Maximum Power Point Tracking of Stirling Generator and Ocean Wave Energy Conversion Systems Using a Two-Stage Power Converter

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Abstract*—Wave energy has become one of the most promising renewable energy resources nowadays. By using a linear generator/alternator, the periodic piston motion of the wave energy conversion system (WEC) can be converted to AC voltage with variable RMS amplitude and frequency; this process is comparable to the operation of a Stirling generator as well. This paper has presented a solution to make use of this output voltage that involves a boost-type single-stage rectifier to regulate the voltage and generate DC output. In this solution, appropriate control scheme has been used with the rectifier to maximize the power generation from the Stirling generator. A single phase H-bridge inverter has then been used after it for practical applications (120V, 60 Hz). Because no real Stirling generator was available in the lab, we have modeled the behavior of the generator and simulated the proposed power converters. Also, a prototype of the boost-type single-stage rectifier has been built and tested to verify our strategy. Compared to conventional passive rectification, this solution improves the circuit's performance significantly.

I. Introduction

In recent years, the power system has been undergoing a profound reconstruction. The traditional view of the power system has been remolded due to the considerations of the economic and environmental incentives as well as the advancement of technologies. Renewable energy resources, for example, solar and wind energy as well as the wave energy are becoming favorable because of their green nature and sustainability. However, there still exist some challenges before a wider development of the renewable energy. In United States, according to the report of "Mapping and Assessment of the United States Ocean Wave Energy Resource"[1], the total amount of wave energy source along the U.S. continental shelf edge is estimated to be 2640 terawatt hours per year (TWH/yr.) by accumulating unit circle wave power densities. As a result, wave energy becomes one of the most promising energy resources.

In addition to wave energy, Stirling engines can be used to transfer heat energy to mechanical movement. Stirling engine, which was invented by Robert Stirling in the year of 1816, is a kind of high efficient external combustion engine. The permanent gaseous working fluid (e.g. Hydrogen or Helium) in the Stirling engine cylinder periodically compresses (cooling) and expands (heating) at different ends of the engine to drive the piston back and forth inside the cylinder. In this way, the heat energy generated by the fuel is transformed into mechanical movement of the piston motion. And then a linear generator can be connected to produce electricity from this piston motion.

The operating principle of ocean Wave Energy Conversion System (WEC) is similar to the Stirling engine mentioned above. Among different types of WECs, Archimedes Wave Swing (AWS) mainly consists of a few inter-connected, air-filled chambers and movable floats. When a wave comes and submerges the movable float, the pressure on the float will cause itself to sink and thus the volume of the chamber to decrease. During a wave trough, contrarily, the volume of the chamber will increase while the floats will go vertically to the surface of the water. Similar to the energy conversion process in the Stirling generator, it is very convenient to generate electricity directly from the linear chamber motion by using a linear generator [2] which makes these two energy conversion system (Stirling engine and WEC) comparable.

In both Stirling engine and WEC, the piston motion changes in a periodic pattern [3]-[4]. By using a linear generator/alternator, this sinusoidal mechanical motion will result in a sinusoidal voltage output according to Faraday's law. For the speed and direction of the translational motion are always changing, the amplitude and frequency of the resulted output voltage vary with time as well. As a result, a proper converter needs to be designed to rectify this voltage and extract maximum power. In this paper, a two-stage AC-AC power converter has been presented to regulate this voltage, and maximum power point tracking (MPPT) can be achieved by using proper control strategy. Unlike conventional two-stage power processing, the proposed circuit accomplishes the rectification and voltage boosting using only one power processing stage thus reducing forward voltage drop and increasing efficiency.

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The proposed two-stage power converter will be introduced in section II and III. Then the simulation results of this converter circuit using Powersim (PSIM) will be presented and analyzed in Section IV. Based on the simulation circuit, an experimental prototype was constructed and experimental results are shown in section V. Finally, in Section VI, the authors will state the conclusion of this paper and the future tasks have been outlined.

II. STAGE I: AC-DC POWER CONVERTER

In conventional energy processing circuits [5]-[8], a full bridge passive rectifier followed by a boost/buck converter is always used, which is shown in Fig. 1. However, this two-stage structure has some disadvantages, such as the DC side inductor needs special design; three semiconductor devices will conduct in the power path at any instant and a bootstrap gate driver is needed to drive two MOSFETs with different grounds.

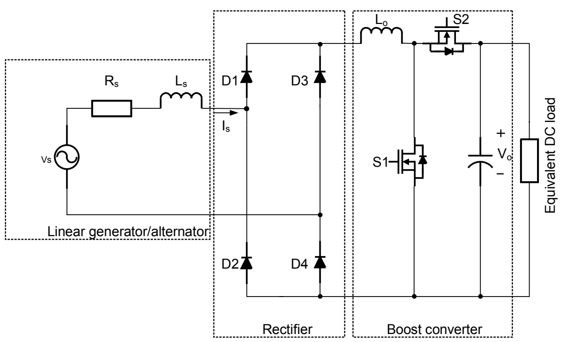


Figure 1: Conventional solution: full bridge passive rectifier with boost converter.

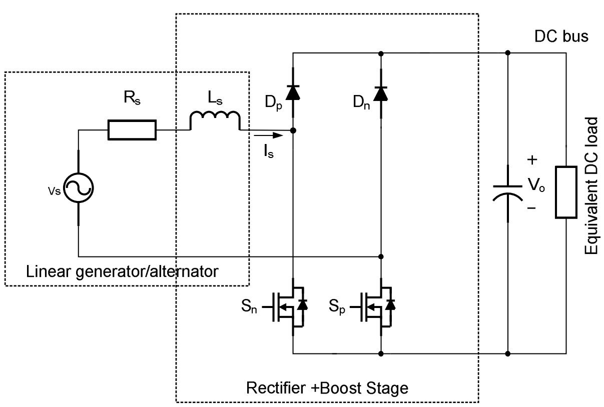


Figure 2: Proposed solution: single-stage rectifier.

In order to address these inherent limitations, a new single-stage power converter has been proposed and shown in Fig. 2. In this new circuit structure, a major change is that the DC side inductor is eliminated and instead, an AC side inductor is built. The internal inductor of the linear alternator/generator can also be used as the AC side inductor [9]. This new circuit diagram has several advantages:

1) *The electro-magnetic interference (EMI) can be reduced with the help of the AC side inductor.*

2) *The number of semiconductor devices in the power path has been reduced from three to two; meanwhile, the total number of semiconductor devices in the entire circuit is four in place of six in the conventional circuit.*

3) *The two IGBTs in the new circuit share the same ground. As a result, isolation circuit or bootstrap gate driver is no longer needed.*

4) *By using proper control strategy, the input current can be shaped to follow the input voltage and thus high power factor is presented on the input side of the circuit.*

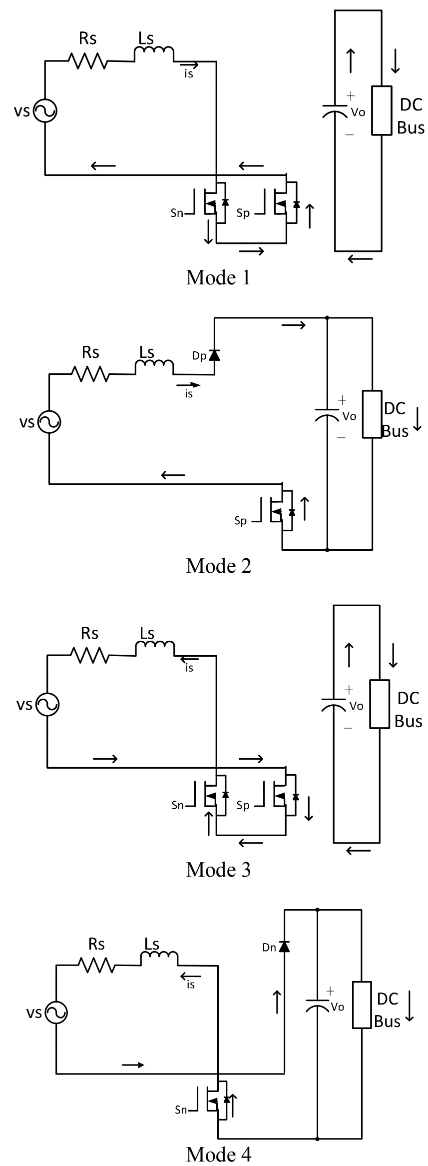


Figure 3: Four conduction modes of the proposed single-stage rectifier.

Fig. 3 shows the four conduction modes for the single-stage power converter. The two switches in the diagram are noted as S_n and S_p, respectively. During the positive half cycle of the input voltage, S_p is ON while S_n is working in PWM conduction mode. Similarly, in the negative working cycle, S_n is ON while S_p is working in PWM conduction mode.

Mode 1: In the positive working cycle, when both of the two switches are off, the input current will flow through the input AC inductor, S_n and S_p in turn. During this mode, the inductor will store energy and the current through the inductor will increase following equation (1). Meanwhile, the output capacitor will release energy to keep the output DC voltage constant.

$$|v_s| - L_s \frac{d|i_s|}{dt} = 0 \qquad (1)$$

v_s, i_s and L_s are the generator voltage, current and inductance respectively.

Mode 2: During the positive cycle with S_n deactivated, the energy stored in the input inductor will transfer to the DC bus and DC bus capacitor through D_p. Then the current will go through S_p and back to the input voltage source. In mode 2, the electrical equation to describe the circuit is，

$$|v_s| - L_s \frac{d|i_s|}{dt} - V_o = 0 \qquad (2)$$

V_o is the DC bus voltage.

Mode 3: During the negative half cycle with both the switches are OFF, the input current will flow through S_p, S_n, and the input AC inductor. In this state the inductor will store energy and the current through the inductor will increase following equation (1). Meanwhile, the output capacitor will release energy to keep the output voltage constant.

Mode 4: In the negative cycle with S_p deactivated, the energy stored in the input inductor will transfer to the DC bus and DC bus capacitor through Dn. Then the current will go through S_n and back to the input voltage source. In mode 4, the electrical equation for the circuit is also in the form of equation (2).

The control strategy for the boost-type single-stage rectifier is illustrated in Fig. 4. PI cascade control has been used to adjust the input power factor and the output DC voltage. The outer control loop is a slower voltage loop; by sensing the input and output voltages of the rectifier, not only the reference signal for input current is generated but also the output voltage is stabled at its expected value. The subtraction result between the reference and sensed input current will then go through another PI controller to produce the waveform to be compared with a triangular carrier wave. After several logic operations, proper PWM signals for the two switches are determined.

III. STAGE II: DC-AC POWER CONVERTER

The Stirling generator or the wave energy harvester generates AC voltage that can widely vary in frequency and amplitude. The output voltage amplitude variation could be as high as 250% and the frequency variation could be 30-40%. Therefore, the voltage present at the DC bus of the proposed rectifier could have high ripple. In order to minimize the influence of the varying output voltage from the linear generator/alternator, an inverter stage was coupled to the DC bus, and the proposed control scheme was able to track the variation to produce constant 120V, 60 Hz AC voltage.

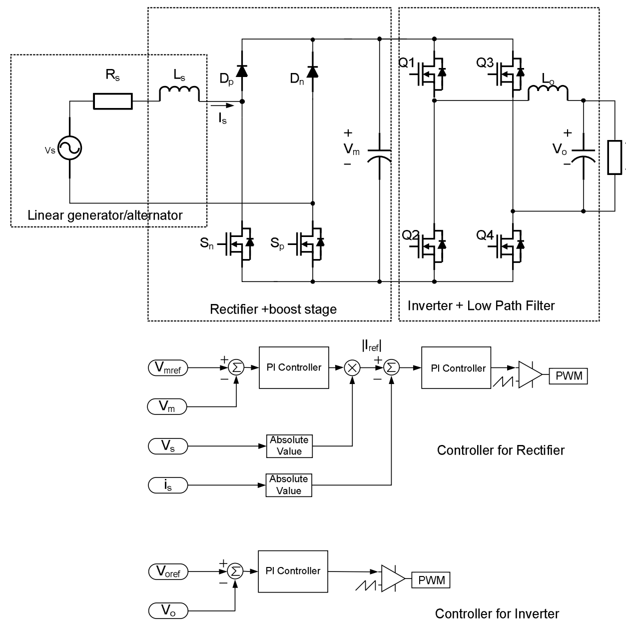


Figure 4: Circuit diagram of the two-stage power converter with controllers.

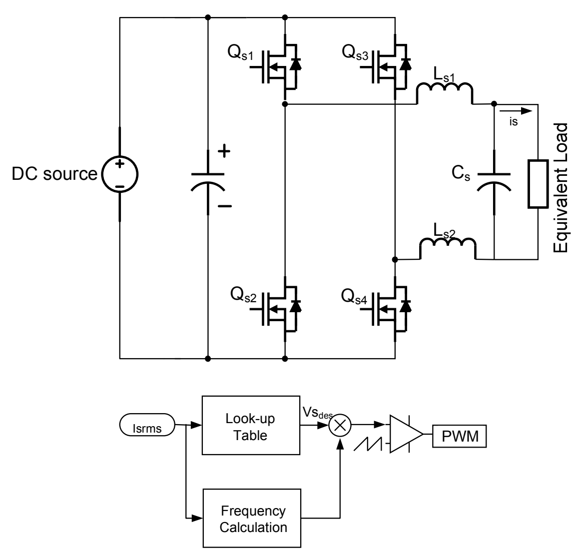


Figure 5: Circuit diagram of Stirling generator emulator.

IV. SIMULATION RESULTS

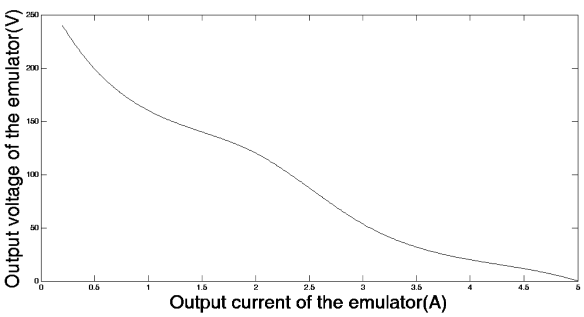
Powersim (PSIM) was used to simulate the operation of the two-stage power converter with controllers in this newly proposed Stirling generator/ wave energy harvester application. In order to emulate the performance of the Stirling generator, an emulator was constructed as shown in Fig. 5 and connected as the input to the two-stage power converter system. As can be seen from Fig. 5, an inverter was used as the core of this emulator. By sensing the output current of the emulator, a proper sinusoidal control voltage was determined to compare with the triangular carrier wave and get the PWM signals for the switches.

The proposed emulator has the following characteristics:

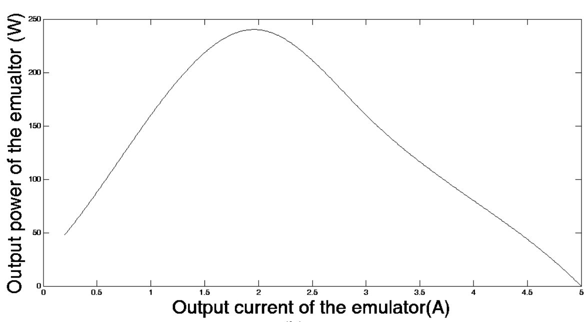
a. For a certain heating condition, there exists a maximum power point for the generated output of the Stirling generator. In our simulation, the maximum output power is set at 240 W when the output voltage and current reach 120V (RMS) and 2A (RMS), respectively. The relationships between output current and output voltage as well as output current and output power are shown in Fig. 6 (a), (b).

b. The frequency of the output voltage will also change along with the variation in the output voltage amplitude. The range of the output frequency has been chosen arbitrarily between 22.5 Hz and 85Hz in this case.

For the output voltage of the second-stage inverter is fixed at 120V, choosing different output AC loads can decide the amount of power flow in the system. As shown in Fig. 7, when the output load is chosen to be 60 Ω, the Stirling generator's output is automatically set to be 120V (RMS) and 2A (RMS) due to the control strategy , which results in a maximum power flow of 240 W in the designed system.



(a)



(b)

Figure 6: Relationships between (a) output current vs. output voltage (b) output current vs. output power.

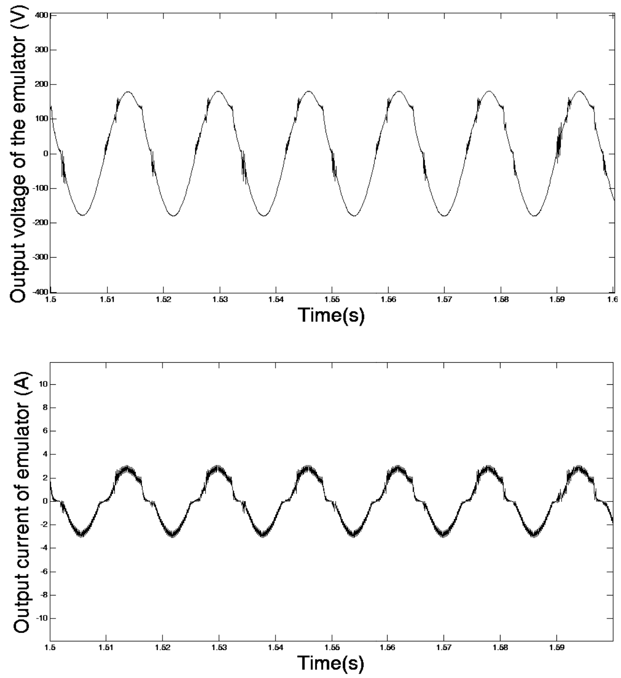


Figure 7: Simulation results of the output voltage/current of emulator.

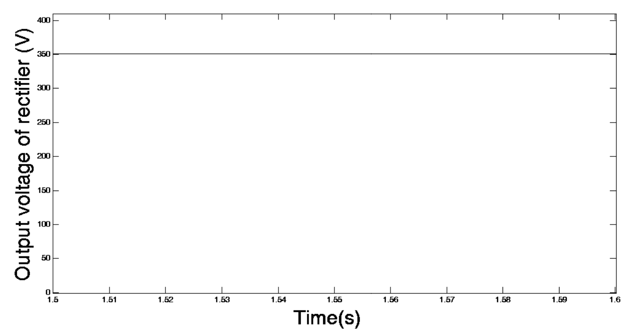


Figure 8: Simulation result of the single-stage rectifier.

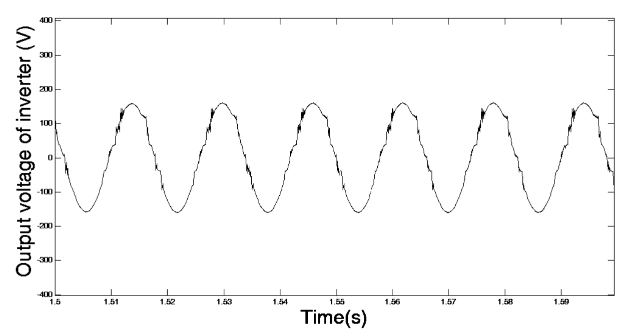
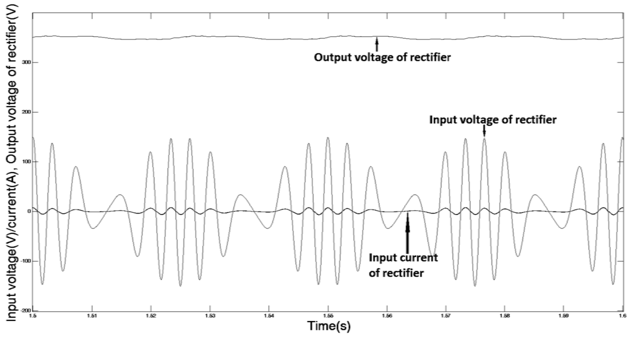
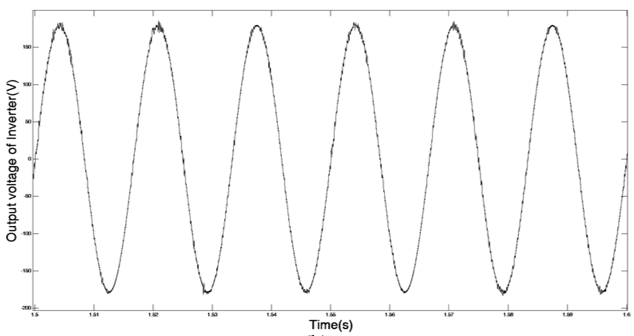


Figure 9: Simulation result of the H-bridge inverter.



(a)



(b)

Figure 10: (a) Input voltage/current and output voltage of rectifier (b) output voltage of the second-stage inverter.

DC voltage can be expected at the output of the single-stage rectifier following the emulator. However, because of the amplitude/frequency variations in the emulator's output voltage, ripple is presented on the DC bus. An inverter is then connected to regulate this DC voltage. Simulation results of the output voltages of the single-stage rectifier and H-bridge inverter are presented in Fig. 8 and 9, respectively.

In the prototype of this power converter (Fig. 11), however, the emulator used above was replaced by combining a function generator with a power amplifier. As has been stated in section I, in both Stirling engine and wave energy conversion system, the piston motion changes in a periodic pattern [3]-[4]. This kind of chamber motion can be expressed as follows,

$$x(t) = \frac{X}{2}\sin(\omega t) \tag{3}$$

Where $\frac{X}{2}$ is the amplitude of the motion, and ω is the angular frequency. If no flux linkage is presented in the linear generator/alternator coil at x=0, the corresponding flux can be described as,

$$\Phi(t) = \Phi_m \sin\left(\frac{2\pi}{\lambda}x(t)\right) \tag{4}$$

Then, based on Faraday's law, the mathematical description of the induced voltage is,

$$v(t) = N\frac{d\Phi}{dt} = V_m \cos(\omega t)\cos\left(\frac{\pi X}{\lambda}\sin(\omega t)\right) \tag{5}$$

Where $V_m = N\Phi_m\omega\frac{\pi X}{\lambda}$. This voltage will be the output voltage of the function generator in the experiment to act as an emulator of the Stirling generator/wave energy harvester.

Simulation results of the emulator voltage/current, rectifier output voltage and inverter output voltage are shown in Fig. 10. The amplitude and frequency of the emulator voltage vary with time which is in accordance with the real situation [10]. Also, as shown in Fig. 10 (a), the emulator current is always in phase with the voltage; this demonstrates a very high power factor on the input side of the power converter which minimizes the THD generated from this power processing system. Because of the operation principle, there exists a ripple in the output voltage of the boost-type rectifier. By using a full-bridge inverter and a simple feedback controller, a 120V/60Hz AC output voltage can be expected at the output of the inverter which is shown in Fig. 10 (b).

V. EXPERIMENTAL RESULTS

The operation of the boost-type rectifier with Stirling generator/WEC emulator was verified by experiment. The diagram of the experimental set-up is shown in Fig. 12 and several experimental parameters are listed in Table 1.

Fig. 13 (a) shows the input voltage/current waveforms of the single-stage rectifier. The output voltage from the function generator has variable amplitude and frequency. Also, it can be seen in this figure that the input current is in phase with the input voltage. As a result, this circuit structure is verified to have a very high input power factor. The output DC voltage of the rectifier is shown in Fig. 13 (b). In this figure, the output voltage ripple, which is 22.7%, can be clearly observed.

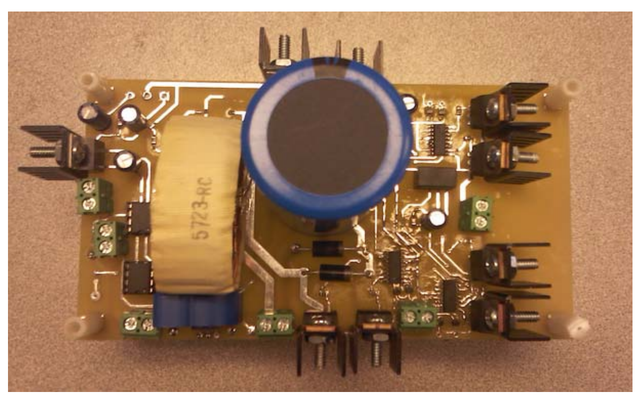


Figure 11: Prototype of the two-stage power converter system.

TABLE I. PARAMETERS OF THE BOOST-TYPE RECTIFIER

Parameter	Value
L_s	1.6mH
R_s	0.6Ω
C_o	0.8mF
R_{load}	47Ω
Output voltage	110V
Power of the prototype system	250W

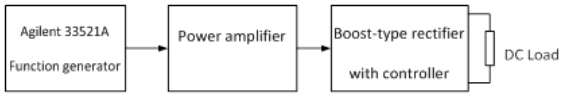
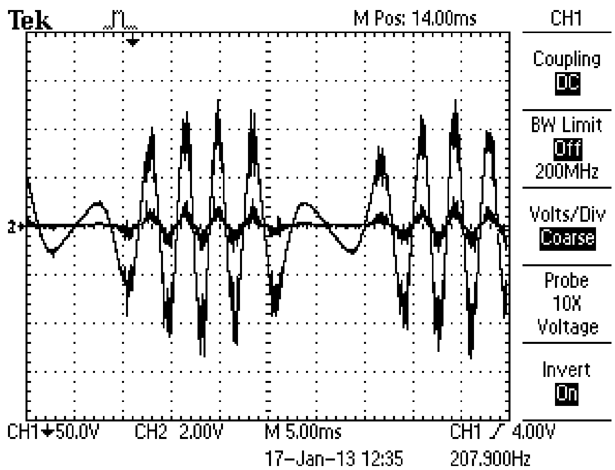
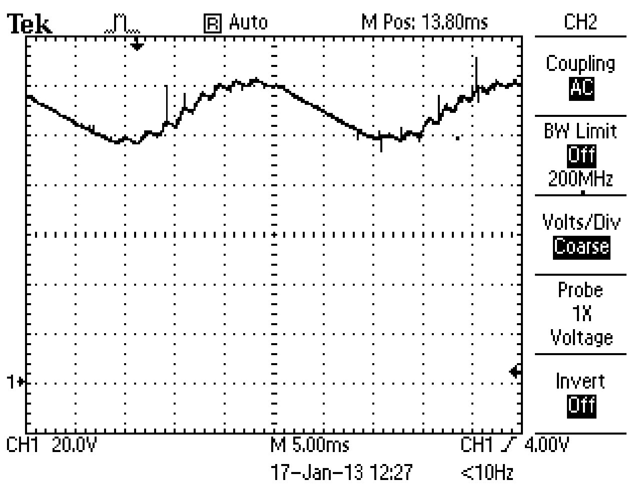


Figure 12: Experimental set-up diagram



(a)



(b)

Figure 13: (a) Input voltage/current waveforms (b) output voltage (110 V, 250W) waveform of the single-stage rectifier.

VI. CONCLUSION AND FUTURE WORK

In this paper, a two-stage power converter was designed and the boost-type rectifier was constructed to regulate the output voltage of the Stirling generator/ wave energy harvester. These two emulators were first simulated using Powersim (PSIM) to mimic the output parameters of the Stirling generator/wave energy harvester. Then a boost-type single-stage rectifier was adopted to obtain a DC output voltage followed by an inverter to produce 120V (RMS), 60 Hz output.

The full-bridge inverter and the boost rectifier have already been constructed on the single board (Fig.11), and they are yet to be fine-tuned for proper operation. Authors are presently working on the control circuit to optimize the operation of this two-stage design so that the simulation results could be validated using this prototype.

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