Review of the Linear Electrical Generator for Electricity Generation from the Oceanic Wave

Selim Molla[1*], Omar Farrok[2]

[1]Department of Electrical Engineering, Shahid Abdur Rab Serniabat Textiles Engineering College, & B Road, Barisal-8200, Bangladesh

[2]Department of Electrical and Electronic Engineering, Ahsanullah University of Science and Technology, Dhaka-1208, Bangladesh

*Corresponding author

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ABSTRACT

The fossil fuel based generation of electricity is very harmful for the environment due to emission of greenhouse gas. In order to avoid the problem, the tendency of renewable energy utilization is urgently required to increase. At present, there are different types of renewable energy such as solar, wind, biomass, geothermal etc. popularly applied to generate electricity. Besides, oceanic wave energy becomes much popular day by day due to having some special features. For harvesting energy, linear electrical generator is widely applied for wave energy conversion. In this paper, electricity generation system in Bangladesh is presented. Further, a comparison among solar, wind, and oceanic wave energy is presented. It is shown that oceanic wave energy has many advantages than solar and wind energy. For this reason, the generation of electricity from this source is highlighted. In addition, the oceanic wave energy conversion system is also explained. Further, the basic structure and working principle of linear generator, list of wave energy projects, and development progress of linear generator have been presented.

Keywords: Energy conversion, linear generator, oceanic wave energy, renewable energy.

1 Introduction

Fossil fuel operated electricity generation system is very harmful for the environment. In addition, it has some disadvantages such as high per unit generating cost, fuel storage system complexity, required huge cultivated or residential land for installation of the plant, and difficult to availability of fuel. This generating system exhausts large amounts of greenhouse gas into the atmosphere. Consequently, the temperature of the atmosphere increases day by day. For this reason, the Arctic world's ice is melting rapidly. Thus, the sea height is increasing day by day and the cultivated land as well as residential areas become part of the sea [1]. So, it is urgently required to control the emission of greenhouse gas. At present, some countries have taken a great initiative to reduce the emission of this gas. As an example, the EU will minimize 43% emission by 2030 than in 2005 [2].

Renewable energies can contribute to overcome those problems. It is a clean energy that can serve the requirement of sustainable development goals. There are various types of renewable energies viz. solar, wind, hydro plant etc. are popularly engaged to generate electricity. Energy storage system is required in case of both solar and wind power systems. Which is not cost effective. On the other hand, the location to install the hydropower is limited. Another one renewable energy i.e oceanic wave is very effective to produce electricity. It has no energy storage system. The sun and wind do not exist in 24 hours. In such case, SWE exists for 24 hours. The energy density of oceanic wave energy is greater

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than both solar and wind [3]. It is also CO2 free energy sources and relatively low visual and environmental impact [4] At present, there are 8000–80000 TWh/year of energy available in the ocean [5]. In which, Oceania continent has the highest energy [6].

Permanent magnet linear generator (PMLG) is developing day by day for the production of electricity from the sea wave. For ensuring maximum power even at irregular oceanic wave, a modern control system for driving PMLG has been proposed [7]. Here, back propagation neural network system has been utilized. Another control scheme whose name is adaptive hierarchical model predictive control for WEC has been described [8]. Which has adaptive mechanism of tuning for the strategy of a model predictive control by estimating the WEC online's dynamic. The utilization of a multistable mechanism for wave energy converter has been presented [9]. Which enhance the energy conversion efficiency of and their safe operation are very important issues in case of design of a WEC. Some modern control technologies of wave energy conversion systems have been presented for consideration by new researchers so that they can develop the existing control system in future [10]. In [11], construction related features of linear generators are presented. A novel design procedure is proposed which has the ability to optimize the linear generator with the help of lower amount of population [12]. Further, the split translator based linear generator has been proposed in order to enhance the efficiency [13]. Operating temperature of a linear generator depends on core loss and copper loss. Considering this matter, core loss of a linear generator is minimized by applying Kool Mµ [14]. But the output power of this generator is less than its conventional counterpart. In order to solve the problem, a machine is designed by M5-CARLITE [15]. Which has low core loss and higher output power than conventional linear generators. Demagnetization effect is one of the key barriers to produce high output power. For this reason, it has been reduced by applying N28EH PM

[16]. But N28EH is a rare earth material. In order to avoid this PM, a rare earth free material named iron nitride has been proposed [17]. In order to enhance the output power, reluctance of linear generator has been minimized by optimizing the stator size [18]. Besides, superconductor is very effective material instead of copper wire for winding to increase the output power [19].

In this paper, the following points have been highlighted

- Electricity generation sources in Bangladesh.
- Comparison among renewable energy sources.
- Explain the wave energy conversion procedure.
- Basic construction and working principle of linear generator.
- List of wave energy projects.
- Recent progress of linear generators.

2 Electricity Generation In Bangladesh

Bangladesh is a small and populated country. Most of the power plant is operated by fossil fuel as presented in Table I [20]. Here, it is also seen that only 3.02% power is generated from renewable energy sources. The mentioned fossil fuel-based power plants emit huge amounts of carbon dioxide which is very harmful for the environment. On the other hand, solar and wind energy are popularly utilized as renewable energy in Bangladesh. There are huge amount of land required to install these plants. Which directly decreases our cultivated and residential land. Therefore, such renewable energy sources to be selected for the generation of electricity which will not be utilized in our land.

TABLE I: INSTALLED CAPACITY OF BANGLADESH POWER DEVELOPMENT BOARD

Types of Sources	Capacity (%)
Coal	1.32
Gas	52.72
Heavy fuel oil	18.96
High speed diesel	8.91
Captive	11.68
Imported	3.48
Renewable	3.02

Considering this matter, the Bay of Bengal can be utilized to generate electricity. Because it has some advantages than solar and wind sources shown as Table II. [21], [22].

TABLE II: INSTALLED CAPACITY OF BANGLADESH POWER DEVELOPMENT BOARD

Name of project	Solar	Wind	Oceanic wave
Energy density (kW/m^2)	0.1–0.3	0.5	2–3
Availability	Low	Low	High
Predictability	Low	Low	High
Installation cost/kWh (USD)	0.9857	0.07075	0.01
Operation and maintenance cost/kWh (USD)	0.025	0.025	0.003313

3 Wave Energy Conversion System

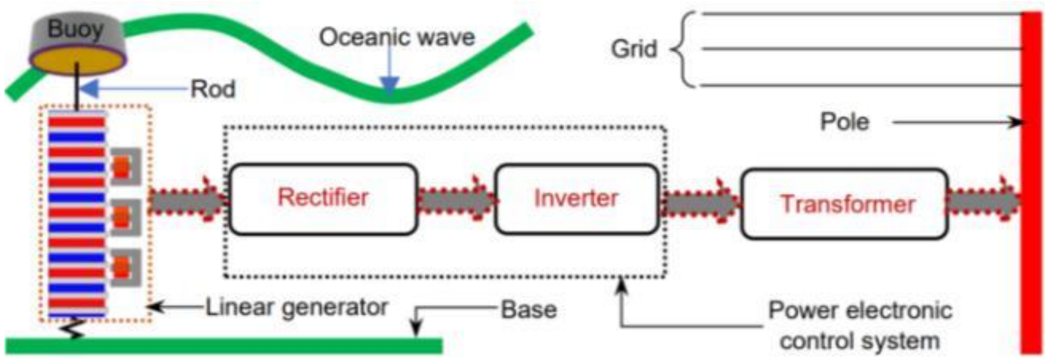

Fig. 1 Wave energy conversion system.

The wave energy converter (WEC) is a system that converts the electrical energy from oceanic wave energy. The complete conversion system is presented in Fig. 1. From here, it is seen that the WEC system has a power buoy, linear generator, rectifier, inverter, and transformer. The buoy always moves upward and downward with the oceanic wave.

The basic diagram of linear generator is plotted in Fig. 2. It is constituted by translator and stator. Where, translator and stator are made by permanent magnet and magnetic core. On the other hand, stator is prepared by magnetic core and windings. In general, copper wire or high temperature superconducting wire is applied to make coils for windings. In this machine, the translator and stator separated by air gap. Different parts of this machine have been identified by arrow symbol.

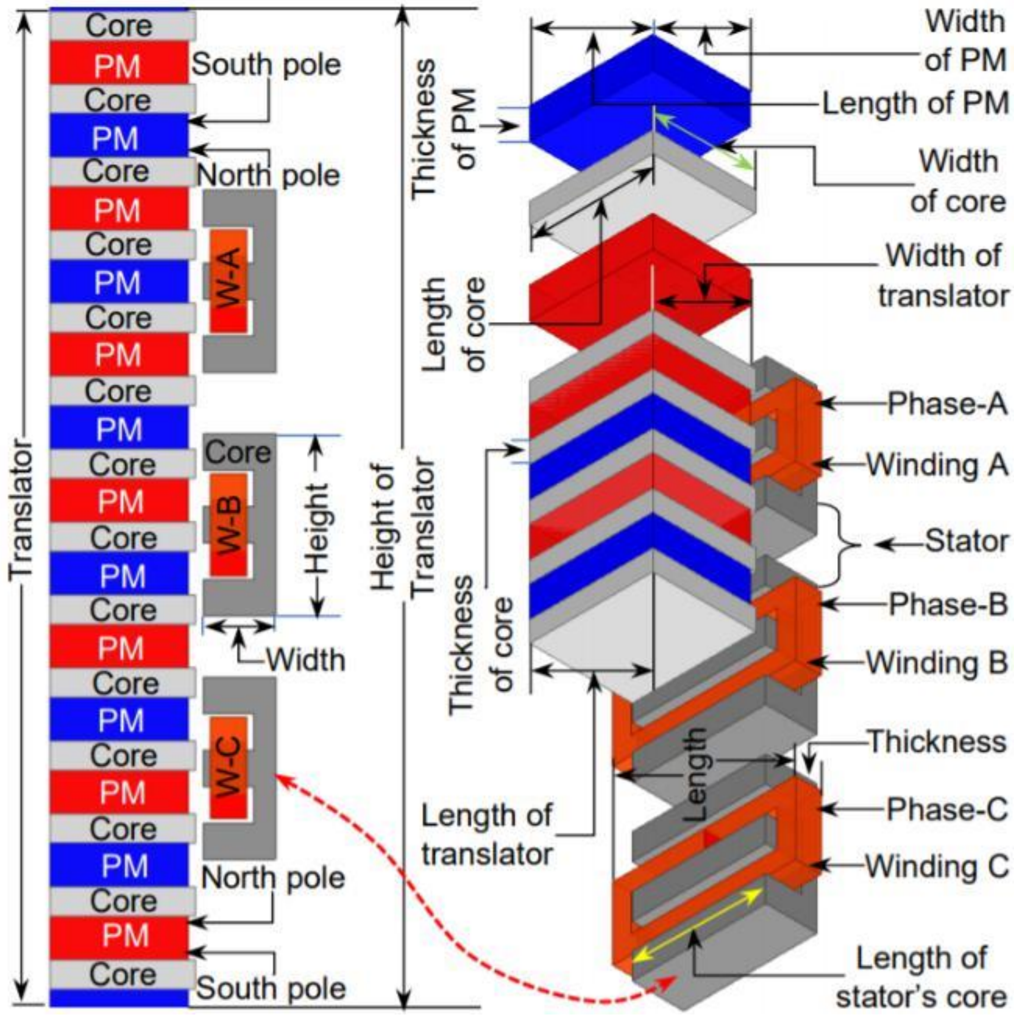

Fig. 2 Basic structure of linear generator.

Since the translator of linear generator is connected to the buoy through the high tensile strength rope or rod, it also moves upward and downward with the buoy. At this time, electromotive force is induced in the windings of stator as per Faraday's law of electromagnetic induction. It is observed that the movement of translator is not constant which varies with respect to the oceanic wave.

Therefore, the induced voltage and frequency are not constant too. In such reason, this voltage is converted to the dc voltage with the help of a rectifier. It can be noted that voltage and frequency of any electrical generator should be generated as per grid requirements. Hence, an inverter is applied in WEC system which prepares voltage and frequency by following the connected grid from the converted dc voltage. Finally, the output of inverter is transferred to the grid through the transformer.

Already some countries have started to generate electricity from this renewable source which is presented in Table III.

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TABLE III: LIST OF WAVE ENERGY PROJECT

Name of project	Capacity (kW)	Country
Coos Bay Project [23]	200000	USA
CETO 6 [24]	1500	Australia
Zhoushan [25]	500	China
Albatern WaveNET [26]	7.5	Netherland
Energen Wave Power [27]	1400	South Africa
The Maren Project [28]	300	Norway

4 Progress of Linear Generator

The development of linear generators has been starting rapidly since 1973 due to the oil crisis in the world. Some significant parts of the development of linear generator are mentioned as follows:

4.1 Novel Design Procedure of Linear Generator

The linear generator is optimized by following different methods. Which are out of multi objectives. A novel procedure has been proposed which optimizes the shape of translator and stator [12]. A comparison between conventional method and proposed method is tabulated in Table IV.

TABLE IV: COMPARISON BETWEEN CONVENTIONAL AND PROPOSED METHOD

Name of parameters	Conventional	Proposed
Surface area of stator (mm^2)	568.6	487.96
Volume of stator (cm^3)	56.86	48.79
Peak output power (W)	9.13	11.78
Peak voltage (V)	9.65	10.81

From the table it is seen that the volume and surface of proposed machine are smaller than existing counterpart. Besides, it can supply 29% more output power and 12% more voltage than conventional linear generators.

4.2 Split Translator Linear Generator

Generally, the efficiency of a linear generator is directly proportional to the weight of translator. Because, the translator always moves in vertical direction with the power buoy. Therefore, a less weight translator requires a lower amount of force to ensure movement. In order to reduce the weight a split translator based linear generator is proposed [13]. Which is able to supply electrical power at much efficiency than its conventional counterpart as shown in Table V.

TABLE V: COMPARISON BETWEEN CONVENTIONAL AND PROPOSED METHOD

Name of parameters	Conventional	Proposed
Peak output power (W)	500	500
Translator width (mm)	24	2X10
Translator mass (kg)	40.6	31.74
Upward force (N)	945.88	859.05
Efficiency (%)	57.93	63.79

4.3 Winding Optimized Linear Generator

It is known that induced voltage is directly dependent on the turn number of the coil of windings. Therefore, more turn numbers mean much output power. On the other hand, the cross sectional area of copper wire is inversely proportional to the turn numbers of coil. From here, it is said that if the cross sectional area of wire is low then the turn number of coil becomes high. But the resistance of copper wire is directly related to its length. Hence, much copper loss is found in case of low cross sectional area based wire. In addition, as large cross sectional wire is applied to the linear generator the turn number of winding becomes low. In this case, copper loss is minimized and output power also becomes low.

Considering the mentioned matter, winding of linear generator is optimized [1]. Here, three different size wires such as 2mm^2, 3mm^2, and 4mm^2 are selected as shown in Fig.3. After optimization, it is seen that the highest output power is found at 3mm^2 where load resistance is 3.6Ω. A comparison between conventional machine and optimized machine is presented in Table VI. From Table VI it is found that the generated voltage, current, and output power of an optimized linear generator are 10.34%, 14.6%, and 30.1% higher than conventional linear generator.

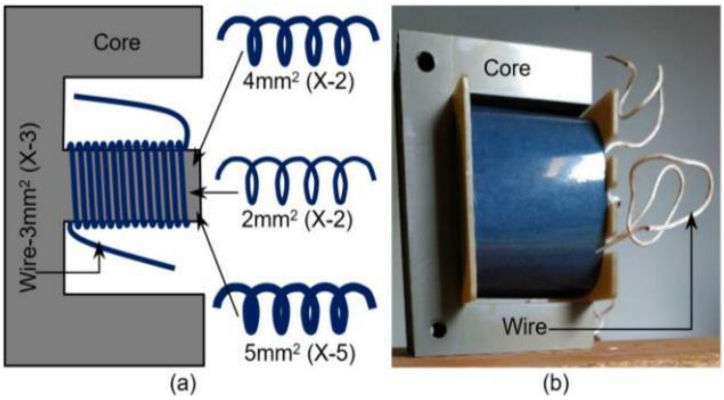

Fig. 3 Magnetic core and copper wire: (a) sketch (b) practical

TABLE VI: COMPARISON BETWEEN CONVENTIONAL AND OPTIMIZED MACHINE

Name of parameters	Conventional	Optimized
Peak voltage (kV)	1.74	1.92
Peak current (A)	411.1	471.1
Peak output power (W)	700	911

5 Minimum Core Loss Linear Generator

In general, conventional linear generator is made of ordinary steel core. Which is able to supply much electrical power but its loss is very high. In order to reduce the loss a magnetic core named Kool Mμ has been applied in linear generator [14]. This core made linear generator contains a lower amount of loss than conventional core made machine as shown in Fig. 4(a). On the other hand, the output power, voltage, and current of conventional machine are greater than proposed core made machine shown as Fig. 4(b), Fig. 4(c), and Fig. 4(d), respectively.

6 Analysis of Linear Generator with Various Magnetic Core

Earlier, it is seen that output characteristics of linear generator is decreased if core loss of it is minimized. Therefore, it is very challenge that the increase of output power with the minimization of core losses.

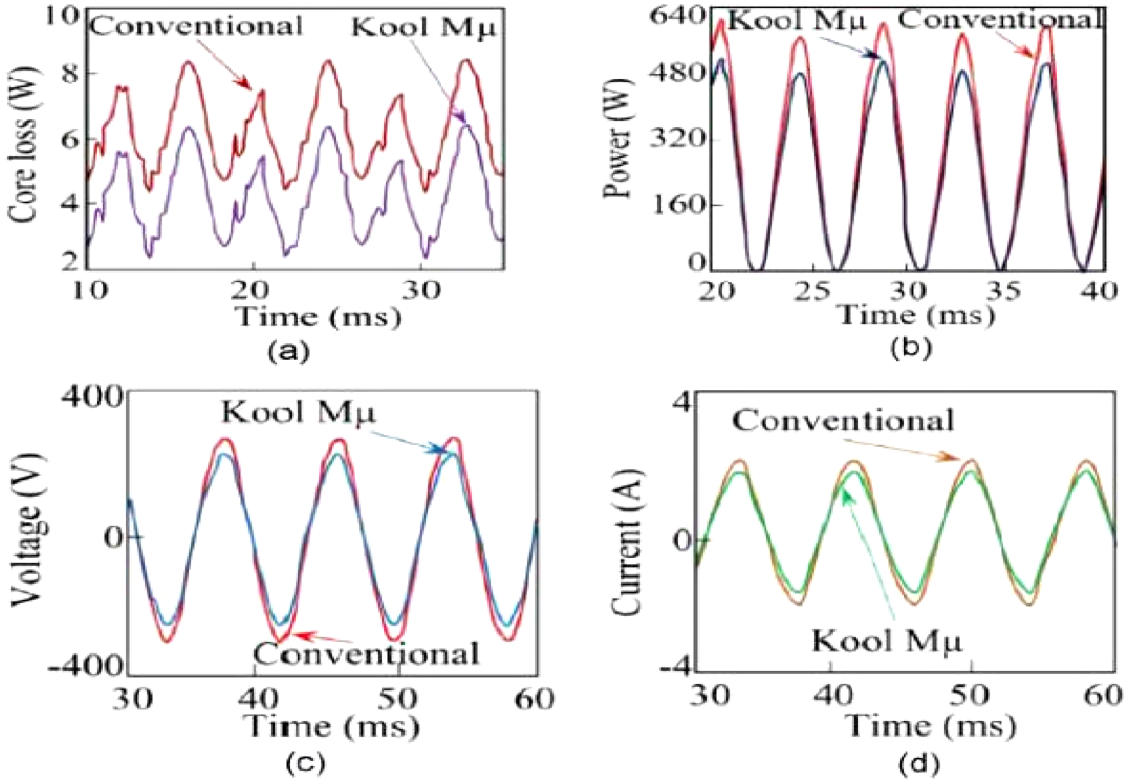

Fig. 4 Output characteristics of linear generator: (a) core loss, (b) power, (c) voltage, and (d) current.

Considering this matter a linear generator is analyzed by three magnetic cores such as DI-MAX HF-10x (10x), Armco DI-MAX M27 (M27), and M5-CARLITE (M5) [15]. The simulation results are presented in Table VII.

TABLE VII: COMPARISON AMONG DIFFERENT CORES MADE LINEAR GENERATOR

Name of parameters	10x	M27	M5
Average power in watt	2842	2905	3146
Force in Newton	3357	3457	3667
Translator speed in meter per second	1	1	1
Average core loss in watt per kilogram	4.41	6.55	2.40
Efficiency in percentage	84.7	84	85.8

From Table VII, it is found that the core loss of 10x made machine is less than M27 made counterpart. But the output power of M27 is higher than 10x. On the other hand, the M5 made linear generator supplies the highest power at the lowest core loss among them. Besides, this core made machine contains the highest efficiency among them.

6.1 Reduce Demagnetization Effect of Linear Generator

The conventional linear is generally made by low grade neodymium iron boron permanent magnet named N35M which is unable to generate much output power due to demagnetization effect. It occurs due to armature reaction. In order to avoid the armature reaction, a high strength magnetic field is required to apply in linear generator. For this reason, a high grade PM named N28EH has been applied to increase the output power [16]. Considering output power, a comparison between N35M and N28EH made machine is presented in Fig. 5.

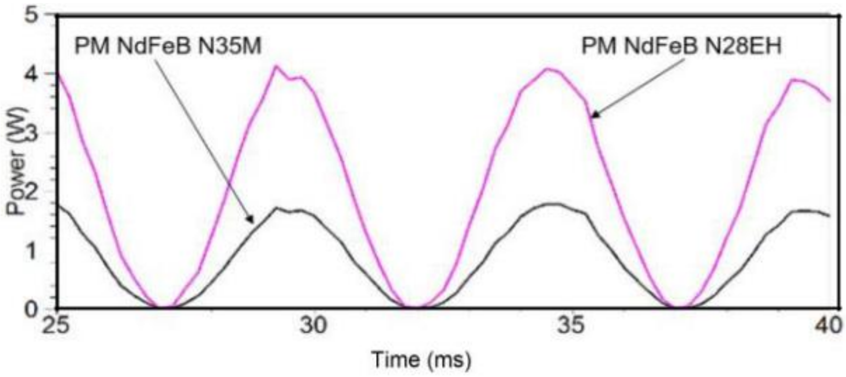

Fig. 5 Comparison between N35M and N28EH made linear generator.

7 Rare Earth Free Material Made Linear Generator

Almost all linear generators are made by either AlNiCo or neodymium iron boron PM. Here, the second one is a rare earth material. The availability of this material is being decreased day by day. Considering this matter, a linear generator is designed by iron nitride (Fe16N2) PM which is very available in nature [17]. In addition, the remanence of it is the highest among rare earth materials. A comparison between AlNiCo and Fe16N2 made linear generators is presented in Table VIII. The iron nitride PM made linear generator supplies 23.6%, 23.6%, 17.9%, and 52.8% much voltage, current, flux linkage, and power than AlNiCo made counterpart.

TABLE VIII: COMPARISON BETWEEN CONVENTIONAL AND OPTIMIZED MACHINE

Name of parameters	Conventional	Optimized
Peak voltage (V)	57.48	71.06
Peak current (A)	14.37	17.76
Peak flux linkage (Wb)	1.51	1.78
Peak output power (W)	826.2	1262.6

7.1 Novel Low Reluctance Linear Generator

We know that the induced EMF depends on the magnetic flux. Therefore, much flux means much output power of a linear generator. Besides, reluctance depends on the length of its flowing path. The dimension of magnetic core of stator of a linear generator is reduced in order to ensure minimum flux flowing path [18]. This machine supplies greater voltage, current, and power than its conventional counterpart as shown in Table IX.

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TABLE IX: COMPARISON BETWEEN CONVENTIONAL AND PROPOSED METHOD

Name of parameters	Conventional	Proposed
Peak output power (kW)	913	1048
Peak generated voltage (kV)	1.36	1.45
Load current (A)	676	695

8 Superconducting Linear Generator

The windings of most of the linear generators are designed by copper wire. This types of machine contains copper loss. In order to minimize the loss, superconductor is applied in a linear generator. This machine can generate much electric power than copper winding made generator [19]. A comparison between copper and superconductor made linear generators is depicted in Fig. 6. From here, it is shown that the output power of superconducting linear generator is greater than copper made machine.

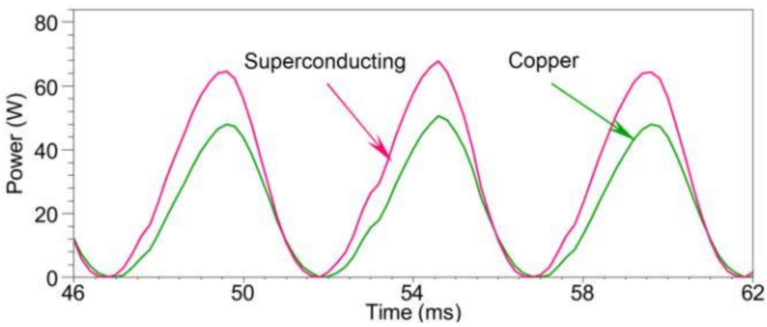

Fig. 6 Comparison between superconductor and copper wire linear generator.

9 Conclusions

This paper presents the disadvantages of fossil fuels and advantages of renewable energies in case of electricity generation. It also describes that the oceanic wave has many advantages among renewable energy sources. Further, the oceanic wave energy conversion system, basic structure and working principle of linear generator, and progress of linear generators are clearly mentioned in this paper. In the progress of linear generator section, in order to get high output power, low core loss, and high efficiency some analysis work has been highlighted. From the study it is concluded that the generation of electricity from the oceanic wave is very significant to ensure clean environment and save the residential and cultivated land. Since Bangladesh is a small country, the electricity generation from this source will be very effective considering its advantages.

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