Increase in Volumetric Electrical Power Density of a Linear Generator by Winding Optimization for Wave Energy Extraction

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Molla, Selim; Farrok, Omar; Rahman, Abidur; Bashir, Md samiul; Islam, Md Rabiul; Zouzani, Abbas Z.; and Mahmud, M. A Parvez, "Increase in Volumetric Electrical Power Density of a Linear Generator by Winding Optimization for Wave Energy Extraction" (2020). Faculty of Engineering and Information Sciences - Papers: Part B. 4428. https://ro.uow.edu.au/eispapers1/4428

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Abstract
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Keywords
wave, energy, extraction, increase, electrical, volumetric, power, density, linear, generator, winding, optimization

Disciplines
Engineering | Science and Technology Studies

Publication Details
S. Molla, O. Farrok, A. Rahman, M. samiul. Bashir, M. Islam, A. Z. Zouzani & M. Parvez. Mahmud, "Increase in Volumetric Electrical Power Density of a Linear Generator by Winding Optimization for Wave Energy Extraction," IEEE Access, vol. Online First, pp. 1-14, 2020.

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ABSTRACT In this article, a method of winding optimization of the linear generator is proposed to increase the electrical power generation from the oceanic wave. A linear generator is designed in the ANSYS/Maxwell environment to analyze the proposed winding optimization method. The electrical and magnetic properties of the generator are extensively analyzed. The cross-sectional area and the number of turns of the copper conductor are optimized to maximize the output power. Load characteristics are also considered for different conductor sizes and turn numbers to determine a suitable operating point. A cooling system is also incorporated in the optimized linear generator to extract the thermal energy produced during the operation, which eventually enhances the electrical power generation. It is found that the optimized linear generator finally generates around 42% more electrical power compared to that of the conventional one. Therefore, the volumetric power density of the linear generator is noticeably increased with the proposed optimization method that also results in the minimization of material cost of the generator. A downsacle prototype of the linear generator is constructed in the laboratory. It is expected that the proposed winding optimization method can be used in designing other linear generators.

INDEX TERMS Cooling system, electrical generator, energy conversion, linear generator, magnetic material, permanent magnet machine, power density, wave energy converter, wave power, winding optimization.

I. INTRODUCTION
To ensure sustainable environment, the United Nations has declared seventeen sustainable development goals in which affordable and clean energy is positioned at number seven. Still, significant amount of electrical power is being generated from fossil fuels. This burning of fossil fuels is highly affecting the environment due to the huge emission of carbon dioxide (CO$_2$). Emission of CO$_2$ is highly affecting the global temperature. The increase in temperature causes melting of glacier ice that continuously raises the sea level. It also increases conflagration in many dry regions and the quality of habitual land is debasing rapidly. On the other hand, burning of huge fossil fuel diminishes the reserve of the natural resources. Considering the environmental degradation and depletion of natural resources, alternative sources of energy, i.e. renewable energy is becoming one of the main sources of energy in many countries [1].

Solar, wind, biogas, hydro, geothermal, and oceanic wave energy are remarkable examples of renewable energy sources. Some of these sources are intermittent in nature such as wind and solar. As a result, production and use of electricity from these intermittent sources require some extra devices and investments [2], [3]. The costly energy storage systems with periodic maintenance are often required for their smooth operation. Hydropower and geothermal energy sources are available only in a few specific locations [4], [5]. On the other hand, oceanic wave is an attractive renewable energy source which does not have the limitation of availability compared to solar and wind energy. In addition, oceanic wave energy
has some other features such as its high energy density and predictability [6]. It is found that, approximately 1–10TW electric power can be extracted from the ocean [7]. The wave power, $P_w$, can be calculated from

$$ P_w = \frac{\rho_w g H_w^2 T}{64\pi} $$

where $\rho_w$ is the mass density of sea water (1025 kg/m$^3$), $H_w$ is the height of wave, $g$ is the gravitational constant (9.81 ms$^{-2}$), and $T$ is the time period of wave [8]. Although, the idea of capturing oceanic wave energy was introduced in 1799 as reported in [9], but the major development was started from 1973 due to oil crisis [10]. Different types of devices are applied to harvest oceanic wave energy such as Pelamis, Wave Dragon, Limpet etc. In most of the cases, direct drive linear generator (DDLG) topology is incorporated, which is illustrated in Fig. 1.

FIGURE 1. Sea wave energy conversion system.

The wave energy converter has mainly five parts viz. buoy, DDLG, converter, inverter, and transformer. The DDLG is generally a three-phase linear electrical generator that consists of a translator and a stator set with three windings. Upper side of the translator is connected with a buoy by a rod. The other side is connected to the base with a spring. When the buoy moves vertically with the sea wave, translator moves along with the buoy. As a result, electromotive force is induced in the stator windings. The generated ac power has variable voltage and frequency. Therefore, it is rectified and fed to the inverter to obtain fixed voltage and frequency. Then the ac power is supplied to the load or grid through the transformer.

At present, linear generators (LGs) are being characterized through mathematical, simulation, and/or experimental approach. A new cycloidal type wave energy converter is explained with numerical simulation to estimate the power absorption annually [11]. A novel dual port LG is proposed in [12], which can generate electrical power even at zero vertical velocity of the buoy with the aid of a driven translator. To ensure the maximum absorption of sea wave energy, a smart controller is designed in [13]. In [14], transient stability of a grid connected wave energy converter is obtained using a proportional-integral controller which is designed with water cycle algorithm. Another study incorporates gravitational search algorithm to control wave energy converter under various operating conditions [15]. The winding of a tubular LG is prepared with the superconductor to obtain high output power [16]. However, a cooling system is required for maintaining cryogenic temperature of the superconductor, which is a challenging task.

The amount of produced thermal energy inside the LG is proportional to the losses: viz. mechanical loss, core loss, and copper loss. On the other hand, the demagnetization effect of permanent magnet (PM) depends on temperature. Hence, the output power of permanent magnet based DDLG depends on its operating temperature. Most of the DDLG are made of conventional PM, which cannot generate enough output power because of their early demagnetization. To solve this problem, the high grade neodymium iron boron (NdFeB) PM, N52 is applied to the LG that delivers more output power than the conventional one [17]. Since neodymium is a rare earth element, the LG is designed with a new rare earth free material named iron nitride (Fe$_2$N$_2$) instead of NdFeB [18]. Core loss of an LG is reduced in [19] by applying DI-Max HF-10X magnetic core because, it enables generating more output power compared to its conventional counterpart. The magnetic circuit of an ordinary LG is asymmetric which results in some shortcomings that impede its performance [20].

It is found from the analysis that, winding optimization significantly increases the electrical power generation of the LG. But, to the best of authors’ knowledge, copper-based winding optimization is still not investigated for power enhancement. Therefore, there is a research gap regarding the winding optimization method which is needful for the enhancement of power generation. For this reason, a novel winding optimization method is proposed in this article that greatly increases the electrical power generation of the LG. The proposed method would enhance the knowledge in this area for the future development of LG. The novelty of this article is summarized as follows:

- A novel winding optimization algorithm is proposed for the DDLG to increase the power generation.
- The proposed winding optimization algorithm is applied to the generator to observe its effectiveness.
- The effect of using an advanced permanent magnet (N45) in the generator is analyzed.
- The cooling system for maintaining magnetic properties of the high graded material is incorporated for further enhancement of the electrical power generation of the generator.
- The volumetric power density of the generator is increased.

This article comprises seven sections. The proposed optimization method is discussed in section II. Construction of
the proposed linear generator is described in section III. Mathematical models of the DDLG and cooling system are presented in section IV. The procedure of cooling method is depicted in section V. Results are provided in section VI. The consequent section concludes the paper.

II. THE PROPOSED WINDING OPTIMIZATION

Winding optimization of the LG is important to minimize the size and weight and to enhance the energy conversion efficiency. In [21], the shape of an LG is optimized for minimizing the volume of steel core in translator and stator by applying the human intervened genetic algorithm. Two-dimensional geometry is considered for the analysis by finite element method. Approximately, 29% more power is measured with the ‘M’ shaped core and copper winding.

The structure of an LG is optimized in [22] to achieve better output voltage and reduced cogging force. The system consists of four translators connected together with a buoy. Magnetic characteristics of the generator are analyzed with the aid of two-dimensional finite element analysis. The generator is further analyzed by using a numerical method. In [23], historical wave data are collected to maximize the voltage and output power. A bang-bang type control mechanism is applied to wave energy converter in [24] for obtaining optimum output power.

Genetic algorithm is applied in [25] to optimize the shape of an LG to achieve maximum output power while minimizing the weight of the translator. In addition, the reduction of core loss and generation of large output power are achieved by applying appropriate magnetic materials [17]–[19]. In addition, the output power is enhanced by applying high graded magnetic materials namely DI-Max HF-10 core, Supermendur core, N52 PM, and iron nitride PM.

Although, the optimization of linear generator is discussed in [12], [23]–[26] with different objectives, winding optimization is not yet investigated. In order to fill the knowledge gap, a method of winding optimization of the linear generator is proposed in this article to increase the electrical power generation from the oceanic wave. Various factors such as mesh setup, boundary conditions, construction, insulating, and active materials are considered. Performance of the LG is observed by analysis through induced voltage, load current, flux linkage, and output power. The simulation continues iteratively until satisfactory results are found. Fig. 2 illustrates the flowchart of the proposed winding optimization method.

Copper loss occurs due to winding resistance that further minimizes output power of the linear generator. Hence, low winding resistance would produce low copper loss. On the other hand, the induced voltage is directly proportional to the number of turns that results in high winding resistance. Hence, the proposed winding optimization solves the dilemma by which suitable turn number and conductor size for maximum power generation are determined. Load characteristics are analyzed to find the operating point for the highest output power.

III. CONSTRUCTION OF THE LINEAR GENERATOR

The proposed generator has mainly two parts, i.e. stator and translator. The translator consists of the magnetic core and PM. On the contrary, each of the stator has a magnetic core and copper winding. Construction of the DDLG and properties of magnetic materials are described in the following subsections. The generated voltage is directly proportional to the turn number of winding, which can be calculated as

\[ e = -N \frac{d\phi}{dt} \]  

where \( e \) is the induced voltage in the stator, \( N \) is the turn number, \( \phi \) is the magnetic flux, and \( t \) is the time.
A. CONSTRUCTION

The stator is made of “E” type ferromagnetic material where different conductor sizes are applied for winding optimization. The design is illustrated in Fig. 3 with a prototype. The conductor sizes are considered 5mm$^2$, 4mm$^2$, 3mm$^2$, and 2mm$^2$ as denoted by X-5, X-4, X-3, and X-2, respectively. The conductor, X-3 is selected in the experimental prototype as shown in Fig. 3(b). Geometry and construction of the proposed three phase LG are presented in Table 1 and Fig. 4, respectively. The “E” shaped magnetic core is shown separately. The conductor coil is placed in the middle of the core forming the stator of phase-A. Other two phases, i.e. phase-B and phase-C are constructed similarly. The stator and translator are placed vertically maintaining air gap.

![Construction of the stator](image)

**FIGURE 3.** Construction of the stator: (a) CAD drawing and (b) the prototype.

**TABLE 1.** Geometry of the proposed LG.

| Name of Parameters       | Magnitude |
|--------------------------|-----------|
| Height of translator, $H_t$ (m)  | 4.34      |
| Length of translator, $L_e$ (m)  | 2.4       |
| Width of translator, $W_t$ (m)  | 2         |
| Core’s thickness of translator, $t_c$ (m) | 0.022 |
| Core’s length of translator, $L_{ctx}$ (m) | 2.4 |
| PM’s thickness of translator, $t_{pm}$ (m) | 0.038 |
| PM’s length of translator, $L_{pm}$ (m)  | 2.4       |
| PM’s width of translator, $W_{pm}$ (m)  | 1.99      |
| Height of stator, $H_s$ (m)  | 0.142     |
| Winding’s length of stator, $L_{w}$ (m) | 2.7 |
| Winding’s width of stator, $W_{w}$ (m) | 0.25 |

The translator is constructed with permanent magnet and magnetic cores. Both faces of a magnetic core are coupled with the permanent magnet following proper orientation. Windings are wound separately on the magnetic core. Space inside the “E” core allocates total 918mm$^2$ cross-sectional area of the coil, which determines $N$ as well. Winding with thin wire requires more turns than that of the large cross-sectional wire. Moreover, thin and long conductors result in high resistance which can be calculated as

$$R = \rho \frac{L}{A}$$ (3)

where $R$ is the resistance, $\rho$ is the resistivity, $L$ is the length of copper wire, and $A$ is the cross-sectional area of the conductor. Thus, with a total 918mm$^2$ cross-sectional space in the stator, the possible maximum number of turns are 460, 306, 230, and 184 for X-2, X-3, X-4, and X-5 wires, respectively. Phasor diagram of the proposed LG is shown in Fig. 5.

![Basic construction of the proposed DDLG](image)

**FIGURE 4.** Basic construction of the proposed DDLG.

**FIGURE 5.** Phasor diagram of the proposed DDLG.

B. PROPERTIES OF MAGNETIC MATERIALS

Demagnetizing curves for both the conventional N30H and high graded N45 permanent magnets are shown in Fig. 6.
expression (7) can be used to calculate the core loss. where \( f \) is the voltage frequency, \( B_m \) is the maximum flux density, \( c \) is the constant that depends on properties of the magnetic material, \( M_c \) is the core loss components. Copper loss can be calculated as

\[
P_{Cu} = I_a^2 r_a
\]  

(8)

B. COOLING SYSTEM MODEL

To control the cooling process, a mathematical model is developed in [26] which is adopted in this article so that the variables for heat reducing method can be calculated. The amount of water that is lost due to evaporation can be assessed by observing the states of air passing through a cooling tower. The block diagram describing the procedure of the proposed cooling system is depicted in Fig. 7.

![Figure 7. Functional block diagram of the proposed chiller.](image)

The first step is to calculate the core and copper losses. After that, the mechanical losses due to friction, inertia etc. are considered. Afterwards, the amount of heat that is generated from the loss is estimated.

Dissipation of heat energy is performed by water evaporation. Thus, the amount of water required to absorb the estimated heat is calculated. Subsequently, flowrates of water and air for viable operation are determined.

The rate of evaporated water loss is expressed with the difference between mass flowrate of water entering the tower, \( m_{te} \) and mass flowrate of water leaving the tower, \( m_{tl} \). It can also be determined by multiplying mass flowrate of air, \( m_a \) with the difference between the moisture content of air leaving the tower, \( \omega_{tl} \) and moisture content of air entering the tower, \( \omega_{te} \). The value of \( m_a \) can be computed as

\[
m_{te} - m_{tl} = m_a (\omega_{tl} - \omega_{te}).
\]  

(9)

The relationship between fan power, \( P \) and \( m_a \) can be expressed as

\[
P = P_r \left( \frac{m_a}{m_{far}} \right)^n
\]  

(10)

where \( m_{far} \) is the nominal mass flowrate of air entering the cooling tower and \( P_r \) is the rated power of the fan. The value of \( n \) is 1 for the constant fan speed. If the fan is operated at variable speed, the value of \( n \) becomes 3 according to cube law. The cooling system for the proposed DDLG incorporates variable speed drive to operate the fan at any speed.

IV. MATHEMATICAL MODEL OF THE PROPOSED SYSTEM

The proposed system consists of two sections. One is the DDLG itself and the other is cooling system. The proposed linear generator is described mathematically in the following sub-section. The losses that occur are also formulated. The proposed cooling system is demonstrated in the successive sub-section.

A. MODEL FOR THE PROPOSED DDLG

In this section, voltage, current, power, core loss and copper loss of the proposed LG are described mathematically using two axis model. The stator voltage of the proposed machine can be computed as

\[
\begin{align*}
V_a &= f_{do} + j f_{dq} \sqrt{3} \\
\bar{V}_d &= r_a I_d + \frac{1}{X_q} I_q + j X_d I_d + j E_F
\end{align*}
\]  

(4)

where \( S_a \) is the stator voltage, \( r_a \) is the resistance of stator winding, \( I_a \) is the stator current, \( I_q \) is the current in quadrature axis (\( q \)-axis), \( I_F \) is the current in direct axis (\( d \)-axis), \( X_q \) is the reactance of \( q \)-axis, \( X_d \) is the reactance of \( d \)-axis, \( f_{do} \) is the voltage of \( d \)-axis without damper, and \( f_{dq} \) is the voltage in \( q \)-axis without damper. Since the proposed DDLG is a synchronous machine, \( E_F \) must be ahead of \( V_d \). The output power, \( P_0 \) can be calculated as

\[
P_0 = \frac{V_l E_F}{X_d} \sin \delta + \frac{V_l^2}{2} \left( \frac{1}{X_q} - \frac{1}{X_d} \right) \sin 2\delta
\]  

(5)

where \( \delta \) is the torque angle. The core loss of the proposed machine is calculated from

\[
P_c = P_e + P_h + P_{ad}
\]  

(6)

where \( P_c \) is the total core loss, \( P_e \) is the eddy current loss, \( P_h \) is the hysteresis loss, and \( P_{ad} \) is the excess loss. The generalized expression (7) can be used to calculate the core loss.

\[
P_c = M_e f^2 B_m^2
\]  

(7)

FIGURE 6. Demagnetizing curves of the conventional N30H and high graded N45 permanent magnets.

TABLE 2. Comparison of magnetic properties between two materials.

| Parameter                  | N30H NdFeB | N45 NdFeB |
|----------------------------|------------|-----------|
| Remanence magnetism (T)    | 1.1        | 1.37      |
| Coercivity (A/m)           | -837999.99 | -650000   |
| Relative permeability      | 1.0446     | 1.173     |
| Bulk conductivity (S/m)    | 625000     | 625300    |
| Mass density (Kg/m³)       | 7550       | 7550      |
The consumed power of the fan is considered 3% of the total power. The minimum flowrate is approximately 10% of the rated flowrate. Hence, if the temperature range is known, fan power can be computed easily.

V. COOLING SYSTEM FOR LINEAR GENERATOR

Any permanent magnet LG works properly under low temperature. With the rise of temperature because of core and copper losses, performance of the LG degrades considerably. Therefore, a cooling system is installed to reduce the temperature of the LG so that the magnetic properties do not get deteriorated. The proposed cooling system is described as follows.

A. COOLING SYSTEM CONSTRUCTION

The complete cooling system for the proposed LG comprises a chiller, control panel, dehumidifier, supply chilled water pipe (SCWP), return chilled water pipe (RCWP), and air management unit (AMU) with dehumidifier (DHF) as illustrated in Fig. 8.

The chiller is an electromechanical device which can noticeably decrease the temperature of water. The underlying components of this device are evaporator, condenser, compressor, expansion valve, solenoid valve, and filter core as shown in Fig. 9.

The control panel maintains the whole process in accordance with the signal of the sensors. The chiller unit is filled with R410a refrigerant. At relaxation mode, suction pressure is maintained at 80PSI whereas at functioning mode, the pressure is reduced and kept at 50–65PSI. In contrast, the discharge pressure at functioning mode is kept at approximately 250PSI. The pressure at relaxation mode is the same for both suction and discharge pressure. After starting the compressor, the pressure of R410a refrigerant rises from 80PSI to 250PSI. Afterwards, it is passed on to the condenser unit. The condenser unit is made of aluminum fins and copper coil. By this time, the temperature on discharge tube increases to 70–80°C. The refrigerant, upon entering the chiller unit, releases its pressure and temperature which changes its state from gas to liquid. Afterwards, it moves through the filter core where the flow is controlled by the solenoid valve. This valve is regulated by the control panel and delivers the refrigerant to the expansion valve. Depending on the signal of a gas operated valve sensor, the refrigerant again changes its state from liquid to vapor inside the expansion valve chamber. Then refrigerant flows through the copper tube of evaporator, where water contacts its outer surface and becomes cool. Then the cooled water reaches to AMU. At the end, the refrigerant is delivered to the compressor through suction tube. Thus, the whole cycle is repeated perpetually.

B. BASIC OPERATION OF AMU ALONG WITH DEHUMIDIFIER

The connection between AMU and dehumidifier is illustrated in Fig. 10. Stainless steel pipes are used to create the network between cooling coils of AMU and the evaporator of chiller. Moreover, a cooled water pump is placed between them. The underlying AMU consists of cooling coil, supply fan motor, mixing box, and filtering unit. The backup water tank (BWT) ensures the uninterruptible water supply. With the help of chilled water pump, the cooled water produced by chiller flows through the SCWP and RCWP. The water entering into the cooling coil is called supply chilled water and water leaving the cooling coil is called return chilled.
water. During the operation of AMU, return air from the linear generator area passes through the cooling coil by supply fan motor. When the air mixes with cooling coil, its temperature decreases. Finally, this low temperature air flows around the proposed LG to make it cool.

Since the air contains water, it could be the main cause of rust formation on magnetic core of both translator and stator. For this reason, the cores could get affected by corrosion gradually and the generator would have poor efficacy. To avoid this problem, water is separated from air by applying a dehumidifier. The operating procedure of dehumidifier is depicted in Fig. 11.

It consists of a disc driving induction motor, blower fan, electric heater, and a silica gel disc. The disc is rotated gradually with an induction motor. When return air coming from the LG area passes through the disc, the water is absorbed by disc materials. The dry air then reaches to the mix up box in AMU. At the same time, the water absorbing portion of the disc nearly saturates. For reactivation of disc, hot air (by heater) requires passing through saturated portion. When the blower fan starts, the natural air flows through the heater and gets heated. Further, the heated air passes through the saturated area of disc and absorbs the water. Finally, the air is exhausted to atmosphere. This procedure is also performed continuously.

The water free air is supplied to the mixing box in AMU which delivers the treated air to the surrounding area of linear generator by its regular working principle.

VI. SIMULATION RESULTS

At first, a DDLG is designed with the built-in computer aided system in the ANSYS/Maxwell. The design incorporates standard PM (N30H NdFeB), conventional magnetic core, X-4 copper wire and 4Ω load resistance. Power rating of the DDLG is 700kW for 1m/s velocity of the translator. Further, the same design is analyzed for copper wires having different cross-sectional sizes such as X-5, X-3, and X-2. To obtain better result, fine mesh setup is selected as shown in Fig. 12. As three-dimensional finite element analysis is performed, each of the element is mathematically represented by tetrahedra. Most of the elements exist around the pole faces. Moreover, with the aid of finite element analysis, the electrical and magnetic properties are analyzed.

The voltage waveforms for different conductor sizes are illustrated in Fig. 13. The rms value of voltages are 0.84kV, 1.23kV, 1.36kV, and 1.37kV for X-5, X-4, X-3, and X-2, respectively. The maximum voltage at the output terminal is observed for the thinnest wire. Fig. 14. shows the current waveforms of DDLG having different size of copper conductors. The currents (rms) are measured 231A, 291A, 316A, and 281A for X-5, X-4, X-3, and X-2 conductors, respectively. Hence, the DDLG with X-3 copper wire flows the maximum current than the others. Generated powers of the DDLG for using different wires are depicted in Fig. 15.
Even though the thinnest wire delivers the maximum power in the beginning, it reduces in its subsequent cycles. However, the power performance prevails for X-3 wire. The rms output powers are found 250kW, 350kW, 446kW, and 400kW for X-5, X-4, X-3, and X-2 conductors, respectively. The peak value of voltage, current, and power are tabulated in Table 3, where the DDLG with X-3 copper wire outperforms the others. Since, copper loss depends on the internal resistance of winding and load, performance of the X-3 winding based DDLG is observed for different load conditions. In this analysis, the load resistances are varied form 1–5Ω. The resistance with the value of 1Ω, 2Ω, 3Ω, 3.6Ω, 4Ω, and 5Ω are denoted by $R_{l1}$, $R_{l2}$, $R_{l3}$, $R_{l3.6}$, $R_{l4}$, and $R_{l5}$, respectively.

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Output voltage and power waveforms are plotted in Figs. 16 and 17, respectively. The maximum voltage is found for 5Ω load whereas maximum power is found for 3Ω load. The generated output power, voltage, and current for various loads are tabulated in Table 4. The peak values of generated voltage, power, and load current for different loads are depicted in Fig. 18. From the results it is observed that, for high load current, generated voltage is low and vice-versa. The maximum generated power is 912kW for the load resistance of 3Ω.

The power output (at the load) and copper loss are presented in Fig. 19 for different loads. The operating point is obtained for X-3 copper wire with 3.6Ω load resistance. The maximum copper loss and power are indicated with dots.
For 3.6Ω load resistance, approximately 810kW of power is delivered to the load, which is the highest power. On the other hand, 790kW is found for 3Ω. The maximum copper loss is 183kW which is also indicated in Fig. 19.

The high grade NdFeB permanent magnet, N45 is applied to the winding optimized DDLG to obtain even more power. In this case, the DDLG is named advanced DDLG (hereafter) and its power waveform is shown in Fig. 20. The rms value of the generated voltage and power are 1.36kV and 456kW, respectively. The comparison in magnetic flux linkage between the optimized and advanced DDLG (with N45) is shown in Fig. 21. It is found that the advanced one has better flux linkage than the other. The load currents of the DDLG are plotted in Fig. 22 where 474A and 506A currents are found for the optimized and the advanced DDLG, respectively.

Voltage comparison between the two DDLGs is depicted in Fig. 23. The advanced DDLG generates more voltage than the other. Fig. 24 shows the generated output power of both the DDLGs where the advanced DDLG generates more output power than the other. A comparison between these two DDLGs is illustrated in Table 5.

The translator is made of magnetic core with permanent magnet and it is found from Fig. 6 that the remanence magnetism and coercivity of PM depends on operating
As the magnetic remanence is low at high temperature, the DDLG cannot generate sufficient output power. To produce adequate output power, the advanced DDLG should be operated at the low temperature. Therefore, a cooling system is incorporated with it. Hereafter in this article, it is called enhanced DDLG.

The peak output voltage of the advanced and enhanced DDLG are compared in Fig. 25. The enhanced DDLG generates 2.3kV whereas the advanced one generates 2.05kV. Load current of the enhanced DDLG increases beyond the advanced one as shown in Fig. 26. Comparison of generated power between the two generators is depicted in Fig. 27. It is found that, the enhanced DDLG (that includes cooling system) generates 6.46% higher output power than the other. The output parameters of the conventional, optimized, advanced, and enhanced DDLGs are shown in Table 6. Fig. 28 shows the magnetic flux density ($B$) and field intensity ($H$) of the optimized DDLG. $B$ and $H$ are also analyzed to prevent demagnetization of the PMs. With the rainbow spectrum, the values of $B$ and $H$ are observed. The minimum value of $B$ is found in the copper winding.

![FIGURE 25. Comparison the voltage between the advanced and enhanced DDLGs (with cooling system).](image1)

![FIGURE 26. Comparison of the current waveforms between the advanced and enhanced DDLGs.](image2)

![FIGURE 27. Comparison of the power between the advanced and enhanced DDLGs.](image3)

![FIGURE 28. Analysis of magnetic property of the proposed enhanced DDLG.](image4)

![FIGURE 29. Magnetic flux density of the stator at: (a) the starting condition ($t = 0$ms) (b) the running condition ($t = 100$ms).](image5)

![FIGURE 29. Magnetic flux density of the stator at: (a) the starting condition ($t = 0$ms) (b) the running condition ($t = 100$ms).](image6)

Magnetic flux density of the stators and their front faces are shown in Figs. 29 and 30. The analysis is required for both the starting and running condition of the DDLG to observe whether there is any magnetic saturation. From the analysis, it is found that the flux density in the stator almost saturates at standstill condition or at the starting condition. But in running condition, the flux density minimizes because of the armature

| DDLG        | Induced voltage (kV) | Current (A) | Generated power (kW) | Load power (kW) |
|-------------|----------------------|------------|----------------------|----------------|
| Conventional DDLG | 1.74               | 411        | 700                  | 676            |
| Optimized DDLG     | 1.93               | 471        | 911                  | 804            |
| Advanced DDLG      | 2.06               | 506        | 1043                 | 922            |
| Enhanced DDLG      | 2.30               | 569        | 1293                 | 1166           |
reaction. The major difference of flux density is identified in the dashed rectangles. The flux density varies over time in both the stators and their front faces. The highest flux density is found on the stator’s front faces as shown in Fig. 30.

**FIGURE 30.** Distribution of magnetic flux density of the stator pole faces at: (a) the starting condition \( t = 0\)ms) (b) the running condition \( t = 100\)ms).

The small-scale prototype of the proposed linear generator is constructed and presented in Fig. 31. It consists of a translator, simulator, and stator. The simulator creates a physical translational motion that moves the translator vertically with respect to the stator. The experimental and simulation results of the terminal voltage are shown in Figs. 31(d) and 31(e), respectively. A little variation is observed in the voltage waveforms. The design and working principle of the proposed DDLG (Fig. 4) and the small-scale prototype as shown in Figs. 31(a)–31(c) are similar. To compare the output voltage, another simulation result with the parameters of the prototype is presented in Fig. 31(e). The cooling system is not considered in the prototype.

The core loss curve of the magnetic material is plotted in Fig. 32. The amount of total core loss is found approximately 7kW after one cycle operation period. Because, the simulation software takes one cycle time to calculate the value properly.

**FIGURE 31.** Construction of the prototype: (a) translator (b) simulator (c) stator (d) experimental result, and (e) simulation result.

**FIGURE 32.** Core loss curve of the proposed DDLG.

The proposed winding topology also minimizes the material cost per unit generation. Considering the total material cost of the DDLG, \( C_t \), the per unit (kW) cost becomes \( C_t /676 \) or 0.00148 \( C_t \). Application of the proposed- optimized, advanced, and enhanced DDLG, per unit (kW) cost would become \( C_t/804 \), \( C_t/922 \), and \( C_t/1166 \), respectively. The calculation of material minimization cost is summarized in Table 7.

| DDLG            | Material cost/kW | Material cost minimization/kW (in each step) | Material cost minimization/kW (w.r.t conventional) |
|-----------------|------------------|---------------------------------------------|---------------------------------------------------|
| Conventional DDLG | 0.00148 \( C_t \) | 0%                                          | 0%                                                |
| Optimized DDLG | 0.00124 \( C_t \) | 16.22%                                      | 16.22%                                            |
| Advanced DDLG   | 0.00108 \( C_t \) | 12.90%                                      | 27.03%                                            |
| Enhanced DDLG  | 0.00086 \( C_t \) | 20.37%                                      | 41.89%                                            |

* w.r.t means with respect to

**TABLE 7.** Minimization of material Cost/kW of all the proposed DDLGs.

**VII. CONCLUSION**

This article proposes a new winding optimization method along with high graded magnetic material and cooling system. To test the performance of the proposed method, an LG is designed and simulated by using finite element method. Electrical and magnetic properties of the LG are observed. It is found that, the proposed optimized and enhanced DDLG produces the highest output. Magnetic properties are also analyzed along with winding optimization. As the core loss is almost fixed for a specific frequency of operation, copper loss is focused because it depends on the load condition. Furthermore, electrical power is again increased by using
high graded N45 NdFeB. During operation, temperature of the LG often rises because of various losses. The rising temperature needs to be minimized as it noticeably decreases the remanence of either standard or high graded PMs. For this reason, a cooling system is proposed and discussed along with winding optimization. From the cost analysis, it is also found that the proposed DDLG greatly minimizes the material cost per unit power (kW) generation. The total core loss is found only 0.6% of its maximum load power. The volumetric electrical power density of the enhanced DDLG is increased by 41.89%. It is expected that the proposed winding optimization method can be used in designing other linear generators to improve their performances.

**APPENDIX**

**NOMENCLATURE**

**ACRONYM**

AMU Air management unit  
BWT Backup water tank  
DDLG Direct drive linear generator  
DHF Dehumidifier  
Fe$_{16}$N$_2$ Iron nitride  
LG Linear generator  
NdFeB Neodymium iron boron  
PM Permanent magnet  
RCWP Return chilled water pipe  
SCWP Supply chilled water pipe

**SYMBOL**

$A$ Cross-sectional area ($\text{mm}^2$)  
$B$ Magnetic flux density ($\text{T}$)  
$B_m$ Maximum flux density ($\text{T}$)  
$c$ Constant that depends on properties of the magnetic material  
$E_F$ Voltage of equivalent field ($\text{V}$)  
$E_f'$ Transient excitation voltage ($\text{V}$)  
$E_f$ Excitation voltage ($\text{V}$)  
$E_i$ Voltage across/behind $X_d$ ($\text{V}$)  
$e$ Induced voltage in stator ($\text{V}$)  
$f$ Voltage frequency (Hz)  
$f_{do}$ Voltage of $d$-axis without damper ($\text{V}$)  
$f_{dq}$ Voltage in $q$-axis without damper ($\text{V}$)  
$g$ Gravitational constant ($9.81 \text{ ms}^{-2}$)  
$H$ Magnetic field intensity ($\text{A-m}^{-1}$)  
$H_i$ Height of stator (m)  
$H_t$ Height of translator (m)  
$H_w$ Height of wave (m)  
$I_a$ Armature current (A)  
$I_d$ Current in $d$ axis (A)  
$I_q$ Current in $q$ axis (A)  
$L$ Length of copper wire (m)  
$L_c$ Core’s length of translator (m)  
$L_m$ PM’s length of translator (m)  
$L_s$ Winding’s length of stator (m)  
$L_t$ Length of translator (m)  
$M_e$ Core loss components  
$m_a$ Mass flowrate of air ($\text{kg-s}^{-1}$)  
$m_{ar}$ Nominal mass flowrate of air entering the cooling tower ($\text{kg-s}^{-1}$)  
$m_{te}$ Mass flowrate of water entering the tower ($\text{kg-s}^{-1}$)  
$m_{tl}$ Mass flowrate of water leaving the tower ($\text{kg-s}^{-1}$)  
$N$ Number of turns  
$P$ Fan power (W)  
$P_{ad}$ Excess loss (W)  
$P_c$ Total core loss (W)  
$P_{cu}$ Copper loss (W)  
$P_e$ Eddy current loss (W)  
$P_h$ Hysteresis loss (W)  
$P_r$ Rated power of the fan (W)  
$P_0$ Output power (W)  
$P_w$ Wave power (W)  
$R$ Resistance ($\Omega$)  
$r_a$ Resistance of stator winding ($\Omega$)  
$S_{dA}$ No load rms stator voltage of phase-A ($\text{V}$)  
$T$ Time period of wave (s)  
$t$ Time (s)  
$t_c$ Core’s thickness of translator (m)  
$t_m$ PM’s thickness of translator (m)  
$V_d$ Voltage in $d$ axis ($\text{V}$)  
$V_q$ Voltage in $q$ axis ($\text{V}$)  
$V_t$ Terminal voltage ($\text{V}$)  
$W_m$ PM’s width of translator (m)  
$W_s$ Winding’s width of stator (m)  
$W_t$ Width of translator (m)  
$X_d$ Synchronous reactance in $d$ axis ($\Omega$)  
$X_d'$ Transient reactance in $d$ axis ($\Omega$)  
$X_q$ Synchronous reactance in $q$ axis ($\Omega$)  
$\delta$ Force angle ($^\circ$)  
$\theta$ Power factor angle ($^\circ$)  
$\rho$ Specific resistivity ($\Omega \cdot \text{m}^{-1}$)  
$\rho_w$ Mass density of sea water ($1025 \text{ kg-m}^{-3}$)  
$\varphi$ Magnetic flux (Wb)  
$\omega_{tl}$ Moisture content of air leaving the tower (kg-$\text{kg}^{-1}$ dry air)  
$\omega_{te}$ Moisture content of air entering the tower (kg-$\text{kg}^{-1}$ dry air)

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