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# The Disk-Magnet Electromagnetic Induction Applied to Thermoelectric Energy Conversions

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## Abstract

The thermoelectric energy conversion technique by employing the Disk-Magnet Electromagnetic Induction (DM-EMI) and improved DM-EMIs is shown, and possible applications to heat engines as one of the energy harvesting technologies are also discussed. The idea is induced by integrating irreversible thermodynamical mechanism of a water drinking bird with that of a Stirling engine, resulting in thermoelectric energy generation different from conventional heat engines. The current thermoelectric energy conversion with DM-EMI can be applied to wide ranges of temperature differences. The mechanism of DM-EMI energy converter is examined in terms of axial flux magnetic lines and categorized as the axial flux generator. It is useful for practical applications to macroscopic heat engines such as wind, geothermal, thermal and nuclear power turbines and heat-dissipation lines, for supporting thermoelectric energy conversions. The technique of DM-EMI will contribute to environmental problems to maintain clean and susceptible energy as one of the energy harvesting technologies.

## Keywords

Thermoelectric Energy Generation (TEG), Thermomechanical Dynamics (TMD), Disk-Magnet Electromagnetic Induction (DM-EMI), Axial Flux Electric Generator (AFEG), Applications to Heat Engines

## 1. Introduction

Heat and energy are the sources of physical changes and motions, which are directly related to the prosperity of human society, technologies and scientific issues. This is the reason why human societies have advanced macroscopic energy generators (MEGs) such as turbines, motors and rotors for wind, hydroelectric, geothermal, fossil-fuel, nuclear power plants, and so forth. The characteristic feature of MEGs is mass production and consumption of heat and energy, resulting in the enormous amount of abandoned heat and chemical substances. Heat and energy are discarded in the form of commercial and industrial wastes, carbon dioxide ($CO_2$) and sulfur oxide ($SO_x$) from fossil fuels, and radioactive wastes from nuclear facilities. All plants and animals need basic chemicals ($H_2O$, $CO_2$, $NO_3^-$, $\cdots$) which transport energy and nutrients indispensable for life. The current circumstances toward mass production and consumption of energy from fossil fuels are not sustainable nor renewable, and wasted heat and chemical substances should be adequately cleaned and restored for living beings and ecosystems on Earth.

It could be possible to resolve environmental problems if wasted heat and chemical substances are recycled as much as possible. For this purpose, the energy harvesting technology (EHT) is essential for an industrial size of application [1] [2] and provides us with technical devices to collect a very small amount of solar, wind, wave and mechanical oscillation energies, as well as restoring the wasted and abandoned heat from thermal and nuclear power plants to usable energies. The heat engines such as a water drinking bird and a Stirling engine are one of EHTs, which converts abandoned very low heat-energy or entropy-flow to mechanical and electric energies [3] [4]. The motion of a drinking bird and a Stirling engine exhibits a sensitive thermomechanical energy conversion which is useful for understanding the theory of nonequilibrium irreversible thermodynamics (NIT) [5] [6] [7].

A mathematical expression of motion for a drinking bird, thermoelectric conversion of motion by a disk-magnet electromagnetic induction (DM-EMI) and the fundamental concept of thermomechanical dynamics (TMD) of non-equilibrium irreversible thermodynamics are explicitly shown and discussed in the papers [8] [9] [10]. The technique of DM-EMI converts low thermal energy into electric energy, activating discarded thermal energy to usable electric energy. The sensitive thermoelectric conversion technique with DM-EMI can assist macroscopic power generators (wind, hydro, geothermal, thermal, nuclear power stations) by reproducing electric energy from dissipated and abandoned thermal energy. The thermoelectric power generation by DM-EMI can be practically applied to environmental energy conservation problems as one of EHTs.

The thermomechanical analysis of heat engines is essential for effective and optimal uses of thermal energies dissipated as waste heat from MEGs. The sensitive heat flow or entropy flow of a drinking bird is converted to mechanical energy and then to electric energy by DM-EMI, whose highly susceptible thermoelectric energy conversions are essential to activate waste heat from MEGs [9] [10]. This is possible by integrating water drinking thermodynamical mechanism with Stirling engines or heat engines in general. One should be careful that DM-EMI produces the pulsation current, or pulse-current (PC) different from the alternating current (AC) produced by turbines and electric generators. The mass energy productions of MEGs require large rpm (revolutions per minute) for turbines to produce a large amount of energy as much as possible, and low thermal energies leading to a low rpm have lower utility, resulting in waste heat. Therefore, the waste heat discarded in the environment from MEGs must be reactivated and restored as electric energy as much as possible with the use of DM-EMI.

The energy conversion technique of DM-EMI is applied to a Stirling engine or heat engines in general. The basic DM-EMI techniques and magnetic flux, produced electric powers and currents are explained in Section 2. The technique of DM-EMI extended to the thermoelectric energy conversion for heat engines and MEGs, in general, is discussed in Section 3. The comparisons of alternating current (AC) and pulse current (PC) are exhibited in Section 4, and analyses of DM-EMI electric generator in terms of the axial and radial magnetic flux lines are discussed in Section 5. Discussions and perspectives are in Section 6.

## 2. The Disk-Magnet Electromagnetic Induction (DM-EMI)

DM-EMI derived from a sensitive thermodynamic mechanism of a drinking bird is a technique for EHTs as explained in the introduction, and it is proposed for collecting wasted and dissipated heat energy from macroscopic heat sources, such as ironworks, metalworking, watercraft and cement industries, ceramic engineering facilities and so forth. Although the waste heat is abandoned heat, it has considerable energy to be collected and activated. Hence, if the huge amount of waste heat can be used as recycled energy, it helps prudent reproduction of consumable energy resources, business management and the electrochemical reduction of $CO_2$, $H_2O$, *etc*. Renewable and sustainable energies are essential for the prosperity of future societies.

The generation of pulse-current (PC) and electric power by DM-EMI is small but the energy can be collected for a number of practical applications. The numerical calculations and the theory of nonequilibrium irreversible thermodynamics for the thermoelectric generation are respectively discussed in detail, and the numerical simulations in the current paper are performed based on the results in [8] [9] [10]; therefore, interested readers are urged to check the results of papers. The basic technique of DM-EMI and mathematical analyses produced by the mechanism of a water drinking bird are briefly reviewed.

The experimental device to produce pulse current (PC) with 1-disk magnet 4-coil electromagnetic induction, which we call 1D4C, is shown in **Figure 1**. The fixed axis rotator with 1-disk magnet is supposed to rotate between the symmetrically positioned 4-coil stators and passes through near the cross-section of each coil. With a given angular velocity, $\omega$, the electric power is generated when the disk magnet passes through coils fixed in the right and left stators; thus, the electric power generation is limited at the moment when the magnetic flux penetrates the coil, producing a pulse current. One should note that the pulse current is simultaneously produced in the right and left coils in stators. The empirical values such as radius, winding number, self-inductance, the resistance of coil and magnetic flux density, …, are inclusively chosen to observe the

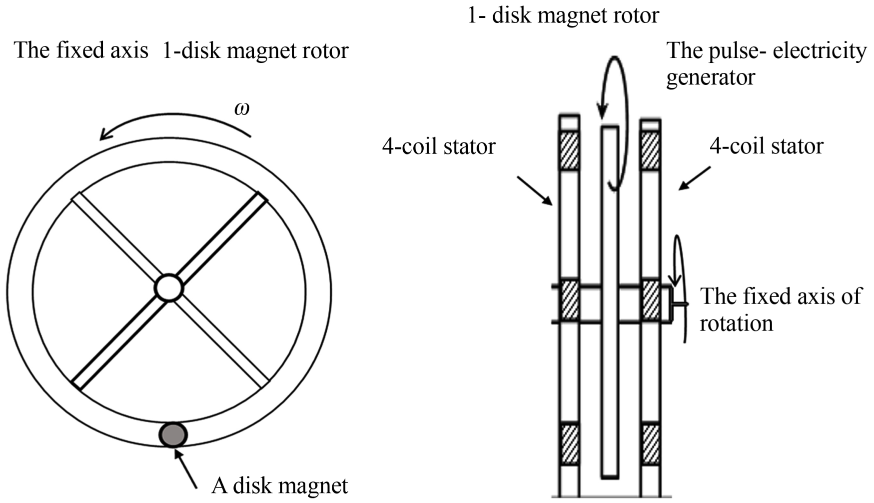


**Figure 1.** The fixed axis 1-disk magnet rotor and 4-coil stators (1D4C).

produced pulse current clearly. The empirical values are supposed to be fixed experimentally in practice.

The disk magnet and the magnetic flux density, $B$, with a coil are illustrated in Figure 2, and for simplicity, the magnetic flux density is assumed constant going straight through the coil. The magnetic flux penetrating a coil is given by magnetic flux density $B$ (Wb/cm$^2$) multiplied by the cross-sectional area of a coil $S(\omega t)$ which is the cross-sectional area overlapped with the magnet, and the cross-sectional area is time-dependent through the angular velocity, $\omega$ (rad/s), of the rotator. The time-dependent magnetic flux is given by $\phi(t) = BS(\omega t)$, with the maximum flux, $\phi_{\max} = B\pi b^2$; $b$ is the radius of the disk magnet and the coil cross-section ($b \approx 1.5\ \text{cm}$, and $B \sim 0.01\ \text{Wb/cm}^2 = 1\ \text{gauss}$).

The magnetic flux, $\phi(t)$, increases suddenly to $\phi_{\max}$ and decreases to 0, like a sharp spike when the disk-magnet passes through coils, and the sharp magnetic flux generates corresponding pulse currents and electric powers. All coils in a stator are connected to make, for instance, an RLC electric circuit with Kanthal-alloy electric line, and the pulse current is induced in succession. In order to understand numerical results, the pulse magnetic flux, the pulse-current and the electric power produced by the 1-disk magnet and 1-coil crossing each other are shown in Figure 3. The magnetic flux density is fixed as $B = 0.05\ \text{Wb/cm}^2$ (5 gauss). The radii of magnet and coil cross-sections are fixed as, $b = 1.5\ \text{cm}$, in numerical calculations. The angular velocity is fixed as, $\omega = \pi(\text{rad/s})$, or 30 rpm, in numerical simulations. The empirical values such as winding numbers of coil, resistance, capacitance, etc., are tentatively chosen to precisely show properties of the pulse electric current in numerical simulations.

In Figure 3, the magnetic flux, $\phi(t)$, abruptly changes like a spike, $\phi_{\max} \sim 0.7$ (wb) and becomes 0 as shown in (a). The corresponding pulse current changes from 0.2 to −0.2 (ampare) in (b), and the pulse electric power becomes sharper changing from 0 to 0.00003 (watt) and needle-like as shown in (c). The vertical lines at the beginning and the end of coil-magnet crossing time come from properties of piecewise continuous unit-step function employed to express the magnetic flux density defined by the disk magnet [9] [10]. It should be considered as an approximation to realistic changes of the magnetic flux in order to show the produced electric current and the electric power during the coil-magnet crossing time, and so, straight vertical lines are irrelevant in physical results.

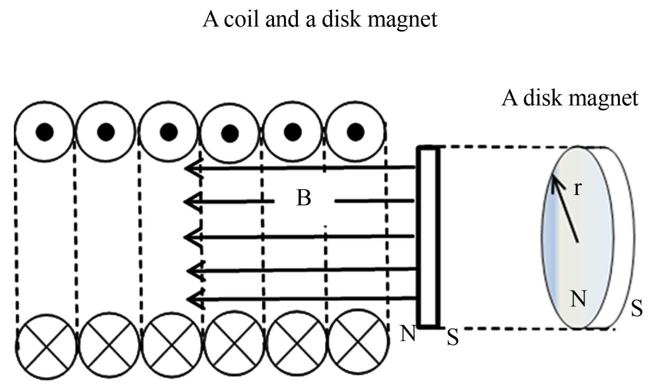


**Figure 2.** The disk magnet and magnetic flux density, *B*, passing through a coil.

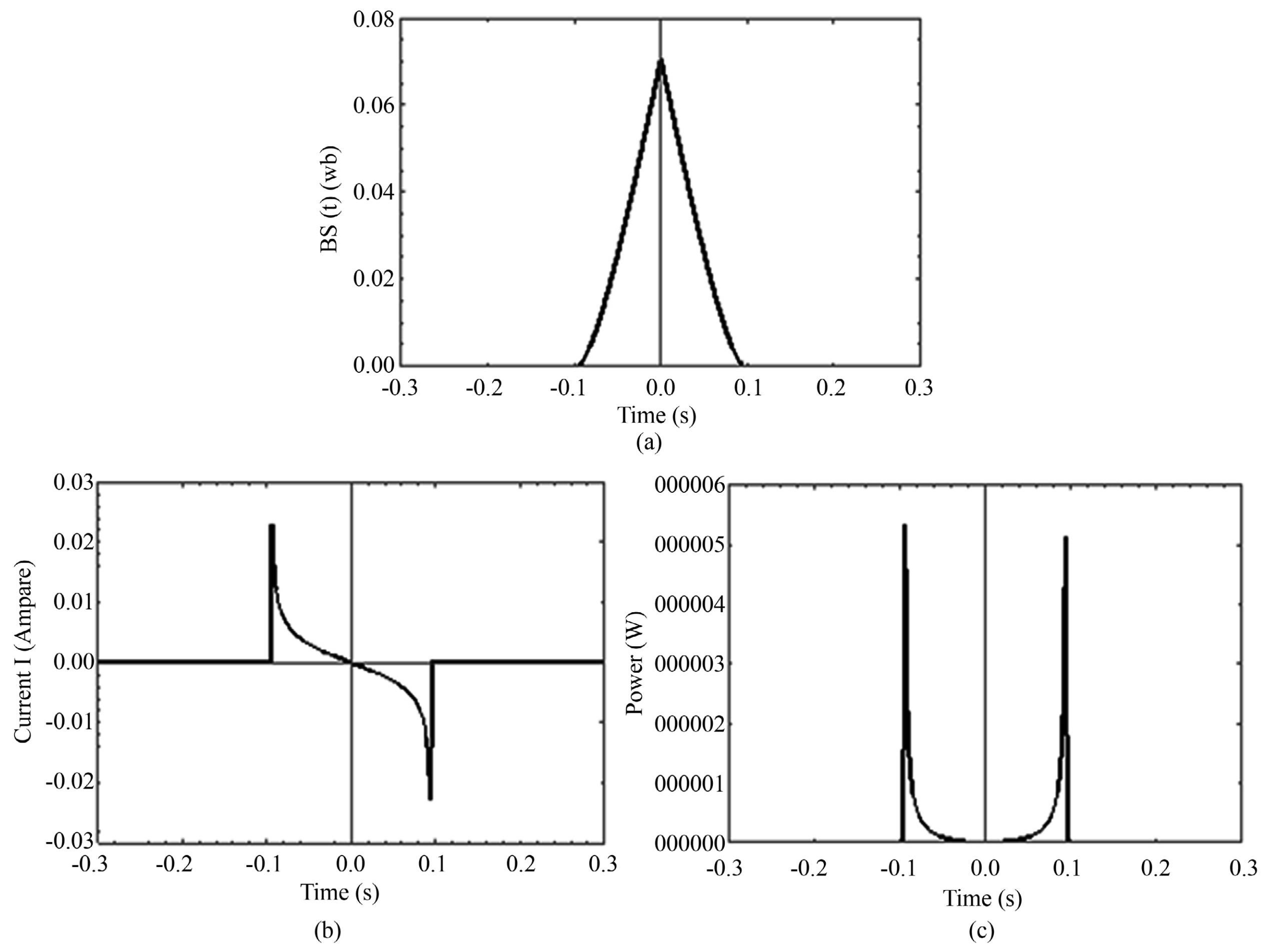


**Figure 3.** The generation of electricity from 1-disk magnet and 1-coil crossing event: (a) the magnetic flux, $\phi(t)$, penetrating a coil, and the corresponding pulse current (b) and the electric power (c) are shown.

Though the pulse electric current and power are exhibited in a magnified fashion in **Figure 3**, they are a very small electric energy because they are activated from low-temperature heat. However, one should note that photovoltaics collects solar power by way of photons which have very microscopic energy. When photon energies are collected and concentrated, it becomes useful in practice, which is the character of photovoltaics. Similarly, the pulse electric energy can be collected and stored, for instance, in a capacitor or a supercapacitor as temporary energy storage.

A suitable rechargeable storage battery, an energy accumulator, or thermal energy storage (molten-salt technology) should be employed for DM-EMI. In general, low-temperature heat is rejected into sea, lake, river or the atmosphere by way of a cooling tower or air cooler. It is difficult to produce energy from discarded heat, but this is the reason why thermodynamic discussions and the sensitive energy conversion obtained from water drinking bird mechanism are essential and useful. The sensitive production of electric power by DM-EMI is suitable for thermoelectric energy conversions. It is possible to scale up the level of energy conversion of DM-EMI and activate more electric power by improving DM-EMI technique to collect energy from waste heat.

## 3. The Improvement of DM-EMI Energy Conversions

We exhibit precisely electric devices to improve the generation of pulse electricity. It is essential to understand the 1-disk magnet rotator 4-coil stators (1D4C) shown in **Figure 1**, producing the pulse magnetic flux, pulse current and pulse power in **Figure 3**. The basic DM-EMI technique and equations to generate electricity are discussed in detail in the paper [9], and based on the results, the improved pulse currents (PC) are calculated.

First, the electricity in one rotation of the 4-disk magnet rotator 4-coil stators (4D4C) shown in **Figure 4** is compared to **Figure 1**. The 4 magnets cross over 4 coils of stator, and the pulse electricities are simultaneously generated each time.

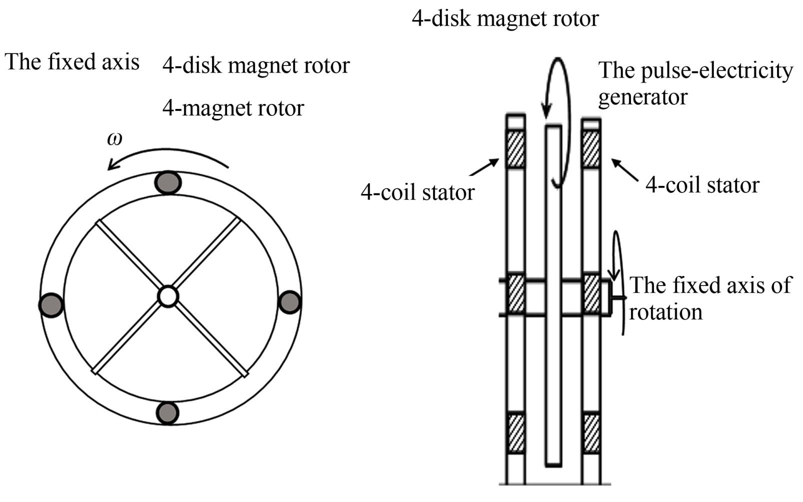


**Figure 4.** The 4-disk magnet 4-coil stator electromagnetic induction (4DM-EMI).

As it is expected from the electromagnetic induction mechanism, the productions of magnetic flux, pulse electric current and power of 4D4C are 4 times larger than those of 1D4C in theoretical calculations, because the magnetic flux is 4 times larger than that of 1D4C. The results are shown in **Figures 5-7**. Though it may be difficult to observe from figures, one would notice that produced electric quantities increase from (a) to (b) of **Figures 5-7**, respectively.

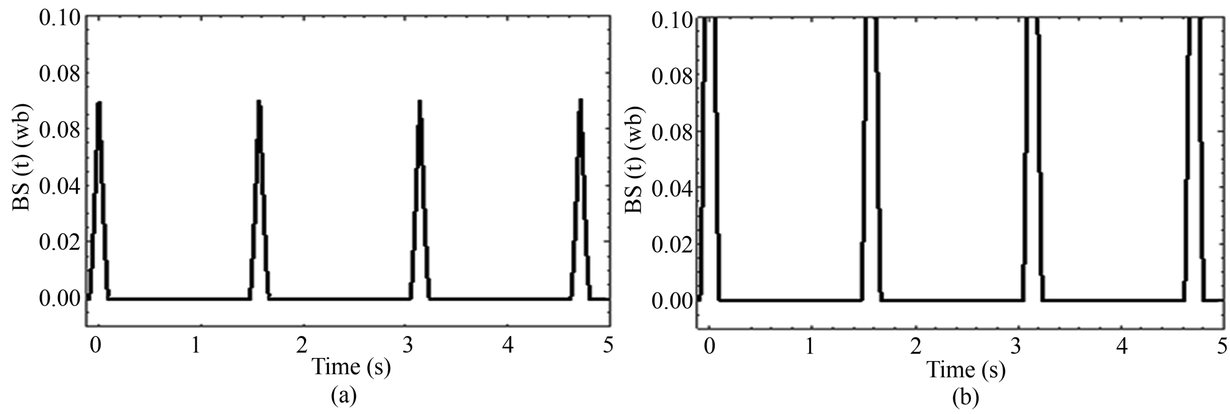


**Figure 5.** The magnetic flux of (a) 1-disk magnet 4-coil stator (1D4C) versus (b) 4-disk magnet 4-coil stator (4D4C).

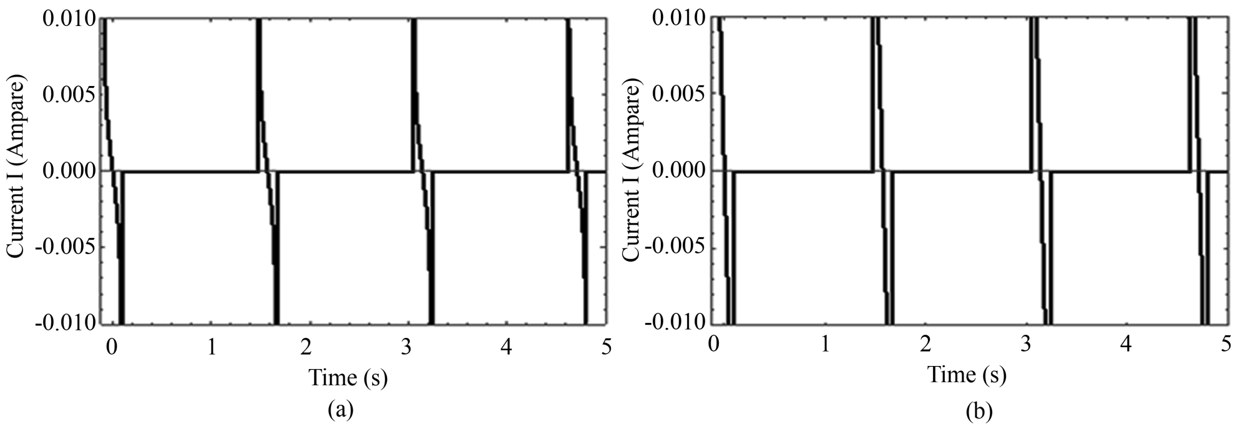


**Figure 6.** The pulse current of (a) 1D4C versus (b) 4D4C.

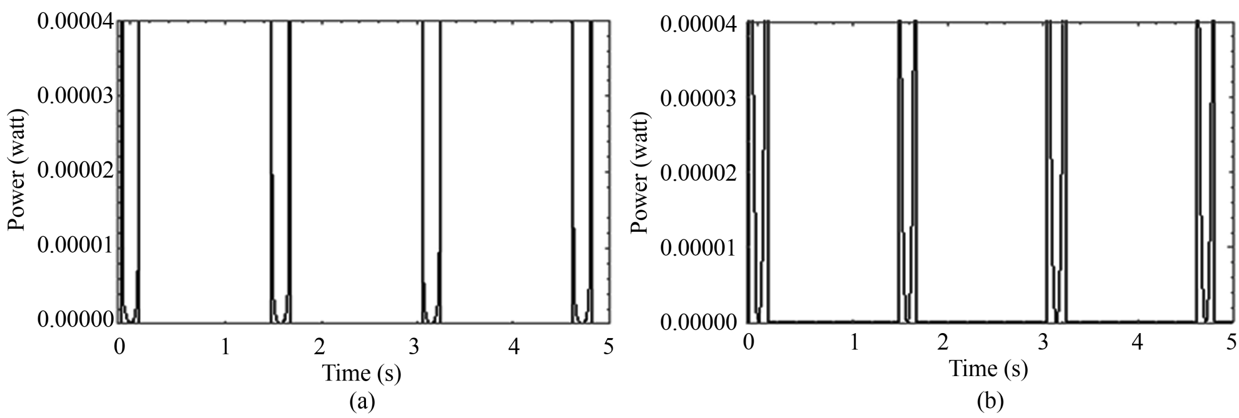


**Figure 7.** The electric power of (a) 1D4C versus (b) 4D4C.

The vertical lines at the beginning and the end of crossing times should not be taken as a physical problem, because it is mathematically produced by properties of piecewise continuous unit-step function as pointed out in Section 2, and straight vertical lines are irrelevant in physical results. The pulse electricity is small but it is produced constantly in rotations, and the electric power generation is effective even at a low rpm, which would be possible with $\omega \sim 20(\text{rpm})$; in other words, the electric generation is possible in a low-temperature Stirling engine, $T \sim 40^{\circ}$, for instance. The susceptible energy conversions of DM-EMI make the activation of waste energy feasible in all temperatures. This is an important property of DM-EMI technology which may become indispensable technology for sustainable development of our societies, solving environmental problems as one of the energy harvesting technologies.

The results of 4DM-EMI can be extended directly to 8DM-EMI, 16DM-EMI, …, and the pulse electric power is similarly increased. In addition, the pulse electricity is reasonably produced by the small angular velocity, $\omega \gtrsim \pi(\text{rad/s})$, or $\omega \gtrsim 30$ revolutions per minute (30 rpm), which facilitates DM-EMI technique applicable from low-temperature water (room temperature < $T$ < 100˚C) to high temperature (100˚C < $T$) heat source as a supporting heat-energy converter of MEGs. Some extensions of magnet-rotator and coil-stator are shown in **Figure 8**.

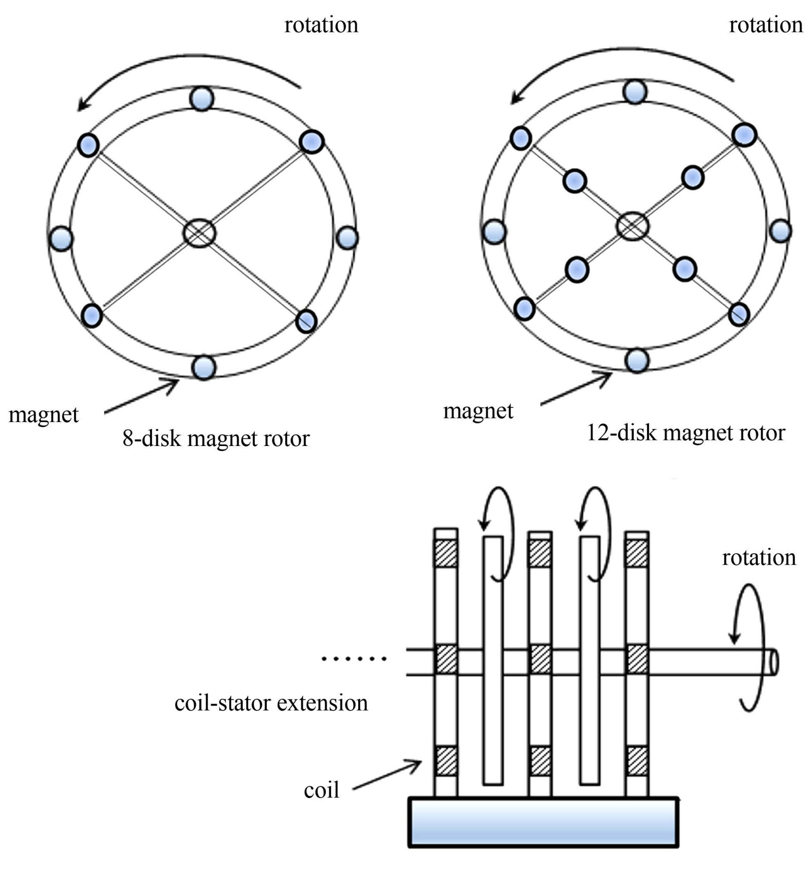


**Figure 8.** Examples of magnet-rotor, coil-stator extensions.

The heat-energy conversions of DM-EMI and the electric power would be leveled off when the revolutions of rotor, $\omega$ (rpm), becomes larger, reaching a steady finite value, which is expected from sharper and narrower magnetic fluxes produced with faster angular velocities. However, the temperature range for energy conversions can be adjusted by changing the radius, the number of magnets and coils, winding numbers of coils and materials of DM-EMI device, according to temperature of heat reservoir. Therefore, DM-EMI devices can be flexibly applied to heat-energy conversions at any temperature (room temperature < $T$).

The turbines of power stations such as wind, hydroelectric, geothermal, fossil-fuel and nuclear power facilities can produce much energy, converting the energy into useful electricity in the form of alternating current (AC). On the contrary, DM-EMI technique is suitable for converting low-temperature heat into electric energy. Although the produced energy is small, properties of DM-EMI can be applied to activate waste of heat-energy discarded and dissipated from macroscopic energy generators (MEGs). It is possible to improve the scale of heat-energy conversions by applying DM-EMI to mechanism of heat engines.

## 4. The Comparison between Discrete Pulse-Current (PC) and Continuous Alternating Current (AC)

As shown in the numerical simulations so far, DM-EMI shows a discrete pulse current (PC), but one may expect that the extensions of DM-EMI as well as the change of angular velocity, $\omega$ (rpm), could demonstrate some similar properties with mechanoelectric alternating current (AC) generator. In order to show certain similarities, we devised the 4-disk magnet rotor in **Figure 4** as the 4NS-pair disk magnet rotor in **Figure 9**. The electromagnetic induction and electricity by the 4-magnet rotor and the 4NS-pair disk magnet rotor are compared in this section.

The 4NS-pair disk-magnet rotor is composed of the pair of $N$ and $S$ magnetic poles in the rotor, and numerical simulations produce an alternating pulse current. The $N$ and $S$ poles respectively induce a reversed pulse-current, examined by the theoretical analysis of electromagnetic induction. The direction of magnetic flux induced in the coils of the stators is completely opposite to the $N$ and $S$ poles, resulting in a reversed pulse electric current.

The pulse current (PC) depends on the angular velocity, $\omega$ (rpm). The higher angular velocity exhibits discrete properties of pulse electric current, whereas the lower angular velocities gradually demonstrate continuous electric properties. The pulse magnetic flux, current and power are compared in **Figures 10-12**. The numerical calculations with $\omega = 120(\text{rpm})$ and $\omega = 30(\text{rpm})$ are respectively compared. In **Figure 10**, the needle-like pulse magnetic fluxes generated at $\omega = 120(\text{rpm})$ shown in (a) become the relatively smooth alternating magnetic fluxes at $\omega = 30(\text{rpm})$ as shown in (b).

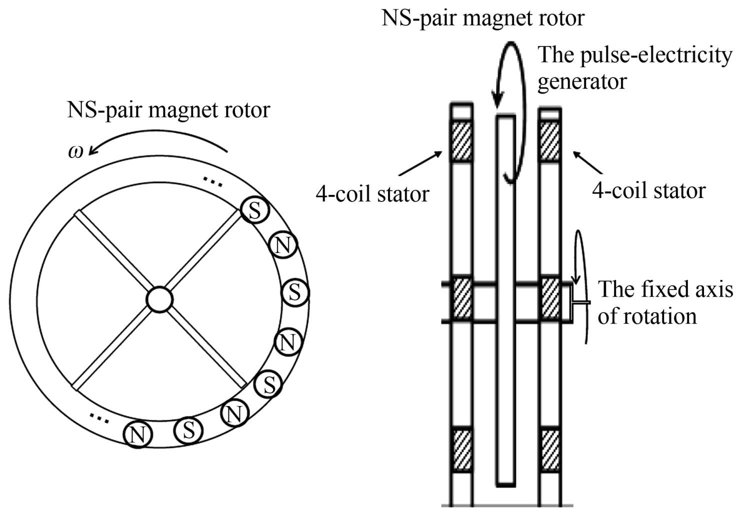


**Figure 9.** The NS-pair disk magnet electromagnetic induction. Note the difference of the rotor from that in **Figure 4**.

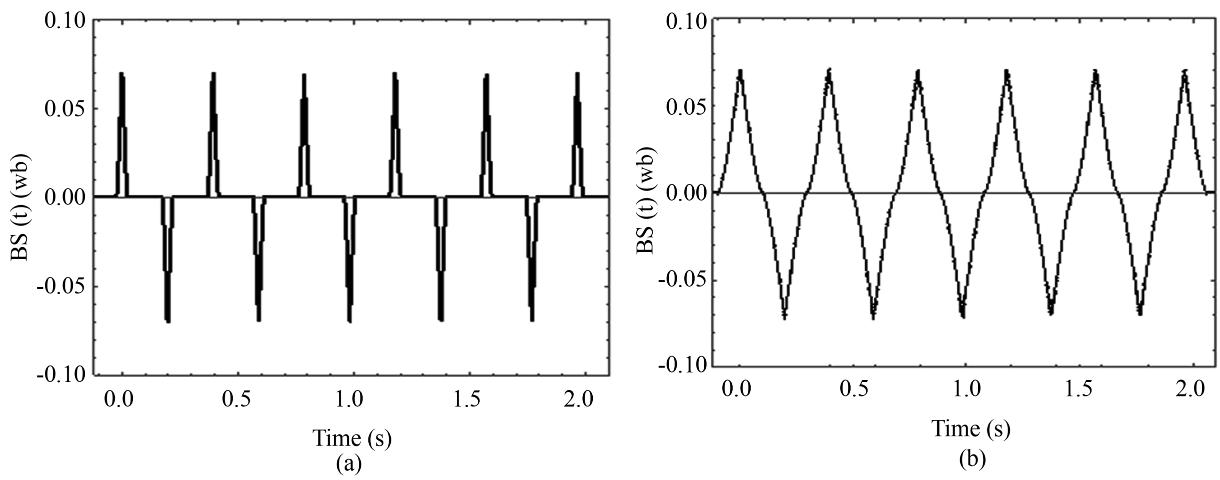


**Figure 10.** The magnetic flux of (a) $\omega = 120(\text{rpm})$ versus (b) $\omega = 30(\text{rpm})$.

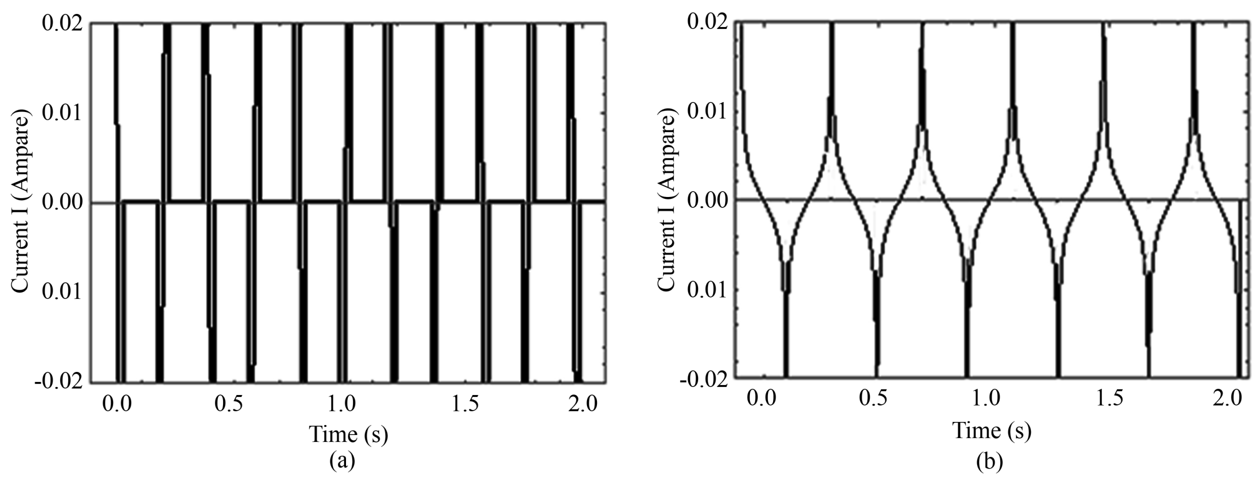


**Figure 11.** The pulse electric current (a) $\omega = 120(\text{rpm})$ versus (b) $\omega = 30(\text{rpm})$.

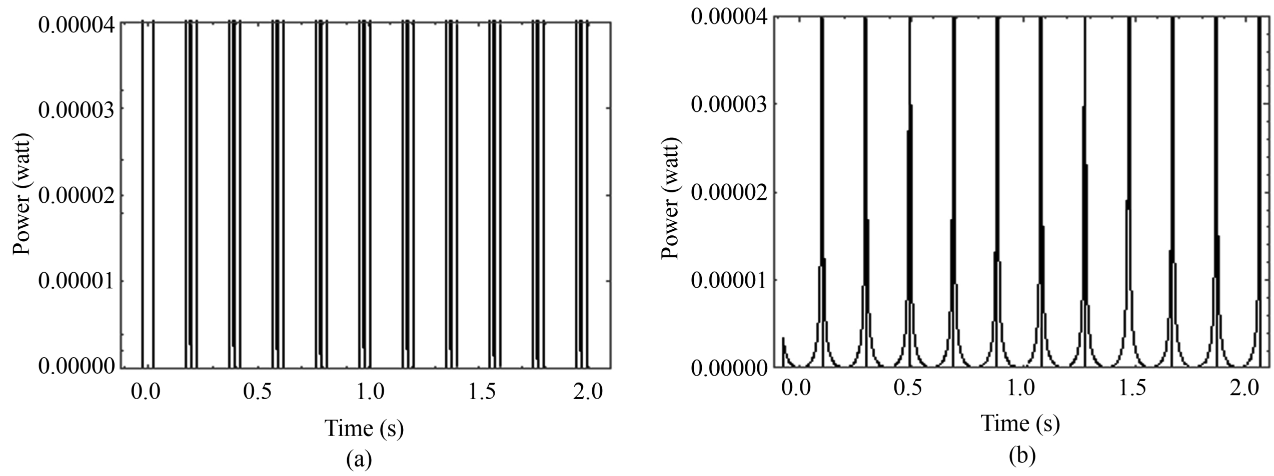


**Figure 12.** The electric power of (a) $\omega = 120(\text{rpm})$ versus (b) $\omega = 30(\text{rpm})$.

The change of magnetic fluxes in **Figure 10** produces the pulse electric current similar to an alternating pulse current when the angular velocity changes from $\omega = 120(\text{rpm})$ to $\omega = 30(\text{rpm})$, as shown in **Figure 11**. The result shows an important property that DM-EMI technique is suitable for a low temperature or a low heat-energy thermoelectric energy conversion. This is the reason why DM-EMI technique is appropriate for resolving environmental energy problems as one of energy harvesting technologies (EHTs). In **Figure 12**, the electric powers of $\omega = 120(\text{rpm})$ to $\omega = 30(\text{rpm})$ are shown. It indicates that the energy conversion at low energy or a low temperature would become better in DM-EMI method. In other words, the restoration of the electric power even at low energy or low temperature seems to become better in DM-EMI method. The results also indicate that an optimal angular speed for restoring electric energy would exist, resulting in maximum pulses of electric currents and powers, which should be experimentally checked with physical parameters of a specific thermoelectric conversion system.

## 5. DM-EMI Electric Generator in Terms of Radial and Axial Magnetic Flux Lines

The technique of DM-EMI is classified as the axial flux electric generator (AFEG), which can be clearly categorized in terms of the radial magnetic flux (RMF) and the axial magnetic flux (AMF) lines. The radial magnetic flux line has been used in traditional motors, and the magnetic flux is perpendicular to the axis of rotation, whereas the axial magnetic flux line is parallel to the axis of rotation. The motors and generators of AMF are relatively new technologies, which are enabled by the development of strong permanent magnets and the research on brushless DC motors [11] [12]. However, since AMF devices are typically much wider than RMF devices, it is known in engineering that there could be some drawbacks in AMF devices, causing increased rotational inertia and centrifugal forces, reducing the maximum rotational speed.

AMF technology has been actively developed as brushless DC motors and applied to aviation and vehicle systems, wind turbines [13] [14] [15] and buoyancy generators [16]. The advantages of AMF structure are that it can be built on flat structure made of materials like PCB, and additions of coils, magnets, bearings, and coil winding processes can be significantly simple. The rotors and stators could be made lighter, but they are typically considered to constitute much wider devices in AMF applications, causing increased rotational inertia and reducing the maximum rotational speed. However, as discussed in the current paper, the disadvantage can be switched to advantage by DM-EMI energy converters, applicable from low-temperature hot water (room temperature < $T$ < 100˚C) to high temperature (100˚C < $T$) heat sources.

The development of the current DM-EMI as an electric generator started from thermodynamic analysis of a water drinking bird [9] [10]. The thermodynamic analysis guided us to a new approach to nonequilibrium irreversible thermodynamics, and in the process of theoretical analysis, it produced DM-EMI technique for EHT of heat-electricity conversions. The rational energy conversion technique developed from thermodynamics of a water drinking bird is useful for activating low-temperature heat-energy and applicable to technologies in order to resolve environmental waste heat-energy problems.

The results shown in the numerical simulations of DM-EMI technique should be studied quantitatively by experimental demonstrations and applied to direct mechanoelectric energy conversions, such as wind turbine systems, heat engines, even to coal-fired plants, heat-energy conversions of decommissioned nuclear plants. DM-EMI technique is applicable to the concept of *a combined cycle power plant*, which is an assembly of heat engines to improve overall thermal efficiency by combining thermodynamic cycles from the same source of heat. The sensitive energy-conversion technique derived from a water drinking bird would provide us with important ideas as a waste heat recovery exchanger.

## 6. Discussions and Perspectives

The dynamics of a drinking bird and a Stirling engine integrates a very sensitive physical problem of the theory of irreversible thermodynamics with technologies of thermoelectric energy conversions. It helps us understand thermomechanical phenomena in terms of energy and work, heat-flow or entropy-flow, producing applicable and testable ideas for heat engines. Thermodynamics of heat engines suggests that energy can be more efficiently produced and used so that the waste of energy should be dramatically decreased. The mechanics of a drinking bird as one of heat engines are applied to EHT technologies. It is helpful to advance our energy productions and consumptions suitable for more energy-efficient ecosystems. The DM-EMI technique has been developed from thermomechanical analyses of a water drinking bird [8] [9] [10], which would be one of efficient devices for low-temperature thermoelectric energy conversions. It could be also applied to wide ranges of temperature difference by improving the DM-EMI technique. We are working on the application of DM-EMI technique to macroscopic energy generators (MEGs).

Energy efficiencies of a drinking bird and a Stirling engine may be compared to those of plants and animals, such as photosynthesis of mitochondria, adenosine triphosphate (ATP), *etc*., as a source of heat and electric energy conversion system employed by biochemical processes. When a concept of heat engines is generalized, the power conversion systems such as wind, coal-fired plants, even nuclear power stations could be understood from the power conversion systems of sensitive mitochondria and biophysical phenomena. The perceptive examinations between mechanical and biological systems in terms of thermomechanical dynamics may help examine and improve the concept of transport engines.

The electrical engineering that deals with the generation, transmission, distribution, and utilization of electric power and apparatus is called the *power engineering* field. The axial flux motors as well as the radial flux motors are actively evolving, and as shown in the paper, the axial flux generators are newly evolving for one of EHTs in the 21st century. The heat-energy productions are essential for the prosperity of human societies. However, the waste heat energy is massively discarded and dissipated from ironworks, metalworking and ceramic factories, watercraft and cement industries. Sustainable energy for human societies demands to resolve environmental problems caused by energy consumptions, and it is desirable that low- or high-temperature waste heat should be activated and reused as much as possible to support ecological systems on Earth. Therefore, cost-effective thermal energy generation, storages, transmission and utilization must be achieved in widely different power engineering fields.

The sensitive heat engines have guided us to the idea of a direct mechanoelectric conversion technique, which should be applied to mechanical rotation and heat transport systems. The generalization of disk-magnet electromagnetic induction, 4DM-EMI, 8DM-EMI, …, axial magnetic disk, would contribute to practical applications for energy harvesting technologies in the near future. In addition, it is imperative to improve DM-EMI structure with a porous ultralight material, such as *aerogel* which is a solid with extremely low density and extremely low thermal conductivity [17], by employing together with high thermal conductivity materials (aluminum alloys…). The rectification and energy storage of pulse power should be developed [18] for efficient use of DM-EMIs. Thermal machines with DM-EMI and technologies in the fields of Stirling engines, Stirling coolers [19], pulse-tube-refrigerators [20], thermoacoustic engines [21], and so forth, should be developed to support the renewable and sustainable ecological society.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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