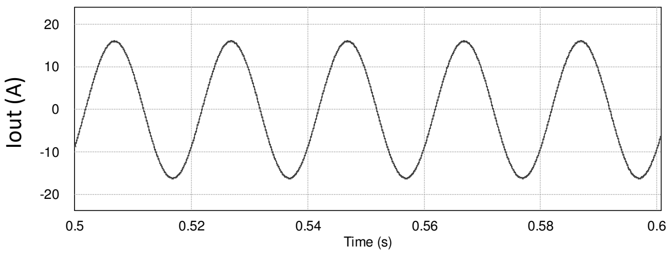

Figure 14. The output current of the inverter.

V. CONCLUSION

Seawater battery is beneficial to alternative power sources of electrical system in fishing boat. In this paper, seawater battery has been modeled with salinity of water fluctuate so it have the range output voltage of battery (V_{bat}). Desain model zeta converter with coupled inductor and capacitor using PI control applied to seawater battery application is proposed. In order to control output voltage to be constant is using PI control. The simulation have verified the proposed algorithm, and the result is the output voltage is always in constant value at 311 Volt in order to get the rated voltage of the load (*Vo-rms* = 220 Volt) when the seawater salinity was fluctuate. The power output quality is good with THD_v = 7,3% and THD_i = 0,17%.

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